IMPROVEMENT OF QUALITY AND YIELD OF GREENHOUSE TOMATO (*SOLANUM LYCOPERSICUM* L.) PLANTS BY MICRO-SPRINKLER IRRIGATION UNDER PLASTIC FILM

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Abstract. This study clarified the applicability of micro-sprinkler irrigation under plastic film (MSPF) in a greenhouse and finding the optimal micropores group spacing and capillary arrangement density. The effects of different micropores group spacing (L1: 30 cm micropores group spacing, and L2: 50 cm micropores group spacing) and capillary arrangement density (C1: one pipe for one row, C2: one pipe for two rows, and C3: one pipe for three rows) with the MSPF on the growth, quality, yield (Y), and water use efficiency (WUE) of tomato were studied. A completely randomized trial design was used, and drip irrigation under plastic film and micro-sprinkler irrigation were used as controls. The results showed that MSPF in a greenhouse can lead to saving water, increase yield, and improve crop quality. Compared to 50 cm micropores group spacing, 30 cm was better for tomato growth and also increased fruit quality, yield, and WUE. Considering our results comprehensively, the combination of one pipe for two rows under a micropores group spacing of 30 cm is recommended as technical parameters for greenhouse tomato cultivation under MSPF in arid and semi-arid sandy loam soils.

Abberviations:

No	Abbreviations	Full name
1	L	Micropores group spacing
2	C	Capillary arrangement density
3	PH	Plant height
4	SD	Stem diameter
5	LAI	Leaf area indices
6	SFW	Weight of single fruit
7	VD	Vertical diameters
8	TD	Transverse diameters
9	TSS	Total soluble solids content
10	TSU	Total soluble sugar
11	SSC	Soluble sugar content
12	TA	Titratable acids
13	SAR	Sugar/acid ratio
14	SP	Soluble protein
15	VC	Vitamin C
16	LY	Lycopene
17	Y	Yield
18	WUE	Water use efficiency
19	CRITIC	Criteria importance though intercrieria correlation
20	TOPSIS	Technique for order preference by similarity to an ideal solution

Introduction

The development of facility agriculture has provided a powerful guarantee for vegetable production in arid and semi-arid sandy loam soils of northwest China. However, the irrigation water used for facilitating agriculture in this region mainly originates from groundwater, and the resulting groundwater resource exploitation has exacerbated the water crisis in these arid and semi-arid areas; therefore, it is urgently required to mitigate the excessive use of irrigation water in this region (Du et al., 2014). Therefore, the realization of a more efficient utilization of water resources has become the current research hotspot in this region. As a common irrigation method for the greenhouse tomato (*Solanum Lycopersicum* L.) in this area, drip irrigation offers the advantages of water-saving, fertilizer-saving, and labor-saving. It has been widely used on tomato, pepper, melon, and other crops (Liu et al., 2012; Zhang et al., 2017; Wang et al., 2018a). Because of the existence of sediment, chemical precipitates, or biomass in the irrigation water body, the emitters in the drip irrigation system clog easily, resulting in decreased irrigation uniformity, accompanied by decreased crop yield and an increased cost (Yu et al., 2010; Feng et al., 2018). Drip irrigation belongs to local irrigation, and the soil wetting body per unit area of tillage layer is limited, which greatly hinders the development of the crop root system (Michelakis et al., 1993; Zhou et al., 2017).

As one of the many development forms of drip irrigation, micro-sprinkler irrigation is an irrigation form, where sprinkler (micro) pores are arranged in groups on the wall of a thin-walled drip irrigation plastic pipe (flat strip after coiling) (Zhang et al., 2009). The emitter energy dissipation structure is removed. Under identical working pressures, the flow velocity of micro-sprinkler irrigation is about 15 times larger than that of labyrinth drip irrigation. This results in strong sediment-carrying capacity and anti-clogging performance of the micro-sprinkler irrigation. This technique can solve the clogging

problem of drip irrigation emitters (Yu et al., 2010; Feng et al., 2018). At the same time, the flow rate of a single group of micro-sprinklers is much higher than that of drip irrigation, which easily increases the ratio of the horizontal and vertical migration distance of soil moisture peaks, and improves the uniformity of the soil wetting body and the water per unit area of tillage layer (Ould et al., 2001; Del et al., 2020). Micro-sprinkler irrigation offers the advantages of decreasing the restriction of horizontal root growth and short irrigation duration (Man et al., 2014; Li et al., 2019a). Therefore, micro-sprinkler irrigation has been used for winter wheat, summer corn, lawn, seedlings, and other crops, where it has achieved good results (Man et al., 2014; Baram et al., 2018; Fletcher et al., 2018; Li et al., 2018a). However, the shape, area, and uniformity of soil wetting in a micro-sprinkler irrigated area are affected by the wind speed. In addition, problems, such as difficulty to control weeds and high damage rate of micro sprinklers currently obstructs micro-sprinkler irrigation treatment (Man et al., 2014, 2017; Li et al., 2019b).

The development of facility agriculture provides a good environment for the application of micro-sprinkler irrigation, since it offers flat land, no wind indoors, and short capillary laying distance (Tsitsimpelis et al., 2016). However, the space of facility agriculture is relatively closed, and micro-sprinkler irrigation water spray atomization easily increases air humidity. High temperature and high humidity have been shown to facilitate crop diseases and insect pests (Gómez-Rodríguez et al., 2003; Er and Gökçe, 2004; Camara et al., 2017), resulting in less use of micro-sprinkler irrigation in facility agriculture. Plastic film mulching provides a solution for the application of micro-sprinkler irrigation in facility agriculture. Plastic film mulching can restrain the water jet of micro-sprinkler irrigation, decrease spray water atomization and ineffective water evaporation, and help to improve irrigation water use efficiency (WUE) (Massatbayev et al., 2016; Wang et al., 2019a). Therefore, the combination of micro-sprinkling irrigation and film mulching technology, and the use of multiple groups of small micro-pores beneath the film can compensate for the shortcomings of the micro-spray pipes used in the greenhouse. This technique is called micro-sprinkler irrigation under plastic film (MSPF, *Fig. 1*). The exploration of MSPF is of great significance to enrich the greenhouse micro-irrigation technology system, expanded the scope of the application of micro-sprinkler irrigation, and decrease the water needed for crops, and increases both the yield and quality of crops.

