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Improving Water Use Efficiency by Optimizing the Root Distribution Patterns under Varying Drip Emitter Density and Drought Stress for Cherry Tomato

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Abstract: The spatial distribution of root systems in the soil has major impacts on soil water and nutrient uptake and ultimately crop yield. This research aimed to optimize the root distribution patterns, growth, and yield of cherry tomato by using a number of emitters per plant. A randomized complete block design technique was adopted by selecting eight treatments with two irrigation regimes and four levels of emitters under greenhouse conditions. The experiment results showed that the root distribution extended over the entire pot horizontally and shifted vertically upwards with increased emitter density. The deficit irrigation resulted in reduced horizontal root extension and shifted the root concentrations deeper. Notably, tomato plants with two emitters per plant and deficit irrigation treatment showed an optimal root distribution compared to the other treatments, showing wider and deeper dispersion measurements and higher root length density and root weight density through the soil with the highest benefit–cost ratio (1.3 and 1.1 cm cm^{-3}, 89.8 and 77.7 µg cm^{-3}, and 4.20 and 4.24 during spring–summer and fall-winter cropping seasons, respectively). The increases in yield and water use efficiency (due to increased yield) were 19% and 18.8%, respectively, for spring–summer cropping season and 11.5% and 11.8%, respectively, for fall–winter cropping season, with two emitters per plant over a single emitter. The decrease in yield was 5.3% and 4%, and increase in water use efficiency (due to deficit irrigation) was 26.2% and 27.9% for spring-summer and fall-winter cropping seasons, respectively, by deficit irrigation over full irrigation. Moreover, it was observed that two, three, and four emitters per plant had no significant effects on yield and water use efficiency. Thus, it was concluded that two emitters per plant with deficit irrigation is optimum under greenhouse conditions for the cultivation of potted cherry tomatoes, considering the root morphology, root distribution, dry matter production, yield, water use efficiency, and economic analysis.

Keywords: root morphology; root length density; root weight density; root-shoot relationships; water use efficiency; benefit-cost ratio; greenhouse

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1. Introduction

Food demands are estimated to be doubled globally by 2050 due to the rapid increase in the population [1]. However, water resource availability has been further limited by changing climate, particularly in areas that favor good food production [2–4]. Therefore, water use efficiency (WUE) improvement has been a primary research topic related to sustainable agricultural production and agricultural-ecological balance [5,6]. Tomato (*Solanum lycopersicum* L.) is an important crop and can be found across the entire world for its nutritional value [7]. Studies have reported various biological and environmental conditions that can profoundly affect their production [8]. The soil water status and soil nutritional status are the most critical abiotic factors that can significantly affect the tomato vegetative and reproductive state. The effects of water and nutritional status have been studied in a series of experiments [9,10].

In addition, the leading irrigation technique with the most effective use of available water in irrigated agriculture is drip irrigation. To date, several research studies have been published on the superiority of drip irrigation over other techniques. However, attempts are still being made to search for new and more successful methods. Compared to drip irrigation, water pillow irrigation resulted in better yield, fruit quality, and WUE [11]. In other studies [12,13], water deficit irrigation was extensively studied to save water and thereby boost WUE, especially for the cultivation of several horticultural crops.

It has been found that soil water increases the accessibility of nutrients and that nutrients increase root growth and crop productivity [14]. The key root morphological features that directly influence the entire root system and indirectly influence the above-ground plant components are the root diameter, root surface area, root length density, and root weight density [15,16]. As we know, crop roots are an essential organ for the uptake of nutrients and water and have a crucial role in the ecosystem of plants and soils [17–19]. Besides, the interactions between soil moisture and crop rooting systems have thus been more intensively studied in recent times. Water scarcity reduces nutrient absorption and restricts root growth and distribution [20,21]. Previous research has shown that water conditions in surplus or deficit could alter the magnitude and distribution of maize root-zones, thus restricting root development [22]. As per spatial distribution of root, the root water uptake is spread over the root zone and regulated by climate demand and the spatial distribution of the availability of soil moisture and root density [23,24]. In relation to soil water's diverse distribution, root development and architecture show significant plasticity during the vegetative growth phase [25] and the final stage [26,27].

Just one side of the root zone is activated by drip irrigation. However, the soil hydraulic conductivity, soil texture, soil structure, and flow rate of the emitter affect the shape and extent of the wetting region formed by the drip emitter [28,29]. Despite these variables, the distribution of soil moisture and, in response, root morphology, root distribution, and root water uptake can also be influenced by the number of water emission points on the soil surface. Since moisture under many irrigation points is more readily accessible to roots, it may be attributed to reduced soil moisture stress. By reducing drought stress, a large root system supports the crops [30]. A study [31] has reported that moisture stress can suppress root morphology and plays a major role in root growth. Another study found that the emitter location can strongly affect the water and salt distribution in the substrate [32]. In addition, Valdés, R et al. revealed that compared to the use of one emitter, the use of multiple emitters per pot increased both the quantity and homogeneity of substrate water in gerbera grown in pots [33]. However, irrigation water quantity and multiple emitters per plant significantly affected the total volume of water applied, as well as root and shoot development in weeping fig [34]. The lower the emitter spacing, the higher the soil moisture distribution and uniformity and WUE and crop yield in drip irrigation systems [35]. Based on the review study, several studies concluded that much information is available on how the tomato root system responds to an irrigation system, irrigation scheduling, and fertilizer management to control tomato fruit yield and quality characteristics [10,36–38]. However, the effects of the emitter density (number of emitters per plant) and irrigation levels on the root distribution and root morphology concerning shoot morphology for cherry tomato crops are yet to be known.

Therefore, in this study, the emitter density under the drip system combined with full and deficit irrigation levels were considered to study the response of cherry tomato cultivated under greenhouse conditions. Moreover, the main objectives of the study were (i) to examine the effects of single and multiple emitters per plant drip irrigation under normal and water-deficit conditions on cherry tomato root morphology and distribution and (ii) to assess the relations between root and shoot morphology and yield for tomato plants. The overall research findings provide a baseline for managing water for cherry tomato production under greenhouse environments.

2. Materials and Methods

2.1. Site Description

The trials were performed as a spring-summer cropping season (SS) and fall-winter cropping season (FW) from 13 March to 14 July 2019 and from 2 September to 31 December 2019, respectively, at a Venlo-type greenhouse located in Zhenjiang City, Jiangsu Province, China (31°56′ N, 119°10′ E). The study region was located in a humid subtropical monsoon climate zone with relative humidity, mean annual air temperature, and average annual rainfall of 76%, 15.5 °C, and 1058.8 mm, respectively [39]. The experimental area's soil was clay loam with a sand, silt, and clay particle distribution of 34%, 23%, and 43%, respectively. Furthermore, the soil had a bulk density, field capacity, and organic matter of 1.31 g cm^{-3}, 0.36 cm^3 cm^{-3}, and 31.23 g kg^{-1}, respectively. On 13 March and 2 September 2019, a 30-day-old seedling with firm roots of cherry tomato ('Fenxiaoke xt-12020') was transplanted to SS and FW, respectively, with a plant density of 3.84 m^{-2}. Moreover, the climatic data for both seasons are presented in Table 1. As can be seen in Table 1, the means of T and RH during SS (from 13 March to 14 July) equaled 23.66 °C and 70%, while during FW (from 2 September to 31 December), the averages were 18.66 °C and 73.5%, respectively.

Table 1. Air temperature and relative humidity observed for both cropping seasons.

Month	March	April	May	June	July	Sep	Oct	Nov	Dec
Mean temperature (°C)	18.25	21.04	23.80	27.22	27.43	26.58	21.77	16.62	10.12
Relative humidity (%)	60.58	66.90	75.95	72.13	70.72	60.73	70.68	78.48	83.57

2.2. Experimental Design

In this study, a total of eight treatments, including irrigation with 1, 2, 3, and 4 emitters per plant (N1, N2, N3, and N4) under full and deficit irrigation (W1; 100% and W2; 75% crop evapotranspiration) using drip irrigation, were selected as test-influencing factors. The emitters placement was as follows: one, two, three, and four emitters per plant were installed in the northwest, northwest, and southeast, one emitter in the northwest and two emitters at an angle of 120° from each other, and in the northeast, northwest, southeast, and southwest quadrants for N1, N2, N3, and N4, respectively. However, the location of the emitters was random and not concerned with the direction of the sun. All emitters were spaced evenly and were located at a radius of 9 cm from the plant, roughly halfway between the plant and pot borders. Moreover, the experimental design for both seasons was 2 factorial factors under a randomized complete block design (RCBD) with 4 replications. The plastic pots (diameter, 40 cm and height, 40 cm) were filled with 57 kg (43,960 cm^3) of air-dried soil per pot for cultivation practice. The used soil was first passed through a 5 mm mesh sieve, and the soil depth in the pots was maintained up to a height of 35 cm to accommodate the roots of tomato plants, following the recommendation of [10], which found that the 0 to 15 cm depth of the surface soil layer consists of tomato root length density (RLD) of up to 70–75% of the whole RLD for the surface drip irrigation system. The plant-to-plant and row-to-row distances were 80 and 25 cm, respectively. To prevent waterlogging in lower soil, all the pots were positioned on a gravel/sand mixture with a height of 3 to 5 cm. The fertigation was carried out as per local tradition. As nitrogen, phosphorus, and potassium sources, urea (46% nitrogen), triple superphosphate (46% P_2O_5), and muriate of potash (60% K_2O) were used, respectively. Additionally, at the beginning of the experiment, 40% of nitrogen and both phosphorus and potassium were added and blended into the soil in powdered forms. Two portions of the remaining 60% nitrogen were provided: 30% each in the first week of fruit emergence and in the first week of fruit ripening. The stages of crop growth were reported as DAT (days after transplantation). The plants were pruned on a weekly basis.

