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Research Article

Effect of Microsprinkler Irrigation under Plastic Film on Photosynthesis and Fruit Yield of Greenhouse Tomato

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The aim of this study is to exam the effect of microsprinkler irrigation technology under plastic film (MSPF) and to evaluate the reasonable micropore group spacing and capillary arrangement density in the greenhouse. Compared with drip irrigation under plastic film (DIPF) and microsprinkling irrigation (MSI) conditions, the effects of different micropore group spacing (L1: 30 cm micropore group spacing, L2: 50 cm micropore 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 photosynthetic characteristics and fruit yield of tomatoes were studied using completely randomized trial design. The results showed that under the same irrigation amount, compared with DIPF and MSI, the photosynthetic rate of tomatoes treated with L1C2 increased by 8.24% and 13.55%, respectively. The total dry matter accumulation, yield, and water use efficiency at condition of L1C2 increased by 12.16%, 19.39%, and 10.03% compared with DIPF and 26.38%, 20.46%, and 31.02% compared with MSI, respectively. The results provide evidence that the MSPF can be applied to greenhouse tomatoes. The photosynthetic rate, total dry matter accumulation, yield, and water use efficiency of tomato leaves cultivated at a micropore group spacing of 30 cm were 1.07, 1.13, 1.14, and 1.13 times higher than those of 50 cm, respectively. With the decrease in capillary arrangement density, the photosynthetic characteristics of the tomato leaves, the total dry matter accumulation, and yield of tomatoes all experienced a decline. It is recommended to use a combination of one pipe for two rows of capillaries at a 30 cm micropore group spacing as the technical parameter of greenhouse tomato with MSPF in arid and semiarid sandy loam soils.

1. Introduction

The development of facility agriculture provides a strong guarantee for vegetable production in arid and semiarid sandy loam. However, the irrigation water for facility agriculture in this area mainly comes from groundwater, and the resulting development of groundwater resources aggravates the water crisis in these arid and semiarid areas, so there is an urgent need to alleviate the overuse of irrigation water in this area [1]. Saving water resources has become a current research hotspot. As a common irrigation method of tomato in this area, drip irrigation is an advantageous approach owing to its water-saving, fertilizer-saving, and labor-saving features. It has been widely used to cultivate tomato, pepper, melon, and other crops [2–4]. Owing to the existence of sediment, chemical precipitates, or biomass in the irrigation water body, it is easy to cause blockage of drip irrigation system, reduce irrigation uniformity, reduce crop yield, increase cost, and so on [5, 6]. Drip irrigation belongs to local irrigation, and the soil wetting body per unit plough layer is limited, which restricts the growth of crop roots [7, 8].

Microsprinkler 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) [9]. The energy dissipation structure of the emitter is removed. Under the same working pressure, the flow rate of microsprinkler irrigation is about 15 times that of labyrinth drip irrigation, and it has a strong sediment-carrying capacity and anticlogging performance. This technique can solve the clogging problem of drip irrigation emitters [5, 6].

At the same time, the flow rate of a single microsprinkler is much higher than that of drip irrigation, which is easy to increase the ratio of soil water peak horizontal to vertical migration distance and improve the water uniformity of soil wetting body and unit tillage layer [10, 11]. It has advantages of decreasing the restriction of horizontal root growth and short irrigation duration [12, 13]. For this reason, microsprinkler irrigation has achieved good results with total growth amount and yield in winter wheat, summer corn, lawn, seedlings, and other crops [12, 14–16]. However, the shape, area, and uniformity of soil wetting in the microsprinkler irrigation area are affected by wind speed. In addition, there are still some problems, such as difficulties in weed control and high damage rate of microsprinklers, which hinder the treatment of microsprinkler irrigation [17–19]. The development of facility agriculture provides a good application environment for microsprinkler irrigation, such as flat land, wind-free chamber, and short capillary laying distance [20]. However, the facility agricultural space is relatively closed, and microsprinkler irrigation spray atomization is easy to increase air humidity. High temperature and high humidity have been proved beneficial to the occurrence of crop diseases and insect pests [21–23], resulting in less use of microsprinkler irrigation in facility agriculture. Plastic film mulching provides a solution for the application of microsprinkler irrigation in facility agriculture. Plastic film mulching can restrain the water jet of microsprinkler irrigation, reduce spray atomization and ineffective evaporation, and improve the utilization efficiency of irrigation water [24, 25]. Therefore, the combination of microsprinkler irrigation and plastic film technology can make up for the deficiency of micropores used in the greenhouse. This technique is called microsprinkler irrigation under plastic film (MSPF, see Figure 1). The exploration of MSPF is of great significance for enriching the greenhouse microirrigation technology system, reducing crop water requirement, and improving crop yield and quality.

Figure 1: Microsprinkler irrigation under plastic film (MSPF).

Tomato, as one of the main vegetables grown in facility agriculture, has rich nutritional value [26, 27]. Photosynthesis is the basis of tomato growth, increasing yield and improving quality. Photosynthesis is affected by heredity, leaf age, leaf angle, leaf shape, and other internal factors, also affected by the external environment, soil water content is one of the main influencing factors of the external environment [18, 28]. In production practice, farmers often use different ways of irrigation, which can not only save water resources but also change the form of irrigation water into the soil, which indirectly affects the distribution of water in the soil and near the ground. Compared with conventional drip irrigation, drip irrigation under plastic film can change soil microenvironment, increase soil volume water content, and help to increase photosynthesis and yield [29]. The emitter spacing of the pipe and capillary arrangement density of the pipe directly determine the distribution of water in the irrigated soil, altering the soil water use efficiency (WUE) and creating a microenvironment for plant growth. Consequently, a foundation was laid out for water-saving crops with high yield, a larger capillary arrangement density results in a more uniform horizontal water content distribution and a higher the leaf photosynthetic rate, chlorophyll, leaf area index, dry matter accumulation, and crop yield. However, the higher capillary arrangement density generally can increase investment cost and reduce crop WUE [8, 30–32]. Previous studies have also shown that different emitter spacing can adjust the volume shape and moisture of moist soil. At the same emitter flow rate, the time for the average soil moisture content between emitters to reach the peak is shorter. When the spacing between emitters is reduced from 80 to 30 cm, the horizontal wetting shape between emitters is approximately rectangular and the more uniform the wetting body is between the two emitter [11]. The application can reduce the irrigation water consumption, improving photosynthesis of leaves and the irrigation water utilization efficiency [33–35]. When the emitter spacing increased from 15 to 30 cm, the onion yield increased at first and then decreased [33–35].

