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Research Article

Effects of Micropore Group Spacing and Irrigation Amount on Soil Respiration and Yield of Tomato with Microsprinkler Irrigation under Plastic Film in Greenhouse

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Microsprinkler irrigation under a plastic film in the greenhouse (MSPF) is a water-saving way which adopts the porous discharge form of a pipe under the plastic film. The effects of different micropore group spacings (L1:30 cm, L2: 50 cm) and irrigation amounts [I1: 0.7 Epan; I2: 1.0 Epan; and I3: 1.2 Epan (Epan is the diameter of 20 cm standard pan evaporation, mm)] of the MSPF on the soil respiration and yield of tomato were studied. A completely randomized trial design was used, and drip irrigation under plastic film (CK1) and microsprinkler irrigation (CK2) were also used as controls. The results showed that under the same irrigation amount, the soil respiration rate, tomato yield, and water use efficiency (WUE) of MSPF in spring and autumn are 8.09% and 6.74%, 19.39% and 4.54%, and 10.03% and 2.32% higher than those of CK1, respectively; they are significantly increased by 31.02% and 20.46%, 49.22% and 38.38%, and 58.05% and 34.66% compared with those of CK2, respectively, indicating that MSPF increased the amount of CO_2 emission, but tomato yield and WUE were effectively improved, and a dynamic balance was reached among them. Compared with the 50 cm micropore group spacing, the spring and autumn tomato yields and WUE under the 30 cm micropore group spacing were significantly increased by 16.00% and 13.01% and 20.85% and 14.25%, respectively, and the micropore group spacing had no significant effect on the soil respiration rate in both root and nonroot zones. When the I increased from 0.7 Epan to 1.2 Epan, the soil respiration rate and yield in the root and nonroot zones of the spring and autumn tomatoes increased at first and then decreased, and the WUE showed a decreasing trend. The relationship of soil respiration rate between the nonroot and root zones obeys a logarithmic function, and the soil respiration rate in the nonroot zone has a quadratic curve relationship with the yield of tomato. This study can provide data support for the development of water-saving irrigation and yield increase of facility agricultural tomato and the analysis of the soil carbon cycling mechanism.

1. Introduction

With global warming, research on global carbon cycling has become the focus of the scientific community. Soil respiration is an important circulation pathway of the global carbon cycle, and it plays a key role in regulating atmospheric CO_2 concentration. According to the IPCC2012 report, agricultural soil is a major contributor to carbon emissions in global carbon cycling, accounting for about 19-29% of global cumulative carbon emissions [1]. Water is one of the five elements in agricultural production, which plays an important role in the carbon cycling of agricultural soil. Rainfall is scarce in arid and semiarid areas of northwest China [2]. Irrigation water accounts for more than 60% of the total water

consumption in this area, which is the main way for local crops to grow, and it is also the focus of this paper [3, 4]. The development of facility agriculture provides a strong guarantee for vegetable production in northwest China. However, the irrigation water for facility agriculture in this area mainly comes from groundwater, and the progress in the exploitation of groundwater resources aggravates the water resource crisis in this region [5–7]. Therefore, under the background of the sharp increase in atmospheric carbon emissions and the shortage of water resources [8], it is of great significance to explore the water-saving technology of facility agriculture for crop growth and soil carbon cycling.

As one of the main microirrigation methods in facility agriculture, microsprinkler irrigation under plastic film (MSPF, see Figure 1; Figure 1 is reproduced from Zhang et al. [9]) is used to irrigate tomato with multiple groups of small holes under the plastic film [10]. The MSPF has obtained good application effects in the facility agriculture tomato irrigation. Compared with the traditional drip irrigation in facility agriculture, under the same working pressure, the single micropore velocity of MSPF is about 15 times that of labyrinth drip irrigation, which has stronger sediment carrying capacity and anticlogging performance, and the MSPF can solve the clogging problem of some drip irrigation emitters [11, 12]. When the irrigation amount is the same, the single group flow of MSPF is about 40 times that of drip irrigation, and the irrigation duration is short, so it is easy to increase the ratio of horizontal and vertical migration distances of the soil water wetting peak. As a result, the soil wetting body per unit area of the tillage layer can be increased, which can reduce the deep transport of soil water and limit the lateral development of roots under water stress [13, 14]. The soil carbon cycle was also changed due to the increase in the soil dry-wet cycle [15, 16]. Compared with the field microsprinkler pipe, the MSPF in facility agriculture can reduce the influence of the external environment on the soil wetting body [17–19]. The MSPF can solve the spray atomization of microsprinkler irrigation, which is easy to increase air humidity. At the same time, it can solve the problems of crop diseases and insect pests caused by high temperature and humidity in the facility's agricultural environment [20–22]. Therefore, the exploration of MSPF is of great significance for enriching the technical system of greenhouse microirrigation, expanding the scope of application of microsprinkler irrigation, saving water and increasing production of crops, and emitting greenhouse gas from the soil.

As one of the main vegetables planted in facility agriculture, the tomato has rich nutrition and health care value. Tomato in the greenhouse belongs to sparse planting crops. The selection of the distance between orifices in the capillary and the irrigation amount has a direct impact on soil water and heat, ventilation, mineralization and decomposition rate of organic matter, nitrogen transformation, microbial biomass, activity, etc. [23, 24]. Therefore, the study on the emission of greenhouse gases in greenhouse tomato farmland and the formation mechanism of tomato yield is of great significance to obtain the best balance point of water saving and yield increase of greenhouse tomato and to formulate measures to reduce greenhouse gas CO_2 emissions in vegetable fields of MSPF. In the practice of facility agricultural production, the capillary distance between orifice outflow and the irrigation amount are often selected according to their own experience. Studies have shown that under the same emitter flow, the smaller the emitter spacing is, the closer the horizontal wetting shape is, the shorter the confluence time of wetting peaks between emitters is, and the larger the soil surface wetting area is [14, 25]. In addition, there is a positive correlation between soil moisture and soil respiration rate, which leads to an increase of CO_2 emission per unit area of soil respiration [1]. The research of Enciso et al. showed that the onion yield increased first and then decreased as the distance between the emitters decreased from 30 to 15 cm [26]. It should be noted that when the emitter spacing is small, the investment and operation cost of drip irrigation equipment will also increase. In practical application, the amount of empirical irrigation by farmers is often much higher than the actual water demand of crops, and the deep leakage of irrigation water is serious, which leads to the waste of water resources [27, 28]. Studies have shown that under the same emitter spacing, the greater the emitter flow rate is, the higher the ratio of the distance between the horizontal and vertical transports of soil water content is [13]. The larger the amount of drip irrigation is, the larger the soil wetting volume is and the lower the ratio of horizontal and vertical migration distance of soil water is. There is a positive correlation between the amount of irrigation and soil water content [14, 29, 30]. Suitable soil water content can enhance root respiration and microbial activity, thus accelerating the decomposition of soil organic matter and increasing yield, as well as increasing CO_2 emission from soil respiration [31–33]. Previous studies have found that reducing the irrigation amount can reduce the soil respiration rate, and excessive irrigation will also inhibit the increase of the soil respiration rate [34, 35]. In tomato and maize under drip irrigation, the irrigation amount was positively correlated with yield and soil CO_2 emission [36–38] and negatively correlated with water use efficiency [23].

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

At present, the research on soil respiration of facility agriculture is mainly focused on drip irrigation with small flow, but there are few studies on water management of MSPF on soil respiration of facility agriculture. Furthermore, there is a lack of qualitative and quantitative descriptions of the correlation between nonroot zone soil respiration and root zone soil respiration in tomato soil respiration, and there is also a lack of quantitative analysis of the relationship between soil respiration rate and yield. Therefore, it is necessary to

study the soil respiration and yield of tomato by changing the distance between capillary orifice outflow (micropore group spacing) and irrigation water quantity of microsprinkler irrigation under plastic film. In this study, the experiment of MSPF was conducted to explore the effects of different micropore group spacing and irrigation amounts on soil respiration, root zone microenvironment, and yield of greenhouse tomato. The method of regression analysis was used to make a quantitative study in order to obtain the best combination model of micropore group spacing and irrigation amount for reducing soil respiration rate (CO_2 emission) and increasing yield and water use efficiency of tomato in greenhouse under MSPF in northwest China. Through greenhouse experiment and regression analysis, this paper is aimed at enriching the greenhouse tomato microirrigation technology system and providing data support for water saving and high yield of protected agricultural crops and soil carbon cycle in this area.

2. Materials and Methods

2.1. Experimental Site and Management. This study was carried out in the greenhouse of Modern Agricultural Science and Technology Convention and Exhibition Center in Xi'an, Shaanxi Province (108°52°E, 34°03°N, 435 m above sea level). The greenhouse is 85 m long and 15 m wide (see Figure 2; Figure 2 is reproduced from Zhang et al. [9]). The average annual temperature is 13.3°C, and the rainfall is about 613.75 mm. The soil type is sandy loam in this area, and the mass fractions of sand, silt, and clay are 63.9%, 29.63%, and 6.47%, respectively. The average bulk density of a 1.0 m soil layer is 1.48 g/cm^3, the field capacity is 27.40%, and the buried depth of the groundwater table is more than 30 m [9]. The content of organic matter, namely, total phosphorus (P), total potassium (K), total nitrogen, available nitrogen, available phosphorus, and available potassium, in the plough layer before sowing was 15.53 g/kg, 10.12 g/kg, 2.01 g/kg, 1.36 g/kg, 0.70 g/kg, 0.11 g/kg, and 0.08 g/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 [9].

