Appropriate supply of irrigation and nitrogen produced higher yields of cherry tomatoes

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Abstract: Accurate irrigation and nitrogen application are essential for promoting the growth and yield of cherry tomatoes. In investigating the effects of irrigation and nitrogen on the growth, photosynthesis, and yield of cherry tomatoes, nine treatments including three levels of both irrigation and nitrogen were conducted over two growing seasons. Transverse stem diameter and horizontal stem diameter had the best performance at the irrigation level of 75% evaporation (E_p), although their responses to nitrogen were different for the two years. Plant height increased with the increase of irrigation and nitrogen. Plant dry matter (PDM) was significantly affected by irrigation and nitrogen interaction. The lowest PDM was found in the highest proportion of root dry matter, which occurred under low nitrogen level. The net photosynthetic rate (Pn) and transpiration rate enhanced with the increase of irrigation. Medium nitrogen showed promotion effect on all photosynthetic parameters in both growing seasons. Six of all fourteen indicators showed significant correlations with yield. Especially, single plant fruit number and PDM in 2018 Fall had significant positive direct effects on yield with the path coefficients of 0.648 and 1.159, while the significant direct path coefficients were 0.362 and 0.294 in Fruit dry matter and Pn for 2019 Spring, respectively. Based on the comprehensive evaluation of growth and yield by TOPSIS, the irrigation level of 75% E_p combined with medium nitrogen application produced higher yields by promoting the growth and photosynthesis of cherry tomatoes. It provides a strategy for water and nitrogen management of cherry tomatoes in Northwest China.
Keywords: cherry tomatoes, yield, growth, irrigation, nitrogen, path analysis
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1 Introduction

Cherry tomatoes are a nutrient-rich and popular horticultural vegetable, which has been widely cultivated in China since the 1980s[1]. Irrigation and fertilization are two crucial factors affecting the growth of cherry tomatoes. Water resources are in short supply in China. Agriculture consumed 61.9% of the total water, with a low irrigation utilization rate of 50%[2]. However, over-irrigation and irregular fertilization still exist since farmers blindly pursue higher yields and economic outputs, which affect the growth and yield of cherry tomatoes, leading to nitrogen leaching and other environmental problems[3,4]. Therefore, improving productivity by efficient use of irrigation and fertilization in agricultural production is the focus of the National Agricultural Sustainable Development Plan for 2015-2030 in China[2].

Efficient application of irrigation and fertilization can increase plant growth, net photosynthetic productivity, and fruit yield by improving the cultivation environment and increasing irrigation water use efficiency[5-7]. For cherry tomato cultivation, increased irrigation amount or limited nitrogen application can promote plant height (PH) and stem diameter and enhance plant dry matter (PDM) efficiently[8-10]. An appropriate increase in irrigation and nitrogen levels can increase net photosynthetic productivity of tomatoes, which in turn leads to a higher tomato yield[11]. For the dynamic growth of tomatoes, good growth in the former stages is the key to final yield formation. High yields of tomatoes were associated with good PDM accumulation and single plant fruit number (SPFN)[12]. Furthermore, deficit irrigation combined with moderate nitrogen application during the final growing stage can produce high tomato yields by increasing net photosynthetic productivity[13]. Fruit yield increases with the proportion of plant biomass allocated to leaves[14]. Meanwhile, aboveground biomass and single fruit weight are important indexes positively affecting yield[15]. These studies on the relation between yield and a single type of growth data such as apparent growth, photosynthetic capacity, and dry matter accumulation under different irrigation and nitrogen regimes have greatly contributed to irrigation-nitrogen management and yield prediction in tomatoes[16-18]. However, yield formation is related to multiple growth parameters, which have different feedback to

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irrigation–nitrogen application. Therefore, understanding the effects of irrigation and nitrogen coupling on different growth indicators and exploring their relationships with yield is necessary, and the good yield performance of tomatoes could be obtained by promoting factors influencing yield formation.

