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YIELD AND QUALITY RESPONSE OF GREENHOUSE TOMATO TO DIFFERENT MICROPORES GROUP SPACING AND IRRIGATION AMOUNT

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ABSTRACT

The micro-sprinkler irrigation under plastic film (MSPF) uses multiple groups of small micropores under plastic film to evenly distribute water in the root zone soil with the help of gravity and capillary suction, and the appropriate micropores group spacing and irrigation amount can realize the efficient utilization of MSPF. This study clarified the applicability of MSPF in a greenhouse and finding the optimal micropores group spacing and irrigation amount. Treatments were ranged in completely randomised design aimed to determine the effects of different micropores group spacing (L1: 30 cm micropores group spacing, and L2: 50 cm micropores group spacing) and irrigation amount [I1:0.7 E_{pan}; I2:1.0 E_{pan}; and I3:1.2 E_{pan} (E_{pan} is the diameter of 20-cm standard pan evaporation, mm)] of the MSPF on the yield and quality of tomato. The results showed that the MSPF can be used as one of the micro-irrigation methods of greenhouse, which can lead to saving water, increase yield, and improve crop quality. Compared to L2, L1 was better for fruit quality, yield, and water use efficiency (WUE). With increasing irrigation amount, the fruit shape and yield increased, but the fruit flavour, nutrition and WUE decreased. The combination of the 30 cm micropores group spacing and 1.0 E_{pan} is recommended for greenhouse tomato under MSPF in arid and semi-arid sandy loam soil of facility agriculture.

Keywords: Micro-sprinkler irrigation under plastic film; Water use efficiency; Principal Component Analysis; Technique for order preference by similarity to an ideal solution

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INTRODUCTION

The development of facility agriculture has provided a powerful guarantee for vegetable production in northwest China. However, the irrigation water for facility agriculture in this region mainly comes from groundwater, and the progress of groundwater resources exploitation has exacerbated the water resources crisis in the arid and semi-arid areas of Northwest China, so it is urgent to save water resources(Du *et al*. 2014). Therefore, the realization of efficient utilization of water resources has become the current research hotspot in this region.

As one of the main micro-irrigation methods in facility agriculture, the micro-sprinkler irrigation under plastic film (MSPF, Figure 1) uses multiple groups of small micropores under plastic film to evenly distribute water in the root zone soil with the help of gravity and capillary suction. Compared with the drip irrigation in facility agriculture, under the same working pressure and irrigation volume, the velocity of single hole in MSPF is about 15 times that of labyrinth drip irrigation, which has stronger sediment-carrying capacity and anti-clogging performance, and can solve the blockage problem of emitters in partial drip irrigation(Feng *et al*. 2018). The single group flow rate of MSPF is about 40 times that of drip irrigation emitter flow, and the irrigation duration is short, so it is easy to increase the ratio of horizontal and vertical migration distance of soil water wetting peak, thus increasing soil wetting body per unit area of tillage layer(Del Vigo *et al*. 2020). it can reduce the deep transport of soil water and limit the lateral development of roots under water stress, and the soil nutrient cycle is also changed due to the increase of soil dry-wet cycle(Li *et al*. 2019). The exploration of MSPF is of great significance for expanding the scope of micro-sprinkler irrigation application and ensuring crop water-saving, yield-enhancement, and quality-improvement.

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

With the improvement of people's quality of life, the quality and yield of tomato has attracted more and more attention. The greenhouse tomato planting interval in this area is relatively large and belongs to the sparsely-planted crop. As a result, the choice of the spacing of the outflow micropores on the capillary pipe and the irrigation amount directly affect the quality and yield of the tomato, and the cost of investment. It is found that under the same dripper flow rate, the smaller the dripper spacing is, the shorter the confluence time of the wetting peak between the dripper is, the more uniform the moisture distribution between the dripper is, and the horizontal wetting shape is approximately rectangular(Elmaloglou & Diamantopoulos 2010). It can also reduce unnecessary irrigation water waste and improve irrigation water use efficiency(Sui *et al*. 2018; Xu *et al*. 2012). The change of emitter flow rate and irrigation amount will also change the soil water distribution. The study shows that under the same emitter spacing, the larger the emitter flow rate, the higher the ratio of soil water horizontal migration to vertical migration distance(Del *et al*. 2020; Nangare *et al*. 2016). Too high or too low irrigation amount in crop planting irrigation will reduce yield (Duan *et al*. 2013; Nangare *et al*. 2016). Sensoy *et al*.(2007) believes that the yield of irrigation amount of 0.9 E_{pan} is higher than 0.6 E_{pan}. However, when sufficient soil water increases yield, fruit quality and crop water use efficiency will decrease, and profit loss will increase(Luo and Li 2018).

Presently, studies assessing the relationship between micropores group spacing and irrigation amount have mainly focused on drip irrigation with small emitter flow; however, few studies have investigated the effects of different micropores group spacing and irrigation amount of MSPF with large flow on greenhouse tomato. Therefore, compared with drip irrigation and micro-sprinkler irrigation, this study explored the applicability of MSPF in greenhouse and the response of tomato quality, yield and water use efficiency to different micropores group spacing and irrigation amount. In addition, the weight of each index was determined by criteria importance though intercrieria correlation (CRITIC) method(Wu *et al*. 2018), which was better than entropy method and standard deviation score method, the comprehensive benefit evaluation model of greenhouse tomato quality, yield and water use efficiency was constructed based on weighted with technique for order preference by similarity to an ideal solution (TOPSIS) method, and different treatments were optimized to obtain the best combination model of micropores group spacing and irrigation amount for tomato quality, yield and water use efficiency under MSPF. This paper provides findings for the enrichment of tomato micro-irrigation technology system in arid and semi-arid sandy loam soil of facility agriculture and offers valuable data support and theoretical basis by greenhouse experiment and multi-objective optimization data analysis for water-saving, yield-enhancement, and quality-improvement of agricultural crops in this region.