The Jingfan 401 of tomato (Jingyan Yinong seed Technology Co., Ltd., Beijing) is planted on a ridge, in which the ridge is 3.4 m long and 1.2 m wide, and the irrigated plot is shown in Figure 2. The row spacing of the tomato is 50 cm and the plant spacing is 40 cm. The distance between each plot is 4 m, and a layer of styrene-butadiene-styrene block copolymer building waterproof film with a depth of 1.0 m is embedded in the middle to prevent the horizontal infiltration and movement of soil moisture and avoid the influence on other plot tests. The pipe of MSPF (Hebei Plentirain Irrigation Equipment Technology Co., Ltd., Hebei, China) adopted thin-walled oblique 3 micropores; the pipe of MSPF structure parameters is shown in Figure 3 (Figure 3 is reproduced from Zhang et al. [9]) and Table 1. The control drip irrigation under plastic film (CK1, Hebei Plentirain Irrigation Equipment Technology Co., Ltd., Hebei, China) with a thin-wall labyrinth tooth channel was selected. The geometric parameters of the channel were 54.3 mm × 1.1 mm × 0.83 mm, the pipe diameter was 16 mm, the distance between drippers was 30 cm, and the dripper flow rate was 2 L/h. The control of the pipe of the microsprinkler irrigation (CK2, Hebei Plentirain Irrigation Equipment Technology Co. Ltd, Hebei, China) adopted thin-walled oblique 3 micropores in which the pipe diameter was 32 mm and the micropore diameter was 0.8 mm. The micropore group spacing was 10 cm [9].

The experiment of planting tomatoes in a greenhouse during spring and autumn was conducted. Spring tomato and autumn tomato were planted on March 27, 2019, and August 23, 2019; irrigation began on April 4, 2019, and August 30, 2019; irrigation was stopped on July 15, 2019, and January 17, 2019; and the tomatoes were harvested on July 25, 2019, and January 30, 2020. The field management measures of all treatments of greenhouse tomato were consistent. In order to ensure the survival rate of tomato, irrigation was done uniformly after planting with reference to the planting experience of local farmers [9].

2.2. Experimental Design. Factors including the micropore group spacing (see Figure 3) and irrigation amount (see Figure 4 and see Table 1) were set up in this study. Among them, the micropore group spacing (L) is set to 2 levels: 30 cm (L1) and 50 cm (L2); the irrigation amount was controlled based on the cumulative evaporation from a 20 cm diameter standard pan (Epan) [39], which was realized by a control coefficient (k_{cp}), The k_{cp} (the crop-pan coefficient) was set to 3 levels: 0.7 (I1), 1.0 (I2), and 1.2 (I3) Epan. The CK1 and CK2 were used as the control treatment. There were a total of 8 treatments, each of which was repeated 3 times, for a total of 24 test areas.

The evaporation amount was measured at 08:00 AM for each irrigation frequency; the irrigation was initiated after the measurement. The irrigation amount (W) was calculated according to formula (1) [23, 40]. The irrigation times and amounts were recorded (see Table 1), taking $k_{cp} = 1.0$ as an example to draw the irrigation time and irrigation amount (see Figures 4 and 5].

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

In the given formula, E_{pan} represents the evaporation within the interval between 2 irrigations (mm), A is the capillary control area, and k_{cp} is the crop pan coefficient. The k_{cp} of control CK1 and CK2 was 1.0 [9].

3. Measurements and Computational Methods

3.1. Soil Respiration Rate (CO_2 Emission). The soil respiration rate under different treatments was measured by an Li-8100 (LI-COR, Inc., USA) infrared gas analyzer. The PVC soil survey ring of diameter 20 cm was injected into the soil 2 days before the measurement and did not destroy the undisturbed soil on the surface. During the measurement, each measuring ring was measured twice to monitor the respiration rate of nonroot zone soil (soil without plant main roots) and root zone soil (soil containing plant main roots) (see Figure 6).

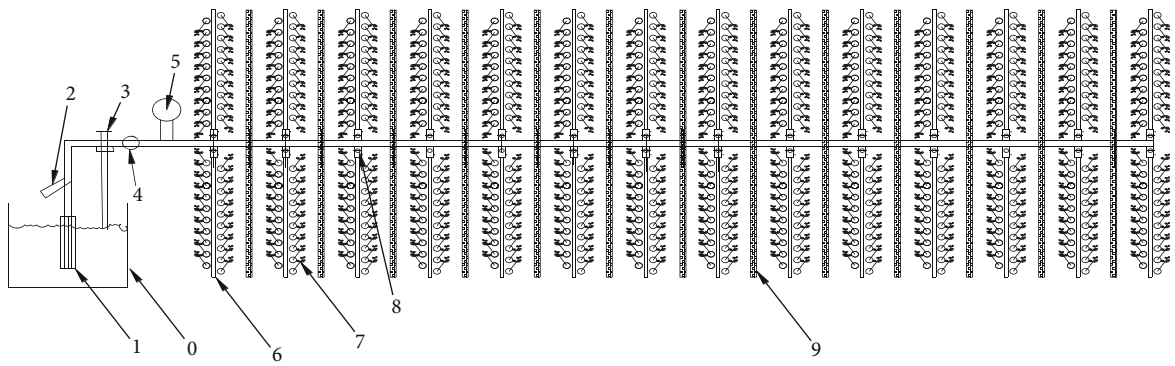

Figure 2: Schematic diagram of the greenhouse plot layout. Note: 0: water tank; 1: the pump (WQD10-12-0.75S, People Pump, Corp., Shanghai, China); 2: filter; 3: backwater valve; 4: electromagnetic flowmeter; 5: pressure gauge; 6: capillary; 7: tomato; 8: capillary valve; 9: plastic screens.

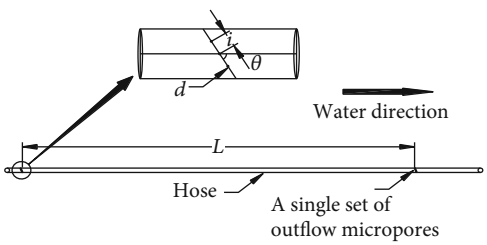

Figure 3: Schematic diagram of microporous group (inside) spacing structure parameters. Note: diameter of micropore is $d = 0.8$ mm; the internal spacing of the microporous group was $I = 0.4$ cm; the angle of micropores is equal to 68; the micropore group spacing is L.

Table 1: Experimental factor and design.

No.	Treatment	Micropore group spacing cm	k_{cp}	Irrigation amount (mm)	
				Spring	Autumn
1	L1I1	30	0.7	247.12	152.73
2	L1I2	30	1.0	353.03	218.19
3	L1I3	30	1.2	423.64	261.83
4	L2I1	50	0.7	247.12	152.73
5	L2I2	50	1.0	353.03	218.19
6	L2I3	50	1.2	423.64	261.83
7	CK1	30	1.0	353.03	218.19
8	CK2	10	1.0	353.03	218.19

Note: L: micropore group spacing of MSPF; I: irrigation amount of MSPF; CK1: drip irrigation under plastic film; CK2: microsprinkler irrigation.

When measuring root zone soil, the aboveground plants were cut. The soil respiration rate was measured at 11:00 AM on the 98th day of the planting of spring tomato and 97th day of the planting of autumn tomato.

3.2. Soil Microenvironment

3.2.1. Soil CO_2 Concentration. The soil CO_2 concentration in the nonroot zone and root zone of tomato was measured by the injector method (see Figure 7), and 0 (CO_2-0) and 20 cm (CO_2-20) samples were taken from the surface. The CO_2 concentration in the sample was determined by gas chromatography, and the determination time was the same as the soil respiration rate.

3.2.2. Soil Temperature and Soil Volume Moisture Content. The soil temperature of the nonroot zone and root zone of tomato was measured by a 15 cm geothermometer. TZS-W (Shanghai Heyi Instruments & Meters Co., Ltd., China) soil moisture meter was used to measure the soil moisture on the same day as the soil respiration rate. Firstly, the soil plane surface of the nonroot zone and root zone of 0~20 cm tomato was dug out, and then the probe was inserted into the 15 cm area away from the surface to determine the soil volume moisture content (see Figure 7) in the nonroot zone and root zone of tomato.

3.2.3. The Water-Filled Pore Space of Soil (WFPS). The nonroot zone and root zone of WFPS were calculated by dividing volumetric water content by total soil porosity. Total soil porosity was calculated by measuring the bulk density of the soil according to the relationship: soil porosity 1/4 (1 soil bulk density/2.65), assuming a particle density of 2.65 mg/m^3 [39].