This study aimed to 1) explore the effect of different irrigation and nitrogen applications on the growth, photosynthetic, and yield parameters of cherry tomatoes; 2) analyze the main growth factors affecting the yield of cherry tomatoes based on correlation and path analysis; and 3) establish a comprehensive evaluation model considering yield and its important forming factors based on TOPSIS to determine adequate irrigation and nitrogen application.

2 Materials and methods

2.1 Experimental site

The experiment was conducted in a greenhouse at Yangling, Shaanxi Province, China (34°16′N, 108°02′E; altitude 450 m) from August 10 to December 10, 2018 (2018F) and March 8 to July 15, 2019 (2019S). This region is categorized as a temperate monsoon climate zone (Dwa) based on the Köppen climate classification law[19]. The east-west orientation greenhouse was constructed from a steel frame with a double-layer polyethylene sheet cover. The length and width of the greenhouse were 100 m and 17 m, respectively. The planting mode was furrow cultivation with drip irrigation systems, and the crop plots were oriented in a north-south direction to minimize differences in solar radiation. In addition, four protection rows were planted close to the exit and innermost side to reduce errors associated with greenhouse microclimates. A tomato variety (Lycopersicon esculentum M. ‘Fenmei 1’) was selected as the test material, with a planting density of 29 985 plants/hm^2. The physico-chemical properties of the test soil (0-40 cm) were measured before planting in each growing season (Table 1).

Table 1 Physico-chemical properties of the test soil

Year	Soil texture	pH	EC/ mS·cm^{-1}	Available nitrogen/ mg·kg^{-1}	Available phosphorus/ mg·kg^{-1}	Available potassium/ mg·kg^{-1}	Bulk density/ g·cm^{-1}	Field capacity/%
2018F	clay	7.35	0.34	43.82	18.37	158.10	1.38	24.30
2019S	clay	7.38	0.35	54.68	14.37	180.11	1.36	24.30

Note: EC refers to soil conductivity.

Cherry tomatoes plants were irrigated using a drip tape (spacing=0.5 m; flow rate=1.5 L/h) and covered with plastic mulch to reduce evapotranspiration and promote irrigation retention. The cultivation spacing of plants was continuous, and it followed the spacing of the drip tape. Each plant was fixed in a vertical direction with a nylon rope. Based on local production habits, five and seven fruit clusters of cherry tomato fruit were retained in 2018F and 2019S, respectively, by cutting off the growth points[20].

2.2 Experimental design

The experiment was set up in a split-plot design with three replicates, including nine treatments, irrigation volume was assigned to the main plot, and nitrogen levels to the subplots (Table 2). The irrigation volume was determined in accordance with the Penman-Monteith formula recommended by FAO−56, including I_1 [50% evaporation (E_p)], I_2 (75%E_p), and I_3 (100%E_p), which can be calculated as follows:

$$I = A \times E_p \times K_{cp} \tag{1}$$

where I is the irrigation amount; A is the surface area of the crop plot area; E_p is the cumulative evaporation of φ20 cm standard evaporating pan−not a standard pan worldwide but recommended in China for measuring evaporation as references[21-23]; K_{cp} is the evaporation pan coefficient was determined by FAO-56 (K_{cini}=0.6, K_{cmid}=1.15, K_{cend}=0.80).

Table 2 Irrigation and nitrogen application rates of different treatments

Treatment	Irrigation level	Irrigation amount/m^3·hm^{-2}		Nitrogen level	Nitrogen amount/ kg N·hm^{-2}	
		2018F	2019S		2018F	2019S
T_1	I_1 (50%E_p)	834.4	1041.7	N_1 (50% F0)	120	100
T_2				N_2 (100% F0)	240	200
T_3				N_3 (150% F0)	360	300
T_4	I_2 (75%E_p)	1251.6	1562.6	N_1 (50% F0)	120	100
T_5				N_2 (100% F0)	240	200
T_6				N_3 (150% F0)	360	300
T_7	I_3 (100%E_p)	1668.8	2083.4	N_1 (50% F0)	120	100
T_8				N_2 (100% F0)	240	200
T_9				N_3 (150% F0)	360	300

F0 was the exact value calculated by target yield.