2.3. Sampling and Measurement

2.3.1. Irrigation and Crop Evapotranspiration

Irrigation was practiced at 8:00, when 20 mm of accumulative pan (20 cm diameter) evaporation (Ep) was achieved [40]. Adjustable flow rate emitters (with increased emitters per plant, the flow rate of emitter decreases to maintain the same irrigation period) were used to produce a uniform amount of water per plant. Before the experiment, the emitters were evaluated for flow rate uniformity. Under each treatment, the irrigation supplied to all pots was regulated using a water flow meter installed at the control unit.

The weight-based water balance equation [41,42] was used to calculate crop evapotranspiration ($ET_{c(CR)}$) by means of a ± 1 g weighing indicator for the control treatment (N1W1, single emitter per plants with 100% crop evapotranspiration). In the control treatment, $ET_{c(CR)}$ was assumed to be the normal water volume applied for the next irrigation, as no drainage was recorded after irrigation, so water applied for irrigation was taken equal to water loss in crop evapotranspiration. Because of the minimum rise between two consecutive waterings, the mass increase was overlooked. In accordance with the allocated proportion of the $ET_{c(CR)}$, the plants with deficit irrigation were irrigated.

2.3.2. Shoot Morphology, Yield, Water Use Efficiency, and Plant Dry Matter

Plant height (cm) (before the main tip) was measured using steel tape (1 mm). Plant stem diameter (mm) was measured using a digital vernier caliper (0.01 mm). The whole plant fruits were counted and weighed (g) using an electric weight balance (0.01 g). Moreover, for all treatments, the overall applied water (l) and tomato fruit yield (kg $plant^{-1}$) were reported at the end of the experiment. Fresh cherry tomato fruit matter was divided by the amount of water used to calculate water use efficiency (kg m^{-3}).

Plants were removed from all pots under each treatment at the end of the season, and the roots, stems, leaves, and fruits were collected separately. The samples were dried to achieve dry matter using an oven at 70 °C for each unit until a constant weight (g) was attained, and the precision indicator (0.0001 g) was finally used to obtain the dry matter.

2.3.3. Root Sampling and Morphological Characteristics

At the end of the cropping season, the entire soil column in the vertical direction (Z-axis) was divided into 5 layers, each with a thickness of 7 cm (Figure 1). Each 7 cm layer was cut into 7 × 7 cm small grids along X and Y axes (X and Y axes were taken along east–west and north-south directions, respectively). Each layer of 7 cm depth was divided into 25 grids of identical shape ($7 \times 7 \times 7$ cm = 343 cm^3), making a total of 125 grids (sampling units) per pot. The samples, symmetrically, were added up along the Y-axis (up to 35 cm) for horizontal root distribution and along the Z-axis (up to 35 cm) for vertical root distribution. The error caused by the reduced soil volume for the four boundary grids (lying partially out of the pot) and unconsidered soil volume at the 4 sides of the pot for each layer was neglected. The soil was cut horizontally and vertically with a sharp blade (Figure 2). To soften the root samples with soil, they were immersed in water for 30 min. The roots were separated from the soil very carefully using water. The roots with diameter < 2 mm only were scanned (because these roots were mainly responsible for soil water uptake [36]) using an Epson Perfection V700 photo flatbed scanner, and then WinRhizo software (Regent Instruments Inc., Quebec, QC, Canada) was used to get root length, root average diameter, root surface area, and root volume from the scanned root images. After that, root length density (RLD, root length/soil volume, cm cm^{-3}) and root weight density (RWD, root dry matter/soil volume, µg cm^{-3}) were calculated.

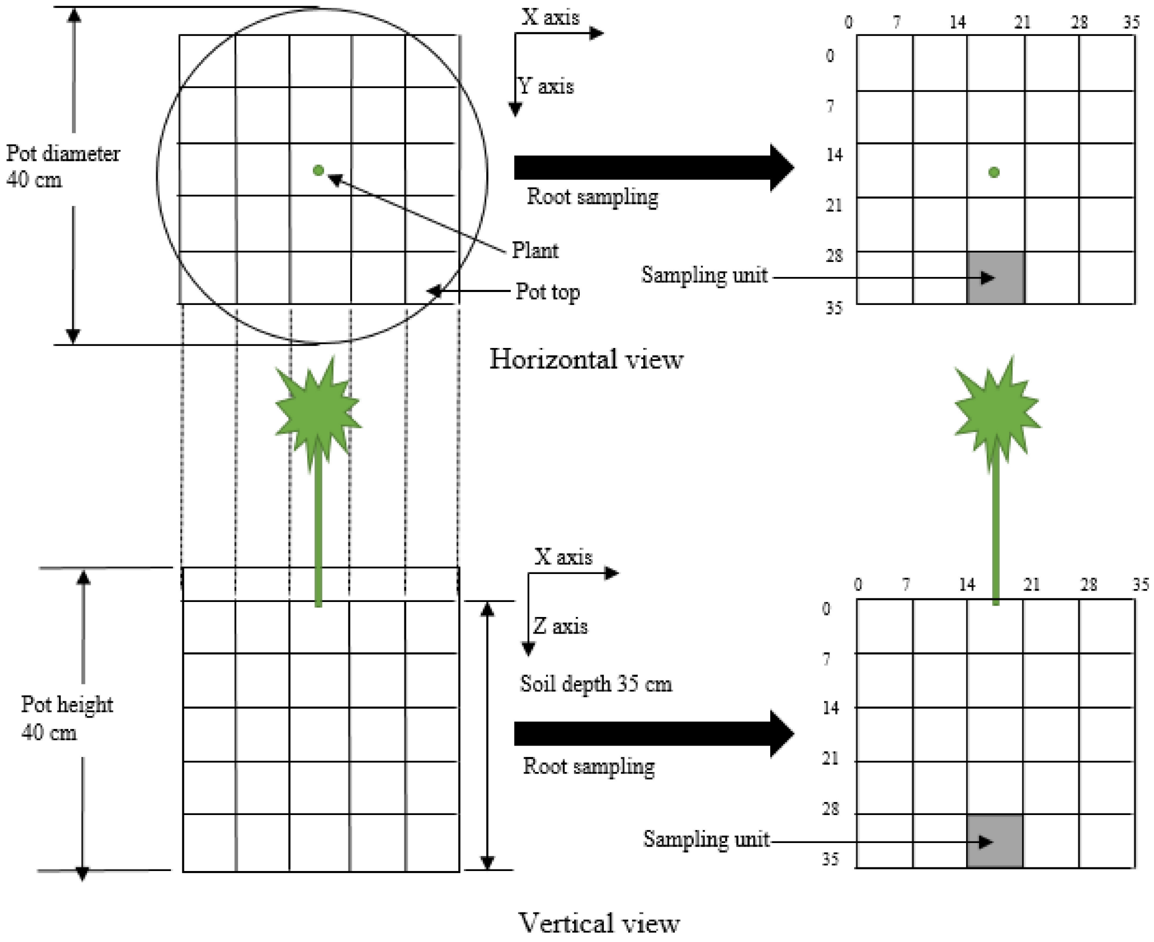


Figure 1. Diagram of a soil pot and root sampling method.

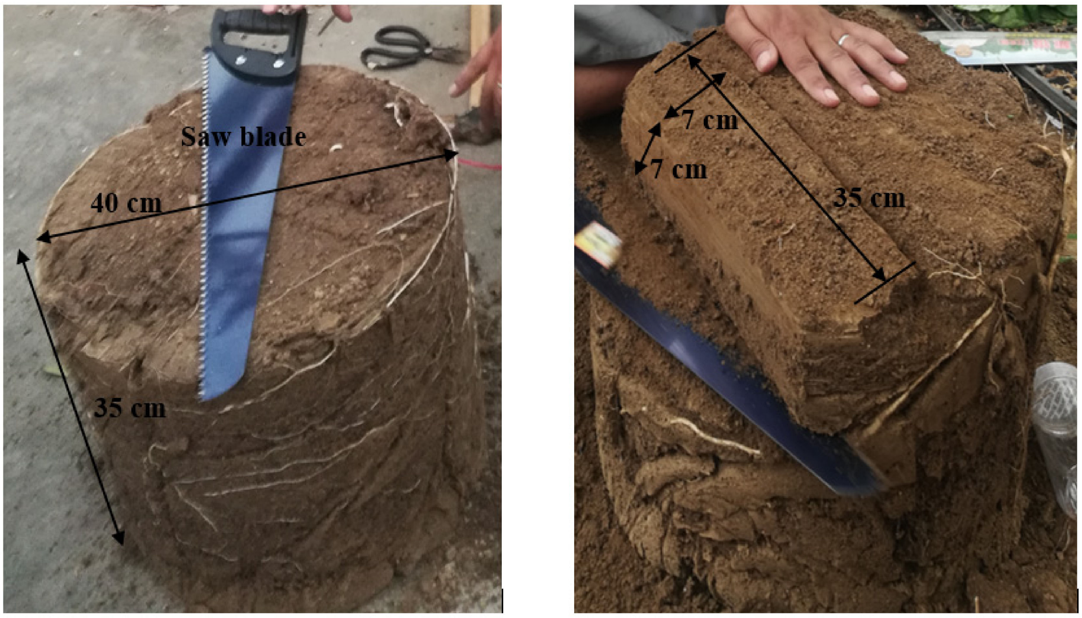


Figure 2. Soil ball and cutting soil ball into 7 × 7 × 7 cm^3 sample grids.