3.2.4. The Tomato Nonrhizosphere and Rhizosphere Soil Total Organic Carbon (TOC), Microbial Biomass Carbon (MBC), Humic Acid Carbon (HA-C), and Fulvic Acid Carbon (FA-C) in Greenhouse. The nonrhizosphere soil adopts the conventional soil drilling method, which is to take out the soil in Figure 7 and mix it well; the rhizosphere soil was collected by the shaking soil method (randomly selecting a plant, digging out the 10~20 cm root system from the soil (see Figure 7), shaking off the soil loosely combined with the root system, and then brushing the root topsoil with a soft brush as the rhizosphere soil sample). The nonrhizosphere and rhizosphere soils were randomly sampled 3 times, and the samples were taken back to the room immediately. The plant residues were removed from the fresh soil and stored in the refrigerator at 20°C after 2 mm sieving. The contents of TOC, MBC, HA-C, and FA-C in the soil were measured within 10 days, and the sampling time was the same as the soil respiration rate. The TOC and MBC were determined by the fumigation extraction method as outlined by Chatterjee et al.

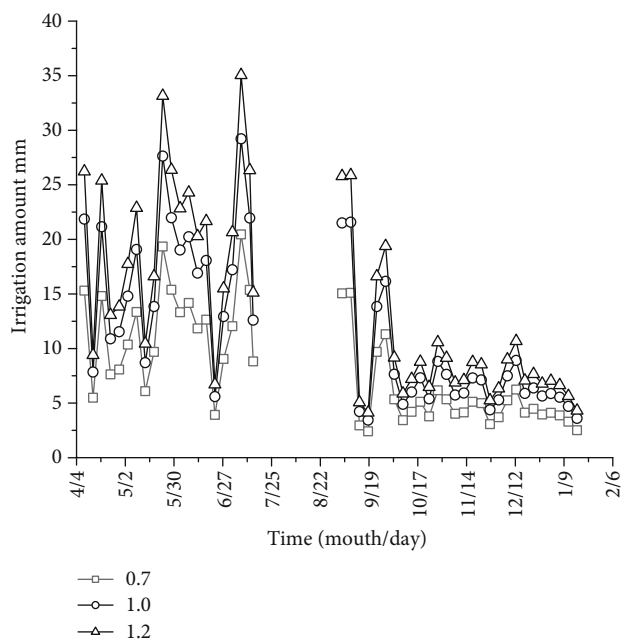

Figure 4: Irrigation records.

[40]. The HA-C and FA-C were extracted from soil samples according to the procedure of Sun et al. [41].

3.3. Yield and Water Use Efficiency. Four tomatoes were randomly selected from each plot, and the yield was measured by 0.01 g precision electronic scale after ripening. After the yield per plant was obtained, the tomato yield per hectare was calculated [9].

The volumetric soil water content of 0~10 cm, 10~20 cm, 20~30 cm, 30~40 cm, 40~50 cm, 50~60 cm, 60~70 cm, and 70~80 cm was measured by a soil moisture sensor (TRIME-PICO-IPH, IMKO, Inc., Ettlingen, Germany). Monitoring before and after planting, two monitoring points were selected in each district (monitoring point 1 was arranged at the outflow micropore, and monitoring point 2 was arranged at the distance m between the two groups of micropores in the vertical flow direction, in which $m = 25$ cm, Figure 6). Crop water consumption (ET_a) and crop water use efficiency (WUE) were obtained by formula (2) and formula (3) [9, 42]:

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

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

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

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

4. Data Analysis

The significant difference of SPSS22.0 (IBM Crop., Armonk, New York, NY, USA) was analyzed by the F test, and the significance level was set to $P < 0.05$. OriginPro2019 (OriginLab Corporation, Northampton, MA, USA) was used to draw the picture. Mathematica12.0 (Wolfram Research, New York, NY, USA) was used for regression analysis.

5. Results

5.1. Effects of Different Treatments on Soil Water and Heat of Tomato in Greenhouse. The micropore group spacing (L) had no significant effect on soil water and heat in the nonroot zone and root zone of tomato ($P > 0.05$, see Table 2). The irrigation amount (I) also exhibited a significant effect on soil water and heat in the nonrhizosphere and root zone of tomato ($P \leq 0.05$).

The nonroot zone soil temperature and root zone soil temperature of spring and autumn tomatoes treated with L1I2 increased by 6.16% and 6.38% and 1.78% and 8.36%, respectively, compared with those of CK1 and 7.58% and 9.45% and 8.58% and 14.78% higher than those of CK2, respectively. The volume water content of the nonroot zone and root zone of tomato treated with L1I2 increased by 8.75% and 3.64% and 0.57% and 3.64%, compared with that of CK1, respectively, and increased by 9.85% and 9.34% and 14.83% and 16.80% compared with that of CK2, respectively. With an increase in irrigation amount, the volume water content of the nonroot zone and root zone of tomato first increased, while the soil nonroot zone temperature and root zone temperature of tomato decreased. The soil nonroot zone temperature, root zone temperature, nonroot zone volume water content, and root zone volume water content of tomato with the micropore group spacing of 30 cm were slightly higher than those of 50 cm by about 0.19% and 2.55%, 2.71% and 2.02%, 2.22% and 6.69%, and 5.59% and 7.38%, respectively.

5.2. Effects of Different Treatments on the Soil CO_2 Concentration in Nonroot Zone and Root Zone of Tomato. The micropore group spacing (L) had no significant effect on CO_2 concentration in the nonroot zone and root zone of tomato soil at different depths (see Table 3). The irrigation amount (I) also exhibited a significant effect on CO_2 concentration in the nonroot zone and root zone of tomato soil at different depths. The interaction between them had no significant effect on the concentration of CO_2 in the nonroot zone and root zone of soil at different depths.

The soil CO_2 concentration of 0 cm of tomato was significantly lower than the depth of the 20 cm soil layer, indicating that as the depth of the soil layer increased, the soil CO_2 concentration increased. With the seasonal change, the soil CO_2 concentration of autumn tomato was lower than that of spring tomato. The CO_2 concentration in the nonroot zone of the 0 cm soil layer and the CO_2 concentration in the root zone of 0 cm soil treated with L1I2 were 2.69% and 1.79% and 0.47%and 1.24% higher than those of CK1 and 6.55% and 4.96% and 7.74% and 12.43% higher than those of

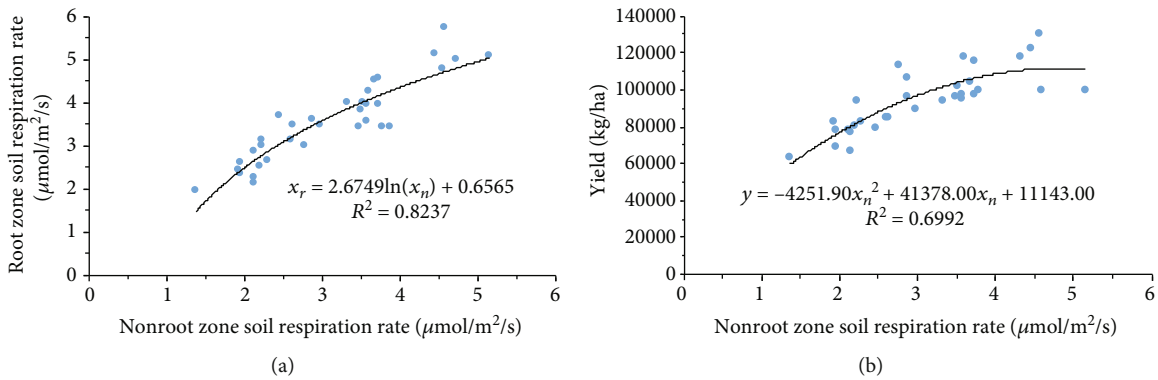

Figure 5: Regression analysis of nonroot zone soil respiration rate (x_n), root zone soil respiration rate (x_r), and yield (y) of spring tomato (a) and autumn tomato (b).

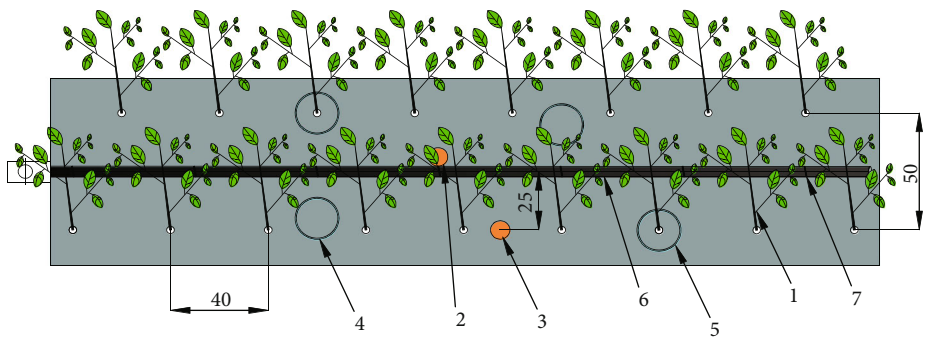

Figure 6: The distribution map of soil respiration monitoring points for greenhouse tomato (unit: cm). Note: 1: tomato; 2: TRIME 1; 3: TRIME 2; 4: nonroot zone soil respiration rate PVC measurement ring; 5: root zone soil respiration rate PVC measurement ring; 6: capillary; 7: single group outflow location.