Figure 1. Micro-sprinkler irrigation under plastic film (MSPF)

The tomato is one of the main vegetables grown in facility agriculture in the arid to semi-arid areas of northwest China. The tomato has rich nutritional value and is the main cash crop with which local farmers increase their income (Malherbe and Marais, 2015;

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Liu et al., 2019). The greenhouse tomato in this area belongs to sparse planting crops. Based on its unique planting structure pattern, the selection and arrangement of orifice flow directly changes the soil water distribution and indirectly affects the WUE and investment cost of tomato plants. The orifice flow position on the capillary pipe (i.e., dripper spacing) and the orifice flow position between the capillary pipe (i.e., capillary arrangement density) are two aspects of the orifice flow position. Therefore, for the sustainable development of the greenhouse tomato industry in this region, it is important to determine the optimal position of the orifice flow position on the capillary pipe and the orifice flow position between the capillary pipe. These values will enable the best balance between increasing production and improving quality while reducing the use of irrigation water. Previous studies on drip irrigation showed that the confluence time of the wetting peaks at two adjacent dippers was shorter at identical dipper flow rate. Moreover, the surface wetting shape of soil moisture under two adjacent emitters was approximately rectangular when the emitter spacing decreased from 80 to 30 cm (Ould et al., 2001; Elmaloglou and Diamantopoulos, 2010). The more uniform the wetting body was, the more irrigation water use could be decreased and irrigation WUE increased (Xu et al., 2012; Sui et al., 2018). When the dipper spacing increased from 15 to 30 cm, the yield of onions first increased and then decreased (Enciso et al., 2007). The smaller the capillary arrangement density is, the more uniform the horizontal water content distribution will be, and the higher the crop dry matter accumulation and yield will be. However, the higher capillary arrangement density easily increases the investment cost. This is also not conducive for the improvement of vegetable flavor, nutrition, and WUE (Bozkurt et al., 2006; Chen et al., 2015; Zhou et al., 2017; Liu et al., 2019; Lv et al., 2019; Yang et al., 2019).

At present, relevant research mainly focused on the orifice flow position on the capillary pipe (i.e., dripper spacing) and the orifice flow position between the capillary pipe (i.e., capillary arrangement density) in the drip irrigation capillary with small flow. However, few studies investigated the influence of the change of the orifice flow position on the capillary pipe (i.e., micropores group spacing) and orifice flow position between the capillary pipe (i.e., capillary arrangement density) on greenhouse crops using MSPF. In production practice, yield is the goal pursued by farmers, quality is the demand of users, and WUE is the core of the effective utilization of agricultural water resources (Wang et al., 2019b). Sufficient soil moisture can increase yield, but fruit quality and crop WUE will both decrease, while profit loss will increase when too much water is used (Luo and Li, 2018). It remains difficult to optimize quality, yield, and WUE. The technique for order preference by similarity to an ideal solution (TOPSIS) method provides a solution for multi-objective decision-making optimization. It has been widely used to comprehensively evaluate both the advantages and disadvantages of the tomato irrigation system. Luo and Li (2018) takes tomato yield, quality and water use efficiency as evaluation indexes, uses principal component standard deviation method to obtain each index weight, and establishes a comprehensive evaluation model based on weighted TOPSIS combination to select the best irrigation mode and irrigation quantity. Liu et al. (2019) used the yield, quality, and WUE of tomato as evaluation index, where the weight of each index was made equal to 1 by an artificial method. A comprehensive evaluation model based on weighted TOPSIS combination was established to optimize the best irrigation frequency and irrigation quantity. At present, the TOPSIS method is relatively rarely applied for comprehensive benefit evaluations of MSPF.

Therefore, compared with drip irrigation and micro-sprinkler irrigation, this study explored the applicability of MSPF in the greenhouse. The responses of tomato growth, quality, yield, and WUE to different micropores group spacing and capillary arrangement density were investigated. In addition, a comprehensive benefit evaluation model of greenhouse tomato quality, yield, and WUE was established by the TOPSIS method to optimize different treatments. The combination model of micropore spacing and capillary arrangement density was obtained for the best quality, yield, and WUE of tomato plants under MSPF. This paper enriched the data on tomato micro-irrigation technology systems in arid and semi-arid sandy loam soil of facility agriculture. Data support and a theoretical basis are provided for water-saving, yield increases, and improved quality of facility agricultural crops in this area by using greenhouse experiments and multi-objective optimization data analysis.

Materials and methods

Experimental site and management

The experiment was conducted from March 27, 2019, to July 23, 2019, in a greenhouse at the Modern Agricultural Science and Technology Exhibition Center of Xi'an City, Shaanxi Province, China (108°52°E, 34°03°N). It has a warm temperate semi-humid continental monsoon climate. The soil is sandy loam, and the mass fractions of sand, silt, and clay are 63.9%, 29.63%, and 6.47%, respectively. The average bulk density of the 1.0 m soil layer was 1.48 g/cm^3, the water holding capacity of field weight was 27.40%, and the depth of groundwater table on the site exceeded 30 m. The content of organic matter, total phosphorus (P), total potassium (K), total nitrogen, available nitrogen, available P, and available K in the plough layer before sowing were 15.53 g/kg, 10.12 g/kg, 2.01 g/kg, 1.36 g/kg, 70.45 mg/kg, 112 mg/kg, and 85.23 mg/kg, respectively. The irrigation water originated from groundwater, the pH of which was 6.8, the chemical oxygen demand (COD) was 53.2 mg/L, the anionic surfactant content was 3.2 mg/L, and the chloride content was 0.48 mg/L.

The greenhouse (85 m long and 15 m wide) was oriented from north to south. The tomato variety 'Jingfan 401' (Jingyan Yinong Seed Sci-tech Co. Ltd., Beijing, China), with a 50 cm row spacing and a 40 cm plant spacing, was planted on a ridge. The length of the ridge was 3.4 m and the width was 1.2 m. The irrigation plot is shown in *Fig. 2*. The distance between each plot was 4 m; one 1.0-m deep building waterproof film made up of styrene-butadiene-styrene block copolymer was buried in the middle to prevent the horizontal infiltration and movement of soil moisture, thus avoiding their effect on other plot experiments. Tomato plants were topped when the four-eared fruit were retained and the field management measures, such as fertilisation, irrigation, and pesticides, were kept similar in all treatments. The source of irrigation water in the region was groundwater. To ensure the survival of seedlings on the day of planting, the irrigation was unified with reference to the local tomato planting experience. Spring tomatoes were planted on 27 March 2019 and irrigation treatment was initiated on 4 April 2019. The irrigation treatment was continued until 15 July 2019 and tomatoes were completely harvested on 25 July 2019. Autumn tomatoes were planted on 23 August 2019, irrigation treatment was continued between 30 August 2019 and 17 January 2020, and tomatoes were complete harvested on 30 January 2020. The micro-sprinkler pipe of MSPF (Hebei Plentirain Irrigation Equipment Technology Co., Ltd., Hebei, China) adopts three thin-walled oblique micropores with a diameter of 32 mm and a micropore diameter of 0.8 mm.