At present, the related studies on crop photosynthetic characteristics, dry matter accumulation, yield, and WUE are mainly focused on emitter spacing and capillary arrangement density with a small flow rate of drip. However, there are few studies evaluating the effects of different micropore group spacing and capillary arrangement density of MSPF on photosynthetic characteristics, dry matter accumulation, yield, and WUE of greenhouse crops. As the focus of tomato yield research in this area, there are a variety of models for analyzing the effects on tomato yield, such as linear regression, principal component analysis, simple correlation analysis, and channel analysis [36–38]. Nonetheless, these methods are difficult to simultaneously obtain the strength of the causal relationships among multiple variables in the system. The AMOS structural equation provides a solution to determine the intensity of causality among multiple variables. It has been widely used in the social science field [39] and ecological field [40]. However, relatively few studies were performed to analyze the relationship between photosynthetic characteristics, dry matter accumulation, and yield of tomato by using AMOS structural equation under plastic film microsprinkler irrigation.

Therefore, this study intends to take the effects of drip irrigation under plastic film (DIPF) and microsprinkler irrigation (MSI) as controls to explore the effects of different micropore group spacing and capillary arrangement density on photosynthetic characteristics, dry matter accumulation, and yield of greenhouse tomato with the MSPF. The relationships among photosynthetic characteristics, dry matter accumulation, and yield of tomato in greenhouse under MSPF was determined by the AMOS structure equation. The most suitable capillary arrangement density and micropore group spacing combination model of MSPF for tomato in arid and semiarid sandy loam soil of facility agriculture was obtained. This paper provides findings for the enrichment of tomato microirrigation technology system and offers valuable data support and theoretical basis by greenhouse experiment data analysis for water saving, yield enhancement, and quality improvement of agricultural crops in this region.

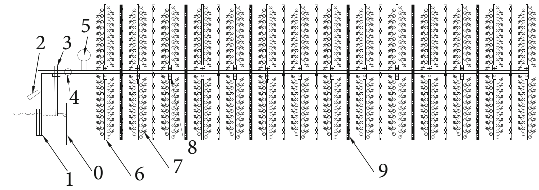

Figure 2: Schematic diagram of greenhouse layout. Note: 0: water tank; 1: the pump (WQD10-12-0.75S, PEOPLE PUMB, Corp., Shanghai, China); 2: filter; 3: backwater valve; 4: electromagnetic flowmeter; 5: pressure gauge; 6: capillary; 7: tomato; 8: capillary valve; 9: plastic screens.

2. Materials and Methods

2.1. Experimental Site and Management. The experiment was carried out from 27 March 2019 to 30 January 2020 in a greenhouse at the Modern Agricultural Science and Technology Exhibition Centre, Xi'an City, Shaanxi Province (108°52′E, 34°03′N). The region exhibits a warm temperate semihumid continental monsoon climate and located at an altitude of 435 m above sea level. The annual average temperature of the region is 13.3°C, and the annual average rainfall is 507.7–719.8 mm. The precipitation from August to October accounts for more than 60% of the annual precipitation and the frost-free period ranges from 219 to 233 days. 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. The width was 1.2 m. The irrigation plot is shown in Figure 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. 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. The microsprinkler pipe of MSPF (Hebei Plentirain Irrigation Equipment Technology Co., Ltd., Hebei, China) adopts thin-walled oblique 3 micropore with a diameter of 32 mm and a micropore diameter of 0.8 mm. The micropore group spacing is shown in the experimental design (see Table 1). The control drip irrigation under plastic film (DIPF, CK1, Hebei Plentirain Irrigation Equipment Technology Co., Ltd., Hebei, China) with thin-wall labyrinth tooth channel was selected. The geometric parameters of the channel were 54.3*1.1*0.83 mm^3, the distance between emitters was 30 cm, and the emitter flow rate was 2 L/h. The control microsprinkler irrigation (MSI, CK2, Hebei Plentirain Irrigation Equipment Technology Co. Ltd., Hebei, China) adopts thin-walled oblique 3 micropore pipe with a diameter of 32 mm and a micropore diameter of 0.8 mm. The micropore group spacing is 10 cm.

Tomato plants were topped when the four-eared fruit were retained, and the field management measures such as fertilizer irrigation, irrigation, and medicine were the same in all treatments. The irrigation water comes from the groundwater in this area. In order to ensure the survival of the seedlings on the day of planting, the irrigation was unified with reference to the local tomato planting experience. It was planted on March 27, 2019; the irrigation treatment began on April 4, 2019 and stopped on July 15, 2019.

2.2. Experimental Design. Two factors were considered in this study: micropore group spacing L (see Figure 3) and capillary arrangement density C (see Figure 4). The micropore 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) and one pipe for three rows (one capillary pipe irrigated three rows of crops, C3). One pipe for two rows were used for 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 (see Table 1).

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. and Liu et al. [41, 42]. 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 (1) [43], and the irrigation times and amounts were recorded (see Figure 5).

$$W = A \times E_{pan} \times k_{cp}, \tag{1}$$

where E_{pan} represents the evaporation within the interval

Table 1: Experimental factor and design.

No.	Treatment	Irrigation method	Micropore 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	DIPF	30	One pipe for two rows	
8	CK2	MSI	10	One pipe for two rows	

Note: *L*: micropore group spacing; *C*: capillary arrangement density.

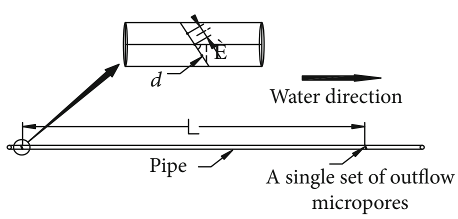

Figure 3: Schematic diagram of micropore group (inside) spacing structure parameters. Note: diameter of micropore is $d = 0.8$ mm. The internal spacing of the micropore group was $I = 0.4$ cm. The angle of micropores is 68°. The micropore group spacing is *L*.

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 [43].

2.3. Measurements and Computational Methods

2.3.1. Photosynthesis. Three conjoined healthy leaves with sufficient light and consistent leaf position were randomly selected, and the gas exchange parameters such as net photosynthetic rate (Pn), stomatal conductance (Gs), intercellular CO_2 concentration (Ci), and transpiration rate (Tr) were measured by the LI-6400 (Li-Cor, Inc., Lincoln, Nebraska, USA) automatic portable photosynthesis system. The CO_2 gas was collected from a relatively stable air of 2 ~ 3 m. The light intensity was set at 800 μmol/(m^2·s) and the flow rate was set at μmol/s. All the samples were measured at the time of 15, 29, 56, 79, 95, and 110 days after planting (DAP) [44].

