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RESPONSE OF GREENHOUSE TOMATO YIELD, ABOVEGROUND BIOMASS AND WATER USE EFFICIENCY TO WATER DEFICIT IN DIFFERENT PERIODS OF FURROW AND DRIP IRRIGATION

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Abstract

The quantitative relationship between tomato yield, water consumption, WUE, aboveground biomass, and root parameters, different deficit irrigation treatments between furrow and drip irrigation systems were conducted in northwest China from August, 2013 to January, 2014 (AW season) and from March to July, 2014 (SS season). Full irrigation treatments were kept as control. Results showed that tomato water consumption, yield, aboveground biomass and fine root length decreased, but WUE and total root length significantly increased by deficit (50% ET_c) at seeding stage and fruit maturation stage. Deficit (50% ET_c) at all stages decreased yield, water consumption, WUE, aboveground biomass and fine root length, but increased the total root length of tomato. The fine root length had a linear correlation with yield, water consumption, WUE and aboveground biomass. Therefore, deficit at seeding stage and fruit maturation stage maintained higher WUE and minimized tomato yield losses. And drip irrigation increased yield, water consumption, WUE and aboveground biomass by 19.2, 19.5, 34.9 and 24.2% than furrow irrigation, respectively.

Introduction

In the past few decades, the greenhouse vegetable cultivation area has increased to about 140,000 hectares in Shaanxi Province. The greenhouse tomatoes are the main vegetable crops in northwest china, especially in winter and spring. In addition to delicious taste, tomatoes are a good source of vitamins C and lycopene. Lycopene is an antioxidant that helps in preventing a variety of cancers (Toor *et al.* 2006).

Due to water shortages in northwestern China, developing water-saving agriculture is especially important for saving fresh water, which is the only source of water for plants in the greenhouse. Deficit irrigation (DI) is a water-saving strategy under which crops are exposed to a certain level of water stress (English and Raja 1996) to control vegetative and reproductive growth. In recent years, DI experiments have been targeted several crops, with either the deficit maintained at a long time, or with the irrigation being deficit only at selected crop's stages (Pandey *et al.* 2000, Patane and Cosentino 2010).

Furrow irrigation is a common irrigation method for greenhouse tomato production in northwestern China. Compared to furrow irrigation, drip irrigation saves water and provides better plant yield and quality because it reduces the humidity in the greenhouse after irrigation and water can be accurately applied to the root zone of the crop and improve water use efficiency, evapotranspiration loss by significantly reducing runoff and crops (Stanghellini *et al.* 2003, Jones 2004, Kirnak and Demirtas 2006).

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Therefore, different irrigation methods were arranged in northwest China, the objectives of the present investigation were (1) to compare aboveground biomass and root of tomato under different deficit treatments; and (2) yield, water consumption and water use efficiency of tomato under different deficit treatments, so as to optimize water-saving irrigation, and thus a suitable irrigation was established to provide a scientific basis for improving the water use efficiency of tomato under greenhouse production.

Materials and Methods

The study was started in August, 2013 in two greenhouse at Northwest A&F University, Yangling, Shaanxi Province (34°17′ 56″ N, 108°04′ 07″ E). Furrow and drip irrigation methods were carried out in both greenhouses. The annual average temperature was 21.9°C in the local greenhouse. The amounts of irrigation and fertilizer application under farmer's traditional vegetable production were about 800 - 1200 mm and 450 - 700 kg N/ha per season, respectively. Characteristics of greenhouse before planting are presented in Table 1.

Table 1. Characteristics of greenhouse test the soil layer (0 - 60 cm).