Note: F0 was the exact value calculated by target yield.

Nitrogen application levels were determined based on the target yield method[24], and the three specific levels were expressed as low nitrogen (N_1: 50% F0), medium nitrogen (N_2: 100% F0), and high nitrogen (N_3: 150% F0), where F0 was the exact value calculated by target yield. The total irrigation and nitrogen fertilizer amounts are presented in Table 2. The application rate of potassium and phosphorus was the same for each treatment, with 200 kg P_2O_5/hm^2 and 350 kg K_2O/hm^2, respectively, which were also determined by the target yield method. Phosphorus fertilizer (superphosphate) was applied as a base fertilizer before planting[11]. In this experiment, nitrogen fertilizers (urea) and potassium fertilizers (potassium sulfate) were applied to the plant roots during sunny day morning, and irrigation was carried out every 3-5 days for 2018F and 2-3 days for 2019S. On rainy days, no irrigation was conducted. Irrigation volumes were recorded using a Hall digital display electronic flowmeter (K24, Lan Bao Technology Co., Ltd, China) at the head of each irrigation treatment. Soil water content was recorded using a soil moisture meter (TDR-300, Spectrum Technologies, Inc., USA).

2.3 Measurements

2.3.1 Meteorological data

Meteorological data were recorded using a small weather station (HOBO Event Data Logger, Onset Computer Corp., USA). Temperature (°C) and relative humidity (%) were simultaneously logged every 5 min. All meteorological data for the experimental site are listed in Table 3.

Table 3 Meteorological data for cherry tomato experiment

Date type		2018F					2019S				
		Aug	Sep	Oct	Nov	Dec	Mar	Apr	May	Jun	Jul
T/°C	T_{max}	44.2	40.4	36.5	31.3	30.2	34.2	36.0	37.7	39.1	43.4
	T_{min}	19.2	17.6	12.7	11.2	10.0	10.3	12.0	11.5	16.4	22.7
	T_{mean}	28.1	24.6	21.8	20.9	18.9	20.2	22.5	23.5	25.6	30.3
RH/%		72.1	75.0	81.4	85.3	86.5	84.4	83.0	81.2	79.9	71.0

Note: T_{max} is monthly maximum air temperature; T_{min} is monthly minimum air temperature; T_{mean} is the monthly mean air temperature.

2.3.2 Growth data

Three representative plants were randomly selected from each treatment to measure plant height (PH), horizontal stem diameter (HSD), transverse stem diameter (TSD), and dry matter accumulation. For dry matter accumulation, it was divided into root (RDM), stem (SDM), leaf (LDM), and fruit (FDM) dry matter. Roots, stems, leaves, and fruit were separated and oven dried to a constant weight of 75°C. Then, the whole plant dry matter accumulation (PDM) was calculated. The root/shoot ratio (RSR) was calculated as the ratio of belowground dry matter accumulation to aboveground (stem, leaf, and fruit) dry matter accumulation.

2.3.3 Photosynthetic parameters

The net photosynthetic rate (Pn), stomatal conductance (Gs), and transpiration rate (Tr) of tomato leaves were measured using a Li–6800 portable photosynthetic apparatus (Li–Cor Inc., USA) on sunny days between 9:00 and 11:00, and these measurements were repeated three times. Measurements were performed on three healthy leaves between the first and second panicles of three randomly selected representative plants from each treatment.

2.3.4 Fruit yield

After fruit ripened and changed color, it could gain regularly, thus, a precision electronic scale (0.01 g) was used to measure single fruit weight (SFW) of 10 randomly selected plants. Simultaneously, single plant fruit number (SPFN) was recorded. All ripe fruits were used to measure yield, which was calculated as the whole plant fruit yield and then converted to hectare yield.