The micropores group spacing is shown in the experimental design (*Table 1* and *Fig. 3*). Drip irrigation under mulch (CK1, Hebei Plentirain Irrigation Equipment Technology Co., Ltd., Hebei, China) with thin-walled labyrinth tooth channel was selected as control. The geometric parameters of the channel were 54.3 × 1.1 × 0.83 mm, the distance between emitters was 30 cm, and the emitter flow rate was 2 L/h. Micro-sprinkler irrigation (CK2, Hebei Plentirain Irrigation Equipment Technology Co. Ltd, Hebei, China) adopted three thin-walled oblique micropore pipes with a diameter of 32 mm and a micropore diameter of 0.8 mm an was also used as control. The micropores group spacing was 10 cm.
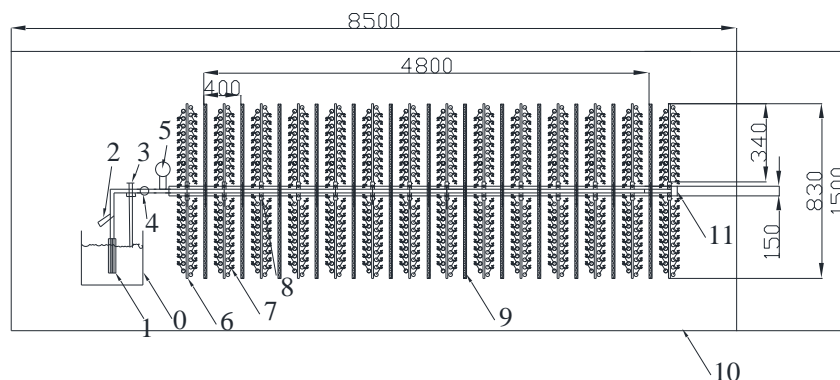
Figure 2. *Schematic diagram of greenhouse layout(cm). Note: 0 - water tank; 1 - the pump (WQD10-12-0.75S, PEOPLE PUMB, Crop., Shanghai, China); 2 - filter; 3 - backwater valve; 4 - electromagnetic flowmeter; 5 - pressure gauge; 6 - capillary; 7 - tomato; 8 - capillary valve; 9 - plastic screens; 10 - greenhouse boundaries; 11 - pathway*

Table 1. *Experimental factor and design*

| No.	Treatment	Irrigation method	Micropores group spacing cm	Capillary arrangement density	Irrigation amount mm
1	L1C1	MSPF	30	one pipe for one row	353.30
2	L1C2		30	one pipe for two rows	
3	L1C3		30	one pipe for three rows	
4	L2C1		50	one pipe for one row	
5	L2C2		50	one pipe for two rows	
6	L2C3		50	one pipe for three rows	
7	CK1	Drip irrigation under plastic film	30	one pipe for two rows	
8	CK2	Micro-sprinkler irrigation	10	one pipe for two rows	

Experimental design

Two factors were set up in this study: micropores group spacing L (*Fig. 3*) and capillary arrangement density C (*Fig. 4*). Of these, the micropores group spacing (L) used two levels: 30 cm (L1) and 50 cm (L2); the capillary arrangement density (C) used three levels: one pipe for one row (one capillary pipe irrigated one crop, C1), one pipe for two rows (one capillary pipe irrigated two rows of crops, C2), one pipe for three rows (one capillary pipe irrigated three rows of crops, C3). One pipe for two rows were used for

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both CK1 and CK2 control treatments. A total of eight treatments were implemented, each of which was repeated three times, for total of 24 test areas (*Table 1*).
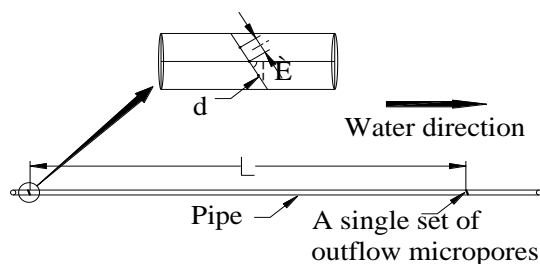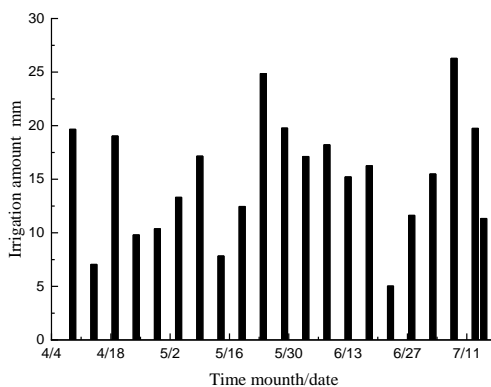

Figure 3. *Schematic diagram of micropores group (inside) spacing structure parameters. Note: diameter of micropore is d=0.7 mm; The internal spacing of the micropores group spacing was i =0.4 cm; The Angle of micropores is =68°; The micropores group spacing is L*
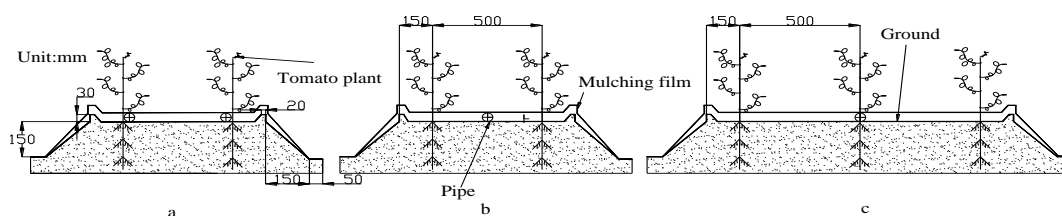
Figure 4. *Schematic diagram of capillary arrangement density (a: one pipe for one row; b: one pipe for two rows; c: one pipe for three rows)*

The irrigation amount was controlled on the basis of the cumulative evaporation from a 20-cm diameter standard pan (E_{pan}, DY.AM3, Weifang Dayu Hydrology Technology Co., Ltd., Shandong, China) following Dinc et al. (2018) and Liu et al. (2013). The evaporation amount was measured at 08:00 am every 5 d. The irrigation amount was evaluated after the measurement. The *W* of irrigation quota was calculated according to Formula (*Eq.1*), and the irrigation times and amounts were recorded (*Fig. 5*).

$$W = A \times E_{pan} \times k_{cp} \qquad (Eq.1)$$

Figure 5. *Irrigation records*

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In the formula: E_{pan} represents the evaporation within the interval of two irrigation, basing on the cumulative evaporation from a 20 cm diameter pan (mm); A represents the capillary control area (mm), and k_{cp} represents the crop- pan coefficient. In this paper, adopting adequate irrigation mode, the crop- pan coefficient of k_{cp} is 1.0 (Zhu et al., 2020).