Soil characteristics	Value	
	Greenhouse a with furrow irrigation	Greenhouse b with drip irrigation
Sand (%)	35	36
Silt (%)	39	40
Clay (%)	26	24
pH (in water solution)	7.9	7.8
Total N (g/kg)	1.09	1.05
NO_3^--N (Kg N/ha)	156	153
P_2O_5 avail. (mg/kg)	35.9	37
K_2O avail. (mg/kg)	490.2	560
Total calcareous (%)	24	25
Organic matter (%)	1.54	1.6
Bulk density (g/cm)	1.36	1.35
Field capacity at −0.03 MPa (g/g dry weight)	0.27	0.26
Field capacity at −1.5 MPa (g/g dry weight)	0.17	0.16

Both greenhouses with five years of vegetable cultivation were selected for experiment. Each greenhouse has an area of 350 m^2. Furrow irrigation and drip irrigation tests were carried out on greenhouse tomatoes in two growing seasons.

The autumn - winter (AW) season was from August, 2013 to January, 2014, and spring - summer (SS) season was from March to July, 2014. Tomato (*Lycopersicon esculentum* Mill, Olina) were transplanted at the four-leaf stage on August 10, 2013 and March 10 2014, respectively. The final harvest dates were on January 10, 2014 and July 10, 2014, respectively. Tomato growth stages were divided as follows: seeding (Stage I, August 10 to September 14, 2013 in AW and March 10 to April 8, 2014 in SS), flowering and fruit development (Stage II, September 15 to November 8, 2013 in AW and April 9 to May 29, 2014 in SS), fruit maturation stage (Stage III, November 9, 2013 to January 10, 2014 in AW and May 30 to July 10, 2014 in SS). In furrow irrigation, the tomato planting mode was traditional wide-narrow row. In drip irrigation, the irrigation water uses a pressure-compensated drip emitter with an emission rate of 3.0 l/h. The wide raw was 0.8 m and narrow row was 0.4 m. Two rows of tomato were evenly transplanted to narrow row (0.4 m between rows and 0.4 m within row) with density of 3 plants m^{-2} per growth season. The tomato planting direction is consistent with the greenhouse.

Eight different irrigation treatments were designed, including four treatments under furrow irrigation: receiving 100% ET, restoration (F = full) at all growth stage (A) (FFA), receiving 50% ET_c restoration (D = deficit) at seeding stage (S), then 100% ET_c restoration (FDS), receiving 50% ET_c restoration (D = deficit) up to flowering and fruit development stage (F), then 100% ET_c restoration (FDF), receiving 50% ET_c restoration (D = deficit) at all growth stage (A) (FDA); and four treatments with drip irrigation: receiving 100% ET_c restoration(F = full) at all growth stage (A) (DFA), receiving 50% ET_c restoration (D = deficit) at seeding stage (S), then 100% ET_c restoration (DDS), receiving 50% ET_c restoration (D = deficit) up to flowering and fruit development stage (F), then 100% ET_c restoration (DDF), receiving 50% ET_c restoration (D = deficit) at all growth stage (A) (DDA). There are three replications of 12 furrow plots and 12 drip plots, respectively, arranged in both greenhouses. Each test plot has an area of 9.6 m^2 (8 m × 1.2 m). In order to prevent interaction between adjacent test plots, the plastic film was placed at a depth of 1 m to separate adjacent plots. In each plot, soil volume water content of 0 to 0.6 m in the soil at intervals of 0.15 m was measured every 5 days using a TDR probe and measured 2 - 3 days after irrigation.

All treatments received the same amount of 300 kg N/ha, 200 kg P/ha, 300 kg K/ha and 40 Mg/ha decomposed organic manure for AW and SS seasons. Before the transplanting seeds, all P acid, potash and organic fertilizer are used as base fertilizer evenly. During the growth period of the tomato, one quarter of these N was applied at 34, 63, 85 and 108 DAT in AW season, and at 25, 53, 75 and 100 DAT in SS season, respectively, which were injected with water via irrigation water.