2.3.5 Data analysis

Excel (Office 2016, Microsoft Inc., USA) was used to organize data and entropy weight analysis. Path coefficient analysis and two-way ANOVA were conducted using SPSS 25.0 (IBM Inc., USA). Treatment effects were assessed using one-way ANOVA, and LSD (p=0.05) was used to identify any significant differences among treatments. The figures were generated using the ggplot2 and corrplot packages in R-studio. Pearson correlation analysis (R^2) of yield components was performed using the corrplot package in R-studio (version 4.0.3; R core team, 2020, USA).

2.4 Multi–level fuzzy comprehensive evaluation

2.4.1 Constructing a fuzzy evaluation factor set

Yield and its main components will be selected to construct a fuzzy evaluation factor set.

$$U_i = \{u_1, u_2, \dots, u_m\} \tag{2}$$

where U_i is the factor set, m=7. Each factor has a set of evaluation values corresponding to the subordinates. The test consisted of nine treatments, generating nine evaluation values.

$$V_i = \{V_1, V_2, V_3, \dots, V_9\} \tag{3}$$

where, V_i is the result subset of each treatment.

2.4.2 Gaining factor weights

1) Determination of factor subjective weights by the analytic hierarchy process (AHP)

The AHP was proposed by Saaty et al.[25] and widely used in agricultural production management[26]. This method of determining subjective weights was characterized by establishing a judgment matrix based on the questionnaire results and then decomposing the overall decision. Specific calculation methods are provided by Han et al.[27].

2) Determination of factor objective weights by the entropy method

As a widely used method for determining objective weights, the entropy method can effectively reflect the information implied by the data with strong operability. In the calculation, the measured data of the factor set were initially standardized, and then the information entropy of the factor set was calculated. The specific calculation process of the entropy method can refer to Du et al.[28].

3) Calculation of the combined weight

The game theory was adopted to calculate the combined weight based on the obtained objective and subjective weight to minimize the deviation and improve the reliability of the final weight[29]. The following formula obtained the comprehensive coefficient of the objective and subjective weight:

$$\min \left\| \sum_{i=1}^{2} \alpha_i W_i^T - W_j^T \right\|_2 \tag{4}$$

where, α_i is the coefficient of the subjective and objective weight subset, x=2, W_i^T, W_j^T are the rank matrix of the subjective and objective weight subset, respectively.

The combined weight was calculated as follows:

$$w_{cj} = \alpha_1 w_{1j} + \alpha_2 w_{2j} \tag{5}$$

where, $\sum_{j=1}^{m} w_{1j} = 1$, $\sum_{j=1}^{m} w_{2j} = 1$, W_{cj} is the combined weight, α_1 and α_2 represent the comprehensive coefficient for AHP weight (w_{1j}) and entropy method weight (w_{2j}), respectively.

2.4.3 Calculation of the comprehensive evaluation value

The comprehensive evaluation of the factor set was performed using the following formula[30]:

$$\mathrm{b}_z = w_{cj} r_{jz} = \begin{bmatrix} w_{c1} & w_{c2} & \dots & w_{cm} \end{bmatrix} \times \begin{bmatrix} r_{11} & r_{12} & \dots & r_{1n} \\ r_{21} & r_{22} & \dots & r_{2n} \\ \vdots & \vdots & & \vdots \\ r_{m1} & r_{m2} & \dots & r_{mn} \end{bmatrix} = \begin{bmatrix} b_1 & b_2 & \dots & b_n \end{bmatrix} \tag{6}$$

where, b_z is the fuzzy evaluation index of the factor set, and r_{jz} is the standardized data.

3 Results

3.1 Effects of irrigation and nitrogen on cherry tomatoes growth

Table 4 shows that nitrogen significantly affected TSD, PH, and HSD in both growing seasons. The significant effects of irrigation on these three indicators were found except for PH in 2018F. In addition, the interaction was only significant for HSD in both years. In 2019S, HSD and PH were 4.4% and 34.8% higher than those in 2018F, respectively, but TSD showed an opposite trend over the two seasons. Although no significant difference was observed between N_2 and N_3, the effect of nitrogen on PH was consistent in the two seasons, which was ranked in a descending order: N_3>N_2>N_1. With regard to the different irrigation levels, I_2 showed the best performance; ranking the first in TSD and HSD of 2018F and HSD of 2019S and second in the remaining three indicators with a slight difference. Among the treatments, T_9 and T_5 achieved the largest HSD and PH, whereas T_5 and T_4 had the highest TSD in 2018F and 2019S, respectively.