Measurements and computational methods

Growth

The growth-related indexes were measured at 26, 51, 73, and 110 days after planting, and three plants were randomly selected from each plot. Plant height (PH) was measured with a ruler (Ma and Upadhyaya, 2016); the stem diameter (SD) was measured with electronic Vernier calipers at the base stem (Ma and Upadhyaya, 2016), and the leaf area index (LAI) was measured by AccuPARLP-80 canopy analyzer (Decagon Devices, Inc., Pullman, Wash. USA).

Three tomato plants were randomly selected in each plot, the stem of the plant was assumed as the center, and a hole was dug with a straight diameter of about 0.2 m and a depth of about 0.4 m to obtain the root system of the plant. Rhizosphere soil was carefully shaken off and the residual root system was slowly washed to remove the soil, using a weak water flow. Then, the root system and soil were placed on a 100-mesh steel screen during flushing to minimize root loss. After washing, the root system was dried in an oven at 105 °C for 15 min, followed by drying at 75 °C to constant weight. Finally, the dry matter mass of the root system was obtained.

Quality

Fruit shape, flavor, and nutritional indexes are the main three factors of tomato quality. Three tomato fruits were randomly selected in each plot when the tomatoes were ripe at the first stage. Individual fruits were homogenized to determine the fruit flavor and nutritional indexes.

Shape indices: The weight of single fruit (SFW) was measured using precision 0.01 g electronic scale. Vertical diameters (VD) and transverse diameters (TD) of the fruit were measured using vernier calipers.

Flavor indices: The total soluble solids (TSS) was measured using a hand-held refractometer with automatic temperature compensation (PR-32α Atago, Tokyo, Japan); the total soluble sugar (TSU) was measured using anthrone method (Decruyenaere et al., 2012). The soluble solid content (SSC) was measured using anthrone method (Liu et al., 2019). Titratable acids (TA) were determined by diluting an aliquot of the blended fruit and titrating against 0.1 mol/L NaOH using phenolpthalein as an indicator. Titratable acids (TA) content was determined by diluting an aliquot of the blended fruit and titrating against 0.1 mol/L NaOH by using phenolphthalein as an indicator. TAs were estimated by mL aliquot of blended fruit (Gould, 1992). Sugar/acid ratio (SAR) was determined by dividing the soluble sugar concentration by titratable acid.

Nutritional indices: the soluble protein (SP) content was measured using Coomassie Brilliant Blue assay (Liu et al., 2019). The vitamin C (VC) was calculated by the classical titration method with 2,6-dichlorophenol indophenols sodium salt solutions (Liu et al., 2019). Lycopene (LY) was extracted with 2% dichloromethane and petroleum as solvents to enhance its solubility and the absorption at 502 nm was measured using ultraviolet spectrophotometer (Cefali et al., 2015).

Yield and water use efficiency

During the maturation period, 4 tomatoes were randomly selected from each plot and the quality of mature tomatoes was measured using an electronic scale. After obtaining yield per plant, the yield per hectare was derived.

Time-domain reflectometry soil moisture sensor (TRIME-PICO-IPH, IMKO, Inc., Ettlingen, Germany) was used to measure the soil volume moisture content of 0–10, 10–20, 20–30, 30–40, 40–50, 50–60, 60–70, and 70–80-cm soil layers. It was measured once before and after each growth period. Two monitoring points were selected in each district as shown in *Figure 6* (monitoring point 1 was arranged at the outflow micropore; monitoring points 2 was arranged at distance m between the two groups of micropore in the vertical flow direction, where m = 25 cm). Water consumption (ET_a) and crop water use efficiency (WUE) were calculated using formula (*Eq.2*) and (*Eq.3*), respectively (Du et al., 2017).
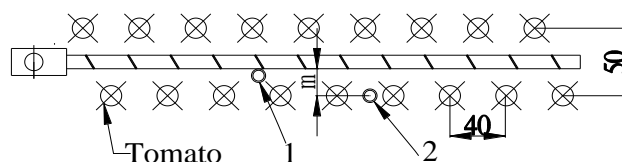
Figure 6. *Schematic diagram of capillary and TRIME pipe arrangement (unit: cm)*

$$ET_a = I \pm 1000 \times H \times (\theta_{t1} - \theta_{t2}) \qquad (Eq.2)$$

In the formula, ET_a represents crop water consumption during growth period (mm); *I* represents the irrigation quota of crop growth period (mm); *H* represents the depth of the wetting layer with plan (H = 0.8 m); θ_{t1} and θ_{t2} represent 80-cm average soil volumetric water content at times $t1$ and $t2$ (cm^3/cm^3), respectively.

$$WUE = Y/ET_a \qquad (Eq.3)$$

In the formula, *WUE* indicates crop water use efficiency (kg/m^3); *Y* indicates crop grain yield (kg/hm^2).

Standardization and homogenization of raw data

In order to eliminate the influence of different evaluation indices dimensions, first standardize the data, and at the same time, in order to ensure that the evaluation indices has the same direction, it is also necessary to carry out the same chemotactic treatment of the data, reference to "Effect of planting row spacing and irrigation amount on comprehensive quality of short-season cultivation tomato in solar greenhouse in northwest china" (Wu et al., 2018), which is convenient for the selection of reference vectors when constructing the comprehensive benefit evaluation model by TOPSIS method.

Data analysis

Data was tested for normal distribution, which was followed by evaluation of the differences between groups, using SPSS22.0 (IBM Crop., Armonk, NY, USA). F test was

used and the significant level was set to $P < 0.05$. OriginPro2019 (Origin Lab Corporation, Northampton, MA, USA) was used to draw plots. Except for special annotations, the data are visualized by showing averages ± standard deviations.

Results

Effects of different treatments on plant height, stem diameter, and leaf area indexes on plant growth of tomato

Table 2 shows the effects of different treatments on PH, SD, and LAI of tomato. With progressing tomato growth, PH and LAI increased first and then decreased, while SD increased. The PH, SD, and LAI of L1C2 were higher than those of CK1 and CK2 by 7.34% and 0.13%, 8.32% and 4.69%, 22.95% and 2.76%, respectively. With decreasing capillary arrangement density, PH, SD, and LAI of tomato decreased, and no significant difference was found between C1 and C2 ($P > 0.05$). C1 and C2 were significantly higher than C3 by about 10.64% and 7.15%, 8.35% and 7.10%, 24.97% and 17.14% ($P < 0.05$), respectively. The PH, SD, and LAI of 30 cm tomato were 1.04, 1.03, and 1.14 times that of the 50 cm micropores group spacing.