2.3.2. Chlorophyll. The leaf pigment was extracted with acetone extract, and the absorption values were measured at 665 nm, 649 nm, and 470 nm by spectrophotometer colorimetry, and the contents of chlorophyll a, chlorophyll b, carotenoid, and chlorophyll (chlorophyll = chlorophyll a + chlorophyll b) were calculated, respectively [45]. The same leaf position was selected to determine the chlorophyll test and photosynthesis.

2.3.3. Dry Matter Accumulation. During the tomato maturity period (112 DAP), 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 stems, leaves, fruits, and roots were dried in an oven at 105°C for 15 min, followed by drying at 75°C to constant weight. Finally, the dry matter mass was obtained [46].

2.3.4. Yield and Water Use Efficiency. During the maturity 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 at different layers of soil (0–10, 10–20, 20–30, 30–40, 40–50, 50–60, 60–70, and 70–80 cm, respectively). 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 formulas (2) and (3), respectively [47]:

$$ET_a = I \pm 1000 \times H \times (\theta_{t1} - \theta_{t2}), \quad (2)$$

where 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), and θ_{t1} and θ_{t2} represent 80 cm average soil volumetric water contents at times $t1$ and $t2$ (cm^3/cm^3), respectively.

$$WUE = 1000 * \frac{Y}{ET_a}, \quad (3)$$

where *Y* indicates crop grain yield (t/hm^2).

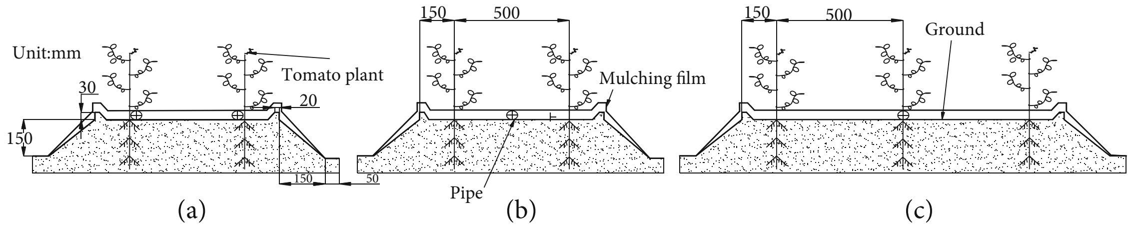

FIGURE 4: Schematic diagram of capillary arrangement: (a) one pipe for one row, (b) one pipe for two rows, and (c) one pipe for three rows.

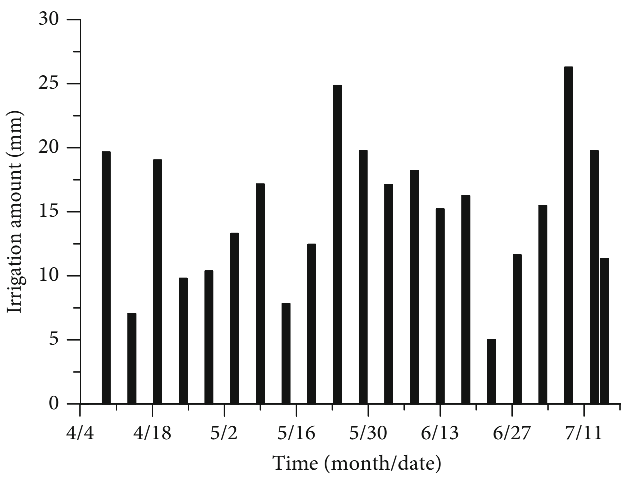

FIGURE 5: Irrigation records.

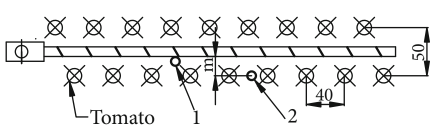

FIGURE 6: Schematic diagram of capillary and TRIME pipe arrangement (unit: cm).

2.3.5. AMOS Structural Equation Analysis. The mean value of photosynthetic rate (Pn), stomatal conductance (Gs), intercellular carbon dioxide concentration (Ci), transpiration rate (Tr), chlorophyll a, chlorophyll b, carotenoid of tomato leaves at 56, 79, 95, and 110 DAP, and total dry matter accumulation at maturity and yield at maturity were measured under MSPF. First of all, the reliability analysis was performed on 9 sets of data (alpha = 0.845, suggesting the reliability is good and AMOS structural equation analysis can be applied here); secondly, the averaging method is used for dimensional processing to eliminate the dimensional influence; finally, the AMOS structural equation analysis is carried out.

2.3.6. Meteorological and Field Microclimate Observations. The meteorological parameters such as air temperature, relative humidity, wind speed, solar radiation intensity, and precipitation were collected by automatic weather station.

2.3.7. Data Analysis. The significant differences between data were analyzed using SPSS22.0 (IBM Crop., Armonk, New York, NY, USA) with F test, and the significant level was set at $P < 0.05$. OriginPro2019 (Origin Lab Corporation, Northampton, MA, USA) was used to draw the picture. Except for special annotations, the data are all average ± standard deviation in the chart. AMOS25.0 (Amos Development Corporation, Chicago, IL, USA) was used to draw the structural equation.

3. Results

3.1. Photosynthetic Characteristics of Leaves. Figure 7 shows that the Pn of tomato leaves increased at first and then decreased with the increase of planting days and reached the peak at 72 DAP, and Pn showed a linear and rapid increasing trend from 13 to 56 DAP. One-way ANOVA showed that there were significant differences among treatments 56 days after planting. The mean values of 56, 79, 95, and 110 days after planting showed that L1C1 treatment was the best (20.478 μmol·m^{-2}·s^{-1}), followed by L1C2 treatment (19.92 μmol·m^{-2}·s^{-1}). The Pn of L1C2 treatment is higher than that of DIPF about 1.09%, 8.24% 1.67%, and 2.03% at 56, 72, 95, and 110 DAP, respectively. The Pn of L1C2 treatment is higher than that of MSI about 1.04%, 13.55%, 7.58%, and 8.94% at 56, 72, 95, and 110 DAP, respectively. The Pn of tomato leaves of 30 cm micropore group spacing was 1.04, 1.11, 1.07, and 1.07 times higher than that of 50 cm. With the decrease of capillary arrangement density, Pn showed a significant downward trend, in which the Pn of C3 was significantly lower than that of C1 and C2 about 12.01% and 7.91%, 14.35% and 10.55%, 15.48% and 12.20%, and 12.73% and 8.78%. The change trend of Gs is similar to that of Pn, because stomata are the main channels for gas exchange between plant leaves and the outside world; O_2, CO_2, and H_2O are diffused through stomata, and their closure directly affects Pn and Tr. The increasing trend of Tr was similar to that of Pn and Gs. In the same growth period of tomato, the stronger the Pn of leaves, the lower the Ci. With the advance of growth period, Ci increased at first and then decreased and reached the peak at 56 DAP.