MATERIALS AND METHODS

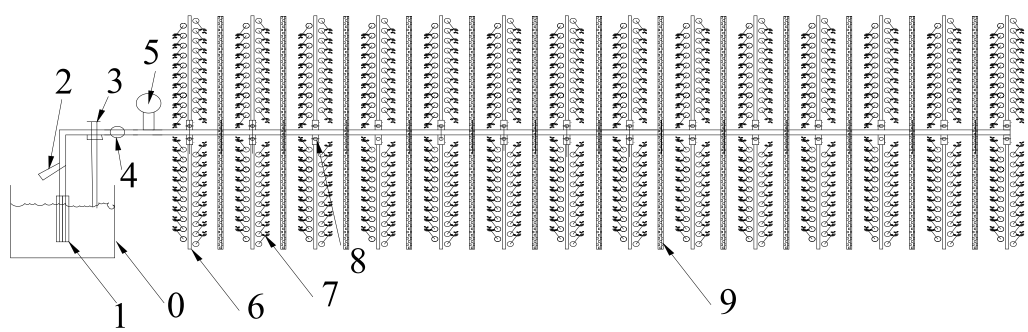
Experimental site and management: The experiment was carried out from 27 March 2019 to 30 January 2020 in a greenhouse at Modern Agricultural Science and Technology Exhibition Centre, Xi'an City, Shaanxi Province (108°52°E, 34°03°N). The region exhibits a warm temperate semi-humid continental monsoon 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 maximum annual sunshine time is 2230 h and the multi-year average wind speed is 2–3 m/s.

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 15530 mg/kg, 10120 mg/kg, 2010 mg/kg, 1360 mg/kg, 70.45 mg/kg, 112 mg/kg and 85.23 mg/kg, respectively. The irrigation water originated from groundwater, the pH of which was 6.8, the chemical oxygen demand (COD) was 53.2 mg/L, the anionic surfactant content was 3.2 mg/L, and the chloride content was 0.48 mg/L.

The greenhouse (85 m long and 15 m wide) was oriented from north to south. The tomato variety 'Jingfan 401' (Jingyan Yinong Seed Sci-tech Co. Ltd., Beijing, China), with a 50 cm row spacing and a 40 cm plant spacing, was planted on a ridge. The length of the ridge was 3.4 m and the width was related to the capillary arrangement density. 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. Simultaneously, plastic barriers were laid in the middle to prevent diseases and insect pests caused by excessive humidity and irrigation treatments, thus avoiding their effect on other plot experiments.

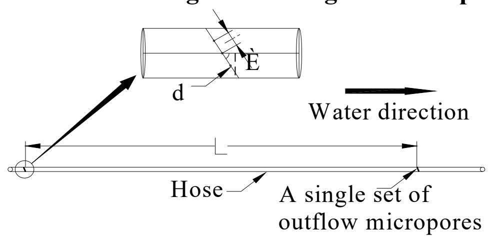
The pipe of MSPF (Hebei Plentirain Irrigation Equipment Technology Co., Ltd., Hebei, China) adopted thin-walled oblique 3 micropores, the pipe of diameter was 32 mm and the micropore of diameter was 0.8 mm. Micropores group spacing is shown in the experimental design (Figure 3 and Table 1). The control drip irrigation under mulch (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 pipe of diameter was 16 mm, the distance between drippers was 30 cm, and the dripper flow rate was 2 L/h. The control of pipe of micro-sprinkler irrigation (CK2, Hebei Plentirain Irrigation Equipment Technology Co., Ltd., Hebei, China) adopted thin-walled oblique 3 micropores which the pipe of diameter was 32 mm and the micropore of diameter was 0.8 mm. The micropores group spacing was 10 cm.

Tomato plants were topped when the four-eared fruit were retained and the field management measures, such as fertilization, irrigation, and medicine, were kept similar in all treatments. The source of irrigation water in the region was groundwater. To ensure the survival of seedlings on the day of planting, the irrigation was unified with reference to the local tomato planting experience. Spring tomatoes were planted on 27 March 2019 and irrigation treatment was initiated on 4 April 2019. The irrigation treatment was continued until 15 July 2019 and tomatoes were completely harvested on 25 July 2019. Autumn tomatoes were planted on 23 August 2019, irrigation treatment was continued between 30 August 2019 and 17 January 2020, and tomatoes were complete harvested on 30 January 2020.



Note: 0, water tank; 1, the pump (WQD10-12-0.75S, People Pumb, Crop., Shanghai, China); 2, filter; 3, backwater valve; 4, electromagnetic flowmeter; 5, pressure gauge; 6, capillary; 7, tomato; 8, capillary valve; 9, plastic screens.

Figure 2. Schematic diagram of the greenhouse plot layout



Note: the diameter of micropore (d) is 0.7 mm; the internal spacing of the microporous group (I) is 0.3 cm; the angle of micropores = 68º.

Figure 3 Schematic diagram of micropores group (inside) spacing structure parameters

Experimental design: Factors including the micropores group spacing (Figure 3) and irrigation amount (Figure 4) were set up in this study. the. Among them, the micropores group spacing (L) is set to 2 levels: 30 cm (L1), 50 cm (L2); 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)(Agbna *et al*. 2017), which was realised by a control coefficient (k_{cp}), The k_{cp} (the crop- pan coefficient)was set to 3 levels: 0.7,1.0, and 1.2 E_{pan}. The CK1 and CK2 were used as the control treatment. There were total of 8 treatments, each of which was repeated 3 times, for total of 24 test area.

The evaporation amount was measured at 08:00 AM for each 5 days; the irrigation was initiated after the measurement. The irrigation amount (W) was calculated according to formula (1)(Duan *et al*. 2013). The irrigation time, times and amount were recorded (Table 1), taking k_c = 1.0 as an example to draw the irrigation time, and irrigation amount (Figure 4).

$$W = A \times E_p \times k_c \quad (1)$$

In the formula: E_p represents the evaporation within the interval of two irrigation, basing on the cumulative evaporation from a 20 cm diameter pan (mm); A represents the capillary control area (mm), and k_c represents the crop-pan coefficient. In this paper, adopting adequate irrigation mode, the crop-pan coefficient of k_c is 1.0.