After 15 DAT, the amount of water to supply was based on the sum of crop evapotranspiration (ET_c). The daily evapotranspiration was calculated as:

$$ET_c = E_0 k_c \tag{1}$$

where ET_c is the daily evapotranspiration (mm); E_0 is the evaporation of class-A pan (mm); k_c is the crop coefficient (Doorenbos and Pruitt 1977). Amount of water needed to fill the soil to a soil depth of 0 - 0.4 m soil depth, most of which are expected to develop (Patane` and Cosentino 2010, Shi *et al.* 2013).

From each plot, the tomato water consumption (ET) of greenhouse was estimated by means of water balance equation as follows (Chen *et al.* 2013):

$$ET = I + \triangle W \tag{2}$$

where ET is tomato water consumption (mm), I is irrigation water amount (mm), ΔW is the change in soil water volume (mm).

At the time of maturity, three plants were destructively sampled from each test plot, and the shoot shoots (stem + leaf + fruit) were dried in a 70°C hot air oven until constant weight for dry biomass measurement. Then, total fruit yield (Mg/ha) was determined.

Water use efficiency (WUE, kg m^{-3}) was calculated from total yield (kg/ha) and total crop water consumption (ET, mm) (Lovelli *et al.* 2007).

Root characteristic parameters (RLD, FRLD, RSA) were measured after fruit harvest. For root studies the soil drill (0.12 m internal diameter, 0.2 m height) was used to sample from each test treatment. Roots were measured in the glass bottomed shallow dish of 30 cm × 22 cm dimension. Washed root was scanned on a 450-dpi resolution scanner (Epson Perfection V700 Photo). Total root length (TRL, m), fine root length (FRL, m) and root surface area (RSA, m^2) were determined by using WinRhizo software. Roots were divided into diameters of 0 - 0.5 mm (fine root) and > 0.5 mm (coarse root) using the Böhm (1979) classification. TRLD was calculated from TRL (Km) and soil volume (m^3). FRLD was calculated from FRL (Km) and soil volume (m^3).

Statistical analysis of yield, WUE, aboveground biomass and root parameters was performed by one-way analysis of variance (ANOVA) using data processing system (DPS). The significance of the difference was assessed using the least significant difference (LSD) test at the $p < 0.05$ level. Based on the aggregated data of the two growing seasons, the relationship between tomato yield, water consumption, WUE, aboveground biomass and root parameters were assessed by regression.

Results and Discussion

Tomato yield varied greatly in different treatments under furrow and drip irrigation (Table 2). Maximum values of yield were found under FFA and DFA in the AW and SS seasons. No significant drop in yield was observed under FFA and FDS, and under DFA and DDS, respectively, in the AW and SS seasons. This indicates deficit irrigation at stage I does not result in a yield reduction under different irrigation methods. But the water amount was saved by 11.6 and 10.6% for FDS and DDS in AW and SS seasons, respectively (Table 3). Compared to FFA, FDF and FDA reduced yield by 17.4 and 34.4%, respectively. And compared to DFA, DDF and DDA yield reduced yield by 16.2 and 33.7%, respectively. Therefore, deficit at Stage I and Stage II saved 34.1% of irrigation water and reduced 7.4% of yield under furrow irrigation, and 33.0% of irrigation water and reduced 16.2% of yield under drip irrigation; deficit irrigation at all growth stage saved 46.2% of irrigation water and reduced 34.4% of yield under furrow irrigation, and 43.9% of irrigation water and reduced 33.7% of yield under drip irrigation. Many studies have shown that water deficits reduce tomato yield to a certain extent (Patanè *et al.* 2011), although to depend on degree of deficit (Zegbe *et al.* 2006). Drip irrigation increased the yield by 21.8 and 16.6% than furrow irrigation in the AW and SS seasons, respectively. Average fruit yield in the SS seasons under different irrigation treatments was 83.5 mg/ha, which was 37.1 mg/ha higher than in AW seasons. The possible reason is that Stage III in the SS season had higher solar radiation, temperature than in AW season.