2.3.4. Economic Optimization

To quantify the net benefits that each treatment produced, an economic analysis was carried out. The net benefits were measured as the difference between the overall costs of production and the total benefits per plant. Cherry tomato production costs ($ plant^{-1}) include system costs (emitters, the small pipe connecting the emitter and lateral joints, lateral joint, and arrow for emitter fixation, as these components vary with varying emitter density) and running costs (water cost, electricity cost, labor cost). Total benefits ($ plant^{-1}) were calculated by the product of the average market price ($ kg^{-1}) and yield (kg plant^{-1}). Finally, total benefits divided by total costs were calculated as the benefit-cost ratio.

2.4. Statistical Analyses

Taking season, emitter density, and irrigation level as fixed effects and including two-way (for an individual season) and three-way (to account for seasonal effect) interactions, the analysis of variance was carried out using the general linear model (GLM) in the SPSS 16.0 software (SPSS Inc., Chicago, IL, USA). The means were separated at $p < 0.05$ by the least significant difference test. Graphical representation was done using Origin Pro 2018 software (OriginLab Corporation, Northampton, MA, USA).

3. Results

3.1. Root Morphology

Figure 3 shows the effects of the emitter density, irrigation level, and cropping season on the root morphology. As can be seen from Figure 3, the seasonal effects were significant on all responses. However, there were significant individual effects of the emitter density and irrigation level on root length, root surface area, root volume, root length density, and root weight density, and non-significant effects on both SS's root average diameter and FW (except irrigation level effect that was significant for SS only). The SS caused an increase in root length, root surface area, root volume, root length density, and root weight density of 21.6%, 13.9%, 6.8%, 21.6%, and 15%, respectively, and a decrease of 3.3% in root average diameter compared to FW. All the root morphological responses were increased with increasing the emitter density and decreased with decreasing the irrigation levels except root average diameter, which was vice versa. Moreover, the treatments N4W1 and N1W2 produced the highest and lowest values in both seasons for all parameters except root average diameter, for which maximum and minimum was against N1W2 and N4W1, respectively.

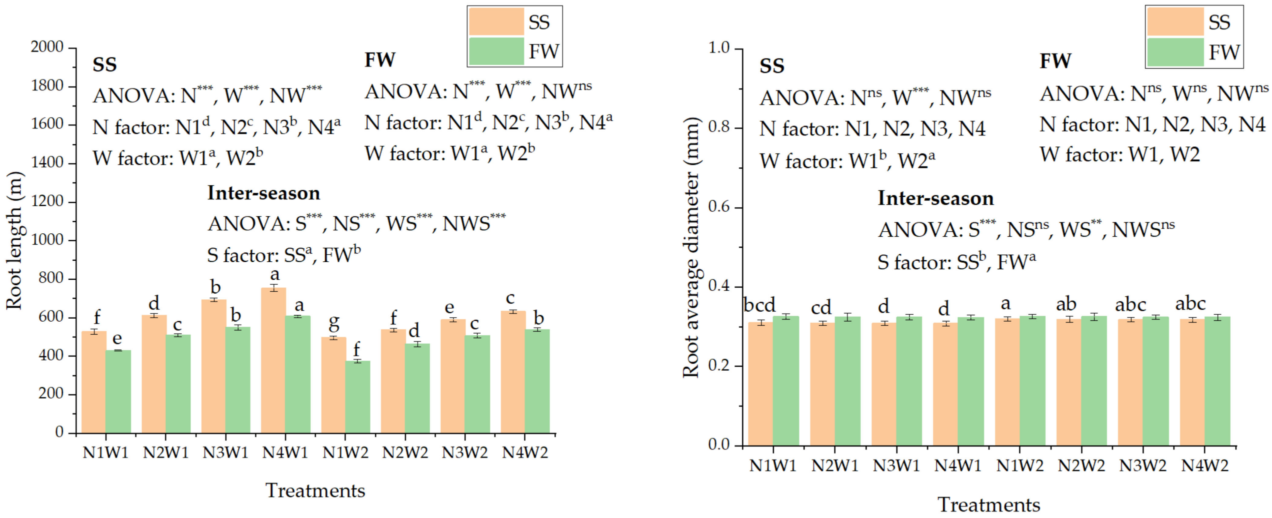


Figure 3. *Cont.*

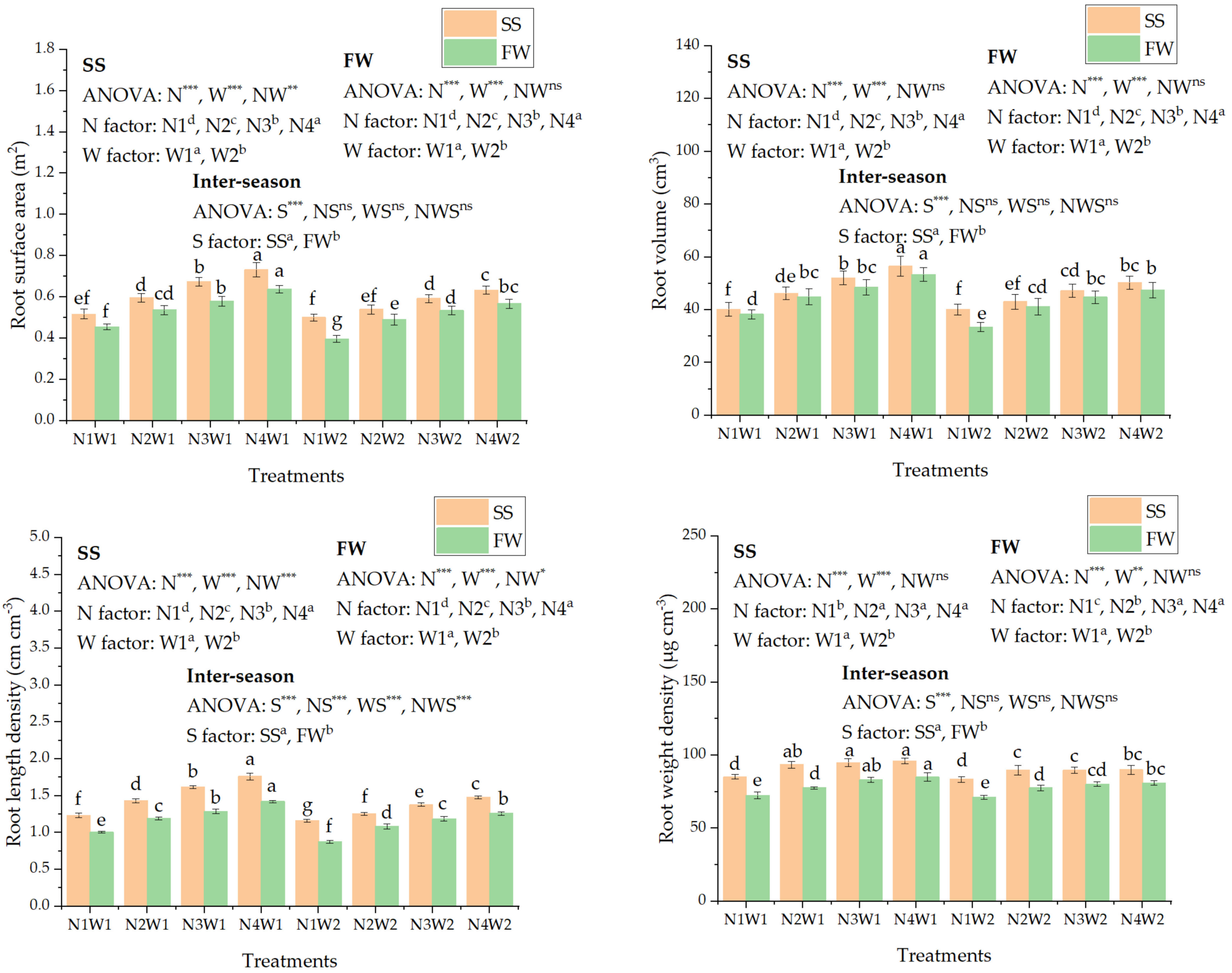
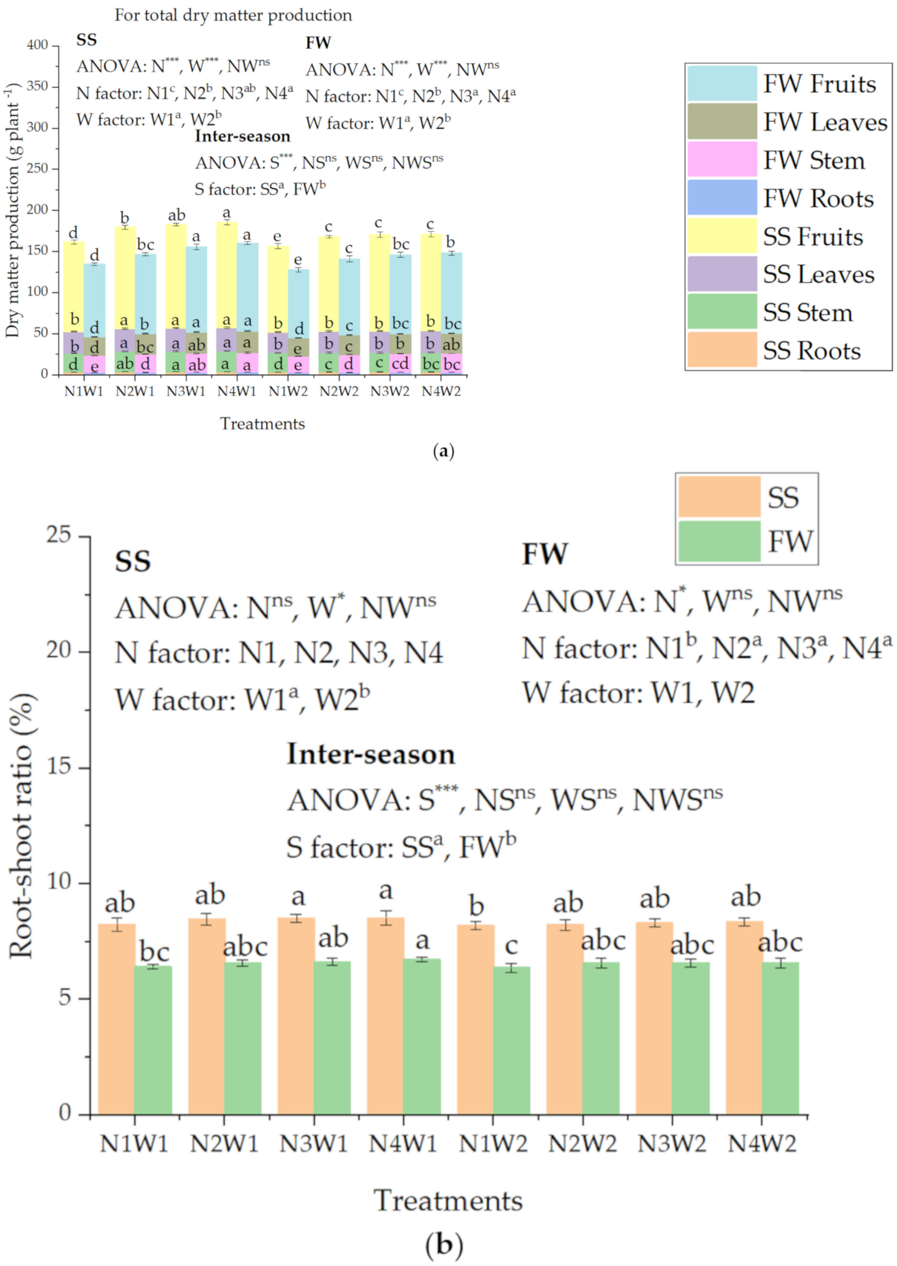