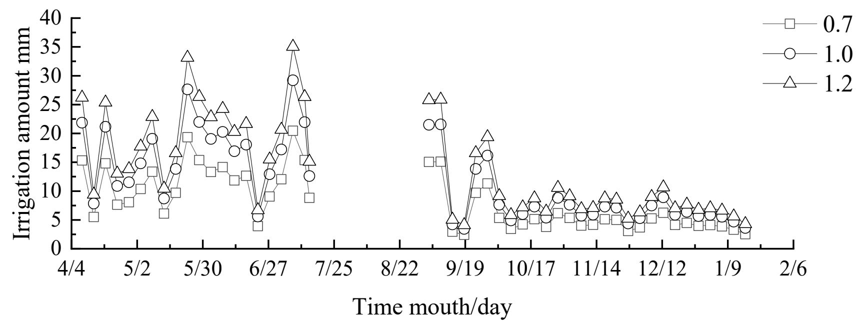


Figure 4. Irrigation records

Table1. Experimental factor and design.

No.	Treatment	Micropores 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 represents the micropores group spacing of MSPF; I represent the irrigation amount of MSPF; CK1 represents the drip irrigation under plastic film; CK2 represents the micro-sprinkler irrigation.

Measurements and computational methods
1)Quality

A）Measurements

Shape indices: The weight of single fruit (SFW) was measured by precision 0.01g electronic scale, and the vertical diameters (VD) and transverse (TD) diameters of fruit were measured by vernier caliper.

Flavour indices: the total soluble solids content (TSS) was measured by a hand-held refractometer with automatic temperature compensation (PR-32α Atago, Tokyo, Japan). the total soluble sugar (TSU) was measured by anthrone method (Decruyenaere *et al*. 2012) .The soluble sugar content (SSC) was measured by anthrone method(Liu *et al*. 2019). Titratable acids (TA) were determined by diluting an aliquot of the blended fruit and titrating against 0.1 mol/L NaOH using phenolpthalein as an indicator. The titratable acids were estimated as (ml NaOH ×acid factor = 0.0064) divided by ml aliquot of blended fruit(Gould 1992). Sugar/acid ratio (SAR) was determined by dividing the soluble sugar concentration by titratable acid.

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

B）Quality comprehensive evaluation

A total of 9 indices, including tomato fruit shape indices [SFW (X1), VD (X2), TD (X3)], tomato flavour indices [TSS (X4), TSU (X5), and SAR (X6)], and tomato nutrition indices [SP (X7), VC (X8), and L (X9)], were used as evaluation variables. Firstly, standardisation and homogenisation were performed, referencing 'Effect of Planting Row Spacing and Irrigation Amount on Comprehensive Quality of Short-Season Cultivation Tomato in Solar Greenhouse in Northwest China' (Wu *et al*. 2018), Secondly, the principal component load matrix of each variable was obtained using principal component analysis (PCA) (Li *et al*. 2016) to evaluate the comprehensive concept quality of tomato and a quantitative comprehensive score was derived for the comprehensive evaluation of tomato quality.

2)Yield and water use efficiency: During the maturation period, 4 tomatoes were randomly selected from each plot and the quality of mature tomatoes was measured using an electronic scale. After obtaining yield per plant, the yield (Y) per hectare was derived.

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

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

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

$$W = Y/E_a \quad (3)$$

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

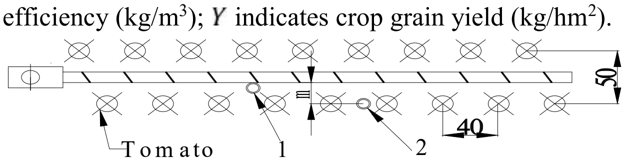


Figure 5. Schematic diagram of capillary and Trime pipe arrangement (unit: cm)

3) Standardization and homogenization of original data: In order to eliminate the influence of different evaluation indices dimensions, first standardize the data, and at the same time, in order to ensure that the evaluation indices has the same direction, it is also necessary to carry out the same chemotactic treatment of the data, reference 'Effect of Planting Row Spacing and Irrigation Amount on Comprehensive Quality of Short-Season Cultivation Tomato in Solar Greenhouse in Northwest China'(Wu *et al*. 2018)", which is convenient for the selection of reference vectors when constructing the comprehensive evaluation model by principal component analysis.

4) Construction of Comprehensive benefit Evaluation Model: Firstly, the Criteria importance though intercrieria correlation (CRITIC) method is used to weight the quality, yield and WUE, in which the quality is quantified by the comprehensive score of principal component analysis(PCA)(Wu *et al*. 2018); secondly, the comprehensive benefit evaluation model of quality, yield and water use efficiency is constructed and evaluated by technique for order preference by similarity to an ideal solution (TOPSIS) method (Zhang *et al*. 2017).

5) 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 which is 500 m away from the greenhouse.

6) Data analysis: The significant difference of SPSS22.0 (IBM Crop., Armonk, New York, NY, USA) was analyzed by F test, and the significant level was set to $P < 0.05$. 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.

RESULTS AND DISCUSSION

Effects of different treatments on quality of tomato

1)Shape indices: The micropores group spacing (L) exhibited a significant effect on the TD and VD of spring tomato ($P \leq 0.05$); the relative contribution of each to the total variance were 10.20% and 10.30%, respectively (Table 2). The irrigation amount (I) also exhibited a significant effect on the SFW, TD, and VD of spring and autumn tomato ($P \leq 0.05$) and the highest relative contribution of each to the total variance were17.70%, 17.40% and 23.80%, respectively.

Compared with drip irrigation under plastic film (CK1), the SFW, TD and VD of spring and autumn tomato under MSPF (L1I2) increased by 28.38% and 6.83% (Spring and Autumn of tomato %, the same as below), 11.70% and -2.08%, 14.43% and 1.20%, respectively; compared with micro-sprinkling irrigation (CK2), the SFW, TD and VD of L1I2 spring and autumn tomato increased by 5.66% and 17.01%, 4.69% and 5.13%, 1.67% and 7.63%, respectively. The TD and VD of L1 were 1.09,1.10 times as much as that of L2. The amount of irrigation increased from I1 to I3, the SFW, TD and VD of tomato showed an increasing trend.

Table 2. Effects of different treatments on tomato fruit shape in spring and autumn.