Table 2. Experimental factor and design Effects of different treatments on PH, SD and LAI

Indices	Treatment	26 days after planting	51 days after planting	73 days after planting	110 days after planting
PH	L1C1	41.96±3.62a	105.12±12.5a	137.2±7.03a	137.13±9.01a
	L1C2	41.72±2.05a	102.47±12.84a	135.17±13.79ab	135.47±14.85a
	L1C3	37.18±2.98bc	95.54±25.77ab	127.08±18.08ab	128.53±14.58ab
	L2C1	40.54±2.24abc	103.09±14.44a	135.28±14.51ab	135.88±12.12ab
	L2C2	38.39±4.38abc	98.13±8.89ab	128.62±8.47ab	129.86±6.36ab
	L2C3	36.43±4.79c	84.49±10.61b	123.79±13.8b	122.73±13.73b
	CK1	37.74±6.66abc	87.09±13.41b	130.88±4.8ab	130.74±3.63ab
	CK2	41.42±3.94ab	103.27±8.84a	134.51±8.44ab	135.08±5.94a
SD	L1C1	8.71±1.13a	10.25±1.28a	12.02±1.21a	12.5±1.18ab
	L1C2	8.93±1.22a	10.65±1.05a	12.32±0.25a	12.88±0.91a
	L1C3	8.29±1.67a	9.9±1.75a	11.78±1.03a	11.54±1.4b
	L2C1	8.84±1.74a	10.5±1.14a	12.46±0.75a	12.31±0.89ab
	L2C2	8.69±1.19a	9.82±1.11a	11.66±0.55a	11.64±0.59b
	L2C3	8.16±1.84a	9.41±1.47a	11.49±0.99a	10.28±0.93b
	CK1	8.4±1.75a	9.42±0.86a	11.68±1.43a	11.83±0.48b
	CK2	8.48±1.58a	10.12±0.85a	11.89±0.87a	12.29±0.81ab
LAI	L1C1	0.97±0.09ab	2.89±0.26a	8.05±0.69a	7.5±0.53a
	L1C2	1.0±0.13a	2.85±0.25ab	8.07±1.04a	7.46±0.54a
	L1C3	0.93±0.12ab	2.58±0.29cd	6.59±2.12cd	6.43±1.57bc
	L2C1	0.89±0.1bc	2.66±0.25bc	7.61±0.67abc	7.36±1.1a
	L2C2	0.82±0.05c	2.4±0.12d	7±1.38abc	5.97±0.76c
	L2C3	0.84±0.02c	2.34±0.06e	5.66±0.82d	4.98±0.27d
	CK1	0.81±0.05c	2.33±0.17e	6.72±1.3bcd	5.9±0.55c
	CK2	0.95±0.08ab	2.89±0.21a	7.92±1.09ab	7.09±1.17ab

Note: PH, Plant height; SD, Stem diameter; LAI, Leaf area indexes, the data are all average ±standard deviation in the chart, different letters in the same column meant significant difference at 0.05 level, the same as blow

Effects of different treatments on tomato quality

In terms of fruit shape indexes (*Table 3*), compared with CK1 and CK2, SFW, VD, and TD of L1C2 increased by 28.38% and 5.66%, 11.70% and 4.69%, 14.43% and 1.67%, respectively. Under the same irrigation amount, with decreasing capillary arrangement density, the SFW, VD, and TD of tomato followed a decreasing trend, and decreased by about 34.10%, 16.38%, and 9.98%, respectively. The SFW, VD, and TD in the 30 cm micropores group spacing were 1.20, 1.04, and 1.10 times higher than that of the 50 cm micropores group spacing.

In terms of fruit flavor indexes (*Table 3*), compared with CK1, the TSS, TSU, and SAR of L1C2 decreased by 0.32%, 3.30%, and 0.31%, respectively. Compared with CK2, the TSS, TSU, and SAR of L1C2 increased by 20.00%, 12.35%, and 26.63%, respectively. The spacing of micropores significantly affected the TSS of tomato ($P < 0.05$), and the capillary arrangement density significantly affected both TSS and SAR ($P < 0.05$). In the micropores group with 30 cm spacing, TSS, TSU, and SAR were 1.06, 1.04, and 1.02 times higher than that of 50 cm spacing. Under the same irrigation amount, TSS, TSU, and SAR increased by 15.38%, 10.30%, and 23.75%, respectively, with decreasing capillary arrangement density.

In terms of fruit nutritional indexes (*Table 3*), compared with CK1, L1C2 tomato flavor indices SP, VC, and LY decreased by 0.12%, 0.08%, and 2.67%, respectively; compared with CK2, these increased by 0.02%, 18.39%, and 9.40%, respectively. The micropores group spacing significantly affected the VC of tomato ($P < 0.05$), and the capillary arrangement density significantly affected the SP, VC, and LY ($P < 0.05$). In the 30 cm micropores group spacing, SP, VC, and LY were 1.05, 1.13, and 0.99 times as much as that of the 50 cm spacing. Under the same irrigation amount, the SP, VC, and LY increased by 8.72%, 16.07%, and 13.28%, respectively, with decreasing capillary arrangement density.
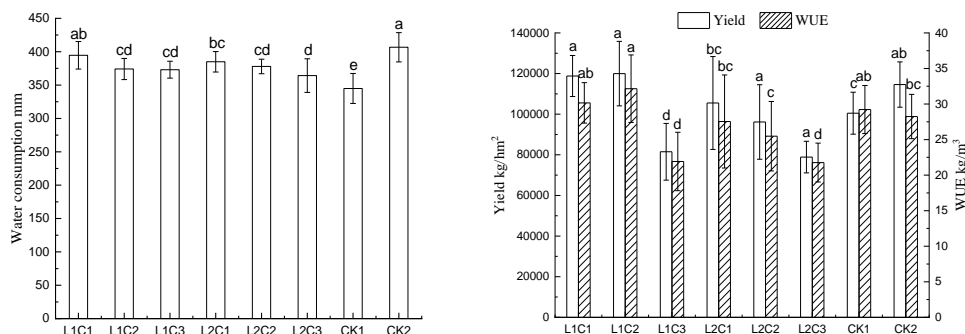
Effects of different treatments on water consumption, yield, and water use efficiency of tomato

Compared with CK1, the water consumption and yield of L1C2 was significantly higher than 8.46%, 19.39% ($P < 0.05$), and there was no significant difference in the improvement of WUE (10.03%, $P > 0.05$; *Fig. 7*). Compared with CK2, there was no significant difference in the increase of L1C2 yield (4.69%, $P > 0.05$); however, the water consumption was significantly decreased by 8.01% ($P < 0.05$) and WUE was significantly increased by 13.87% ($P < 0.05$). Compared with L1C1, L1C3, L2C1, L2C2, and L2C3, the yield and WUE of L1C2 increased by 0.99% and 0.99%, 47.18% and 47.18%, 13.69% and 13.69%, 24.74% and 24.74%, as well as 52.08% and 52.08%, respectively. At the same time, the micropores group spacing and capillary arrangement density significantly affected yield and WUE ($P < 0.05$), and the interaction of both factors had significant effects on WUE ($P < 0.05$). With decreasing capillary arrangement density, the water consumption, yield, and WUE of tomato decreased. The yield and WUE of C1 and C2 were significantly higher than those of C3 by about 39.85% and 34.76%, 32.10% and 31.94% ($P < 0.05$); however, there was no significant difference in yield and WUE between C1 and C2 ($P > 0.05$). The water consumption, yield, and WUE of the 30 cm micropores group spacing were 1.01, 1.14, and 1.13 times higher than that of the 50 cm micropores group spacing.