Table 2 shows the water consumption (ET) and irrigation amount of tomato as influenced by methods of irrigation in AW and SS seasons. ET under FFA and DFA treatments were higher than other treatments. Water shortages lead to lower ET. No significance effects were found on total ET in FFA and FDS, respectively, and in DFA and DDS, respectively. Compared to FFA, ET was reduced by 19.6 and 30.2% under FDF and FDA, respectively. And compared to DFA, ET was reduced by 20.2 and 28.3% under DDF and DDA, respectively. Many studies have reported the similar results that reducing irrigation water can decrease tomato water consumption (Chen *et al.* 2013).

Water use efficiency (WUE) varied greatly in different treatments through furrow and drip irrigation (Table 2). Maximum values of WUE were processed under FDF and DDF in AW and SS seasons. But the minimum values of WUE were found under FDA and DDA in AW and SS seasons. Drip irrigation increased the WUE by 35.3 and 34.5% than furrow irrigation in AW and SS seasons, respectively.

Aboveground biomass and harvest indices (HI) varied widely under furrow and drip irrigation (Table 3). The weight of leaves and stem are between 1.99 mg/ha of DDA and 2.60 mg/ha of FDS and DDS in the AW season, with no significant change of shoot weight under furrow and drip irrigation, and between 2.09 mg/ha of FDA to 3.21 mg/ha of DDS in the SS season, with higher shoot dry weight under drip irrigation than furrow irrigation. Within irrigation treatments, deficit at seeding stage generally did not decrease shoot dry weight. Therefore, long-term deficit treatments decreased the tomato shoot. The fruit harvest indices (HI) were found to approximately 0.51 to 0.63 in the AW season, and 0.61 to 0.67 in the SS season. Drip irrigation increased the HI by 13.4 and 4.0% than furrow irrigation in the AW and SS seasons, respectively.

Table 2. Tomato fruit yield, water consumption (ET), irrigation amount (mm) and water use efficiency (WUE) as influenced by methods of irrigation.

Season	Treatments	Yield (mg/ha)	ET (mm)	Irrigation amount (mm)	WUE (kg m^{-3})
AW season	FFA	58.2a	162.3	223.4	34.7b
	FDS	58.1a	160.8	186.1	35.0b
	FDF	48.5b	131.2	144.1	36.3a
	FDA	38.5c	117.6	126.7	31.0c
	DFA	70.6a	147.2	184.1	46.3b
	DDS	70.6a	146.1	157.4	46.0b
	DDF	59.2b	118.8	118.1	48.6a
	DDA	47.2c	104.7	107.1	44.2c
SS season	FFA	89.2a	189.9	264.8	47.0b
	FDS	88.2a	189.2	247.7	46.6b
	FDF	72.9b	151.7	178.1	48.1a
	FDA	58.1c	127.6	134.5	45.5c
	DFA	103.0a	162.0	201.3	63.6b
	DDS	102.8a	163.0	187.8	63.1b
	DDF	86.2b	127.9	140.8	67.4a
	DDA	67.7c	117.2	108.9	57.8c

Values sharing same letters in a vertical column differ non-significantly ($p > 0.05$), same as below.

Minimum values of fruit dry biomass were found under FDA and DDA in the AW and SS seasons (Table 3). Compared to FDA, fruit dry biomass increased by 10.5, 14.8 and 9.3% for FFA, FDS and FDF, respectively. And compared to DDA, fruit dry biomass increased by 8.8, 15.2 and 8.3% for DFA, DDS and DDF, respectively. But there was no significant decline of fruit dry biomass under FFA, FDS and FDF in furrow irrigation, and under DFA, DDS and DDF in drip irrigation, respectively.

Table 4 shows that the total root length density (TRLD), fine root length density (FRLD) and root surface area (RSA) were affected by methods of irrigation in the AW and SS seasons. Minimum values of TRLD were observed under FFA and DFA in the AW and SS seasons (Table 4). No significant effects were found on TRLD under FFA and FDS, respectively, and under DFA and DDS, respectively. Compared to FDA, TRLD increased by 10.1 and 16.7% for FDF and FDA, respectively. And compared to DDA, TRLD increased by 7.2 and 13.4% for DDF and DDA, respectively.