Treatment	Spring			Autumn		
	SFW(g)	VH (mm)	TD (mm)	SFW(g)	VH (mm)	TD (mm)
L1I1	106.16±35.23[bc]	48.69±7.1[b]	57.58±9.94[cd]	113.23±36.48[bc]	45.23±3.54[c]	50.25±4.64[b]
L1I2	139.42±25.75[ab]	57.86±4.17[a]	67.39±3.17[ab]	161.52±31.06[a]	51.75±3.36[a]	62.86±3.54[a]
L1I3	144.14±37.97[a]	59.36±6.85[a]	70.46±11.22[a]	153.37±30.21[ab]	51.47±7.01[ab]	58.2±3.04[a]
L2I1	87.98±42.06[c]	47.22±7.61[b]	55.12±10.37[d]	109.14±39.21[c]	44.48±6.24[bc]	54.7±6.54[b]
L2I2	113.92±45.17[abc]	53.21±7.72[ab]	59.58±7.86[bcd]	152.61±47.77[ab]	51.83±5.81[a]	61.46±6.52[a]
L2I3	142.47±31.48[ab]	58.35±5.18[a]	69.55±11.77[a]	158.44±44.38[a]	52.59±5.48[a]	61.98±6.61[a]
CK1	133.32±39.2[ab]	59.27±7.66[a]	66.31±8.48[abc]	151.2±42.6[ab]	51.74±7.19[a]	62.11±6.23[a]
CK2	105.2±19.69[bc]	49.74±5.44[b]	58.67±6.49[bcd]	115.68±41.55[bc]	45.19±5.85[bc]	53.6±7.88[b]
F-value						
L	2.272[ns](4.5)	1.768[ns](3.6)	2.075[ns](4.1)	0.063[ns] (0.1)	2.438[ns](4.8)	0.011[ns](0.1)
I	7.273[**](23.3)	13.014[**](35.2)	9.285[**](27.9)	8.216[**](25.5)	16.288[**](40.4)	10.215[**](29.9)
L*I	0.494[ns](2.0)	0.409[ns](1.7)	0.653[ns](2.6)	0.151[ns](0.6)	1.606[ns](6.3)	0.135[ns](0.6)

Note：SFW, Single fruit weight; VH, Vertical height; TD, transverse diameter; the bracketed number is total variance relative contribution %; *, $P≤0.05$; **, $P≤0.01$; ns, $P > 0.05$.

2) Flavour indices: L exhibited a significant effect on the TSS of spring and autumn tomato and the highest relative contribution of TSS to the total variance was 15.70% (Table 3). I exhibited a significant effect on the TSS and SAR of spring and autumn tomato; the highest relative contribution of each were 38.80% and 28.30%, respectively. The interaction between L and I had no significant effect on the flavour-related indices of tomato. Compared with CK1, the TSS, TSU and SAR of the spring and autumn tomatoes in L1I2 tomato decreased by 0.32% and 2.99%, -0.08% and 0.57%, 0.33% and 5.18%, respectively. Compared with CK2, the TSS, TSU and SAR of L1I2 tomato increased by 20.00% and 21.14%, 16.09% and4.23%, 26.58% and 9.02%, respectively. Compared with L2, the TSS of L1 tomato increased significantly by 6.23% and 9.96%. With decrease in I, the TSS, TSU and SAR of tomato first increased and then decreased, while the TSS, TSU, and SAR of tomato decreased with increase in irrigation amount.

Table 3. Effects of different treatments on tomato fruit flavor quality in spring and autumn.

Treatment	Spring			Autumn		
	TSS (%)	TSU(%)	SAR	TSS (%)	TSU(%)	SAR
L1I1	5.54±0.27a	8.7±0.88a	8.33±1.23a	5.17±0.55a	7.35±0.87a	6.89±1.24a
L1I2	5.17±0.66ab	7.75±1.6ab	8.2±1.61a	4.94±0.47ab	7.06±0.84a	6.35±1.18ab
L1I3	4.95±0.51bc	6.97±1.37b	6.25±1.26b	4.41±0.81bc	6.25±0.98a	5.55±0.75bc
L2I1	5.5±0.08a	7.6±1.18ab	8.23±2.04a	4.64±0.56abc	6.57±1.84a	6.6±1.13ab
L2I2	4.57±0.13cd	7.26±1.03b	7.98±1.69a	4.4±0.28bc	6.55±2.14a	6.26±1.57ab
L2I3	4.84±0.42bc	6.97±1.37b	6.25±1.26b	4.06±0.68c	6.39±1.29a	4.72±1.3c
CK1	5.19±0.56ab	8.01±1.7ab	8.23±0.47a	5.09±0.84a	7.1±0.87a	6.68±1.47ab
CK2	4.31±0.38d	6.68±1.32b	6.48±1.8b	4.08±0.53c	6.77±1.01a	5.83±1.1abc
F-value						
L	5.276[*](9.9)	2.358ns(4.7)	0.069ns(0.1)	8.948[**](15.7)	1.003ns(2.0)	1.490ns(3.0)
I	15.208[**](38.8)	3.938[*](14.1)	9.491[**](28.3)	6.098[**](20.3)	0.995ns(4.0)	8.347[**](25.8)
L*I	2.670ns(10.0)	0.850ns(3.4)	0.024ns(0.1)	0.146ns(0.6)	0.500ns(2.0)	0.431ns(1.8)

Note：TSS, Total soluble solids; TSU, Total soluble sugar; SAR, Sugar / acid content ratio; the bracketed number is total variance relative contribution %; *, $P≤0.05$; **, $P≤0.01$; ns, $P > 0.05$.

3) Nutritional indices: L exhibited a significant effect on VC of tomato and the highest relative contribution of each to the total variance was 23.0% (Table 4). I exhibited a significant effect on SP, VC, and LY of tomato and the highest relative contribution of each to the total variance were 19.8%, 21.2% and 22.7%, respectively.

Compared with CK1, the SP, VC and LY of L1I2 spring and autumn tomato decreased by 0.12% and 1.44%、0.08% and -1.34%、2.60% and -0.76%, respectively. and CK2, the SP, VC and LY of L1I2 spring and autumn tomato increased by 0.02% and 6.88%、18.39% and

15.57%、9.40% and 4.37%, respectively. Compared with L2, the VC of L1 with spring and autumn tomatoes increased significantly by 12.86% and 18.06%. With decrease in I, the SP, VC, and LY of tomato showed a decreasing trend, indicating that with the increase of irrigation amount, the nutritional value of tomatoes has decreased.

Table 4. Effects of different treatments on tomato fruit nutritional quality in spring and autumn.