3.2. Chlorophyll Content. Figure 8 shows that with the increase of planting days, chlorophyll a, chlorophyll b, carotenoid, and chlorophyll in tomato leaves increased at first and then decreased, reaching the peak about 79 DAP. The means of the leaf pigment measured at 56 DAP showed that chlorophyll a, chlorophyll b, carotenoids, and chlorophyll in L1C2 treatment were higher than those in DIPF and MSI about 3.56% and 16.86%, 0.99% and 1.20%, 1.21% and 1.50%, and

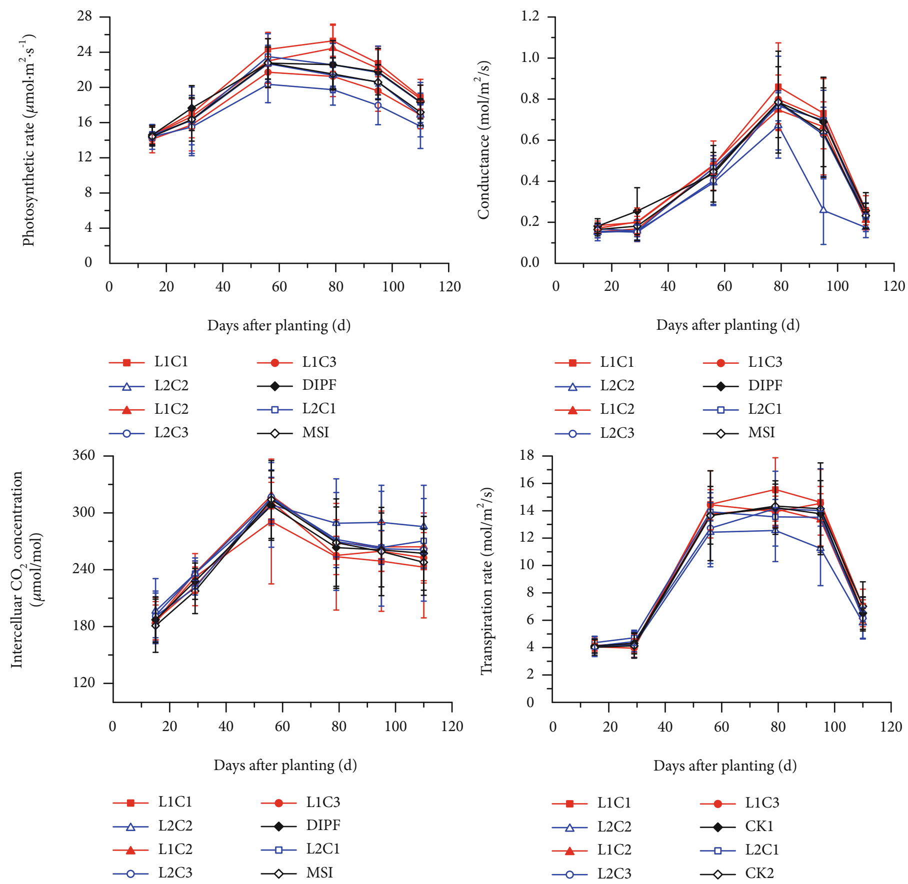

Figure 7: Effects of different treatments on photosynthetic characteristics of Tomato leaves. Note: the data are all average ± standard deviation in the figure.

1.04% and 1.12%, respectively. The levels of chlorophyll a, chlorophyll b, carotenoid, and chlorophyll of 30 cm micropore group spacing were about 13.22%, 9.47%, 15.75%, and 11.24% higher than those of 50 cm. With the decrease of capillary arrangement density, chlorophyll a, chlorophyll b, carotenoids, and chlorophyll showed a decreasing trend. Among them, the levels of chlorophyll a, chlorophyll b, carotenoids, and chlorophyll in C3 treatment were lower than those in C1 and C2 by 23.77% and 20.19%, 20.44% and 13.69%, 40.25% and 36.15%, and 21.27% and 19.76%, respectively.

3.3. Dry Matter Accumulation. Figure 9 shows that the accumulation of fruits, leaves, stems, roots, and total dry matter in L1C2 treatment were higher than those in DIPF and MSI about 6.46% and 14.84%, 7.84% and 18.53%, 10.56% and 30.05%, 24.56% and 24.93%, and 12.16% and 26.38%, respectively. The accumulations of fruit, leaf, stem, root, and total dry matter of tomatoes cultivated at a micropore group spacing of 30 cm were 1.15, 1.15, 1.10, 1.23, and 1.13 times as much as those cultivated at spacing of 50 cm. With the decrease in capillary arrangement density, the accumulation of fruit, leaf, stem, and total dry matter showed a decrease, while the accumulation of root dry matter increased at first and then decreased. The accumulation of fruit, leaf, stem, and total dry matter of C1 was significantly higher than that of C3 about 16.63%, 34.87%, 21.26%, 29.56%, and 32.04%, respectively. The accumulation of fruit, leaf, stem, and total dry matter of C2 was significantly higher than that of C3 about 30.57%, 29.62%, 36.63%, 37.83%, and 33.18%, respectively.

3.4. Yield and Water Use Efficiency. Table 2 shows that the relative contributions of micropore group spacing to yield, water consumption, and WUE were 16.30%, 2.10%, and 11.80%, respectively. The relative contributions of capillary arrangement density to yield, water consumption, and WUE were 47.40%, 21.6%, and 36.9%, respectively. The relative contributions of the interaction of 2 factors to yield, water consumption, and WUE were 7.70%, 3.30%, and 8.90%, respectively. Compared with L1C1, L1C3, L2C1, L2C2, and L2C3, the L1C2 of yield increased by about 0.99%, 47.18%, 13.69%, 24.74%, and 52.08%, respectively. Compared with L1C1, L1C3, L2C1, L2C2, and L2C3, the L1C2 of WUE increased by about 6.62%, 46.70%, 16.74%, 26.22%, and 47.76%, respectively.