Figure 3. Effects of emitter density, irrigation level, and season on root morphology for both spring–summer (SS) and fall-winter (FW). N1, N2, N3, N4, W1, W2, SS, and FW: one emitter per plant, two emitters per plant, three emitters per plant, four emitters per plant, full irrigation, deficit irrigation, spring–summer cropping season, and fall-winter cropping season, respectively. *, ** and ***, ns; significant at $p < 0.05$, significant at $p < 0.01$, significant at $p < 0.001$, and non-significant at $p > 0.05$. Values that are followed by different letters within the same columns differ significantly at $p < 0.05$. Data are given in means ± standard deviations ($n = 4$) shown by vertical bars.

3.2. Plant Dry Matter Production

Figure 4 shows the effects of the emitter density, irrigation level, and season on cherry tomato plant dry matter production and root/shoot ratio. The experiment results in Figure 4 indicated that the SS resulted in more dry matter components (15%, 8.6%, 10%, 23.2%, and 18.6% more dry root, dry stem, dry leaves, dry fruit, and total dry matter, respectively) and root/shoot ratio (27.4%) than FW. The order of significance of responses for the treatment factors was S > N > W. The total and components of dry matter and root/shoot ratio increased with the increasing emitter density and decreased with deficit irrigation. However, N4W1 and N1W2 produced the highest (185.9 and 160.4 g total dry matter and 8.5 and 6.7% root/shoot ratio for SS and FW, respectively) and lowest (82.5 and 156.7 g total dry matter and 8.2 and 6.4% root/shoot ratio for SS and FW, respectively) values, respectively. Further, the root/shoot ratio was mainly affected by season.



(**a**)

(**b**)

Figure 4. Effects of emitter density, irrigation level, and season on (**a**) dry matter production and (**b**) root/shoot ratio (root dry matter/(stem and leaves dry matter × 100, %) for both SS and FW. N1, N2, N3, N4, W1, W2, SS, and FW; one emitter per plant, two emitters per plant, three emitters per plant, four emitters per plant, full irrigation, deficit irrigation, spring-summer cropping season, and fall-winter cropping season, respectively. *, ***, ns: significant at $p < 0.05$, significant at $p < 0.001$, and non-significant at $p > 0.05$. Values that are followed by different letters within the same columns differ significantly at $p < 0.05$. Data were given in means ± standard deviations ($n = 4$) shown by vertical bars.

3.3. Root Distributions

Figures 5–8 show the isogram distributions of tomato root length density (RLD) distribution and root weight density (RWD) distribution both horizontally and vertically. Both emitter density and irrigation level had significant effects on the spatial distributions of cherry tomato RLD and RWD. The RLD and RWD distributions are shown for FW only because both seasons resulted in similar distribution patterns. The distributions expanded horizontally and focused greatly on the surface soil layer with increasing the emitter density due to improved root growth. For both the RWD and RLD, deficit irrigation led to smaller (horizontally) and deeper (vertically) concentration areas. Considering the emitter density (N), the average RLD and RWD were 1.1 cm cm^{-3} and 77.5 µg cm^{-3}, respectively, in W2 treatment, which were 10.6% and 3.8% lower compared to W1 treatment (1.2 cm cm^{-3} and 79.6 µg cm^{-3}), respectively. In comparison with the W factor, the N factor had more significant influences on the horizontal and vertical distribution of RLD and RWD, and root distribution responses varied with water levels (Figures 5–8). In the N1 treatments, both RLD and RWD concentration areas showed eccentricity horizontally (Figures 5 and 7) and dense and deeper extension vertically towards the emitter's region (Figures 6 and 8). This indicated that the tomato root system generated narrower and deeper distributions with steeper growth angles under the N1 conditions than multiple emitters per plant. Unlike horizontally, it was shown that the shape of RLD and RWD distributions showed negligible differences vertically among N2, N3, and N4 under both W conditions. Therefore, the N2W2 treatment presented an optimal root distribution throughout all N and W treatments, with an average of 1.1 cm cm^{-3} in RLD and 77.7 µg cm^{-3} in RWD, respectively. Its root dispersion range was wider horizontally across the entire pot (Figures 5 and 7) and deeper vertically throughout the soil profile (Figures 6 and 8).

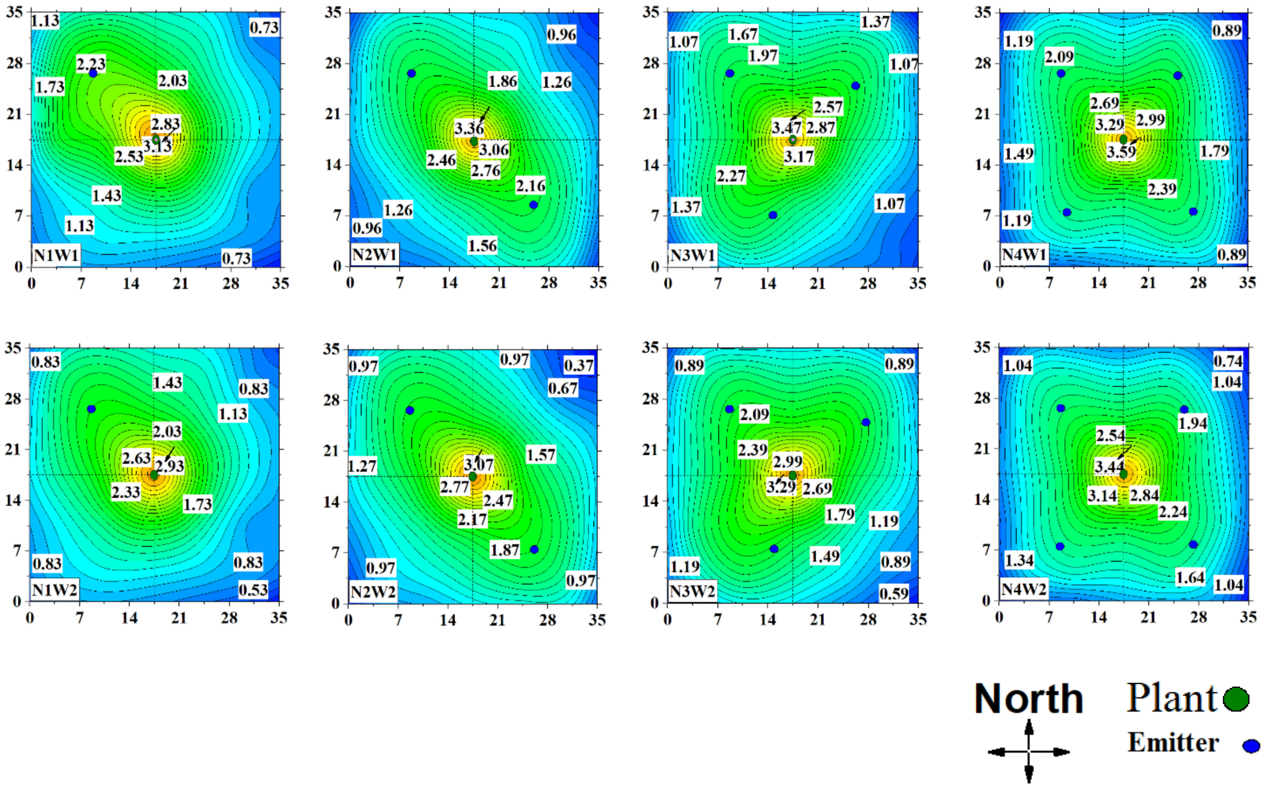


Figure 5. Effects of emitter density and irrigation levels on horizontal root length density (RLD, cm cm^{-3}) distribution for the fall-winter cropping season (at the end of the cropping season; the maximum value is marked by a solid arrow).