Treatment	Spring			Autumn		
	SP (mg/g)	VC (mg/g)	LY (%)	SP (mg/g)	VC (mg/g)	LY (%)
L1I1	5.7±0.51a	20.85±4.24a	65.73±7.15a	5.2±0.15a	17.86±1.82a	61.3±5.12a
L1I2	5.39±0.39ab	19.19±2.44ab	62.48±8.15ab	5.1±0.55ab	17.36±0.54ab	59.31±3.74a
L1I3	5.07±0.32b	16.83±2.62bc	54.54±10.93b	4.87±0.34ab	15.51±1.37bc	54.53±6.12ab
L2I1	5.26±0.46ab	17.35±1.62bc	63.42±7.97ab	4.9±0.62ab	15.66±1.85bc	57.57±7.8ab
L2I2	5.15±0.47b	16.22±1.55c	60.41±8.34ab	4.67±0.39bc	14.34±3.27cd	56.72±8.19ab
L2I3	5.07±0.32b	16.83±2.62bc	54.54±10.93b	4.25±0.56c	12.97±1.6d	51.48±10.1b
CK1	5.39±0.51ab	19.21±2.07ab	64.15±9.75ab	5.18±0.47a	17.12±1.38ab	58.86±6.32a
CK2	5.39±0.25ab	16.21±1.91c	57.11±7.26ab	4.78±0.51ab	15.02±1.75c	56.83±4.59ab
F-value						
L	3.775ns(7.3)	8.851**(15.6)	00.353ns(0.7)	12.642**(20.8)	24.429**(33.7)	2.571ns(5.1)
I	4.261*(15.1)	3.329*(12.2)	5.815**(19.5)	5.285**(18.0)	7.922**(24.8)	4.004*(14.3)
L*I	1.199ns(4.8)	2.258ns(8.6)	0.089ns(0.4)	0.525ns(2.1)	0.210ns(0.9)	0.029(0.1)

Note：SP, Soluble protein; VC, Vitamin C; LY, Lycopene; the bracketed number is total variance relative contribution %; *, $P < 0.05$;**, $P < 0.01$; ns, $P > 0.05$.

Synthesize the above description, the content of tomato flavour and nutrition-related index of MSPF(L1C1) was lower than that of drip irrigation under plastic film (CK1), which may be due to the high moisture content of tomato fruit under MSPF, and the content of fruit flavor and nutrition was diluted by excessive water content per unit mass. it is consistent with the previous research that with the increase of irrigation water, the soil volume water content increases, and it is easy to reduce the flavor and nutrition content of tomato fruit(Li *et al*. 2020; Meek *et al*. 1992; Topp, 1969). The droplet atomization of micro-sprinkler irrigation(CK2) is beneficial to increase air humidity, and the water has a higher specific heat capacity, which reduce the temperature difference between day and night in greenhouse, as a result, the contents of tomato flavor and nutrition related indexes of micro-sprinkler irrigation were lower than those of MSPF(Max *et al*. 2009; Luo *et al*. 2016; Sun *et al*. 2016).

The flavour and nutrition of tomato with 30 cm (L1) micropores group spacing were better than 50 cm (L2), indicating that the soil moisture distribution of 30 cm micropores group spacing was the suitable spacing for greenhouse tomato under MSPF. This study also found that micropores group spacing had a significant effect on TSS of tomato, which was inconsistent with the conclusion of (Enciso *et al*. 2007), who concluded that dripper spacing had no significant effect on TSS of onion, mainly because all tomato water requirements came from irrigation water, Juan onion water requirements were also affected by rainfall and could provide similar irrigation water and optimal soil moisture conditions in all treatments.

The TSS, TSU, SP, VC and LY of tomato decreased with the increase of irrigation amount. It may be due to the low soil volume moisture content, increasing root drought stress, increasing the transport resistance of phloem sap to fruit, reducing the flow from xylem to fruit, resulting in the increase of juice solute concentration and improving fruit quality (Chen *et al*. 2014; Guichard *et al*. 2001). In addition, low irrigation amount increases the activities of sucrose synthase and sucrose phosphate synthase and also increases the conversion rate of sucrose to fructose and glucose, thus improving tomato flavour and taste(Wang *et al*. 2011). In this study, changes in TSS, TSU, SP, VC, and LY of tomato under drip irrigation were observed, which is consistent with findings of Agbna (2017). Initial increase and subsequent decrease in TSS, SP, VC, and LY of tomato with increase in irrigation amount under drip irrigation has been reported earlier(Wang *et al*. 2020), which is inconsistent with our finding indicating a decreasing trend under MSPF. It might be due to the difference in irrigation water control mode. In the study conducted by Wang (2020), drip irrigation was based on the percentage of soil field water holding capacity to control irrigation water (204.78–309.89 mm); however, we based our experiments on multiple control of pan evaporation [247.12–423.64 mm (Spring) and 152.73–261.83 mm (Autumn)].

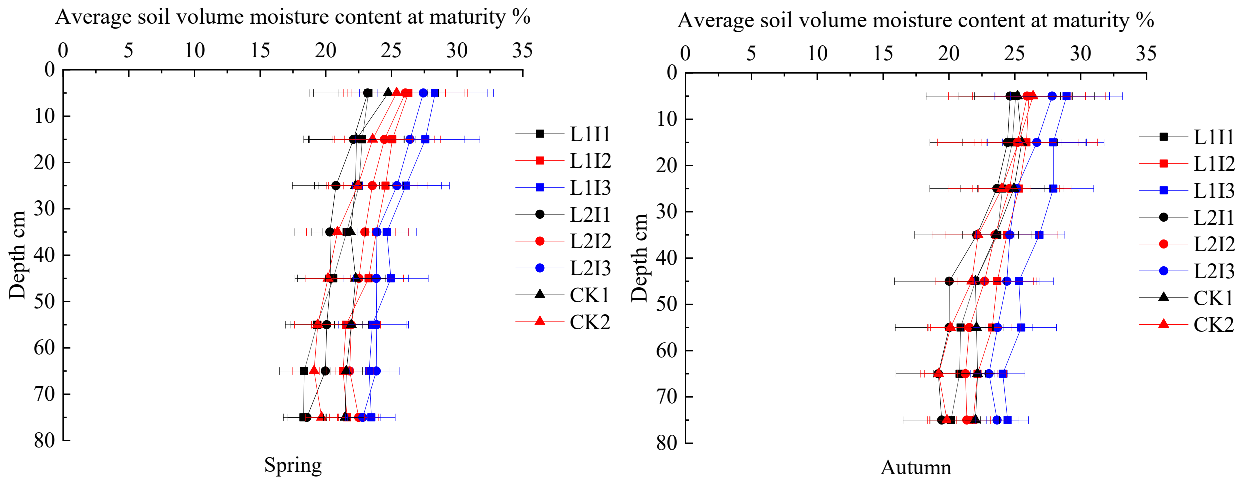
Table 5. Effects of different treatments on tomato yield and water use efficiency.