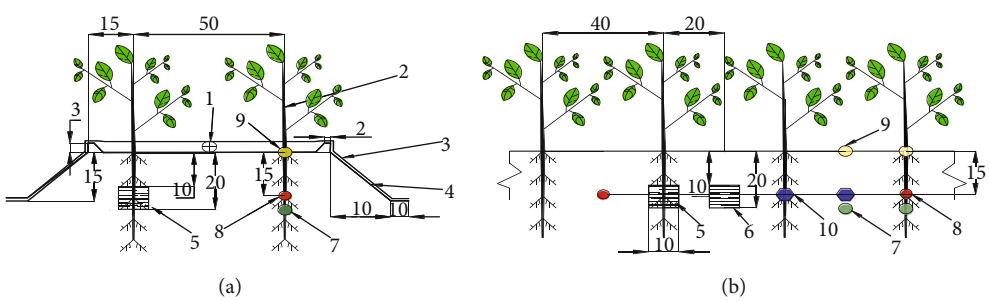

Figure 7: Schematic diagram of the position of sampling points (unit: cm). Note: 1: pipe; 2: tomato; 3: plastic film; 4: surface soil; 5: root zone of soil sampling point; 6: nonroot zone of soil sampling points; 7: the CO_2 concentration of 20 cm measurement point; 8: temperature measurement point; 9: the CO_2 concentration of 0 cm measurement point; 10: soil volume moisture content measurement point.

CK2, respectively. The CO_2 concentration in the nonroot zone of the 20 cm soil layer and the CO_2 concentration in the root zone of the 20 cm soil treated with L1I2 were 4.06% and -1.32% and 1.68% and 3.89% higher than those of CK1 and 11.03% and 2.20% and 8.07% and 20.97% higher than those of CK2, respectively.

With the increase of irrigation amount, the soil CO_2 concentration in the nonroot zone and root zone of tomato at different depths increased first and then decreased. The CO_2 concentration in the nonroot zone of 0 cm soil, the CO_2 concentration in the root zone of 0 cm soil, the CO_2 concentration in the nonroot zone of 20 cm soil, and the CO_2 concentration in the root zone of 20 cm soil were higher than those of 50 cm in tomato soil with a micropore group spacing of 30 cm.

5.3. Effects of Different Treatments on Soil Respiration Rate of Greenhouse Tomato. Figure 8 shows that the micropore group spacing had no significant effect on the respiration rate of the nonroot zone and root zone of tomato soil. The irrigation amount had a significant effect on the respiration rate of the nonroot zone and the root zone of tomato soil ($P \leq 0.05$).

Table 2: Effects of different treatments on soil moisture and temperature in nonroot zone and root zone of tomato in greenhouse.

Treatment	Spring				Autumn			
	Temperature (°C)		Soil volume moisture content (%)		Temperature (°C)		Soil volume moisture content (%)	
	Nonroot zone soil	Root zone soil	Nonroot zone soil	Root zone soil	Nonroot zone soil	Root zone soil	Nonroot zone soil	Root zone soil
L1I1	26.1 ± 0.71^{abc}	25.07 ± 0.87^{ab}	20.55 ± 5.97^{c}	19.56 ± 3.18^{c}	20.14 ± 0.52^{a}	18.69 ± 0.5^{ab}	22.04 ± 3.92^{bc}	20.55 ± 3.44^{cd}
L1I2	26.99 ± 0.22^{a}	25.57 ± 1.18^{a}	27.73 ± 7.56^{ab}	27.48 ± 3.84^{ab}	20.15 ± 0.93^{a}	19.61 ± 2.75^{a}	28.22 ± 3.98^{a}	28.22 ± 3.39^{ab}
L1I3	25.32 ± 1.13^{bc}	23.31 ± 2.49^{bc}	31.44 ± 3.31^{a}	29.21 ± 5.12^{a}	17.57 ± 1.66^{c}	16.91 ± 1.48^{bc}	28.72 ± 4.67^{a}	28.72 ± 2.77^{a}
L2I1	26.37 ± 2.34^{abc}	24.93 ± 1.8^{ab}	20.06 ± 4.28^{c}	18.32 ± 3.34^{c}	19.67 ± 1.53^{ab}	19.25 ± 0.61^{a}	19.81 ± 3.83^{ab}	18.32 ± 2.92^{d}
L2I2	26.77 ± 0.81^{ab}	24.84 ± 1.97^{ab}	27.73 ± 4.06^{ab}	26.91 ± 3.35^{ab}	19.34 ± 1.14^{ab}	18.49 ± 1.07^{ab}	25.75 ± 2.24^{c}	25.62 ± 3.37^{ab}
L2I3	25.12 ± 1.36^{c}	22.23 ± 1.37^{c}	30.2 ± 3.07^{ab}	26.99 ± 3.69^{ab}	17.41 ± 0.98^{c}	16.37 ± 1.98^{c}	28.47 ± 2.18^{a}	28.22 ± 3.51^{ab}
CK1	25.43 ± 1.13^{abc}	25.12 ± 1.66^{ab}	25.5 ± 1.74^{bc}	27.32 ± 2.35^{ab}	18.94 ± 0.6^{abc}	18.09 ± 1.01^{abc}	27.23 ± 5.12^{a}	27.23 ± 3.47^{ab}
CK2	25.09 ± 1.14^{c}	23.55 ± 0.93^{abc}	25.24 ± 2.28^{bc}	23.93 ± 2.25^{b}	18.41 ± 1.91^{bc}	17.08 ± 0.31^{bc}	25.81 ± 2.02^{ab}	24.16 ± 2.01^{bc}
F value								
L	0.014^{ns}	1.311^{ns}	0.091^{ns}	1.124^{ns}	1.456^{ns}	0.464^{ns}	1.588^{ns}	2.697^{ns}
I	5.168^{*}	7.567^{**}	13.453^{**}	21.070^{**}	15.497^{**}	8.708^{**}	17.142^{**}	26.607^{**}
L ∗ I	0.145^{ns}	0.230^{ns}	0.043^{ns}	0.143^{ns}	0.223^{ns}	0.851^{ns}	0.173^{ns}	0.362^{ns}

Note: L: micropore group spacing; I: irrigation amount. The data are all average ± standard deviation in the chart; different letters in the same column mean significant difference at 0.05 level, $^{*}P < 0.05$; $^{**}P < 0.01$; ns: $P > 0.05$, the same as below.

The soil nonroot zone and root zone respiration rates of autumn tomato were about 2.81% and 4.14% lower than those of spring tomato, respectively. The soil respiration rate in the root zone of spring tomato and autumn tomato was about 14.66% and 16.25% higher than that in the nonroot zone, respectively.

Compared with CK1, the soil nonroot zone respiration rate and root zone respiration rate of L1I2 spring tomato and an autumn tomato increased by 11.39% and 6.22% and 4.80% and 7.26%, respectively, and increased by 27.08% and 39.70% and 42.25% and 37.06%, respectively, compared with CK2. With the increase of irrigation amount, the respiration rate of tomato soil nonroot zone and root zone increased first and then showed a slight decreasing trend. The soil respiration rate of 30 cm with the micropore group spacing is higher than 50 cm.

5.4. Effects of Different Treatments on the Related Carbon Content of Soil in Greenhouse Tomato. It can be seen from Table 4 that the micropore group spacing has no significant effect on TOC, MBC, HA-C, and FA-C in the nonrhizosphere and rhizosphere of soil with spring tomato and autumn tomato; irrigation amount has a significant effect on TOC, MBC, HA-C, and FA-C in the nonrhizosphere and rhizosphere of soil with spring tomato and autumn tomato. The TOC, MBC, HA-C, and FA-C of the rhizosphere soil of spring tomato and autumn tomato were 27.94% and 26.97%, 19.47% and 25.23%, 19.47% and 22.20%, and 8.15% and 2.78% higher than those of the nonrhizosphere soil, respectively.

In terms of nonrhizosphere of soil with spring tomato and autumn tomato, the TOC, MBC, HA-C, and FA-C of L1I2 treatments were higher than those of CK1 by about 8.24% and 4.44%, 2.36% and 6.03%, 2.09%and 6.23%, and 0.36% and 2.72%, respectively, and also higher than those of CK2 by about 13.19% and 5.59%, 7.22% and 10.69%, 9.72% and 16.15%, and 6.89% and 11.24%, respectively. For the rhizosphere soil of spring tomato and autumn tomato, the TOC, MBC, HA-C, and FA-C of L1I2 treatments were higher than those of CK1 by about 6.64% and 1.60%, 2.38% and 1.14%, 3.37% and 3.49%, and 1.32% and 2.57%, respectively, and also higher than those of CK2 by about 10.12% and 10.31%, 11.39% and 11.30%, 17.55% and 7.55%, and 6.39% and 12.86%, respectively. With the increase of irrigation amount, the TOC, MBC, HA-C, and FA-C of nonrhizosphere and rhizosphere soils of spring tomato and autumn tomato increased at first and then decreased. The TOC, MBC, HA-C, and FA-C of nonrhizosphere and rhizosphere soils of spring tomato and autumn tomato in the micropore group spacing of 30 cm was higher than 50 cm.