The yield of L1C2 was significantly higher than that of DIPF by about 19.39%, and the WUE was improved (10.03%), but there was no significant difference; the yield was about 20.46% higher than that of MSI, and the WUE was significantly increased by 31.02%. The yield, water consumption, and WUE of tomato cultivated at a micropore

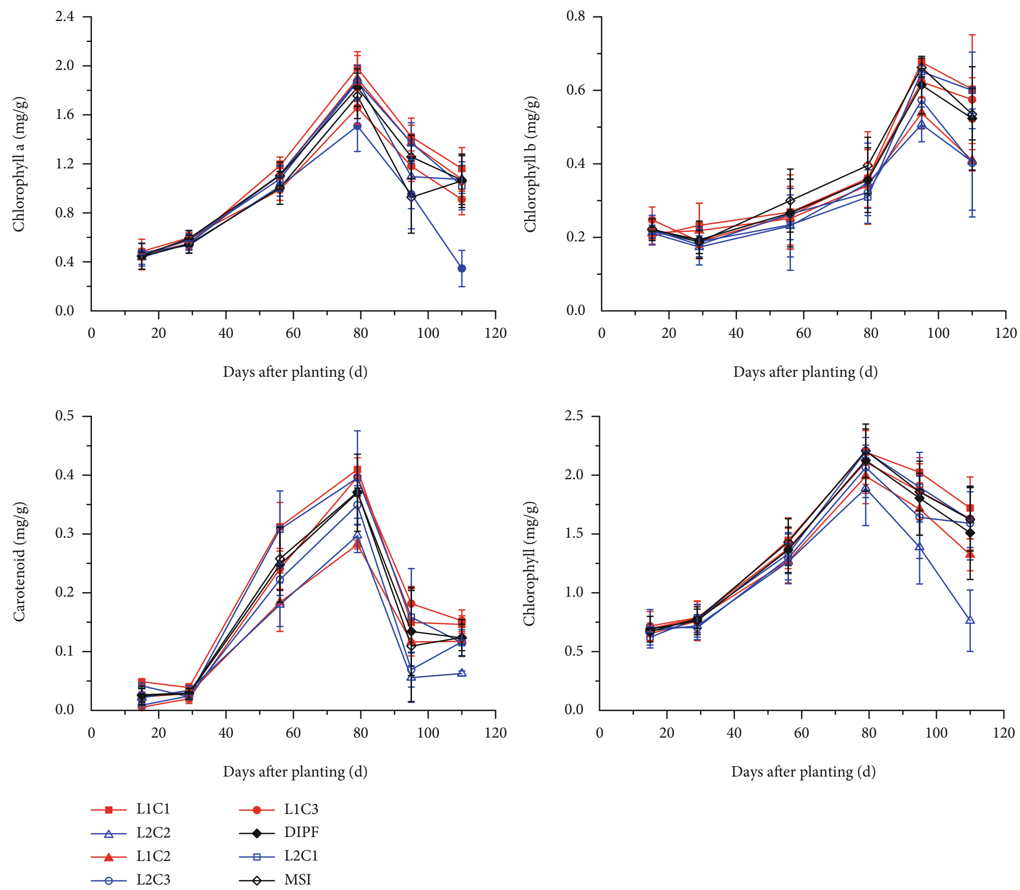

Figure 8: Effects of different treatments on chlorophyll content of functional leaves. Note: the data are all average ± standard deviation in the figure.

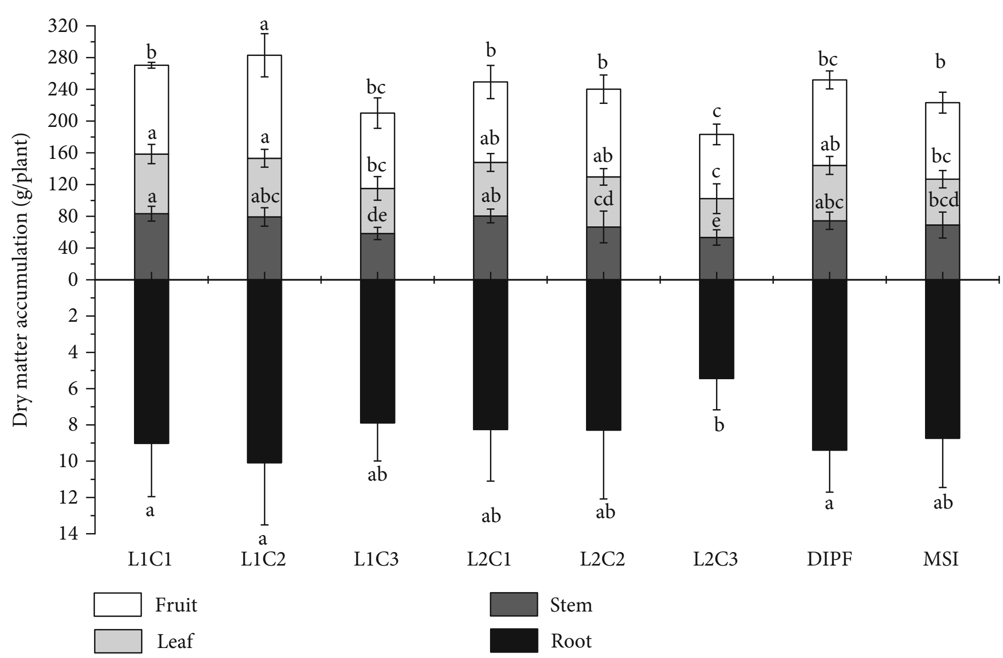

Figure 9: Effects of different treatments on dry matter accumulation of tomato. Note: the data are shown as average ± standard deviation in the figure, different letters in the same color column meant significant difference at 0.05 level, the same as below.

Table 2: Effects of different treatments on tomato yield and WUE.