The average TRLD values were 0.29 - 0.56 km m^{-3} in this study at the 0 - 60 cm soil layers around the tomato plant (Table 4). Deficit at long times would significantly increased TRLD. The tomato root length under both irrigation methods at full irrigation was less than treatments at deficit irrigation, except FDS and DDS. A similar conclusion was proved by that deficit irrigation which can increase root length density (Sharma *et al.* 2014). Root growth may be due to mild soil dryness stimulating root penetration to offset crop water requirements imbalance and allowing plants to absorb more water from soil reserves (Ahmadi *et al.* 2010).

Table 3. Dry biomass of aboveground and harvest indices (HI) of tomato as influenced by methods of irrigation during the AW and SS seasons.

Treatment	Dry biomass				Harvest indices (HI)	
	Shoot (mg/ha)		Fruit (mg/ha)			
	AW	SS	AW	SS	AW	SS
FFA	2.51a	2.58a	2.66ab	4.05a	0.51b	0.61c
FDS	2.60a	2.69a	2.77ab	4.20a	0.52b	0.61c
FDF	2.01b	2.13b	2.63ab	4.01a	0.57a	0.65a
FDA	2.00b	2.09b	2.49b	3.55b	0.56a	0.63b
DFA	2.51ab	3.10a	3.65ab	5.29ab	0.59c	0.63b
DDS	2.60a	3.21a	3.88a	5.58a	0.60bc	0.63b
DDF	2.21bc	2.51ab	3.75ab	5.11ab	0.63ab	0.67a
DDA	1.99c	2.36b	3.43b	4.76b	0.63a	0.67a

Values sharing same letters in a vertical column differ non-significantly ($p > 0.05$), same as below.

Drip irrigation increased the TRLD by 8.1 and 16.3% than furrow irrigation in the both growth seasons, respectively. This might be due to drip irrigation applying water directly to the root zone by a dripper placed below the surface of the soil (Leskovar *et al.* 2001). Drip irrigation plants receive water at shorter intervals (about 3 - 4 days intervals) in which water is applied at larger intervals (about 6 - 8 days intervals) in furrow irrigation. At the lower irrigation of drip irrigation, the root length gradually increases. Although crops receive water at shorter intervals in drip irrigation, water applied during water deficit irrigation is less (Table 2). Soil water deficits have been reported to generally reduce shoot growth, thus more biomass being distributed to the roots (Kramer and Boyer 1995, Kage *et al.* 2004).

The observed trend between FRLDs at different irrigation rates is very similar to RLD (Table 4). There is no statistically significant difference between FFA and FDS, DFA and DDS on FRLD in the AW and SS seasons. FRLD decreased from 0.32 Km m^{-3} for FFA to 0.27 and 0.21 Km m^{-3} for FDF and FDA, respectively, and from 0.38 Km m^{-3} for DFA to by 0.34 and 0.27 m m^{-3} for DDF and DDA, respectively. Drip irrigation increased the FRLD by 17.6 and 25.0% than furrow irrigation in AW and SS seasons, respectively.

FFA, FDS, DFA, and DDS treatments assigned the highest root length distribution for fine root scores (87 - 94%), while FDA and DDA had the highest length distribution among AW and root scores (41 - 51%) in AW and SS seasons (Table 4). The percentage of fine roots under drip irrigation with a higher proportion at 0 - 0.6 m shallow depths than under furrow irrigation treatments.

There was no statistically significant difference between FFA and FDS, DFA and DDS on RSA in the AW and SS seasons (Table 4). RSA increased from 0.10 m^2 for FFA to 0.11 and 0.12 m^2 for FDF and FDA, respectively, in furrow irrigation, and from 0.11 m^2 for DFA to by 0.13 and 0.14 m^2 for DDF and DDA, respectively, in drip irrigation. Drip irrigation increased the RSA by 11.4 and 20.8 % than furrow irrigation in AW and SS seasons, respectively.