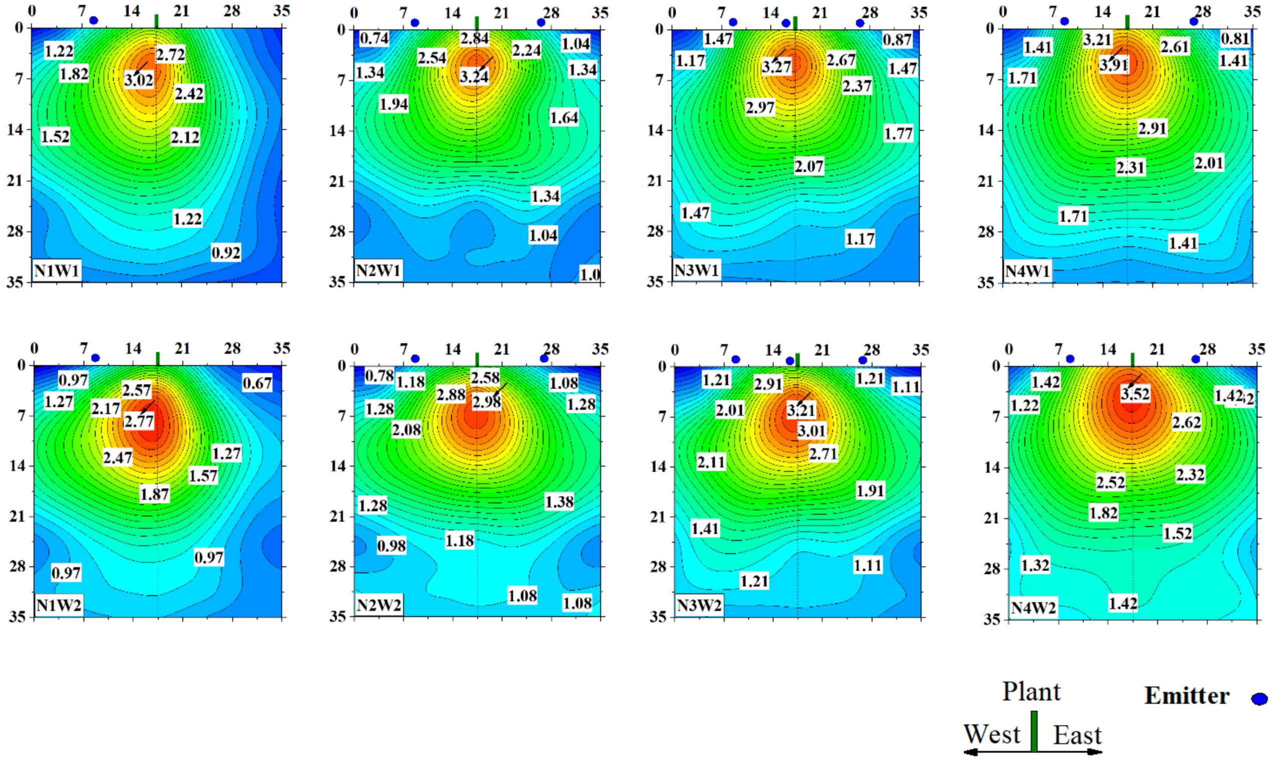


Figure 6. Effects of emitter density and irrigation levels on vertical root length density (RLD, cm cm^{-3}) distribution for the fall-winter cropping season (at the end of the cropping season; the maximum value is marked by a solid arrow).

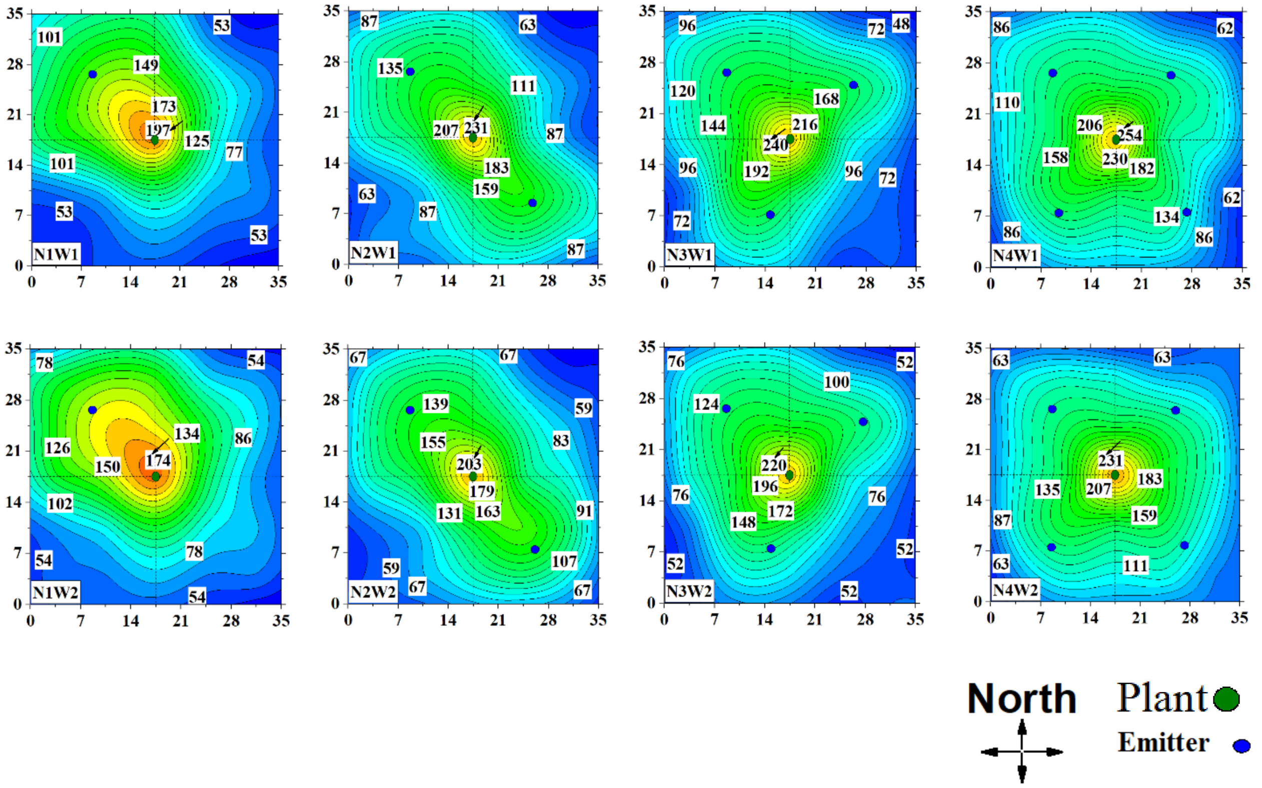


Figure 7. Effects of emitter density and irrigation levels on horizontal, vertical root weight density (RWD, µg cm^{-3}) distribution for the fall-winter cropping season (at the end of the cropping season; the maximum value is marked by a solid arrow).