5.5. Effects of Different Treatments on Tomato Yield and Water Use Efficiency. As can be seen from Figure 9, the micropore group spacing had a significant effect on the yield and water use efficiency of spring and autumn tomatoes ($P \leq 0.05$). The irrigation amount had a significant effect on the yield and water use efficiency of spring and autumn tomatoes.

Compared with CK1, the yield and water use efficiency of spring tomato and autumn tomato treated with L1I2 increased by 19.39% and 4.54% and 10.03% and 2.32%, respectively. Compared with CK2, the yield and water use efficiency of spring tomato and autumn tomato treated with L1I2 increased by 20.46% and 49.22% and 31.02% and 58.05%, respectively. The yield of spring tomato and autumn tomato treated with L1I2 was about 31.88% and 28.03%, 0.96% and 1.43%, 47.73% and 44.49%, 24.74% and 21.09%, and 12.21% and 7.48% higher than that of L1I1, L1I3, L2I1, L2I2, and L2I3, respectively. With the increase of irrigation amount, the yield of spring tomato and autumn tomato increased, while the water use efficiency of spring tomato and autumn tomato decreased. The yield and water use efficiency of spring tomato and autumn tomato with micropore group spacing 30 cm were higher than those of 50 cm by about 16.00% and 13.01% and 20.85% and 14.25%, respectively.

Table 3: Effects of different treatments on soil CO_2 concentration of greenhouse tomato at different depths.

Treatment	Spring				Autumn			
	The CO_2 concentration of 0 cm (μmol/mol)		The CO_2 concentration of 20 cm (μmol/mol)		The CO_2 concentration of 0 cm (μmol/mol)		The CO_2 concentration of 20 cm (μmol/mol)	
	Nonroot zone soil	Root zone soil	Nonroot zone soil	Root zone soil	Nonroot zone soil	Root zone soil	Nonroot zone soil	Root zone soil
L1I1	430.93 ± 22.38^{b}	448.28 ± 37.33^{ab}	11549.36 ± 3088.94^{b}	15387.65 ± 3353.14^{b}	354.37 ± 17.44^{b}	362.06 ± 33.02^{b}	9911.93 ± 1542.99^{b}	12220.01 ± 2087.97^{b}
L1I2	460.74 ± 14.86^{a}	475.31 ± 32.63^{a}	$13909.31 \pm 2817.28^{ab}$	$18369.31 \pm 3474.77^{ab}$	409.53 ± 25.36^{a}	457.31 ± 53.35^{ab}	$11910.05 \pm 2638.63^{ab}$	$14832.84 \pm 3354.07^{ab}$
L1I3	445.51 ± 23.51^{ab}	468.43 ± 19.07^{ab}	15238.13 ± 4111.09^{a}	19529.57 ± 3560.48^{a}	406.69 ± 42.87^{a}	424.605 ± 45.46^{ab}	13106.25 ± 3051.99^{a}	15800.78 ± 2645.28^{a}
L2I1	429.97 ± 29.42^{b}	$433.85 \pm 32.33b$	11116.69 ± 1199.53^{b}	15209.09 ± 3858.32^{b}	347.53 ± 27.89^{b}	356.79 ± 47.27^{b}	9894.33 ± 2011.61^{b}	12087.22 ± 2232.93^{b}
L2I2	450.31 ± 19.7^{ab}	476.66 ± 24.27^{a}	13466.39 ± 4681.6^{ab}	$17815.02 \pm 5512.68^{ab}$	402.3 ± 32.05^{a}	435.43 ± 32.39^{ab}	$11663.94 \pm 3104.59^{ab}$	$14547.37 \pm 3466.27^{ab}$
L2I3	446.74 ± 23.26^{ab}	474.06 ± 30.25^{a}	14979.31 ± 2576.25^{a}	19353.99 ± 2662.52^{a}	402.22 ± 47.14^{a}	421.88 ± 63.02^{ab}	12829.23 ± 2418.95^{a}	15614.11 ± 3259.88^{a}
CK1	448.66 ± 13.2^{ab}	473.11 ± 17.92^{a}	$13366.68 \pm 1382.84^{ab}$	$18065.81 \pm 2218.28^{ab}$	402.34 ± 18.45^{a}	451.73 ± 44.67^{ab}	$12069.23 \pm 2366.66^{ab}$	$14276.91 \pm 3646.29^{ab}$
CK2	432.44 ± 5.09^{b}	441.15 ± 17.82^{ab}	$12527.66 \pm 2109.63^{ab}$	$16997.02 \pm 2780.95^{ab}$	390.18 ± 12.52^{a}	406.75 ± 27.51^{ab}	$11653.99 \pm 2744.25^{ab}$	12261.35 ± 1285.67^{b}
F value								
L	0.202^{ns}	0.062^{ns}	0.180^{ns}	0.084^{ns}	0.303^{ns}	0.405^{ns}	0.069^{ns}	0.066^{ns}
I	3.766^{*}	4.810^{*}	6.101^{**}	5.458^{*}	10.369^{**}	11.013^{**}	6.756^{**}	7.202^{**}
L ∗ I	0.225^{ns}	0.374^{ns}	0.004^{ns}	0.014^{ns}	0.006^{ns}	0.146^{ns}	0.014^{ns}	0.003^{ns}

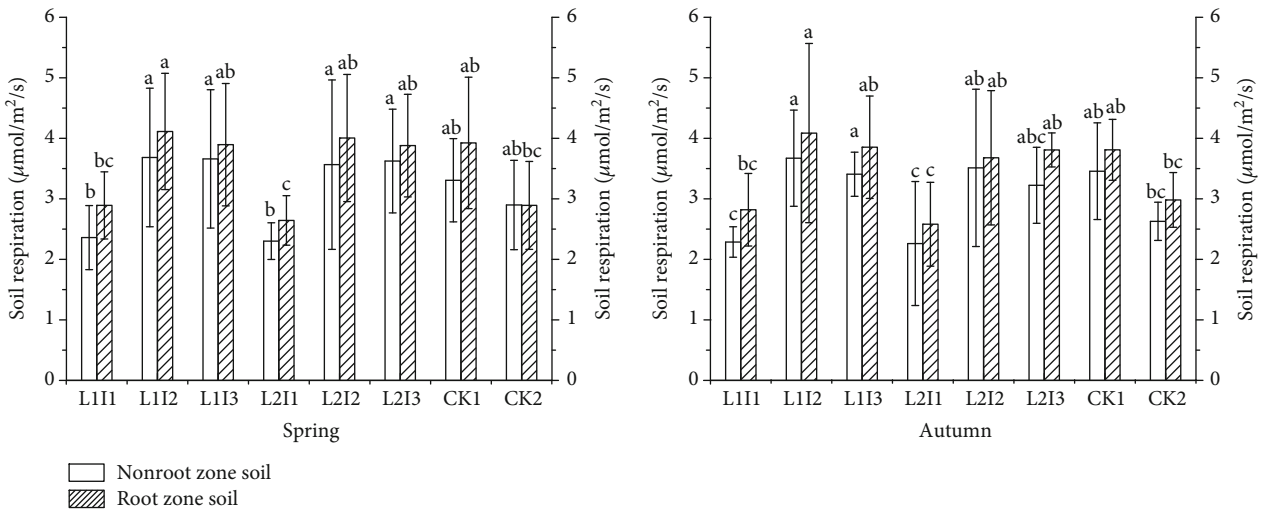

Figure 8: Effects of different treatments on soil respiration rate of tomato in greenhouse. Note: the data are all average ± standard deviation in the figure; different letters in the same column meant significant difference at 0.05 level, the same as below.

5.6. Regression Analysis of Soil Respiration Rate and Yield of Microsprinkler Irrigation under Plastic Film. As can be seen from Figure 5, there is a logarithmic relationship between x_n and x_r (formula (4)) and a conic relationship between x_n and y (formula (5)).

$$x_r = 2.6749 \ln (x_n) + 0.6565, \quad (4)$$

$$y = -0.425.90x_n^2 + 41378x_n + 11143. \quad (5)$$

Through the simultaneous establishment of the above two equations, the relationship between x_r and y can be obtained, that is, $y = 2602.13e^{0.7478x_r} + 32370.01e^{0.3739x_r} + 11143$. In the regression model (4), the determination coefficient of x_n and x_r regression is $R^2 = 0.8237$, indicating that the degree to which x_n can explain x_r in this model is up to 82%, and the coefficient x_r can be predicted by x_n. In the regression model (5), the determination coefficient of x_n and y regression is $R^2 = 6992$, indicating that the degree to which x_n can explain y in this model is up to 69%, and the coefficient y can be predicted by x_n.