Treatment	Yield (t/hm^2)	Water consumption (mm)	WUE (kg/m^3)
L1C1	118.79 ± 10.10^a	394.6 ± 20.63^{ab}	30.16 ± 2.84^{ab}
L1C2	119.96 ± 15.86^a	374.12 ± 15.82^{cd}	32.16 ± 4.75^a
L1C3	81.50 ± 13.96^c	373.05 ± 12.7^{cd}	21.92 ± 4.11^d
L2C1	105.51 ± 22.85^b	384.93 ± 15.34^{bc}	27.55 ± 6.54^{bc}
L2C2	96.17 ± 18.34^b	377.93 ± 10.89^{cd}	25.48 ± 4.88^{cd}
L2C3	78.88 ± 7.77^c	364.18 ± 25.2^d	21.76 ± 2.73^d
DIPF	100.48 ± 10.35^b	344.94 ± 22.42^e	29.23 ± 3.38^{ab}
MSI	99.58 ± 11.17^b	406.69 ± 22^a	24.54 ± 3.03^{cd}
F value			
L	12.884**(16.3)	1.425^{ns}(2.1)	8.814**(11.80)
C	29.683**(47.4)	9.080**(21.6)	19.304**(36.9)
$L \times C$	2.747^{ns}(7.7)	1.127^{ns}(3.3)	3.212*(8.9)

Notes: WUE: water use efficiency; the bracketed number is total variance relative contribution %, $^*P < 0.05$; $^{**}P < 0.01$; and $^{ns}P > 0.05$.

group spacing of 30 cm were 1.14, 1.01, and 1.13 times higher than that of 50 cm. With the decrease in capillary arrangement density, the yield and water consumption decreased, while the value of WUE increased. Overall, compared with C3, the yield and WUE of C2 were significantly increased by 34.76% and 31.94%.

3.5. Analysis of the AMOS Structural Equation. In the structural equation model (see Figure 10), the value of RMSEA is less than 0.08, the value of CFI is higher than 0.90, and the value of CMIN/DF is less than 3.00. The results indicated that the model has a good fitness. The structural equation model explains the interaction between photosynthetic characteristics with leaves, chlorophyll content with leaves, and total dry matter accumulation of tomato, including direct effects, indirect effects, and the total effect of the sum of the two. In this model, Pn, Tr, Ci, chlorophyll a, chlorophyll b, carotenoids, and total dry matter accumulation can explain 66% of the yield variability. In terms of direct effect, Pn, Tr, chlorophyll a, chlorophyll b, carotenoids, and total dry matter accumulation all had positive effects on yield, among which Tr had the greatest effect (0.39); Ci and Gs had a negative effect on yield, among which Gs had the greatest effect. There was also an interaction between Pn, Tr, Ci, chlorophyll a, chlorophyll b, and carotenoids. There was a negative correlation between Pn and Ci, Ci and Gs, and Ci and chlorophyll a and a positive correlation between chlorophyll and carotenoids. The positive correlation between chlorophyll a and carotenoids was the highest, followed by Pn and Gs.

In addition to direct effects, Pn, Tr, Ci, chlorophyll a, chlorophyll b, and carotenoids also play an important role in yield through various indirect effects. Pn, Tr, chlorophyll a, and carotenoids all had positive effects on yield through dry matter accumulation, among which chlorophyll a and carotenoids had significant effects (0.096); Gs and Ci all had negative effects on yield through dry matter accumulation, and Gs had a greater effect (-0.042). The total effects of various factors on yield were as follows: Gs > Tr > Pn > carotenoids > total dry matter accumulation > Ci > chlorophyll a > chlorophyll b.

4. Discussion

4.1. Effects of Irrigation Methods on Photosynthetic Characteristics, Dry Matter Accumulation, and Yield of Tomato in Greenhouse. Previous studies have shown that there is a positive correlation between chlorophyll content and leaf photosynthetic rate. Under drought conditions, soil water content limits the water supply of roots, promotes root production of ABA, reduces stomatal opening, restricts leaf gas and water exchange [48, 49], and reduces leaf net photosynthetic rate [50]. Through the experimental determination, it was found that the average soil volume moisture content of the 0-40 cm soil layer under MSPF was 9.34% higher than that of DIPF (see Figure 11). The appropriate increase of soil moisture created stable conditions for the increase of photosynthetic rate of microsprinkler irrigation leaves under plastic film (see Figure 7) and further led to the increase of tomato dry matter accumulation by 12.16%. This study also found that the yield and WUE of tomato plants under MSPF were 19.39% and 10.03% higher compared with DIPF (see Table 2). This may be ascribed to the flow rate of MSPF that was about 45 times higher than that of the single group with DIPF 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 [51]. This provided a strong guarantee for the stable yield of greenhouse tomato [11, 51, 52], 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% (see Table 2). 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.

In this study, the average volume water content in layer 0 ~ 40 cm under MSI was lower than that of MSPF at maturity stage of tomato about 7.48% (see Figure 11). At the same time, the canopy humidity of tomato in MSI was more than 70%, which was 1.56 times higher than that of MSPF (see Figure 12). The results show that under the same irrigation amount, MSI can reduce irrigation amount, and part of irrigation water was used to increase air humidity [53]. Previous studies have shown that leaf water condensation easily occurs in high humidity environment, causing leaf surface cell rupture, reducing leaf photosynthesis, and limiting dry matter accumulation and fruit morphological development [54, 55]. The aforementioned information may be one of the reasons for the decrease of tomato yield under microsprinkler irrigation in this study. We also found that the WUE of