With regard to dry matter accumulation, irrigation significantly affected LDM, FDM, and PDM in both growing seasons. LDM, FDM, and PDM showed poor performance in I_1, and no significant difference was observed between I_2 and I_3. The adverse effect of high irrigation was found in SDM, with the lowest SDM under I_3 for both years. N_2 remarkably promoted dry matter accumulation in all organs, although the effect of nitrogen was not consistent in the two growing seasons. Meanwhile, the significant interaction of irrigation and nitrogen was found in LDM and PDM in 2018F, and in all indicators except for LDM in 2019S (Table 5).

Table 4 Effects of irrigation and nitrogen level on cherry tomato growth

Treatment		2018F			2019S		
		Transverse stem diameter/mm	Horizontal stem diameter/mm	Plant height/cm	Transverse stem diameter/mm	Horizontal stem diameter/mm	Plant height /cm
Irrigation	I_1	9.75 ± 0.25^{a}	9.67 ± 0.16^{a}	83.04 ± 2.97	9.22 ± 0.19^{a}	10.03 ± 0.15^{a}	108.27 ± 4.00^{b}
	I_2	9.79 ± 0.55^{a}	9.71 ± 0.43^{a}	85.43 ± 2.06	9.21 ± 0.38^{a}	10.11 ± 0.40^{a}	116.74 ± 4.30^{a}
	I_3	9.15 ± 0.69^{b}	9.24 ± 0.96^{b}	85.62 ± 2.87	9.00 ± 0.44^{b}	9.74 ± 0.49^{b}	117.50 ± 2.55^{a}
Nitrogen	N_1	9.02 ± 0.56^{b}	9.07 ± 0.63^{b}	82.19 ± 1.82^{b}	9.44 ± 0.14^{a}	10.23 ± 0.12^{a}	110.78 ± 6.24^{b}
	N_2	9.74 ± 0.53^{a}	9.66 ± 0.65^{a}	85.20 ± 2.77^{ab}	9.28 ± 0.19^{a}	10.17 ± 0.21^{a}	115.65 ± 5.13^{a}
	N_3	9.92 ± 0.24^{a}	9.88 ± 0.33^{a}	86.70 ± 2.88^{a}	8.71 ± 0.27^{b}	9.49 ± 0.34^{b}	116.08 ± 4.53^{a}
Irrigation×Nitrogen	T_1	9.63 ± 0.25^{abc}	9.81 ± 0.26^{abc}	80.30 ± 6.03	9.45 ± 0.12^{ab}	10.20 ± 0.18^{ab}	105.03 ± 3.84^{d}
	T_2	9.74 ± 0.31^{abc}	9.67 ± 0.40^{bc}	82.91 ± 7.37	9.19 ± 0.43^{bc}	10.06 ± 0.21^{bc}	108.47 ± 9.73^{cd}
	T_3	9.88 ± 1.05^{abc}	9.52 ± 0.26^{bc}	85.93 ± 1.90	9.03 ± 0.14^{cd}	9.85 ± 0.06^{cd}	111.33 ± 11.49^{cd}
	T_4	9.04 ± 0.64^{cd}	9.13 ± 0.03^{bc}	83.1 ± 1.50	9.59 ± 0.24^{a}	10.37 ± 0.11^{ab}	111.89 ± 13.31^{bcd}
	T_5	10.30 ± 0.09^{a}	10.17 ± 0.19^{ab}	87.72 ± 4.27	9.31 ± 0.57^{abc}	10.40 ± 0.02^{a}	121.94 ± 15.12^{a}
	T_6	10.03 ± 0.07^{ab}	9.84 ± 0.03^{abc}	85.46 ± 0.74	8.73 ± 0.18^{d}	9.55 ± 0.42^{d}	116.38 ± 6.32^{ab}
	T_7	8.41 ± 1.12^{d}	8.28 ± 0.76^{d}	83.17 ± 1.32	9.28 ± 0.02^{ab}	10.12 ± 0.46^{abc}	115.43 ± 6.01^{abc}
	T_8	9.18 ± 1.44^{bcd}	9.16 ± 1.06^{bc}	84.98 ± 5.14	9.35 ± 0.03^{abc}	10.05 ± 0.11^{bc}	116.55 ± 3.19^{ab}
	T_9	9.85 ± 0.43^{abc}	10.28 ± 0.66^{a}	88.72 ± 7.12	8.38 ± 0.18^{e}	9.06 ± 0.33^{e}	120.52 ± 1.46^{ab}
Irrigation		*	*	ns	*	**	**
Nitrogen		**	**	*	**	**	*
Irrigation×Nitrogen		ns	**	ns	*	*	ns