6. Discussion

6.1. Effects of Irrigation Methods on Soil Microenvironment and Soil Respiration Rate. Previous studies have shown that different irrigation methods lead to different forms of water entering the soil. It can change the shape of the soil wetting body, the size of the dry and wet zones, and the number of cycles and affect the mineralization decomposition rate of soil organic matter, microbial biomass, and soil enzyme activity and then increase or decrease the concentration of CO_2 in soil. Under the concentration gradient drive, the diffusion rate of soil CO_2 to the surface increases or slows down [38, 43]. There is a positive correlation between soil respiration rate and soil moisture in arid and semiarid areas, in which the limitation of soil moisture is mainly reflected in reducing the availability of soil organic matter and the death of soil microorganisms caused by low water potential [44, 45]. In this study, the soil respiration rate of tomato with MSPF was higher than that of drip irrigation under plastic film (see Figure 8). It is possible that under the same working pressure and irrigation amount, the effluent velocity of drip irrigation under plastic film is about 0.067 times that of MSPF, and the irrigation duration increases, so that the ratio of horizontal to vertical migration distance of soil water in drip irrigation under plastic film is smaller than that of MSPF, and the higher horizontal movement of soil water is easy to increase the wetting volume of the tillage layer (0~40 cm) per unit area [46]. The soil moisture of tomato with drip irrigation under a plastic film is mainly concentrated under the emitter, and there is an obvious dry-wet zone and a long dry-wet duration, which restricts the activities of microorganisms and enzymes in the dry area, and the soil water content is too high in the wet area, which reduces the soil gas exchange. As a result, the soil respiration rate of drip irrigation under plastic film is lower than that of MSPF. Burger et al. found that the peak of CO_2 emission from tomato soil respiration occurred when WFPS was about 60% [47]. It is mainly due to the fact that soil moisture is the main factor limiting soil respiration when WFPS < 60%. Too high or low soil moisture will reduce the stability of soil aggregates. The destruction of soil aggregates is usually accompanied by the increase of the utilization rate of organic carbon sources, which can increase the activities of microorganisms and enzymes and increase the mineralization of soil carbon [48, 49]. At the same time, the increase of soil moisture increased microbial activity and plant physiological activities; increased soil TOC, MBC, HA-C, and FA-C; and further supplied energy sources for microbial activities and increased soil microbial respiration. When WFPS > 60%, higher soil moisture occupies a large number of soil pores, reducing soil oxygen content, and limiting soil gas diffusion rate [39]. In this study, the WFPS of MSPF is close to 60%, and the moisture and temperature of MSPF are higher than 5.77% and 4.30% and 3.99% and 13.47% (see Table 5) of drip

Table 4: Effects of different treatments on soil related carbon content of greenhouse tomato.

			Treatment								F value		
			L1I1	L1I2	L1I3	L2I1	L2I2	L2I3	CK1	CK2	L	I	L ∗ I
Spring	TOC (%)	Nonrhizosphere	0.96 ± 0.12^{c}	1.18 ± 0.11^{a}	1.16 ± 0.09^{a}	0.95 ± 0.17^{c}	1.17 ± 0.07^{a}	1.16 ± 0.09^{a}	1.09 ± 0.04^{ab}	1.04 ± 0.07^{bc}	0.032^{ns}	21.533^{**}	0.016^{ns}
		Rhizosphere	1.31 ± 0.09^{b}	1.46 ± 0.14^{a}	1.45 ± 0.11^{a}	1.3 ± 0.17^{ba}	1.46 ± 0.09^{a}	1.46 ± 0.1^{a}	1.37 ± 0.05^{ab}	1.33 ± 0.09^{b}	0.001^{ns}	9.964^{**}	0.029^{ns}
	MBC (mg/kg)	Nonrhizosphere	108.27 ± 17.47^{bc}	121.53 ± 8.38^{a}	121.31 ± 10.36^{a}	107.35 ± 13.48^{c}	120.78 ± 6.35^{a}	121.55 ± 11.58^{a}	108.17 ± 4.7^{ab}	115.34 ± 7.53^{abc}	0.022^{ns}	7.804^{**}	0.012^{ns}
		Rhizosphere	128.11 ± 14.12^{c}	147.64 ± 10.26^{a}	145.27 ± 15.19^{a}	125.88 ± 10.7^{c}	142.4 ± 12.98^{ab}	145.56 ± 15.5^{a}	144.21 ± 8.09^{ab}	132.55 ± 8.21^{bc}	0.439^{ns}	11.295^{**}	0.196^{ns}
	HA-C (g/kg)	Nonrhizosphere	1.63 ± 0.29^{b}	2.07 ± 0.14^{a}	2.04 ± 0.24^{a}	1.64 ± 0.5^{b}	2.05 ± 0.24^{a}	2.07 ± 0.36^{a}	2.03 ± 0.3^{a}	1.89 ± 0.12^{ab}	0.001^{ns}	10.806^{**}	0.021^{ns}
		Rhizosphere	2.07 ± 0.6^{b}	2.47 ± 0.18^{a}	2.39 ± 0.26^{ab}	2.08 ± 0.43^{b}	2.4 ± 0.23^{ab}	2.37 ± 0.15^{ab}	2.39 ± 0.31^{ab}	2.1 ± 0.37^{b}	0.073^{ns}	5.721^{*}	0.060^{ns}
	FA-C (g/kg)	Nonrhizosphere	2.15 ± 0.45^{bc}	2.66 ± 0.31^{a}	2.59 ± 0.4^{a}	2.06 ± 0.34^{c}	2.57 ± 0.37^{a}	2.57 ± 0.34^{a}	2.65 ± 0.38^{a}	2.48 ± 0.37^{ab}	0.386^{ns}	10.462^{**}	0.053^{ns}
		Rhizosphere	2.46 ± 0.27^{ab}	2.82 ± 0.26^{a}	2.72 ± 0.46^{ab}	2.36 ± 0.43^{b}	2.77 ± 0.39^{a}	2.76 ± 0.37^{a}	2.79 ± 0.26^{a}	2.65 ± 0.42^{ab}	0.156^{ns}	5.760^{*}	0.162^{ns}
Autumn	TOC (%)	Nonrhizosphere	0.92 ± 0.07^{b}	1.07 ± 0.05^{a}	1.07 ± 0.07^{a}	0.9 ± 0.07^{b}	1.07 ± 0.05^{a}	1.05 ± 0.05^{a}	1.03 ± 0.07^{a}	1.01 ± 0.11^{a}	0.657^{ns}	39.2936^{**}	0.225^{ns}
		Rhizosphere	1.18 ± 0.08^{b}	1.34 ± 0.06^{a}	1.35 ± 0.07^{a}	1.16 ± 0.09^{b}	1.34 ± 0.07^{a}	1.35 ± 0.07^{a}	1.32 ± 0.08^{a}	1.22 ± 0.11^{b}	0.034^{ns}	33.320^{**}	0.045^{ns}
	MBC (mg/kg)	Nonrhizosphere	92.31 ± 6.01^{b}	107.48 ± 7.51^{a}	107.14 ± 8.85^{a}	94.5 ± 17.2^{b}	107.52 ± 10.74^{a}	106.96 ± 7.42^{a}	101.37 ± 11.89^{ab}	97.1 ± 7.65^{ab}	0.060^{ns}	10.881^{**}	0.073^{ns}
		Rhizosphere	119.39 ± 7.6^{c}	134.61 ± 9.5^{a}	134.31 ± 11.2^{a}	118.83 ± 20.62^{c}	133.68 ± 13.96^{a}	134.08 ± 9.39^{a}	132.74 ± 16.58^{ab}	120.94 ± 6.66^{bc}	0.027^{ns}	8.320^{**}	0.003^{ns}
	HA-C (g/kg)	Nonrhizosphere	1.7 ± 0.31^{bc}	2.05 ± 0.12^{a}	1.94 ± 0.26^{ab}	1.63 ± 0.31^{c}	1.95 ± 0.19^{ab}	1.96 ± 0.26^{ab}	1.93 ± 0.3^{ab}	1.76 ± 0.36^{abc}	0.530^{ns}	9.415^{**}	0.240^{ns}
		Rhizosphere	2.13 ± 0.39^{c}	2.49 ± 0.16^{a}	2.46 ± 0.21^{a}	2.15 ± 0.27^{bc}	2.29 ± 0.18^{abc}	2.36 ± 0.27^{abc}	2.41 ± 0.18^{ab}	2.32 ± 0.29^{abc}	1.6767^{ns}	6.337^{**}	0.871^{ns}
	FA-C (g/kg)	Nonrhizosphere	2.14 ± 0.21^{b}	2.58 ± 0.46^{a}	2.57 ± 0.39^{a}	2.12 ± 0.36^{b}	2.52 ± 0.44^{ab}	2.55 ± 0.39^{a}	2.51 ± 0.43^{ab}	2.32 ± 0.39^{ab}	0.090^{ns}	7.410^{**}	0.017^{ns}
		Rhizosphere	2.3 ± 0.25^{ab}	2.65 ± 0.4^{a}	2.57 ± 0.38^{ab}	2.21 ± 0.26^{b}	2.59 ± 0.4^{ab}	2.59 ± 0.36^{ab}	2.58 ± 0.42^{ab}	2.35 ± 0.3^{ab}	0.188^{ns}	6.041^{*}	0.096^{ns}

Note: TOC: soil total organic carbon; MBC: soil microbial biomass carbon; HA-C: soil humic acid carbon; FA-C: soil fulvic acid carbon.