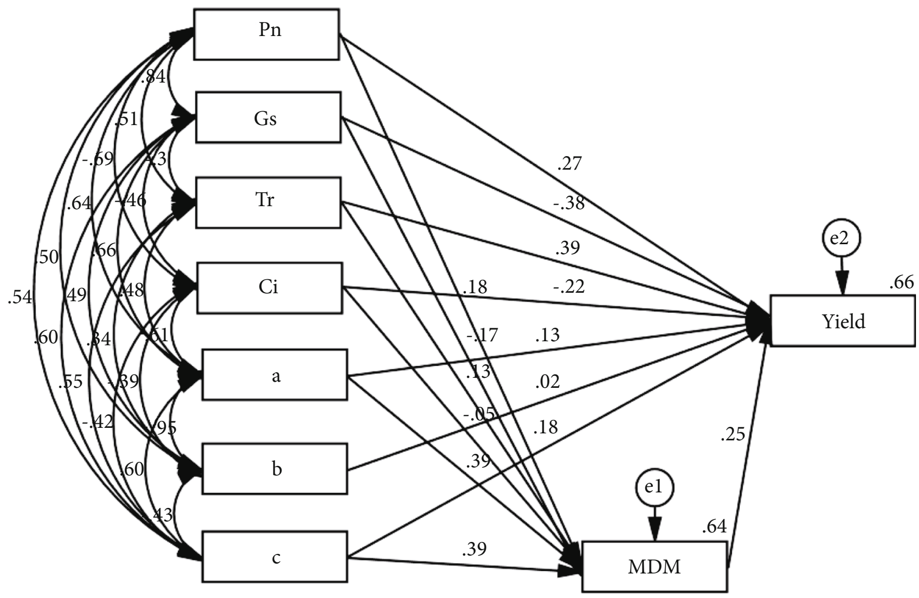

Figure 10: AMOS of structural equation model. Note: the rectangular box indicates the observation variable; e1 ~ e2 are the random values of the observation variables; one-way arrow represents the causal relationship between variables, starting as the cause and pointing to the result. The number above the variable box is the determination coefficient, which indicates the total interpretation rate of the independent variable on the dependent variable. The number on the one-way arrow is the direct effect of standardization. Pn: photosynthetic rate; Ci: intercellular CO_2 concentration; Tr: transpiration rate; Gs: conductance; a: chlorophyll a; b: chlorophyll b; c: carotenoids; MDM: total dry matter accumulation; and Yield: yield.

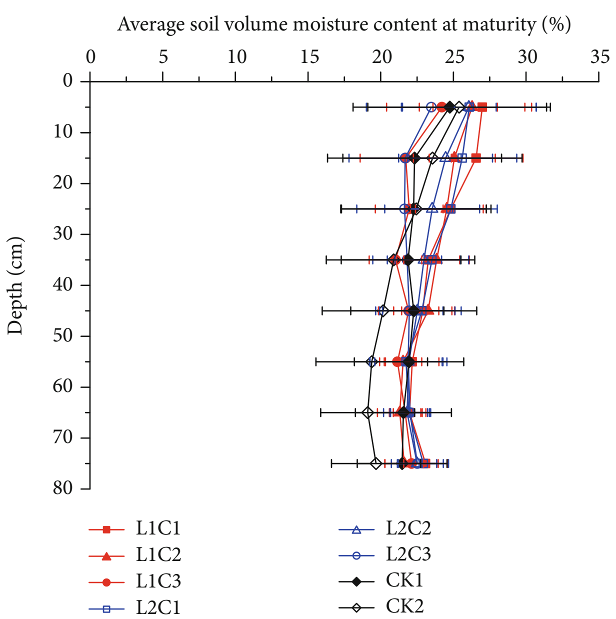

Figure 11: Average soil volume moisture content in different treatments at maturity stage (70 days after transplant). Note: the data are all average ± standard deviation in the figure.

tomato MSPF was significantly higher than that of MSI by 31.02%, possibly due to the large number of micropores per unit length of MSI, high atomization of water droplets, and increase of ineffective water transpiration [12]. As a result, the water consumption of tomato under MSI was significantly higher than that of MSPF 8.71% (see Table 2).

4.2. Effects of Micropore Group Spacing on Photosynthetic Characteristics, Dry Matter Accumulation, and Yield of Tomato in Greenhouse. Compared with the tomato cultivated at a micropore group spacing of 50 cm, the average soil volumetric moisture content of the 0 ~ 40 cm soil layer of the 30 cm during tomato maturity stage was increased by 1.60% (see Figure 11). It may be that that the effect of the change of micropore group spacing of MSPF on soil wetting body is similar to that of DIPF, and there is a phenomenon of intersection of wetting peaks between two groups of adjacent micropores on the pipe. The difference is that the single group flow of MSPF is higher than that of DIPF under the same working pressure and irrigation amount, and a larger flow rate is easy to increase the ratio of horizontal to vertical migration distance of soil water wetting peak and reduce the confluence time of adjacent wetting peaks. It has the phenomenon of the overall migration of soil moisture between the two groups of micropores on the pipe, which improves the soil volumetric water content and water dispersion per unit area of the tillage layer [10, 11]. The higher soil volumetric moisture content of the tillage layer provides a strong guarantee for the photosynthetic rate, dry matter accumulation, and yield of tomatoes [56–58]. It may also be one of the reasons why the photosynthetic rate (see Figure 7), dry matter accumulation (see Figure 9), and yield (see Table 2) of 30 cm micropore group spacing are better than 50 cm.

In this study, it was found that the tomato yield at a micropore group spacing of 30 cm was significantly higher than that of 50 cm (14.15%), which was inconsistent with the conclusion that there was no significant difference between the cucumber yield of 50 cm drip irrigation and 30 cm by Wang et al. [59] drip irrigation, which may be due

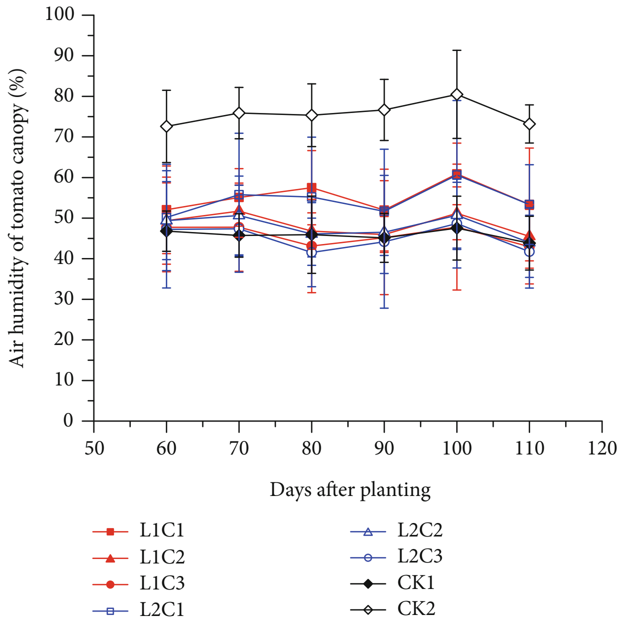

Figure 12: Effects of different treatments on air humidity in tomato canopy. Note: the data are all average ± standard deviation in the figure.