Table 3. *Effects of different treatments on the quality of greenhouse tomato*

Treatment	Shape indices			Flavor indices			Nutritional indices		
	SFW g	VD mm	TD mm	TSS %	TSU%	SAR	SP mg/g	VC mg/g	LY %
L1C1	138.56±21.99a	56.7±7.24a	64.28±8.36a	4.14±0.39d	6.97±1.34a	6.62±0.96bc	5.19±0.67ab	15.98±2.28bc	54.36±10.32b
L1C2	139.42±25.75a	57.86±4.17a	66.28±5.06a	5.17±0.66a	7.75±1.6a	8.2±1.61ab	5.39±0.39ab	19.19±2.44a	62.48±8.15ab
L1C3	106.59±43.91ab	52.09±3.88ab	58.93±10.33ab	4.92±0.47ab	7.87±1.47a	8.54±2.03a	5.63±0.48a	19.1±2.63a	65.58±11.39a
L2C1	119.65±31.97ab	58.88±7.19a	59.28±5.14ab	4.07±0.53d	6.84±1.32a	6.34±2.15c	4.89±0.56b	14.63±1.46c	58.75±10.13ab
L2C2	113.92±45.17ab	53.21±7.72ab	59.58±7.86ab	4.57±0.13bc	7.39±1.25a	8.19±1.71ab	5.15±0.47ab	16.22±1.55bc	60.48±8.59ab
L2C3	85.96±55.67b	47.23±11.69b	53.52±11.13ab	4.79±0.17ab	7.53±1.06a	8.45±1.2a	5.42±0.51ab	17.38±2.89ab	64.85±9.05a
CK1	108.6±49.35ab	51.8±10.09ab	57.92±11.04b	5.19±0.56a	8.01±1.7a	8.23±0.47ab	5.39±0.51aab	19.21±2.07a	64.15±9.75ab
CK2	131.95±33.22a	55.26±6.05a	65.19±7.21a	4.31±0.38cd	6.9±1.7a	6.48±1.8c	5.39±0.25ab	16.21±1.91bc	57.11±7.26ab
F-value									
L	1.4353ns (2.9)	6.368* (11.7)	0.618ns (1.3)	5.112*(9.6)	0.569ns(1.2)	0.079ns(0.2)	3.022ns(5.9)	10.651**(18.2)	0.044ns(0.1)
C	5.722** (19.3)	3.355* (12.3)	15.539** (39.3)	17.943**(42.8)	1.787ns(6.9)	7.698**(24.3)	3.833*(13.8)	8.513**(26.2)	3.633*(13.1)
L×C	1.301ns (5.1)	0.950ns (0.2)	11.741** (32.9)	2.044ns(7.8)	0.036ns(0.2)	0.031ns(0.1)	0.033ns(0.1)	0.628ns(2.5)	0.551ns(2.2)

Notes: SFW, Single fruit weight; VH, Vertical height; TD, Transverse diameter; TSS, Total soluble solids; TSU, Total soluble sugar; SAR, Sugar / acid content ratio; SP, Soluble protein; Vc, Vitamin C; LY, Lycopene; the bracketed number is total variance relative contribution %, *: $P < 0.05$; **: $P < 0.01$; ns: $P > 0.05$

Figure 7. *Effects of different treatments on tomato water consumption, yield and WUE. Note: the data are all average ±standard deviation in the figure, different letters in the same column meant significant difference at 0.05 level, the same as blow*

Optimal evaluation of comprehensive benefit of tomato quality, yield and water use efficiency based on the technique for order preference by similarity to an ideal solution method

The SFW, VD, TD, TSS, SP, TSU, VC, LY, SAR, yield, and WUE of tomato were selected as evaluation variables in *Table 4*. Firstly, these 11 indexes were weighted by Criteria Importance Though Intercrieria Correlation (CRITIC) method (*Table 4*). The calculation method is referred to the "effect of planting row spacing and irrigation amount on comprehensive quality of short-season cultivation tomato in solar greenhouse in northwest China" (Wu et al., 2018). The comprehensive benefit evaluation model is constructed by the TOPSIS method (*Table 5*), and the calculation method is referred to "optimizing irrigation frequency and amount to balance yield, fruit quality and WUE of greenhouse tomato" (Liu et al., 2019). The order of weight obtained by the CRITIC method was as follows: Yield > SFW > SAR > WUE > VD > LY > VC > TSS > TD > TSU > SP, among which, the yield weight was highest (0.150). The evaluation results of the TOPSIS comprehensive benefit evaluation model showed that the comprehensive benefit of L1C2 was best ($C_i = 0.939$), followed by L1C1. The comprehensive benefit of drip irrigation under mulch ranked 4th, and micro-sprinkler irrigation ranked 3rd.

Table 4. *Weighting values of each evaluation indices*

Indices	SFW	VD	TD	TSS	TSU	SAR	SP	VC	LY	Yield	WUE
Weight	0.144	0.081	0.067	0.074	0.054	0.124	0.040	0.076	0.070	0.150	0.120

Table 5. *The ranking of irrigation schedule calculated using TOPSIS for all the treatments*

Treatment	D⁺	D⁻	C_i	Ranking
L1C1	0.015	0.034	0.696	2
L1C2	0.003	0.039	0.939	1
L1C3	0.029	0.019	0.388	7
L2C1	0.021	0.023	0.518	5
L2C2	0.021	0.020	0.490	6
L2C3	0.036	0.014	0.282	8
CK1	0.018	0.024	0.575	4
CK2	0.016	0.030	0.647	3