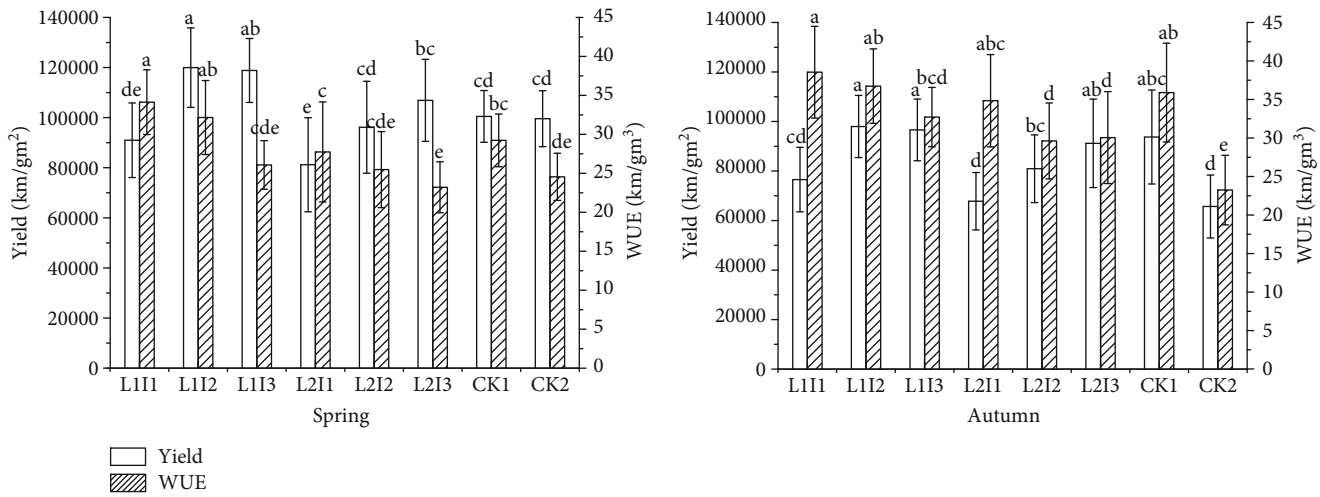

Figure 9: Effects of different treatments on tomato yield and water use efficiency.

irrigation under plastic film, respectively, which may also be one of the reasons for the higher soil respiration of MSPF.

It was found that the soil respiration rate of the tomato root zone was higher than that of the nonroot zone. It may be due to the fact that the soil in the crop root zone contains plant roots. Previous studies have shown that the diversity, abundance, and activity of microorganisms in the plant rhizosphere soil are high [50], and the respiration of microorganisms and plant roots is easy to increase soil respiration rate (CO_2 emission) [51, 52]. In this study, it was also found that the soil respiration rate of spring tomato was higher than that of autumn tomato. Mainly because the soil temperature of spring tomato is 32.19% higher than that of autumn tomato (L1I2, see Table 2), lower temperature can reduce cell activity, which is not conducive to microorganisms and crop respiration [53]. Previous studies have found that the effect of irrigation on the soil respiration rate is attributed to the increase of crop yield to stimulate root autotrophic respiration and the change of soil water content to stimulate soil heterotrophic respiration [54]. In this study, the yield of tomato and soil moisture of MSPF were higher than those of drip irrigation under plastic film by 19.39 and 4.54% (see Figure 9) and 5.77 and 4.30% (see Table 2), respectively, indicating that MSPF can increase soil respiration rate and lead to the increase of the soil CO_2 emission rate. The increase of the soil respiration rate in greenhouse agriculture contributes to the formation of greenhouse tomato yield, which can achieve a new dynamic balance among tomato crop water use efficiency, yield, and CO_2 emission from greenhouse vegetable fields.

This study found that the humidity of spring tomato and autumn tomato canopy under MSPF was about 36.03% and 25.20% lower than that of microsprinkler irrigation (see Figure 10), respectively. This may be due to the large number of micropores per unit length of microsprinkler irrigation, so the water spray is easy to atomize, and the increase of surface wetting area also easily increases ineffective water transpiration, which leads to a significant increase in air humidity in the microenvironment of tomato growth, which is consistent with the finding of Man et al. [15] who explored the mechanism of action of microsprinkler irrigation. The results also showed that the soil respiration rate of tomato under MSPF was higher than that of microsprinkler irrigation, and the yield of tomato under MSPF was 4.69% and 49.22% higher than that of microsprinkler irrigation (see Figure 9), which was consistent with the conclusion of Scheer et al. [54]. Mainly due to the low oxygen content of the air humidity, it will reduce the soil aerobic respiration microbial activity, and its byproduct CO_2 emissions will also be reduced. The increase in crop yield will further stimulate the autotrophic respiration of roots, resulting in a higher soil respiration rate of MSPF. This study also found that the soil WFPS of 0~10 cm under MSPF was about 60%, which was higher than 10.15% and 6.33% of microsprinkler irrigation. At the same time, the soil moisture volume content of 20 cm under MSPF was 7.96% and 7.22% (see Table 2) higher than that of microsprinkler irrigation, indicating that soil moisture was also one of the main reasons affecting the soil respiration rate of tomato under MSPF.

6.2. Effects of Micropore Group Spacing and Irrigation Amount on Soil Respiration Rate. In this study, the micropore group spacing has little effect on the soil respiration rate, which may be due to the large flow rate and short irrigation duration of the single group of MSPF. When the flow of WFPS is greater than the soil infiltration rate, it is easy to produce local microrunoff, which increases the soil water horizontal transport distance and reduces the effect of relatively small micropore group spacing. There is no significant difference in 0~10 cm soil WFPS between the two groups ($P > 0.05$). It was also found that the micropore group spacing had no significant effect on soil moisture and temperature. Previous studies have found that water and heat changes directly affect soil microorganisms and enzyme activities, thus changing soil TOC, MBC, HA-C, and FA-C cycles [38, 55]. There was no significant difference in soil TOC, MBC, HA-C, and FA-C among different micropore group spacings, which further indicated

Table 5: Effects of different treatments on soil water-filled porosity of tomato.

Treatment	Spring		Autumn	
	Nonroot zone soil (%)	Root zone soil (%)	Nonroot zone soil (%)	Root zone soil (%)
L1I1	55.69 ± 10.04^{ab}	54.41 ± 10.89^{ab}	54.25 ± 9.78^{ab}	49.85 ± 12.37^{b}
L1I2	62.55 ± 9.26^{ab}	61.76 ± 5.81^{a}	60.52 ± 8.52^{ab}	58.05 ± 7.4^{ab}
L1I3	63.2 ± 5.35^{a}	62.29 ± 8.05^{a}	63.49 ± 10.09^{a}	63.09 ± 8.88^{a}
L2I1	53.72 ± 8.72^{b}	50.82 ± 7.17^{b}	50.47 ± 8.79^{b}	47.85 ± 13.4^{b}
L2I2	56.77 ± 6.99^{ab}	57.17 ± 6.54^{ab}	55.39 ± 12.51^{ab}	54.34 ± 8.03^{ab}
L2I3	63.92 ± 9.08^{a}	58.56 ± 8.79^{ab}	63.55 ± 9.63^{a}	62.34 ± 8.91^{a}
CK1	62.63 ± 6.31^{ab}	61.84 ± 4.79^{a}	60.13 ± 7.72^{ab}	57.82 ± 13.7^{ab}
CK2	57.68 ± 11.19^{ab}	55.18 ± 9.51^{ab}	56.82 ± 7.96^{ab}	54.69 ± 7.44^{ab}
F value				
L	1.052^{ns}	3.289^{ns}	1.181^{ns}	0.617^{ns}
I	5.039^{*}	5.042^{*}	5.635^{**}	8.516^{**}
L ∗ I	0.682^{ns}	0.021^{ns}	0.328^{ns}	0.097^{ns}