to the difference of irrigation amount in the experiment, the irrigation amount was controlled by evaporation pan, the cumulative irrigation water was 353 mm in growth period, while Wang controlled the lower limit of soil irrigation and irrigated 385 mm during growth period. It is also inconsistent with the conclusion that there is no significant difference in the onion yield under different drip irrigation spacing by Enciso et al. [60]. The maximum spacing of emitters set by Enciso et al. is 30 cm, which is much smaller than that of 50 cm in this study. The soil water distribution in the smaller spacing is uniform, and it is not easy to cause yield difference due to drought stress on crops [11, 61]. It is consistent with the conclusion of Meshram et al. [62] that the pomegranate yield of 50 cm emitter spacing is significantly lower than that of 30 cm. This study also found that the WUE of the 30 cm of micropore group spacing was 1.13 times higher than that of 50 cm. Due to the micropore spacing 30 cm, the tillage layer soil volume is moist and uniform and there is no obvious high water and small water area, which can meet the water needs of plants more timely and accurately [63]. It led to a significant increase in tomato yield (1.14 times), while there was no significant increase in water consumption between 30 cm of micropore group spacing (see Table 2), which finally showed a significant improvement in WUE [44, 59]. Elmaloglou and Diamantopoulos [35] believes that reducing the spacing between the emitters can shorten the irrigation duration and increase the irrigation efficiency, which is consistent with the conclusion that reducing the 30 cm of micropore group spacing can improve water use efficiency.

4.3. Effects of Capillary Arrangement Density on Photosynthetic Characteristics and Dry Matter Accumulation and Yield of Tomato in Greenhouse. It was found that the total dry matter accumulation of tomato in C1 and C2 was significantly higher than that in C3 (approximately, 32.04% and 33.18%, respectively, see Figure 9). This is mainly due to the fact that under the same single group flow rate, micropore group spacing, and irrigation amount, the denser the capillary arrangement density, the larger the unit area flow, which is easy to increase the surface wetting area and increase the soil volume moisture content of the tillage layer. The results showed that the average soil volumetric moisture content of C1 and C2 at mature stage was significantly higher than that of C3 about 8.07 and 5.81% (see Figure 11). Higher soil volumetric moisture content reduced root drought stress, limited root ABA accumulation, and promoted leaf photosynthesis (see Figure 7) [64, 65], leading to an increase in dry matter accumulation [66]. Zhou et al. [8] found that the dry matter accumulation of C2 of maize under drip irrigation was less than that of C1; it is inconsistent with the conclusion that the total dry matter accumulation of C2 tomato under MSPF is higher than that of C1. It may be due to the fact that the soil volume moisture content of the 0-20 cm soil layer in the C1 layout mode is about 3.31% higher than that of the C2. Higher shallow soil moisture tends to increase soil water-filled porosity and reduce soil aeration, making the total dry matter accumulation of C1 is slightly lower than C2 by about 0.86% [8]. Wang et al. [46] study found that Pn and Gs of muskmelon leaves increased at first and then decreased with the increase of capillary arrangement density, which was inconsistent with the conclusion that Pn and Gs of tomato leaves increased with the increase of capillary arrangement density. It may be due to the fact that the difference of irrigation control methods, Wang et al. adopt the percentage control of field water holding rate, so it is difficult to ensure that the irrigation quantity of different capillary arrangement density is the same. This study is based on evaporation control, and different capillary arrangement density irrigation quantity is the same.

Liu et al. [67] found that the cotton yield of one pipe and two rows was not significantly higher than that of one pipe and four rows. However, Zhou et al. [8] found that the yield of maize in one pipe of two rows in drip irrigation was significantly lower than that in one pipe and one row. The reasons for the above differences may be due to differences in soil types, crop types, climate, precipitation, and other factors. Whether the capillary arrangement density of MSPF has a consistent effect on yield under different environments needs to be demonstrated by further experiments. Wang et al. [4] found that the yield of muskmelon under drip irrigation in the greenhouse increased at first and then decreased with the increase of capillary arrangement density, which was inconsistent with the conclusion that tomato yield decreased with the decrease of capillary arrangement density in this study. It is mainly due to the difference of total irrigation amount, soil type, and irrigator during the growth period. It may also be caused by the difference of capillary arrangement density of drip irrigation. In this study, the maximum distance between one pipe and two rows of Wang et al. is the maximum distance between the arrangement of one pipe and two rows of drip irrigation. The difference of tomato yield between three pipes and four rows of MSPF needs to be demonstrated by further experiments. Cantrell et al. [68]

studied the yield of drip irrigation bermudagrass, Lv et al. [32] drip irrigation spring wheat yield, and Bozkurt et al. [31] drip irrigation corn yield showed a decreasing trend with the decrease of capillary arrangement density. These conclusions are consistent with the conclusion of this study on the yield change of MSPF. It shows that MSPF and drip irrigation have similar effects on crops in terms of capillary arrangement density. This study also found that the WUE of tomato showed a decreasing trend with the increase of capillary arrangement density. It may be due to the increase of soil wetting area and ineffective water consumption in the tillage layer with the increase of capillary arrangement density. At the same time, when the soil water stress decreased, the vegetative growth of tomato was exuberant and the photosynthetic rate increased. The effective evapotranspiration of plant water [69] also increased, resulting in the tomato water consumption increasing by 5.74% (see Table 2). The increase of tomato yield (29.85%) was less than that of water consumption (5.74%), which led to the decrease of tomato WUE by 32.1% with the increase of capillary density.

5. Conclusions

By exploring the effects of different micropore group spacing and capillary arrangement density on the photosynthetic characteristics and yield of greenhouse tomato, it was found that the photosynthetic rate of tomato leaves of MSPF increased by 8.24% and 13.55% compared with DIPF and MSI. The yield and WUE of MSPF were higher than those of DIPF and MSI about 19.39% and 20.46% and 10.03% and 31.02%, respectively. It was shown that MSPF is suitable for greenhouse crop irrigation. The yield-increasing effect is better than DIPF, and the water-saving effect is better than MSI. In a certain range, with the decrease in micropore group spacing, the more beneficial it is to the improvement of tomato photosynthetic characteristics of leaves and yield. Along with the decrease of capillary arrangement density, the tomato photosynthetic characteristics of leaves and yield decreased. In AMOS of the structural equation model, Pn, Tr, Ci, chlorophyll a, chlorophyll b, carotenoids, and total dry matter accumulation can explain 66% of the yield variability. Considering comprehensively, MSPF is aimed at saving water and low cost without significantly reducing yield; it is recommended to use the optimal combination mode of micropore group spacing 30 cm and one pipe for two rows is recommended. This study can enrich the water-saving irrigation technology of facility agriculture and provide theoretical basis and technical guidance for the sustainable development of greenhouse tomato industry in arid and semiarid 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 of greenhouse spring tomato, but it remains an open question that further experiments are needed to investigate of autumn tomato.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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