Treatment	Spring			Autumn		
	Yield (kg/ha)	Water consumption (mm)	WUE (kg/m^3)	Yield (kg/ha)	Water consumption (mm)	WUE (kg/m^3)
L1I1	90964.34±14880.36^{de}	265.59±17.24^{f}	34.13±4.15^{a}	76527.78±13027.18^{cd}	198.19±9.19^{e}	38.54±5.95^{a}
L1I2	119961.18±15863.47^{a}	374.12±15.82^{c}	32.16±4.75^{ab}	97979.17±12550.56^{a}	266.97±7.57^{cd}	36.73±4.83^{ab}
L1I3	118823.08±12774.65^{ab}	457.08±21.81^{a}	26.07±3.12^{cde}	96597.22±12447.91^{a}	294.99±8.01^{a}	32.72±3.85^{bcd}
L2I1	81201.21±18784.7^{e}	293.59±19.01^{e}	27.74±6.42^{c}	67812.5±11594.92^{d}	194.83±10.59^{e}	34.84±5.99^{abc}
L2I2	96170.08±18341.02^{cd}	377.93±10.89^{c}	25.48±4.88^{cde}	80916.67±13678.07^{bc}	273.19±11.06^{c}	29.63±4.93^{d}
L2I3	106903.34±16345.91^{bc}	460.61±25.78^{a}	23.2±3.27^{e}	91159.72±17869^{ab}	303.78±10.53^{a}	30.05±5.96^{d}
CK1	100482.01±10345.32^{cd}	344.94±22.42^{d}	29.23±3.38^{bc}	82888.89±13111.43^{bc}	260.18±14.67^{d}	31.87±4.86^{cd}
CK2	99582.82±11169.57^{cd}	406.69±22^{b}	24.54±3.03^{de}	65659.72±12688.55^{d}	282.85±18.46^{b}	23.24±4.52^{e}
F-value						
L	15.580**(19.1)	6.909*(9.5)	24.328** (26.9)	10.412**(13.6)	2.956ns(9.0)	12.853**(16.3)
I	18.436**(35.8)	534.597** (94.2)	11.819** (26.4)	16.870**(33.8)	733.740**(95.7)	6.201* (15.8)
L*I	1.290ns(3.8)	3.276* (9.0)	1.296ns (3.8)	1.152ns(3.4)	2.676ns(7.6)	1.149ns (3.4)

Note：WUE, Water use efficiency; the bracketed number is total variance relative contribution %; *, $P \leq 0.05$; **, $P \leq 0.01$; ns, $P > 0.05$.

Effects of different treatments on yield and water use efficiency in spring and autumn : L exhibited a significant effect on Y, water consumption and WUE of tomato ($P \leq 0.05$), and the highest relative contribution of each to the total variance were 19.10%, 9.50%, and 26.90%, respectively (Table 5). I exhibited a significant effect on Y, water consumption and WUE of tomato, and the highest relative contribution of each to the total variance were 35.8%, 95.70% and 26.40%, respectively. The interaction between L and I had a significant effect on water consumption, and the highest relative contribution of water consumption of spring tomato to the total variance was 9.00%.

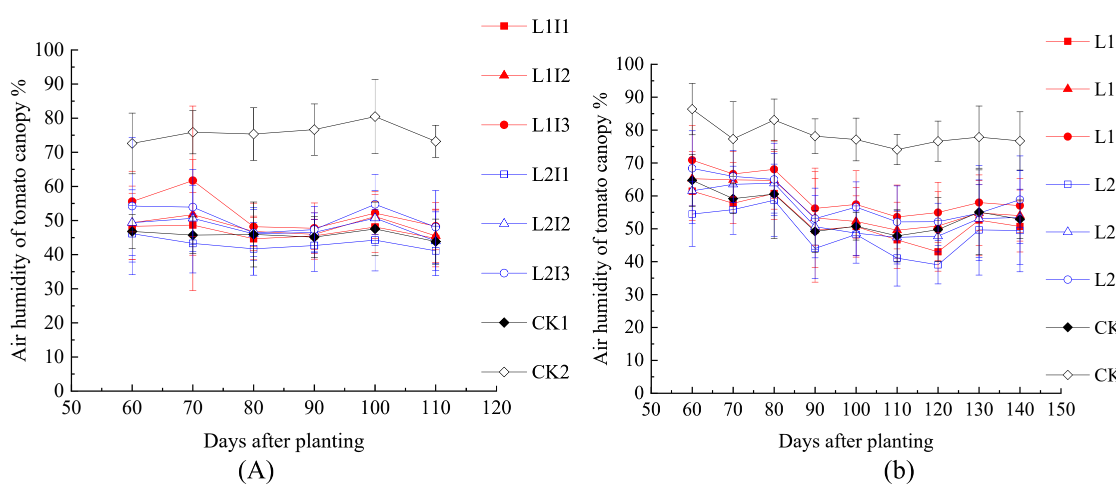
Compared with drip irrigation under plastic film (CK1), the yield of spring and autumn tomato of MSPF(L1I2) increased by 19.39% and 18.21%, respectively. It may be that the flow rate of MSPF is about 45 times that of drip irrigation under plastic film under the same working pressure. At the same irrigation amount, the irrigation duration of MSPF is shorter, the ratio of horizontal to vertical migration distance of soil water increases, the larger surface wetting area increases the wetting volume per unit area of tillage layer, and at the same time, reduce the difference of soil water and deep-water transport in the same layer(Zotarelli *et al*. 2009). After determination, it was found that the average soil moisture content (Figure7) of 0~40 cm during tomato maturity under drip irrigation under plastic film was about 4.80% and 2.38% lower than that of MSPF, and the lower average soil moisture content was easy to increase root drought stress, which was not conducive to the formation of tomato yield(Ould *et al*. 2001). However, the moist soil in the tillage layer of MSPF was dispersed, which provided a suitable soil microenvironment for tomato vegetative growth, resulting in an increase in leaf area index and soil water evapotranspiration, resulting in a significant increase in water consumption by 8.46% and 2.61% (Table5). The increase of yield of MSPF was higher than that of water consumption (9.36% and 15.60%). Therefore, the water use efficiency of MSPF was higher than that of drip irrigation under plastic film (10.03% and 15.25%).