Table 4. Total root length density (TRLD), fine root length density (FRLD) and root surface area (RSA) as influenced by methods of irrigation during the AW and SS seasons.

Treatment	TRLD (km m^{-3})		FRLD (km m^{-3})		RSA (m^2)	
	AW	SS	AW	SS	AW	SS
FFA	0.29c	0.41c	0.26a	0.38a	0.08c	0.11c
FDS	0.30c	0.43c	0.26a	0.38a	0.08c	0.11c
FDF	0.32b	0.45b	0.22b	0.32b	0.09b	0.12b
FDA	0.33a	0.49a	0.17c	0.24c	0.10a	0.14a
DFA	0.32c	0.49c	0.30a	0.45a	0.09c	0.13c
DDS	0.32c	0.49c	0.30a	0.45a	0.09c	0.14c
DDF	0.34b	0.53b	0.26b	0.42b	0.10b	0.15b
DDA	0.36a	0.56a	0.21c	0.33c	0.11a	0.16a

Values sharing same letters in a vertical column differ non-significantly ($p > 0.05$), same as below.

Figs 1 - 4 show interaction effects of irrigation methods on fine root length density (FRLD) in AW and SS seasons. In the AW and SS seasons, the fine root length density of 0 - 0.15 m soil layer is about 44 - 55% in the furrow irrigation (Figs 1 and 3), and about 45 - 70% in drip irrigation (Figs 2 and 4). Below 0.15 m, the FRLD decreased 25 - 33% being present at 0.15 - 0.30 m in furrow irrigation, and about 20 - 33% in drip irrigation; 15 - 17% at 0.30 - 0.45 m depth in furrow irrigation, and 7 - 9% in drip irrigation; and 2 - 7% at the lowest (0.45 - 0.60 m) soil layer in furrow irrigation, and about 3 - 6% in drip irrigation. Drip irrigation increased the FRLD between 0 - 0.15 m of the soil layer by 0.18 - 0.27 km m^{-3} than furrow irrigation in the AW and SS seasons. The FRLD in the 0.15 - 0.30 m soil layer was not slightly significant between under furrow irrigation (0.24 km m^{-3}) and under drip irrigation (0.26 km m^{-3}), and the trend shows similar in 0.45 - 0.60 m soil layer. The observation of the FRLD in 0.30 - 0.45 m soil layer was slightly higher under furrow irrigation (0.13 km m^{-3}) is more of less similar to Zotarelli *et al.* (2009). Most of RLD (51 - 78 %) was found between 0 - 0.15 m soil layer and Shi *et al.* (2013) suggested that 78 - 88 % of the root were between 0 - 0.30 m soil layer.

Fig. 5 shows that the yield increased with increasing fine root length (FRL), linear model developed using FRL and yield indicated that 0.99 and 0.95 relationship between yield and FRL under two irrigation methods, respectively. Fig. 6 shows the ET increased as FRL increased, linear model developed with FRL and ET showed that 0.82 and 0.45 relationship between ET and FRL under two irrigation methods, respectively. Fig. 7 shows that the WUE increased with the increase of FRL, linear model developed with FRL and WUE showed 0.60 and 0.81 relationship between WUE and FRL under two irrigation methods, respectively. Fig. 8 shows that the aboveground biomass increased with the increase of FRL, linear model developed with FRL and aboveground biomass showed that 0.92 and 0.95 relationship between aboveground biomass and FRL under two irrigation methods, respectively. Hence, FRL can be used as an indicator for evaluating the yield, ET, WUE and aboveground biomass of tomato.