Note: Analysis of variance (ANOVA) results were shown (*, **=Significant at 0.05, 0.01 probability levels; ns=not significant). Within a column, means with different lowercase letters are significantly different ($p<0.05$), and means that share a lowercase letter are not significantly different ($p>0.05$).

Table 5 Effects of irrigation and nitrogen level on root dry matter accumulation (RDM), stem dry matter accumulation (SDM), leaf dry matter accumulation (LDM), fruit dry matter accumulation (FDM), and whole plant dry matter accumulation (PDM) of cherry tomatoes

Treatment		2018F					2019S				
		RDM/g	SDM/g	LDM/g	FDM/g	PDM/g	RDM/g	SDM/g	LDM/g	FDM/g	PDM/g
Irrigation	I_1	4.91 ± 0.27	55.67 ± 2.21^{a}	65.90 ± 2.72^{b}	34.32 ± 2.22^{b}	160.80 ± 2.60^{b}	7.78 ± 0.30^{a}	73.59 ± 3.90	76.08 ± 5.06^{b}	19.16 ± 0.88^{b}	176.60 ± 9.40^{b}
	I_2	5.04 ± 0.18	55.61 ± 2.02^{a}	69.45 ± 4.00^{a}	39.86 ± 4.02^{a}	167.00 ± 9.00^{a}	7.93 ± 0.65^{a}	76.65 ± 5.22	83.37 ± 5.08^{a}	20.38 ± 1.93^{a}	188.30 ± 11.10^{a}
	I_3	4.85 ± 0.12	52.92 ± 0.94^{b}	71.32 ± 8.12^{a}	37.91 ± 1.66^{a}	167.00 ± 9.20^{a}	7.05 ± 0.64^{b}	72.38 ± 3.36	82.23 ± 2.24^{a}	20.46 ± 0.40^{a}	182.10 ± 4.60^{ab}
Nitrogen	N_1	4.74 ± 0.15^{b}	53.12 ± 1.35^{b}	64.07 ± 3.57^{b}	35.84 ± 1.85^{b}	157.80 ± 3.10^{c}	$7.70\pm0.17\ 0^{a}$	72.77 ± 2.83^{b}	76.16 ± 5.30^{b}	19.19 ± 0.96^{b}	175.8 ± 9.0^{b}
	N_2	5.03 ± 0.21^{a}	55.39 ± 2.40^{a}	73.22 ± 5.68^{a}	39.72 ± 4.38^{a}	173.40 ± 8.00^{a}	7.79 ± 0.77^{a}	77.35 ± 5.13^{a}	82.93 ± 4.82^{a}	21.11 ± 1.44^{a}	189.2 ± 10.30^{a}
	N_3	5.03 ± 0.14^{a}	55.69 ± 1.78^{a}	69.37 ± 4.29^{a}	36.52 ± 3.03^{b}	166.60 ± 4.90^{b}	7.28 ± 0.77^{b}	72.49 ± 3.78^{b}	82.59 ± 2.46^{a}	19.70 ± 0.89^{b}	182.1 ± 5.10^{ab}
Irrigation		ns	**	**	**	**	**	ns	*	*	**
Nitrogen		*	*	**	*	**	*	*	*	**	**
Irrigation× Nitrogen		ns	ns	**	ns	**	**	*	ns	**	**