Discussion

### *Effects of irrigation methods on quality and yield of greenhouse tomato*

The yield and WUE of tomato plants under MSPF were 19.39% and 10.03% higher compared with drip irrigation under plastic film (*Fig. 7*). This may be because the flow rate of MSPF was about 45 times higher than that of the single group with drip irrigation under plastic film and identical working pressure. Under identical irrigation amount, the flow rate of the single group of MSPF exceeded that of drip irrigation with smaller orifice flow, and the irrigation time was shorter, so that the ratio of soil water horizontal to vertical migration distance increased. The larger surface wetting area increases the wetting volume and irrigation uniformity per unit area of the tillage layer, and decreases the deep transport of soil water (Topp, 1969; Zotarelli et al., 2009; Elmaloglou and Diamantopoulos, 2010; Selim et al., 2013). The average soil volume moisture content of the 0-40 cm soil layer under MSPF was 9.34% higher than that of drip irrigation under plastic film (*Fig. 8*) and root dry matter accumulation (*Fig. 9*). This provided a strong guarantee for the stable yield of greenhouse tomato (Ould et al., 2001), resulting in higher yield of tomato under MSPF. However, because of the large surface wetting area of MSPF and the vigorous growth of tomato plants, soil water evaporation was further intensified. Compared with drip irrigation under plastic film, the water consumption of tomato under MSPF increased by 8.46% (*Fig. 7*). The yield increase of MSPF (19.39%) was about 2.29 times that of its water consumption (8.46%); therefore, the WUE of crops under MSPF was higher than that of drip irrigation under plastic film. This study found that TSS, TSU, SAR, SP, VC, and LY of MSPF decreased by 0.32%, 3.30%, 0.31%, 0.12%, 0.08%, and 2.67% compared with drip irrigation under plastic film. This may be due to the higher moisture content of tomato fruits under MSPF and excessive water dilution of fruit flavor and nutrition index content per unit mass. This is consistent with previous studies, which showed that with increasing irrigation water, the soil volume and water content increased, which reduce the tomato fruit flavor and nutritional content (Topp, 1969; Meek et al., 1992; Li et al., 2020).
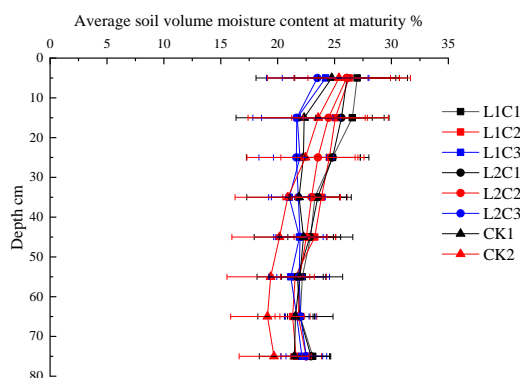

Figure 8. Average soil volume moisture content in different treatments at mature stage (70 days after transplant). Note: the data are all average ±standard deviation in the figure

Compared with micro-sprinkler irrigation, the yield of tomato under MSPF increased by 4.69%, because the micro-sprinkling irrigation water flows through the capillary pipe and is sprayed out through the micropore water flow on the capillary pipe wall. The spray height reached more than 1 m under normal working pressure. The spray water flow could

easily be atomized and increase air humidity, thus resulting in tomato canopy humidity as high as 70%, which is 1.56 times higher than that of MSPF (*Fig. 10*). Previous studies have shown that high-humidity environments can easily cause leaf moisture condensation, leaf cell rupture, decreased leaf photosynthesis, limited dry matter accumulation, and delayed fruit morphological development (Mortensen, 1992; Panchal et al., 2016). It is also possible that under the same amount of irrigation, part of the water is used to increase air humidity, which decreases soil water infiltration. The average volumetric moisture content of the 0-40 cm soil during the mature period was 7.48% lower than that of MSPF (*Fig. 8*). The lower soil volumetric moisture content decreased the increase of tomato yield. This study found that the WUE of tomato under MSPF was significantly higher (by 13.87%) than that of micro-sprinkler irrigation. This may be because the yield of micro-sprinkler irrigation was lower than that of MSPF, and the water consumption of tomato under MSPF was significantly lower than that of micro-sprinkler irrigation (by 8.01%; *Fig. 7*). This study also showed that the related indexes of tomato flavor and nutrition in micro-sprinkler irrigation were lower than those of MSPF. This may be due to the atomization of water droplets in micro-sprinkler irrigation, which increases air humidity and decreases the temperature difference between day and night in the greenhouse; these effects are not conducive to the accumulation of tomato flavor and nutritional indexes (Max et al., 2009; Luo et al., 2016; Sun et al., 2016).
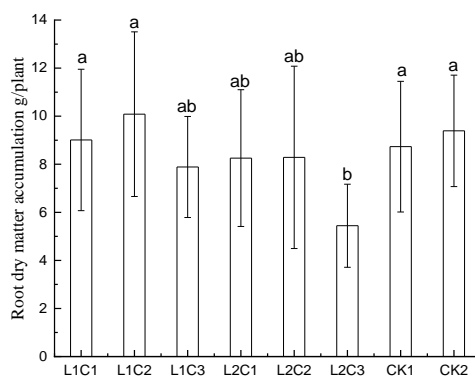
Figure 9. Effects of MSPF on dry matter accumulation of tomato root during mature stage. Note: the data are all average ±standard deviation in the figure, different letters in the same column meant significant difference at 0.05 level, the same as blow
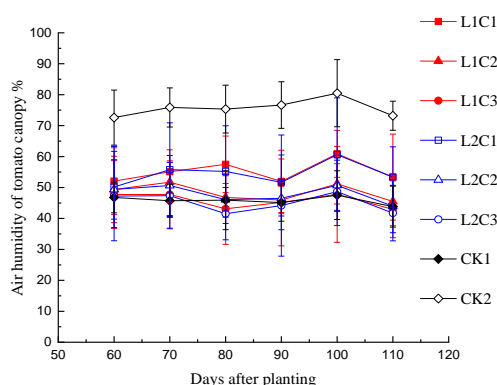
Figure 10. Effects of different treatments on air humidity in tomato canopy. Note: the data are all average ±standard deviation in the figure

Effects of micropores group spacing on quality and yield of greenhouse tomato

This study found that the PH, SD, LAI, and yield of tomato plants with the 30 cm micropores group spacing were better than that of those with 50 cm (*Table 2*). Maybe, the influence of the change of micropores group spacing with MSPF on the soil wetting body is similar to that of dripper spacing with drip irrigation under plastic film, and a phenomenon of intersection of wetting peaks between two groups of adjacent micropores on the capillary pipe was identified. The difference is that under the same working pressure and amount of irrigation, the single group flow of MSPF is higher than that of drip irrigation. Moreover, a larger flow rate easily increases the ratio of horizontal to vertical migration distance of soil water wetting peak. Shortening the confluence time of adjacent wetting peaks is beneficial to the overall deep transport of soil water between the two groups of micropores in the capillary, and improves the soil volume moisture content and irrigation uniformity in the tillage layer per unit area (Ould et al., 2001; Del et al., 2020). Diameter measurement showed that the 30 cm micropores group achieved better tomato maturity than that of the 50 cm micropore group, the average soil volume moisture content of the 0-40 cm soil layer increased by 1.60% (*Fig. 8*), and the higher soil volume moisture content of the tillage layer provided a strong guarantee for tomato growth (Abdelhafeez et al., 1975; Silveira et al., 2020). This is consistent with the conclusion that PH, SD, LAI, and yield of pomegranate, as studied by Meshram et al. (2019), were higher than that of 50 cm.