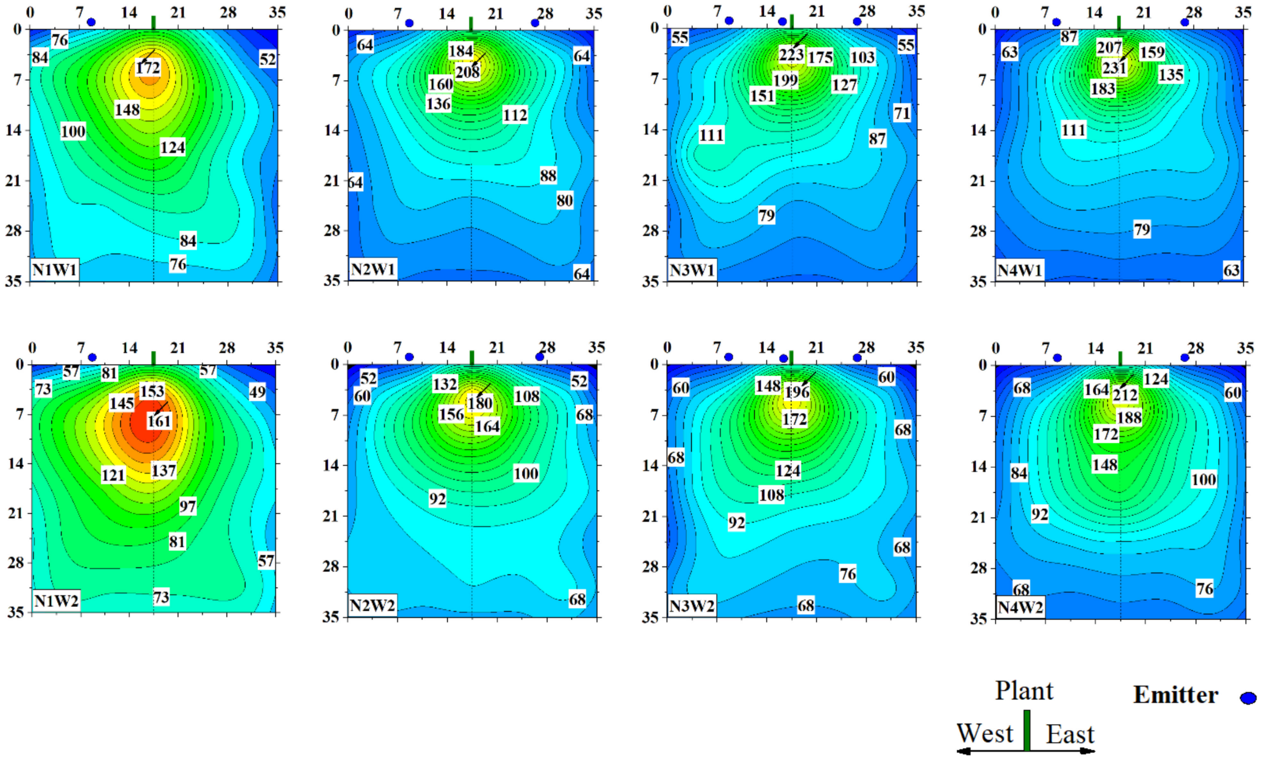


Figure 8. Effects of emitter density and irrigation levels on vertical root weight density (RWD, μg cm^{-3}) distribution for the fall-winter cropping season (at the end of the cropping season; the maximum value is marked by a solid arrow).

3.4. Shoot Morphology and Yield

The two seasons' analyzed results (Figure 9) showed that the SS performed better in terms of plant height (138.8–168.6 cm, 21.5%), stem diameter (7.5–9.1 mm, 21.2%), and yield (1.9–2.4 kg $plant^{-1}$, 25.2%) but reduced water use efficiency (49.6 to 43.3 kg m^{-3}) (WUE) (due to fewer water requirements in FW) (12.7%) than FW. The impact of N4W1 was found to be most significant, and the impact of N1W2 was least significant except for WUE, for which the maximum and minimum were against N4W2 and N1W1, respectively, for both seasons. The N4 and N1 effects were most and least significant on all parameters for both seasons. The increase in yield and WUE (due to increased yield) was 19% (2.0–2.4 kg $plant^{-1}$) and 18.8% (37.5–44.6 kg m^{-3}), respectively, for SS and 11.5% (1.7–1.9 kg $plant^{-1}$) and 11.8% (44.6–49.9 kg m^{-3}), respectively, for FW for N2 over N1. The increase in the corresponding values was similar for multiple emitters per plant over N1. Compared to W1, the decrease in yield was 5.3% (2.4–2.3 kg $plant^{-1}$) and 4% (1.9–1.8 kg $plant^{-1}$), and the increase in WUE (due to deficit irrigation) was 26.2% (38.3–48.3 kg m^{-3}) and 27.9% (43.5–55.7 kg m^{-3}) for SS and FW, respectively, by W2.

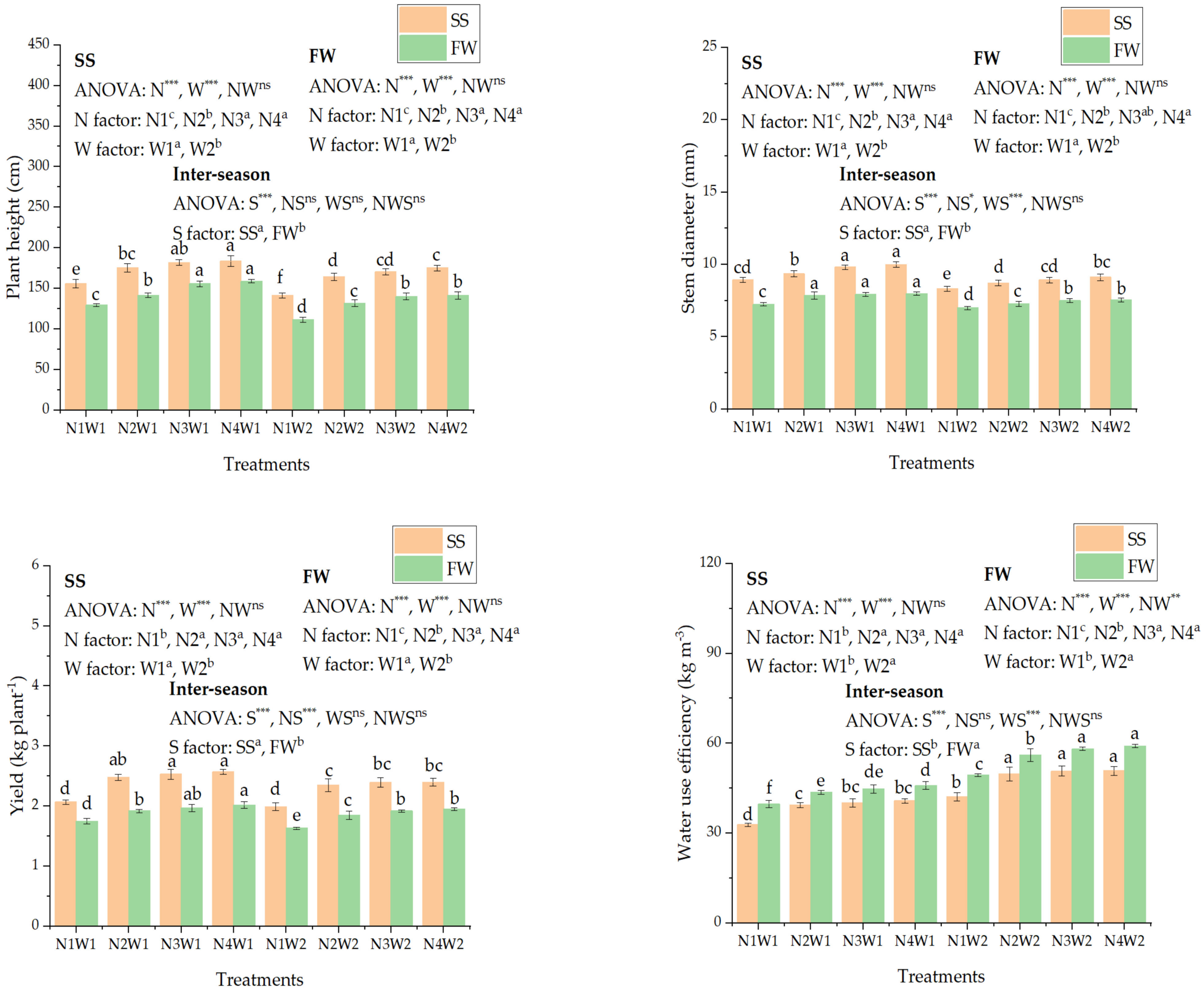


Figure 9. Effects of emitter density, irrigation level, and season on plant height, stem diameter, tomato yield, and water use efficiency for both SS and FW. N1, N2, N3, N4, W1, W2, SS, and FW: one emitter per plant, two emitters per plant, three emitters per plant, four emitters per plant, full irrigation, deficit irrigation, spring-summer cropping season, and fall-winter cropping season, respectively. *, **, ***, ns; significant at $p < 0.05$, significant at $p < 0.01$, significant at $p < 0.001$, and non-significant at $p > 0.05$. Values that are followed by different letters within the same columns differ significantly at $p < 0.05$. Data are given in means ± standard deviations ($n = 4$) shown by vertical bars.

3.5. Relationships between Root Growth, Shoot Growth, and Plant Yield

The relationships for leaf area index, plant height, stem diameter, plant yield, and total dry matter versus root morphological parameters like root length, average root diameter, root surface area, root volume, and root dry matter for both SS and FW are shown in Table 2. All the relationships were significant ($p < 0.001$). There were linear and quadratic relationships within each season, also for inter-season. The R^2 for root average diameter versus above ground parameters was lowest (0.487 (FW)–0.629 (SS)). For the most part, the relationships for root surface area and root volume versus above-ground parameters were quadratic. No relationship was found between the root morphology and WUE.

Table 2. Relationship between root morphology and plant above ground components for both SS and FW (n = 32).