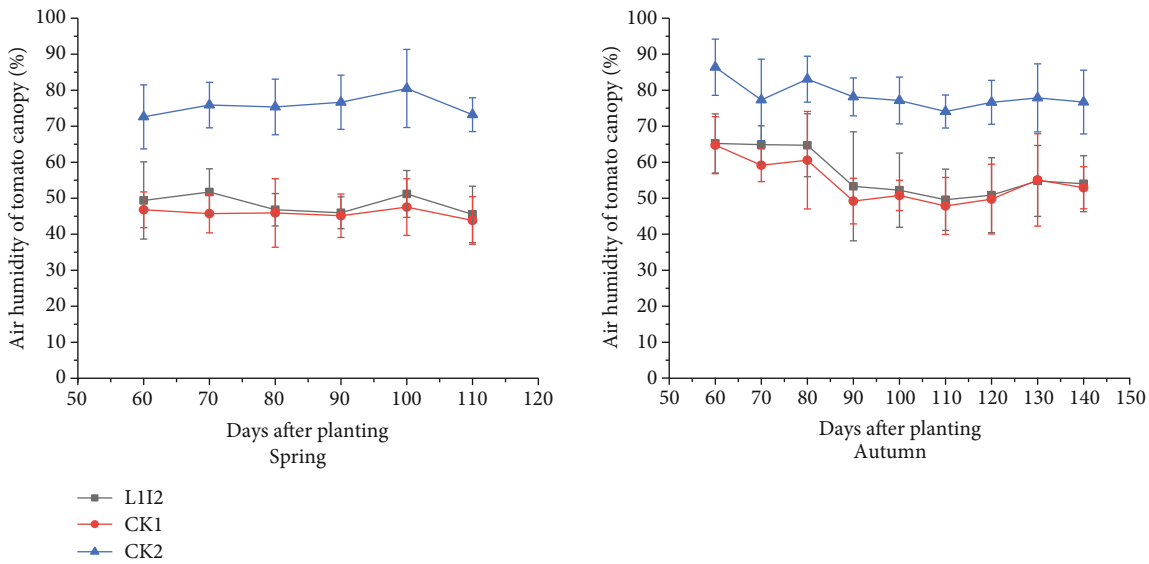

Figure 10: Effects of different treatments on air humidity in tomato canopy with spring and autumn.

that the micropore group spacing had little effect on soil respiration rate.

Previous studies have found that properly reducing the irrigation amount can reduce the soil respiration rate. With the increase of irrigation amount, soil water stimulates root respiration and soil microbial activity, resulting in an increase in the soil respiration rate [34, 35]. However, when the irrigation amount increased to a certain extent, crop root aerobic respiration and soil microbial activity were gradually inhibited and further inhibited soil respiration rate [56, 57]. This may also be one of the reasons why the soil respiration rate increased at first and then decreased with the increase of irrigation amount in this study. Chen et al.'s [39] study shows that the soil respiration rate increases with the increase of the irrigation amount, which is inconsistent with the conclusion of this paper. It may be caused by the difference in irrigation amount. The highest irrigation amount in Chen et al.'s study was 1.0 Epan, while the highest in this study was 1.2 Epan. Agbna et al. [58] and Zhu et al. [59] found that when the irrigation amount of drip irrigation with tomato increased from 0.5 Epan to 1.0 Epan, the yield increased while the WUE decreased. It shows that the effect of MSPF on tomato yield and water use efficiency was similar to drip irrigation, and the MSPF was suitable for greenhouse tomato irrigation.

6.3. Correlation between Soil Microenvironment, Soil Respiration Rate, and Yield of Tomato with Microsprinkler Irrigation under Plastic Film. Previous studies have shown that when the protected agricultural space is relatively closed and the irrigation water is limited, reducing the irrigation amount and increasing greenhouse CO_2 concentration can improve the yield and quality of greenhouse tomato [60, 61]. In this study, it was found that there was a significant

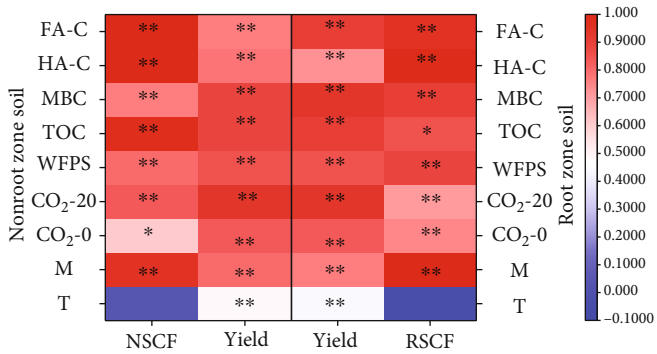

Figure 11: Correlation between soil microenvironment, soil respiration rate, and yield of tomato. Note: WFPS: water-filled pore space of soil; CO_2-20: soil CO_2 concentration of 20 cm; CO_2-0: soil CO_2 concentration of 0 cm; M: soil moisture; T: soil temperature; NSCF: soil respiration rate in nonroot zone; RSCF: soil respiration rate in root zone. Different color depth means correlation difference; correlation value is showed by the value of the number from -0.1 to 1. $*$ means significance correlation ($P < 0.05$); $**$ means significance correlation ($P < 0.01$), the same below.

positive correlation between the soil respiration rate and yield (see Figure 11), which was consistent with the conclusion that Mancinelli et al. [62] found that there is a positive correlation between the CO_2 emission rate of tomato soil and yield under drip irrigation. It may be because the greenhouse microenvironment is relatively closed and the CO_2 content is limited. For tomatoes with a high photorespiration rate, increasing atmospheric CO_2 concentration in a certain range can not only provide more sufficient raw materials for photosynthesis but also increase the activity of (RuBP) carboxylase of ribulose 5-diphosphate, which is beneficial to accelerate the binding of RuBP in chloroplasts to CO_2 entering chloroplasts, thus enhancing the ability of photosynthesis to fix CO_2, formatting 3-phosphoglyceric acid (PGA), and further synthesizing photosynthetic carbohydrate through C3 cycling [63, 64]. In this study, there was a positive correlation between soil moisture and soil respiration rate (see Figure 11), which was consistent with that obtained by Wei et al. [65] when soil moisture content in maize planting under drip irrigation was lower than the field water holding capacity. This study also found that there was a synergistic change of TOC and MBC in the soil of tomato under MSPF, which was positively correlated with the soil respiration rate (see Figure 11). It is consistent with the finding of Han et al. [66] to study the changes of soil TOC and MBC under drip irrigation, which shows that the effect of MSPF on soil TOC and MBC is similar to that of drip irrigation under plastic film.

Previous studies have found that there is a significant positive correlation between the soil temperature and soil respiration rate [34, 65, 67]. However, there was no significant difference in the positive effect of temperature on the soil respiration rate in this study. It may be that the soil water distribution of MSPF is relatively uniform, the soil moisture in the root zone and the nonroot zone of tomato is not too high or too low, and the soil microenvironment is relatively stable, which lead to the decrease of the effect of temperature on the soil respiration rate. Wang et al. [68] believe that when the WFPS of the soil is less than 60%, there is a positive correlation between the soil respiration rate and soil WFPS; otherwise, there is a negative correlation between them. In this study, there was a positive correlation between soil WFPS and the soil respiration rate of greenhouse tomato, which is inconsistent with the conclusion that there was a negative correlation between the soil respiration rate and soil WFPS under drip irrigation [69]. It is possibly due to the differences in soil types, irrigation methods, and the irrigation amount controlled by the experiment. Chen used drip irrigation of tomato in *Yangling* soil (brown loam), and the irrigation amount increased from 0.6 Epan to 1.0 Epan. However, in this study, tomato was irrigated with MSPF on sandy loam (yellow cinnamon soil), and the irrigation amount increased from 0.7 Epan to 1.2 Epan.

7. Conclusion

In this paper, by exploring the response mechanism of greenhouse soil microenvironment, soil respiration rate, and yield of tomato under different micropore group spacing and irrigation amount of MSPF, the suitable micropore group spacing and irrigation amount of MSPF for greenhouse tomato growth were obtained. The results showed that compared with drip irrigation under a plastic film, and the yield of spring tomato and autumn tomato increased by 19.39% and 4.54%, respectively. Compared with microsprinkler irrigation, tomato yield, water use efficiency, and soil respiration rate under MSPF for spring and autumn were increased by 20.46% and 49.22%, 31.02% and 58.05%, and 34.66% and 38.38%, respectively. In this study, greenhouse tomato under MSPF increased the soil respiration rate (CO_2 emission); however, the tomato yield and WUE were also improved, indicating that the MSPF could achieve an effective dynamic balance among greenhouse CO_2, yields and WUE. The micropore group spacing had no significant effect on the soil respiration rate. Compared with 50 cm of micropore group spacing, the 30 cm micropore group spacing increased the yield and WUE of tomato by 16.00% and 13.01% and 20.85% and 14.25%, respectively. With the increase of irrigation amount, the soil respiration rate in the root and nonroot zones and the yield of spring tomato and autumn tomato

increased at first and then decreased, and the WUE showed a decreasing trend. As for the soil respiration rate, it is higher in the root zone than it is in the nonroot zone, and there exists a logarithmic function relationship between the soil respiration rate in the nonroot zone and the soil respiration rate in the root zone, and there is a quadratic relationship between the soil respiration rate and the yield in the nonroot zone. Considering our results comprehensively, the combination of the 30 cm micropore group spacing and 1.0 Epan is recommended for greenhouse tomato under MSPF in northwest China. This study can provide theoretical data and experimental support for water-saving irrigation and yield increase of facility agricultural tomato and analysis of the soil carbon cycle mechanism of MSPF. Although the results of this study explain the effects of different micropore group spacings and irrigation amounts on the soil respiration rate and yield of tomato, it is still an open question how to change the soil enzyme activity and microbial community structure to further drive the change of the soil respiration rate and yield under different micropore spacings and irrigation amounts.

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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