Among different organs, LDM accounted for the largest proportion of PDM with the highest value of 45.4% and 46.3% in the two years, followed by SDM and FDM, and RDM accounted for the smallest proportion, with the lowest value of 2.8% and 3.6% in the two growing seasons, respectively. In particular, the highest proportion of RDM was the lowest proportion of PDM, which was observed under N_1 in both years. The I_2 combined N_2 application remarkably promoted the PDM, and T_5 achieved the greatest PDM, with 17.8% and 23.3% higher than that in T_7 of 2018F and T_1 of 2019S, respectively (Figure 1).

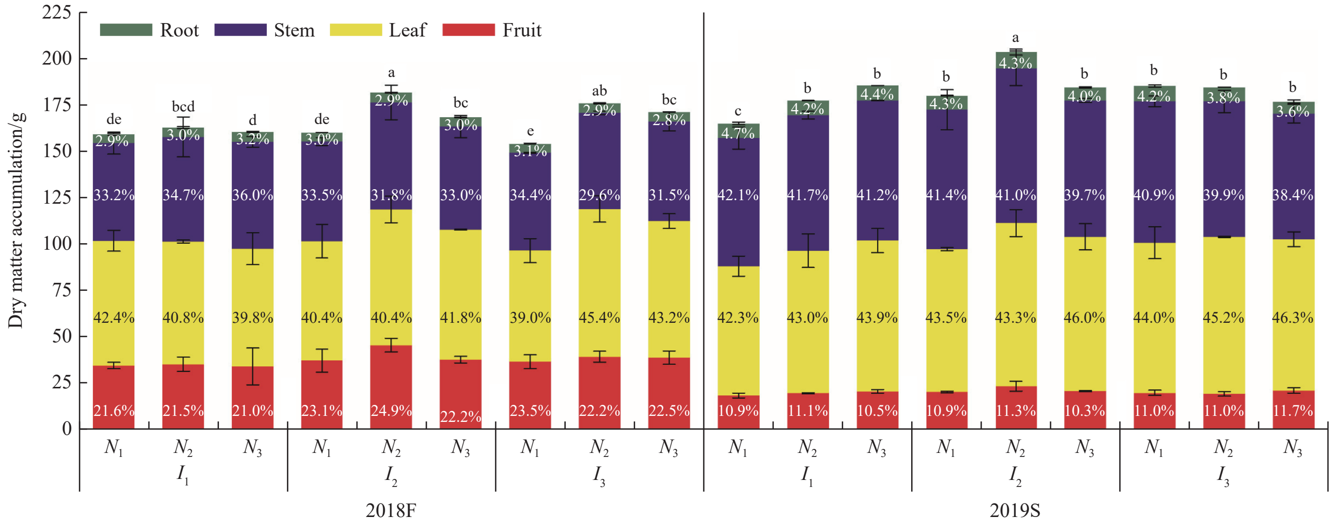
3.2 Effects of water and nitrogen on photosynthetic parameters of cherry tomatoes

Pn, Gs, and Tr were significantly affected by irrigation and nitrogen, but the interaction was only significant in Gs of 2019S (Table 6). In the two seasons, the three photosynthetic parameters showed higher values in 2019S. Based on the irrigation level, I_3 achieved the highest values of the three photosynthetic parameters except Gs of 2019S, although there was no significant difference with I_2 in 2018F. Considering the different nitrogen effects, N_2 and N_3 performed better than N_1 in all three photosynthetic parameters of 2018F, while N_1 and N_2 exhibited better promotion than N_3 in 2019S.

In 2018F, T_5 achieved the highest Pn, whereas T_8 and T_9 performed the best in Tr and Gs, respectively. The lowest values of the three photosynthetic parameters were observed in T_1. In 2019S, T_7 performed the best in Pn and Tr, which were 11.6% and 8.6% higher than those in T_3. As for Gs, T_5 performed the best, which was 29.6% higher than the smallest Gs of T_9 (Figure 2).