The present study showed that micropores group spacing had a significant effect on tomato yield. Wang et al. (2005), did not find a significant difference in cucumber yield between 50 and 30 cm drippers spacing when drip irrigation was used, which may be due to the different amounts of irrigation in their experiment. In this study, the irrigation amount was controlled by evaporation pan, and the cumulative amount of irrigation was 353 mm, while Wang controlled the lower limit of soil irrigation and irrigated 385 mm during the growth period. Enciso et al. (2007) found no significant difference in onion yield under different dripper spacings, and the conclusion that the micropores group spacing had a significant effect on tomato yield, as found in this study, is also inconsistent. Because the maximum spacing of dripper set by Enciso was 30 cm (which was much smaller than 50 cm in this study), the soil water distribution was uniform, and could not easily cause yield differences because of drought stress on crops (Ould et al., 2001; Jiménez et al., 2010). Furthermore, the WUE of micropores group spacing at 30 cm was 1.13 times higher than that of 50 cm (*Fig. 7*). It is possible that the soil volume of the tillage layer with a micropores group spacing of 30 cm is moist and uniform, and there is no obvious high water and bottom water area, which can accurately and in time meet the water demand of plants (Li et al., 2018b), resulting in a significant increase in tomato yield. At the same time, the water consumption of the 30 cm micropores group spacing did not significantly increase (*Fig. 7*), and finally showed a significant improvement in WUE (Wang et al., 2005; Li et al., 2019c). Elmaloglou and Diamantopoulos (2010) suggested that decreased dripper spacing can shorten irrigation duration and improve irrigation efficiency, which is consistent with the conclusion that reducing the micropores group spacing to 30 cm can improve WUE.

Previous studies found that too high or too low soil moisture can decrease the contents of soluble solids, VC, and lycopene (Wu et al., 2018). This study showed that the flavor and nutrition of tomato with the 30 cm micropores group spacing were better than that of 50 cm, indicating that the soil moisture distribution at 30 cm micropores group spacing was more suitable spacing for greenhouse tomato under MSPF. This study also found that

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micropores group spacing had a significant effect on tomato TSS, which was inconsistent with the conclusion of Enciso et al. (2007) who reported that dripper spacing had no significant effect on onion solids. The reason for this difference is mainly because all water required by tomato plants originated from irrigation water, while Enciso's onion water requirements were also met by rainfall, which could provide similar irrigation water and optimal soil moisture conditions in all treatments.

Effects of capillary arrangement density on tomato quality and yield in greenhouse

The study of the capillary arrangement density of tomato in the greenhouse showed that the PH, SD, LAI, yield, and water consumption of tomato plants decreased with decreasing capillary arrangement density. Because the same single group flow rate, micropores group spacing, and irrigation amount were used, the higher the capillary arrangement density, the higher the amount of flow per unit area. This makes it easy to increase the surface wetting area, which is conducive to the overall decreasing movement of surface soil moisture and decreases the deep migration of soil moisture. The average soil volume moisture content of one tube and two rows of tillage layer (0-40 cm) was significantly higher than that of one tube and three rows (*Fig. 8*). The higher soil volume moisture content in the higher tillage layer provides a strong guarantee for the growth and stable yield of tomato (Tracy et al., 2013).

With the decrease of capillary arrangement density, a lower surface wetting rate can easily reduce soil ineffective water evapotranspiration, and the lower LAI decreases leaf transpiration, resulting in decreased tomato water consumption. Wang et al. (2018a) found that the yield of tomato under greenhouse drip irrigation increased first and then decreased with decreasing capillary arrangement density. This was inconsistent with the decreasing trend the tomato yield showed in this study, which was mainly because of the different of soil types and irrigators used, and possibly also because of differences of capillary arrangement density used for drip irrigation. In this study, the arrangement of one tube and two rows was the maximum spacing of Wang's drip irrigation. With regard to the differences of tomato yield between three tubes for four rows and one tube and two rows with MSPF, further experiments are needed. The bermudagrass yield of Cantrell et al. (2009), the spring wheat yield of Lv et al. (2019), and the maize yield of Bozkurt et al. (2006) for drip irrigation decreased with decreasing capillary arrangement density. This conclusion is consistent with the conclusion of tomato yield with MSPF in this study.

Furthermore, TSS, TSU, SP, VC, and LY increased with decreasing capillary arrangement density (*Table 3*), which may be because under the same irrigation amount, the smaller the capillary arrangement density was, the longer the irrigation duration was. This aggravated the deep soil water transport and decreased the soil volume moisture content per unit area, thus resulting in a decrease of tomato fruit moisture content and increases of TSS, TSU, SP, VC, and LY concentration per unit weight tomato fruit (Patanè and Cosentino, 2010; Wang et al., 2018a,b). Wang et al. (2018a) found that the SAR of muskmelon in northwest China increased with decreasing capillary arrangement density under drip irrigation, which was consistent with the conclusion of SAR of tomato fruit in this study. This indicates that the effect of capillary arrangement density of micro-sprinkler irrigation on tomato taste was consistent with that of drip irrigation in this area.

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Conclusions

Under the same amount of irrigation, the spring and autumn tomato growth, fruit morphology, yield, and WUE were better with MSPF than with drip irrigation and micro-sprinkler irrigation. Improvements were about 7.34% and 0.13%, 8.32% and 4.69%, 22.95% and 2.76%, 28.38% and 5.66%, 11.70% and 4.69%, as well as 14.43% and 1.67%, respectively. Compared with drip irrigation under plastic film, no significant decreases in fruit flavor and nutrition were found. TSS and VC were significantly higher than that of micro-sprinkler irrigation by about 20.00% and 19.39%, indicating that MSPF was suitable for greenhouse tomato irrigation. With decreasing capillary arrangement density, tomato growth, fruit shape, yield, and WUE decreased, while tomato fruit flavor and nutrition increased. Compared with 50 cm micropores group spacing, 30 cm was beneficial for tomato growth, fruit quality, yield, and WUE. The comprehensive benefit evaluation model of tomato quality, yield, and WUE by the TOPSIS method and the comprehensive evaluation results of yield and WUE identified the L1C2 treatment as better. With the goal of improving WUE and low-cost investment without significantly reducing yield, it is recommended to use a combination of one pipe for two rows with a micropores group spacing of 30 cm in arid and semi-arid sandy loam soils. This study provides a theoretical basis and data support for the large-scale promotion of MSPF. While the presented results describe the optimum irrigation if the row spacing is 50 cm, but it remains an open question that the further experiments are needed to investigate other row spacings.

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