Note: the data are all average ±standard deviation in the figure.

Figure7. Average soil volume moisture content in different treatments at maturity of tomato in spring and autumn

This study found that the water consumption of micro-sprinkler irrigation (CK2) was significantly higher than that of MSPF by 8.71% and 5.94%, probably due to the large number of micropores per unit length of micro-sprinkler irrigation, high atomization of water droplets, increased ineffective water transpiration(Mana *et al.* 2014), and most of the water was used to increase air humidity (Figure 8). It was found that the average volumetric water content of 0~80 cm in the mature stage of micro-sprinkler irrigation decreased by 8.99% and 7.19% compared with that of MSPF, indicating that the irrigation amount of micro-sprinkler irrigation will be divided into soil water and air water. This study also found that the spring and autumn tomato yield of MSPF was about 20.46% and 49.22% higher than that of micro-sprinkler irrigation, which may be due to the water jet of micro-sprinkler irrigation, which decreased the soil temperature of tomato, resulting in the decrease of soil enzyme and microbial activity. At the same time, air humidity is easy to reduce light intensity, further limit the accumulation of photosynthetic organic matter in tomato leaves, and reduce the yield of tomato under micro-sprinkler irrigation(Li *et al.* 2019; Shi *et al.* 2008).



Note: the data are all average ±standard deviation in the figure.

Figure 8. Effects of different treatments on air humidity in tomato canopy in spring (A)and autumn (B)

The effect of the change of L of MSPF on soil wetting body was similar to that of drip irrigation under plastic film. There is a phenomenon of intersection of wetting peaks between two groups of micropores adjacent to the capillary. The difference is that the flow of MSPF is higher than that of drip irrigation under the same working pressure and irrigation amount, and a larger flow is easy to increase the ratio of horizontal to vertical migration distance of soil wetting peak. Reducing the confluence time of adjacent wetting peaks is beneficial to the overall migration of soil moisture between the two groups of micropores on the capillary. In this study, it was found that the tomato yield of micropores group spacing 30 cm was higher than that of 50 cm about 6.00% and 13.01% (Table5).It may be due to the difference between increasing the volumetric soil moisture content per unit area of tillage layer and decreasing the soil moisture content of the same soil layer(Del *et al*. 2020; Ould *et al*. 2001), the average soil volumetric moisture content of 30 cm micropores group spacing is 3.48% and 4.22% (Figure 7) higher than that of 50 cm at mature stage, and the higher soil volumetric moisture content of plough layer provides a powerful guarantee for tomato growth(Silveira *et al*. 2020). It is consistent with the conclusion that the pomegranate yield of 30 cm drip spacing is higher than that of 50 cm studied by Meshram (2019).Wang *et al*.(2005) found that there was no significant difference in cucumber yield between 50 cm and 30 cm dripper spacing of drip irrigation. It was inconsistent with the conclusion that micropores group spacing had a significant effect on tomato yield, which may be due to the different irrigation amount in the experiment. In this study, the irrigation amount was controlled by evaporation pan, the cumulative irrigation amount was 353 mm, while Wang (2005) was based on the lower limit of soil irrigation and irrigated 385mm during the growth period. Enciso *et al*. (2007) were of the view that there was no significant difference in onion yield under different drip irrigation dripper spacing, which was inconsistent with the conclusion that the micropores group spacing had a significant effect on tomato yield. Because the maximum spacing of emitters set by Enciso (2007) was 30 cm, which was much smaller than 50 cm in this study, the soil water distribution was uniform, and it was not easy to cause yield difference due to drought stress on crops(Wang *et al*. 2014).

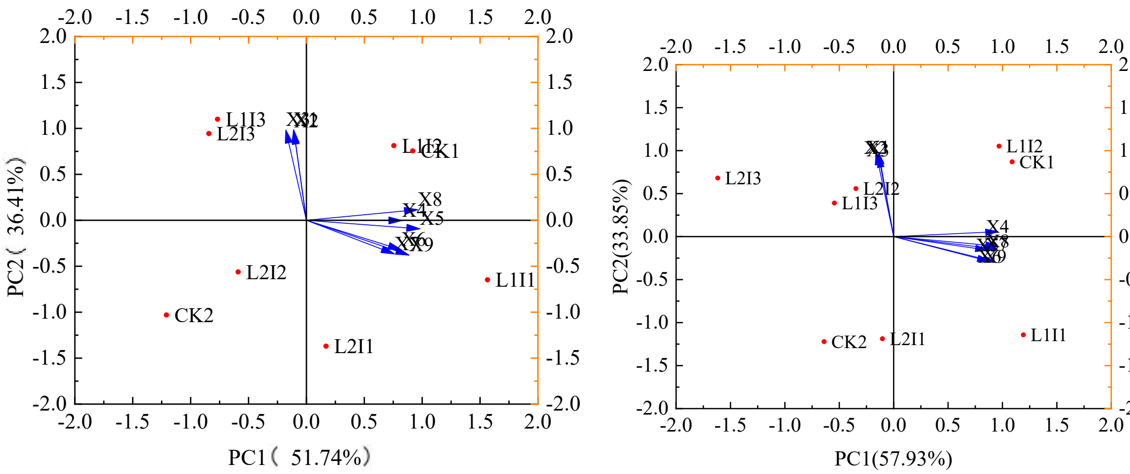
This study also found that the WUE of micropores group spacing 30 cm was higher than 20.85% and 14.25% of 50 cm spacing (Table 5). It may be due to the uniform soil volume of 30 cm plough layer with micropore spacing, and there is no obvious dry and wet duration in dry and wet zone for a long time, which can reduce the negative effects of water stress and air oxygen stress on tomato yield (Li *et al*. 2018), resulting in a significant increase in tomato yield. At the same time, the water consumption of 30 cm micropores group spacing did not increase significantly (Table5), and finally showed a significant improvement in WUE(Li *et al*. 2019).(Elmaloglou and Diamantopoulos, 2010) were of the view that decreasing drip spacing can shorten irrigation duration and improve WUE, which is consistent with the conclusion that reducing micropores group spacing from 50 to 30 cm can improve WUE. Previous studies found that too high or too low soil moisture could reduce the contents of TSS, VC and LY(Wu *et al*. 2018).