Function	Model	R	R^2	Adj R^2	ANOVA F	Sig.
SS						
The relation between leaf area index and						
Root length	$y = 0.00001x^2 + 0.021x - 5.14$	0.857	0.734	0.720	51.17	0.000
Average root diameter	$y = 129.79x^2 - 49.96x + 6.25$	0.912	0.832	0.823	91.54	0.000
Root surface area	$y = 6.79x - 0.30$	0.948	0.899	0.897	339.76	0.000
Root volume	$y = 0.064x\ 0.59$	0.974	0.949	0.948	708.62	0.000
Root dry matter	$y = 2.83x - 6.95$	0.975	0.950	0.948	716.77	0.000
The relation between plant height and						
Root length	$y = 0.0004x^2 + 0.67x - 89.05$	0.931	0.866	0.859	119.51	0.000
Average root diameter	$y = 613.51x - 34.58$	0.810	0.657	0.648	72.65	0.000
Root surface area	$y = -140.29x^2 + 316.23x + 26.79$	0.964	0.929	0.925	242.38	0.000
Root volume	$y = -0.011x^2 + 2.47x + 71.37$	0.957	0.916	0.911	200.65	0.000
Root dry matter	$y = 52.22x - 33.75$	0.943	0.890	0.887	307.33	0.000
The relation between stem diameter and						
Root length	$y = 0.008x + 4.35$	0.892	0.796	0.790	148.00	0.000
Average root diameter	$y = 30.11x - 0.83$	0.863	0.745	0.738	111.07	0.000
Root surface area	$y = 6.05x + 5.30$	0.962	0.925	0.923	471.58	0.000
Root volume	$y = 0.056x + 6.15$	0.969	0.940	0.938	590.58	0.000
Root dry matter	$y = 2.45x - 0.35$	0.961	0.924	0.921	458.78	0.000
The relation between plant yield and						
Root length	$y = 0.000005x^2 + 0.009x - 1.24$	0.905	0.819	0.809	83.46	0.000
Root average diameter	$y = 8.66x - 0.519$	0.793	0.629	0.619	64.43	0.000
Root surface area	$y = -2.002x^2 + 4.48x + 0.34$	0.939	0.882	0.876	138.93	0.000
Root volume	$y = 0.0002x^2 + 0.035x + 0.97$	0.933	0.871	0.864	125.10	0.000
Root dry matter	$y = 0.754x - 0.574$	0.945	0.893	0.891	318.34	0.000
The relation between total dry matter production and						
Root length	$y = 0.144x + 84.98$	0.872	0.760	.0754	120.25	0.000
Root average diameter	$y = 575.16x - 18.18$	0.885	0.783	0.777	136.80	0.000
Root surface area	$y = -80.16x^2 + 218.28 + 67.42$	0.959	0.919	0.915	210.66	0.000
Root volume	$y = -0.007x^2 + 1.90x + 9172.10$	0.974	0.949	0.946	342.41	0.000
Root dry matter	$y = -10.70x + 47.23$	0.994	0.987	0.987	2917.12	0.000
FW						
The relation between leaf area index and						
Root length	$y = 0.008x - 1.01$	0.879	0.773	0.767	129.30	0.000
Average root diameter	$y = 126.91x^2 - 49.86x + 6.60$	0.889	0.790	0.778	69.45	0.000
Root surface area	$y = 7.18x - 0.33$	0.974	0.949	0.948	711.92	0.000
Root volume	$y = 0.072x + 0.40$	0.993	0.987	0.986	2793.26	0.000
Root dry matter	$y = 0.47x^2 - 0.572x + 0.14$	0.970	0.941	0.938	294.21	0.000
The relation between plant height and						
Root length	$y = 0.214x + 31.96$	0.967	0.934	0.932	539.77	0.000
Average root diameter	$y = 542.17x - 31.45$	0.698	0.487	0.474	36.10	0.000
Root surface area	$y = -106.08x^2 + 271.90x + 31.36$	0.976	0.952	0.949	364.18	0.000
Root volume	$y = -0.014x^2 + 2.75x + 54.44$	0.946	0.894	0.889	156.48	0.000
Root dry matter	$y = 52.44x - 37.80$	0.926	0.858	0.855	230.06	0.000
The relation between stem diameter and						
Root length	$y = 0.007x + 4.27$	0.822	0.676	0.667	79.19	0.000
Average root diameter	$y = 25.99x - 0.62$	0.928	0.860	0.857	234.01	0.000
Root surface area	$y = 5.75x + 4.70$	0.941	0.886	0.882	291.90	0.000
Root volume	$y = 0.0005x^2 + 0.098x + 4.49$	0.980	0.961	0.959	454.17	0.000
Root dry matter	$y = 1.92x + 1.08$	0.941	0.885	0.882	292.36	0.000

Table 2. *Cont.*

Function	Model	R	R^2	Adj R^2	ANOVA F	Sig.
The relation between plant yield and						
Root length	$y = 0.002x + 0.87$	0.892	0.795	0.790	147.55	0.000
Root average diameter	$y = 6.36x - 0.13$	0.813	0.661	0.652	74.07	0.000
Root surface area	$y = -1.44x^2 + 3.085x + 1.17$	0.962	0.925	0.921	229.63	0.000
Root volume	$y = 0.0002x^2 + 0.032x\ 0.92$	0.964	0.930	0.926	244.28	0.000
Root dry matter	$y = 0.54x + 0.04$	0.952	0.907	0.904	369.77	0.000
The relation between total dry matter production and						
Root length	$y = 0.171x\ 59.80$	0.939	0.882	0.879	284.73	0.000
Root average diameter	$y = 521.26x - 18.44$	0.815	0.665	0.656	75.38	0.000
Root surface area	$y = 138.38x + 76.82$	0.993	0.986	0.985	2600.12	0.000
Root volume	$y = -0.01x^2 + 2.20x + 75.79$	0.990	0.980	0.979	918.36	0.000
Root dry matter	$y = 45.90x - 9.33$	0.985	0.971	0.970	1266.11	0.000

3.6. Optimization of the Emitter Density and Irrigation Level

Table 3 shows that the total cost and total benefits increased with an increase in the emitter density and decrease with decreasing irrigation level. For N2, the net benefits and benefit–cost ratio were maximum, there was no significant effect of irrigation level on net income, but the benefit–cost ratio was significantly affected by the level of irrigation and was higher against W2. The optimization of the emitter density and irrigation level based on economic returns was calculated by calculating the benefit–cost ratio. Table 3 shows that the optimized emitter density and irrigation level management strategy is N2W2, giving the highest benefit–cost ratio, 4.20 and 4.24 for SS and FW, respectively.

Table 3. Effects of emitter density, irrigation level, and season on economic analysis for both SS and FW.

Factor	Total Costs ($ Plant^{-1})		Total Benefits ($ Plant^{-1})		Net Benefits ($ Plant^{-1})		Benefit–Cost Ratio (-)	
Season	SS	FW	SS	SS	FW	FW	SS	FW
Emitter density (N)								
N1	1.12	0.85	3.96 ± 0.13b	3.30 ± 0.14c	2.84 ± 0.11c	2.45 ± 0.07c	3.57 ± 0.38b	3.91 ± 0.30a
N2	1.23	0.94	4.71 ± 0.20a	3.68 ± 0.12b	3.48 ± 0.15a	2.74 ± 0.10a	3.88 ± 0.37a	3.94 ± 0.34a
N3	1.44	1.16	4.80 ± 0.20a	3.79 ± 0.09a	3.37 ± 0.15ab	2.63 ± 0.09b	3.36 ± 0.24c	3.29 ± 0.24b
N4	1.54	1.26	4.85 ± 0.21a	3.87 ± 0.11a	3.31 ± 0.11b	2.61 ± 0.08b	3.17 ± 0.18d	3.08 ± 0.19c
Irrigation level (W)								
W1	1.46	1.14	4.70 ± 0.42a	3.73 ± 0.22a	3.25 ± 0.30a	2.59 ± 0.12a	3.24 ± 0.21b	3.31 ± 0.34b
W2	1.20	0.96	4.45 ± 0.37b	3.58 ± 0.26b	3.25 ± 0.27a	2.62 ± 0.15a	3.75 ± 0.37a	3.79 ± 0.45a
NW								
N1W1	1.25	0.94	4.04 ± 0.07d	3.41 ± 0.10d	2.79 ± 0.07c	2.47 ± 0.10cd	3.23 ± 0.06d	3.63 ± 0.10b
N2W1	1.36	1.03	4.84 ± 0.10ab	3.74 ± 0.05b	3.48 ± 0.10a	2.71 ± 0.05ab	3.56 ± 0.07c	3.63 ± 0.05b
N3W1	1.56	1.25	4.93 ± 0.17a	3.84 ± 0.11ab	3.37 ± 0.17ab	2.59 ± 0.11bc	3.16 ± 0.11de	3.07 ± 0.09e
N4W1	1.66	1.35	5.01 ± 0.09a	3.94 ± 0.11a	3.35 ± 0.09ab	2.59 ± 0.11bc	3.02 ± 0.05e	2.92 ± 0.08f
N1W2	0.99	0.76	3.88 ± 0.13d	3.18 ± 0.03e	2.89 ± 0.13c	2.42 ± 0.03d	3.92 ± 0.13b	4.18 ± 0.04b
N2W2	1.09	0.85	4.58 ± 0.21c	3.61 ± 0.14c	3.49 ± 0.21a	2.76 ± 0.14a	4.20 ± 0.19a	4.24 ± 0.16a
N3W2	1.31	1.07	4.67 ± 0.15bc	3.74 ± 0.04b	3.36 ± 0.15ab	2.67 ± 0.04ab	3.57 ± 0.12c	3.50 ± 0.03c
N4W2	1.41	1.17	4.68 ± 0.13bc	3.80 ± 0.04b	3.27 ± 0.13b	2.63 ± 0.04ab	3.32 ± 0.10d	3.25 ± 0.03d
Season (S)								
SS	1.33		4.58 ± 0.41a		3.25 ± 0.28a		3.50 ± 0.39b	
FW	1.05		3.66 ± 0.25b		2.61 ± 0.13b		3.55 ± 0.46a	
Analysis of variance								

Table 3. *Cont.*

Factor	Total Costs $(\$\ \text{Plant}^{-1})$		Total Benefits $(\$\ \text{Plant}^{-1})$		Net Benefits $(\$\ \text{Plant}^{-1})$		Benefit–Cost Ratio (-)	
Season	**SS**	**FW**	**SS**	**SS**	**FW**	**FW**	**SS**	**FW**
N			***	***	***	***	***	***
W			***	***	ns	ns	***	***
NW			ns	ns	ns	ns	**	**
S			***		***		*	
NS			***		***		***	
WS			ns		ns		ns	
NWS			ns		ns		ns	

N1, N2, N3, N4, W1, W2, SS, and FW; one emitter per plant, two emitters per plant, three emitters per plant, four emitters per plant, full irrigation, deficit irrigation, spring–summer cropping season, and fall–winter cropping season, respectively. *, ** , ***, ns: significant at $p < 0.05$, significant at $p < 0.01$, significant at $p < 0.001$, and non-significant at $p > 0.05$. Values that are followed by different letters within the same columns differ significantly at $p < 0.05$. Data are given in mean ± standard deviation (n = 4). The prices are \$0.105 per emitter, \$0.06 per arrow, \$0.18 per meter small pipe, \$0.195 per joint, \$0.75 per m^{-3} water, and \$0.075 per kWh, \$3.6 per hour labor, and \$1.95 per kg cherry tomato. The irrigation system is assumed to work for 2 seasons. Benefit–cost ratio (-): total benefits/total costs.