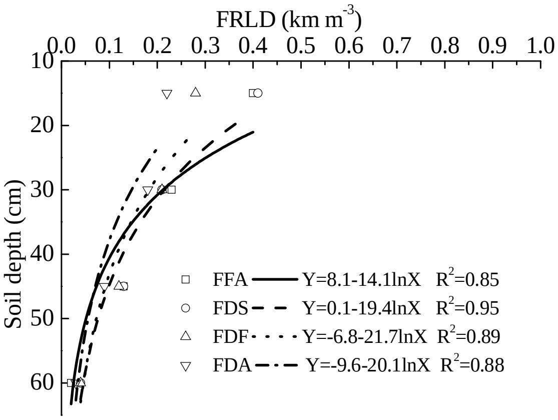

Fig. 1. Relationships between soil depth and fine root length density (FRLD) in AW seasons under furrow irrigation.

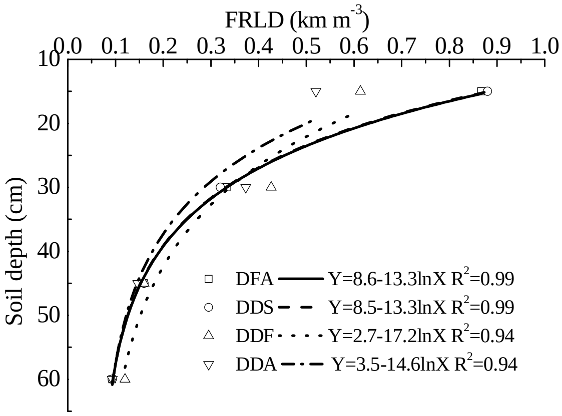

Fig. 2. Relationships between soil depth and fine root length density (FRLD) in AW seasons under drip irrigation.

The study showed that half of the irrigation amount (50% ET_c) in the seedling period has no significant effect on tomato yield, water consumption, WUE, aboveground biomass and root parameters. Therefore, saving water by 11.1% with no obvious reduction in production at seedling stage observed. Water consumption, fruit size, total yield, aboveground biomass and fine root length of tomato was decreased, but WUE and total root length significantly increased by deficit (50% ET_c) at seeding stage and fruit maturation stage. Deficit (50% ET_c) at all stages had decrease yield, water consumption, WUE, aboveground biomass and fine root length, but increased the total root length of tomato. Tomato fine root length can be used as an indicator to assess yield, ET, WUE and aboveground biomass of tomato. Therefore, it is hypothesized that a balance between maintaining higher WUE and minimizing loss of yield may be achieved under water deficit during seeding and fruit maturation stages.

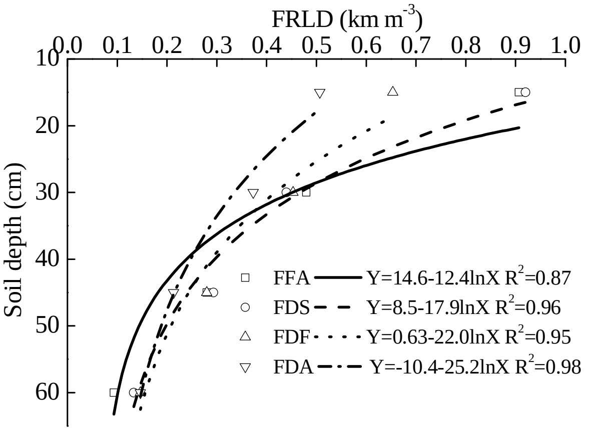

Fig. 3. Relationships between soil depth and fine root length density (FRLD) in SS seasons under furrow irrigation.

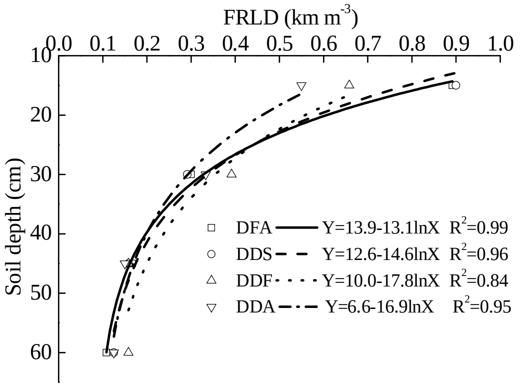

Fig. 4. Relationships between soil depth and fine root length density (FRLD) in SS seasons under drip irrigation.