With the increase of irrigation amount, the yield and water consumption increased, and the WUE decreased. Compared with I1, the yield of I2 and I3 increased significantly by 25.54% and 23.94%、31.11% and 30.08%, but there was no significant difference between I2 and I3. However, the WUE of I1 and I2 was significantly higher than that of I3 by about 25.57% and 16.91% 、 16.98% and 5.71%, but there was no significant difference between I1 and I2. Previous studies have shown that soil water stress causing decrease in tomato yield might be attributed to water stress, leading to a decrease in tomato fruit number and SFW(Duan *et al*. 2013). In the present study, the spring and autumn tomato yield and Water consumption increased with increase in irrigation amount (Table 5). It might be because of the decrease in horizontal movement of soil water and the wet body per unit of the irrigated area of the tillage layer with decrease in irrigation amount, due to which a part of the soil stay in the arid area for a long time, the soil water stress increases, and the stability of soil microbial community structure and nitrogen cycle rate decreases. Tomato, particularly the plant with newly developed tissues (during flowering and fruit setting expansion period), is more sensitive to water stress(Shang *et al*. 2020). It led to a significant decrease in SFW (Table 2) of tomato in this study, and adversely effected the yield. In this study, decrease in WUE of tomato with increase in irrigation amount, possibly because of the soil humid body in the tillage layer, was observed. Additionally, increase in more inefficient water consumption with increase in irrigation amount was noted. Suitable soil moisture strengthens the tomato vegetative growth and increases the plant water effective evapotranspiration (Patanè *et al*. 2011). In the present study, the Water consumption of spring and autumn tomato also increased (Table5); however, the increase in tomato yield was lesser than the increase in water consumption, resulting in a decrease in tomato WUE with increase in irrigation amount. (Zhu *et al*. 2020) found that when the irrigation amount of drip irrigation tomatoes increased from 0.5 E_{pan} to 1.0 E_{pan}, the yield showed an increasing trend and the water use efficiency showed a decreasing trend, indicating that MSPF on tomato yield and water use efficiency was similar to that of drip irrigation, which was suitable for greenhouse tomato irrigation.

Comprehensive evaluation of tomato quality based on principal component analysis: When evaluating the quality of principal component analysis (PCA) comprehensively, the principal components analysis (PCA) were extracted according to the principle that the eigenvalue is greater than 1 (Figure 6). The cumulative contribution rate of the first PC (PC1) and second PC (PC2) was more than 85%. The PC1 exhibited a variance contribution rate of more than 51%, mainly reflecting the 3 appearances of SFW (X1), VD (X2), and TD (X3), directly related to the commodity value of tomato.

Therefore, PC1 can be called a commodity factor. The PC2 exhibited a variance contribution rate of more than 33%, reflecting mainly the 6 appearances of TSS (X4), TSU (X5), SAR (X6), SP (X7), VC (X8), and L (X9), directly related to the tomato flavour and nutrition indices. Therefore, PC2 could be considered the taste and nutrition factor. Figure 6 shows that tomatoes treated with L1I2 are in the positive range of PC1 and PC2 in spring and autumn, indicating that L1I2 could possibly be an appropriate treatment for tomato.

Comprehensive benefit evaluation of TOPSIS Model based on tomato quality, yield and water use efficiency: The weight of quality, yield and water use efficiency of spring and autumn tomato was obtained by CRITIC method (Table 6): Yield > WUE > Quality. The TOPSIS comprehensive evaluation model weighted by CRITIC method (Table 7) shows that the comprehensive benefit of L1I2 is the best, and is better than CK1 and CK2. It shows that MSPF is suitable for greenhouse as well as drip irrigation under mulch, and the comprehensive benefit is better than that of micro-sprinkler irrigation.



(A) (B)

Figure 6. Load and score graph of quality principal component analysis of spring tomato (A) and autumn tomato (B)

Table 6 Weighting values of each evaluation indices.

	Quality	Yield	WUE
Spring	0.148	0.555	0.297
Autumn	0.165	0.492	0.343

Table 7 Ranking of irrigation schedule calculated using TOPSIS for all the treatments.

Treatment	Spring				Autumn			
	D+	D-	*Ci*	Ranking	D+	D-	*Ci*	Ranking
L1I1	0.056	0.046	0.451	6	0.045	0.062	0.580	4
L1I2	0.000	0.082	1.000	1	0.007	0.085	0.926	1
L1I3	0.002	0.073	0.971	2	0.023	0.074	0.766	2
L2I1	0.074	0.017	0.190	8	0.065	0.044	0.402	7
L2I2	0.046	0.030	0.397	7	0.049	0.040	0.450	6
L2I3	0.025	0.049	0.664	3	0.036	0.059	0.622	3
CK1	0.037	0.044	0.541	4	0.040	0.049	0.550	5
CK2	0.039	0.036	0.477	5	0.089	0.001	0.016	8

Note：D+, Distance of positive ideal solution; D-, Negative ideal solution distance; *Ci*, the relative closeness.

Conclusions: It can be concluded that MSPF may improve the quality of tomato, the effect of increasing yield was better than that of drip irrigation under mulch, and the effect of water saving was better than that of micro-sprinkler irrigation. When the irrigation water amount increased from 0.7 E_{pan} to 1.2 E_{pan}, the fruit shape and yield increased, but the fruit flavour, nutrition and WUE decreased. Compared with 50 cm micropores group spacing, the fruit quality, yield and water use efficiency of 30 cm tomato was better. The comprehensive benefit model constructed by TOPSIS method based on tomato quality, yield and WUE showed that L1I2 was the best.

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Authors' contributions: M. Z. Zhang performed the experiments and writing-review, W.Q. Niu analyzed the data, Z.G. Lu proposed test design plan, Q.J. Bai managed the project administration, Y. Li provides Methodology, D.L. Wang determined the quality of tomato, Z.Q. Wang managed the tomato of greenhouse, Z.X. Zhang proofread the language. All authors have read and agreed to the published version of the manuscript.

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