4. Discussion

Roots are involved in acquiring nutrients and soil water as a vital part of plant organs [43,44]. Root diameter and length are significant morphological parameters that affect soil water and nutrient absorption [45]. In this study, the root length (Figure 3) and root dry matter (Figure 4) were increased with increasing emitter density (24.2% and 31.5% (root length), and 9.5% and 12.4% (root dry matter) for spring–summer (SS) and fall–winter cropping season (FW), respectively) and irrigation level (12.8% and 10.2% (root length), and 4.5% and 2.6% (root dry matter) for SS and FW, respectively). The root average diameter was affected negligibly. This is because increasing the emitter density would reduce the drought stress to the root, and in turn, the root morphology is enhanced by the improved moisture distribution uniformity and wetting pattern around the plant roots [46]. The same phenomenon occurs as the irrigation level was increased from W2 to W1, which is in agreement with [31]. The main parameters for characterizing root systems are root length density (RLD) and root weight density (RWD) [47,48]. RLD and RWD increased with an increased emitter density and decrease with decreasing irrigation level (Figure 3), as was the case with root length (Figure 3) and root dry weight (Figure 4).

The RLD and RWD distributions expanded horizontally (Figures 5 and 7) and concentrated heavily into the topsoil layer (Figures 6 and 8) due to the increased emitter density and decreased emitter discharge (with increased emitters per plant, the flow rate of the emitter decreases to maintain the same irrigation period). This is in agreement with [35,49], which showed that the radial and vertical distributions of moisture were higher, respectively, at lower and higher flow rates. Further, [50] reported that the supply of soil water affects the morphology of the root. In well-watered conditions, the roots near the soil's surface are considered to be in the prime position of water and nutrient absorption [51,52]. Deficit irrigation resulted in smaller-concentration regions horizontally (Figures 5 and 7) and deeper vertically in the RLD and RWD (Figures 6 and 8) because the roots moved deeper in search of moisture. Several research studies reasoned the yield and water use efficiency enhancement to the enhanced deep soil layer water uptake and use [53,54] as restricted irrigation would encourage roots to expand into deeper soil layers [30,55]. Quinoa (Chenopodium quinoa Willd.) plasticity was investigated in dry and wet soil, and drier soil enhanced the tap root's growth more than wet soil to allow water to be absorbed in deeper soil **[56]**. Enlarged deep root biomass, lengthier seminal roots, and improved development of small root diameter at depths were included in root morphological parameters in drying soil [52]. The growth of the roots, especially the deep roots, had an important impact on the stable yield and, under drought conditions, absorbed greater quantities of water from the deep soil [57].

There may have been two explanations for the relationship between the root morphology and the emitter density and irrigation level. First, one reason for cherry tomato root propagation at different irrigation levels is the differences in soil bulk density [10,58]. Secondly, the finding that the root growth of increased emitter density and irrigation level is higher than that of single emitters per plant and deficit irrigation could be derived from the accumulation of dry matter (Figure 4), which has been attributed to plant roots offering a broader spatial range to absorb water and nutrients under increased emitter density and higher levels of irrigation [59,60]. Water stress can limit the development and distribution of roots in the soil [61] and lower the RLD [21]. Tomato plants with two emitters per plant with deficit irrigation treatment showed an optimal root distribution compared to the other emitter density and irrigation level treatment in the current research, describing wider and deeper dispersion measurements and higher RLD and RWD through the soil and thus showed less scarcity of plant growth reactions and increased yield and WUE with the highest benefit–cost ratio (4.20 and 4.24 (Table 3) for SS and FW, respectively). In view of root distribution and yield, optimization of emitter density and irrigation level based on economic benefits was achieved by measuring the net profits (3.49 and 2.76 \$ plant^{-1} for SS and FW, respectively) and benefit–cost ratio (4.20 and 4.24 for SS and FW, respectively) (Table 3).

The total dry matter (Figure 4), tomato shoot morphology, and yield (Figure 9) increased with increasing emitters per plant (10.8% and 14.10% (root length), 17.9% and 20.3% (plant height), 8.1% and 7.9% (stem diameter), and 20.9% and 14.7% (yield) for SS and FW, respectively) and decreased with deficit irrigation (6.7% and 6.7% (root length), 6.6% and 10.5% (plant height), 7.9% and 5.4% (stem diameter), and 5.3% and 4.1% (yield) for SS and FW, respectively). This is due to the fact that the spatial distribution of root systems in a soil directly affects soil water and nutrient absorption and root morphology, thereby affecting crop growth and productivity **[62]**. Another reason is that plant nutrient absorption benefits from a good root structure, which will help achieve different leaf areas and dry weight [63,64]. Water-logged soil causes the leaf growth rate and dry matter accumulation by the shoots to decrease [65]. The reduced overall dry matter production and water consumption cause poorer cherry tomato yield under the drought stress [4,66,67]. Drought and waterlogging induce a drastic decrease in dry matter accumulation, causing low fruit yield [68–70]. Previous studies have shown that irrigation deficits have reduced vegetative growth and fruit yield, in line with current findings [71–74]. One reason for the reduced yield was that dramatically reduced photosynthesis of plants decrease the quantity and energy of metabolites necessary for appropriate plant growth under drought stress [71,75].

Plant performance has indeed been deeply related to the root system that provides water and nutrients to the shoot, as is well known. Highly significant results were found between root morphology and dry root matter versus plant abov- ground parameter (R^2 ranges from 0.487 to 0.993) (Table 2). The explanation for this is that root growth and shoot growth patterns are closely related [48,76–78], both growing in this study with an increased emitter density, which can be considered the main factor promoting increased yield. Greater root biomass, which led to greater yield and WUE, was significantly correlated with higher shoot biomass [37,79].

WUE is a crucial physiological parameter reflecting in a water-scarce area the capacity of crops to retain water as it integrates resistance to drought and great potential yield [55,80,81]. WUE increases with an increased emitter density (37.5–45.8 kg m^{-3} for SS and 44.6–52.5 kg m^{-3} for FW) and a decreased irrigation level (38.3–48.3 kg m^{-3} for SS and 43.5–55.7 kg m^{-3} for FW) (Figure 9).WUE is mainly a function of water input [37,82,83], which increases by deficit irrigation [4,84–88] and is the most significant measure of the agricultural production system [89]. It may be attributed to a decrease in the transpiration rate due to deficit irrigation, which eventually results in the stomata's partial closure [90,91].

The spring–summer cropping season resulted in the improved root (499–606.5 m (root length) and 3.4–3.9 g (root dry matter)) and shoot morphology (145.2–172.3 g (total dry matter), 6.6–8.4% (root/shoot ratio), 138.8–168.6 cm (plant height), and 7.5–9.1 mm (stem diameter)) and yield 1.9–2.4 kg plant^{-1} (yield), but reduced water use efficiency (49.6–43.3 kg m^{-3}) and benefit–cost–ratio (3.6–3.5) relative to fall–winter cropping season, but for both seasons, the root distribution patterns were the same. The explanation was that the constant low temperatures in the later winter period (6.5 °C in late December) negatively affected the maximum growth rate during the rapid growth period and consequently reduced the yield [92]. Numerous reports have said that the optimal temperature of the tomato crop varied around 20 and 24 °C to maintain greater fruit yield, and 12 and 36 °C have been the growth temperature limits [93]. Furthermore, for two, three, and four emitters per plant, there were no significant effects on response parameters, and the obtained results were identical for both seasons, except for root distribution patterns.

5. Conclusions

The spring–summer cropping season resulted in improved root and shoot morphology and dry matter production relative to the fall–winter cropping season, but for both seasons, the root distribution patterns were the same. The individual factors of the emitter density and irrigation level significantly affected the root distribution patterns along with root morphology, which affects shoot morphology and finally tomato yield and water use efficiency. All measured parameters were more sensitive to the emitter density except water use efficiency, which was more affected by irrigation level. In addition, the results indicated that plant height, stem diameter, fruit yield, and dry matter production were closely linked to root morphology and root dry matter. Compared with the other emitter density and irrigation level treatments in the present study, tomato plants with two emitters per plant with deficit irrigation treatment indicated an optimal root distribution, showing broader and deeper dispersion measures and greater root length density and root weight density through the soil, and hence presented lesser scarcity reactions of plants growth and gained improved yield and water use efficiency with the highest benefit–cost ratio (4.20 and 4.24 for spring–summer and fall–winter cropping seasons, respectively). Based on the results, it was concluded that among all the treatments, two emitters per plant with deficit irrigation is optimum under greenhouse conditions for the cultivation of potted cherry tomatoes, considering the root morphology, root distribution, dry matter production, yield, water use efficiency, and economic analysis. It is recommended to vary emitter location around the plant to investigate its impact on root distribution and growth, which will eventually affect plant yield.

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