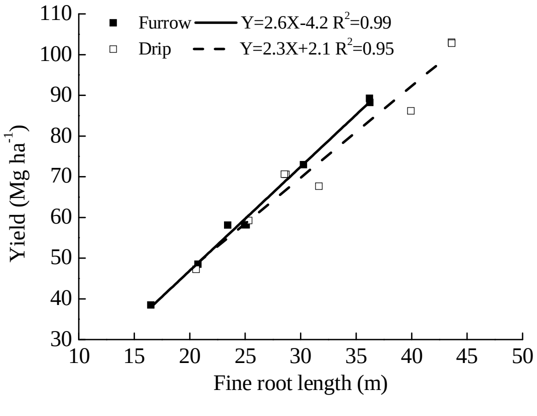

Fig. 5. Relationships between yield and FRL under furrow and drip irrigation methods.

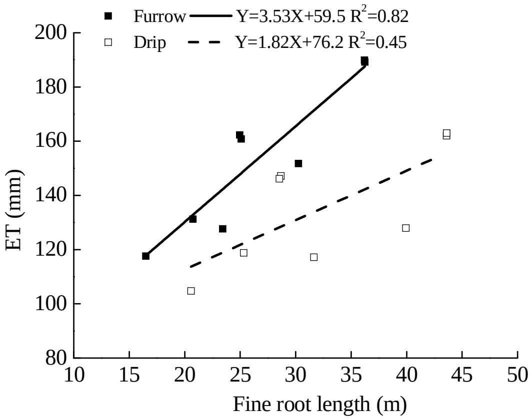

Fig. 6. Relationships between ET and FRL under furrow and drip irrigation methods.

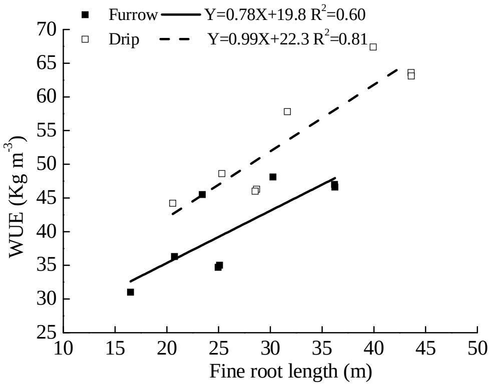

Fig. 7. Relationships between WUE and FRL under furrow and drip irrigation methods.

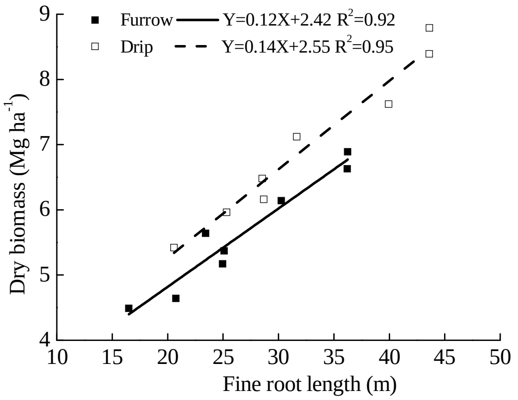

Fig. 8. Relationships between aboveground biomass and FRL under furrow and drip irrigation methods.

Drip irrigation increased yield, ET, WUE, aboveground biomass by 19.2, 19.5, 34.9 and 24.2% than furrow irrigation, respectively, and decreased the RH of greenhouse by 3.7%. More reasonable irrigation system and methods with a balance between yield and WUE of tomato should be revealed by optimization irrigation methods considering linear relationship between yield, water consumption, WUE, aboveground biomass and root parameters of tomato step by step in greenhouse.

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