3.3 Effects of water and nitrogen on the yield of cherry tomatoes

Yield was significantly affected by irrigation, although SFW and SPFN exerted negligible difference at different irrigation levels. I_2 reached the highest yield in 2018F, and ranked second with an insignificant difference from I_3 in 2019S. From the level of nitrogen application, N_2 achieved the highest yield in both years although effect of nitrogen application was only significant in 2018F. Meanwhile, the significant interaction of water and nitrogen was only found in yield of 2018F. Among the treatments, T_5 had the highest yield in both growing seasons, which was 20.2% and 11.3% higher than that of T_7 in 2018F and T_1 in 2019S with low nitrogen



Note: Different lowercase letters indicate significant differences between treatments at $p<0.05$. The percentages from top to bottom in a column indicate the proportion of dry matter accumulation in each organ to the whole plant.

Figure 1 Dry matter accumulation of various organs under different irrigation and nitrogen treatments

Table 6 Effects of irrigation and nitrogen level on photosynthetic parameters of cherry tomatoes.

Treatments		2018F			2019S		
		Pn/μmol·m^{-2}·s^{-1}	Gs/mmol·m^{-2}·s^{-1}	Tr/mmol·m^{-2}·s^{-1}	Pn/μmol·m^{-2}·s^{-1}	Gs/mmol·m^{-2}·s^{-1}	Tr/mmol·m^{-2}·s^{-1}
Irrigation	I_1	10.94±0.61^{b}	480.00±54.00^{b}	8.15±0.48^{b}	16.30±0.50^{b}	551.40±29.90^{b}	9.44±0.18^{c}
	I_2	12.64±1.35^{a}	542.30±44.30^{a}	9.05±0.43^{a}	17.15±0.48^{a}	587.30±46.00^{a}	9.70±0.17^{b}
	I_3	12.72±1.55^{a}	546.10±57.80^{a}	9.49±0.60^{a}	17.54±0.24^{a}	544.30±34.90^{b}	9.92±0.15^{a}
Nitrogen	N_1	10.85±0.88^{b}	467.00±55.00^{b}	8.40±0.67^{b}	17.12±0.61^{a}	576.70±10.90^{a}	9.81±0.24^{a}
	N_2	12.69±1.18^{a}	559.20±55.20^{a}	9.05±0.57^{a}	17.28±0.50^{a}	587.90±44.00^{a}	9.73±0.25^{a}
	N_3	12.77±1.45^{a}	542.30±12.90^{a}	9.23±0.72^{a}	16.60±0.67^{b}	518.30±22.70^{b}	9.52±0.18^{b}
Irrigation		*	*	**	**	**	**
Nitrogen		*	**	*	*	**	*
Irrigation×Nitrogen		ns	ns	ns	ns	*	ns

Note: Abbreviation: Pn is net photosynthetic rate; Gs is stomatal conductance; and Tr is transpiration rate.

application, respectively. T_5 also had the highest SPFN, which was 13.1% and 15.8% higher than that of T_7 and T_3, respectively, in 2018F and 2019S (Table 7).

3.4 Correlation and path analysis of growth indicators and yield

Correlation analysis was performed on growth data, photosynthetic parameters, and yield indicators (Figure 3). Among the 98 interrelationships, 20 of them showed significant correlation in both growing seasons. Yield showed significant correlation with Pn, PH, LDM, FDM, PDM, and SPFN among the 14 indicators in both years, with an additional correlation indicator (Tr) in 2019S, and the greatest correlation coefficients were observed in SPFN of 2018F (0.76) and FDM of 2019S (0.78), respectively. SPFN was significantly and positively correlated with Pn in both growing seasons and with PH in 2018F and PDM in 2019S. Among all growth parameters, TSD and HSD had the strongest positive correlation (2018F: 0.91; 2019S: 0.94) in the 2 years.

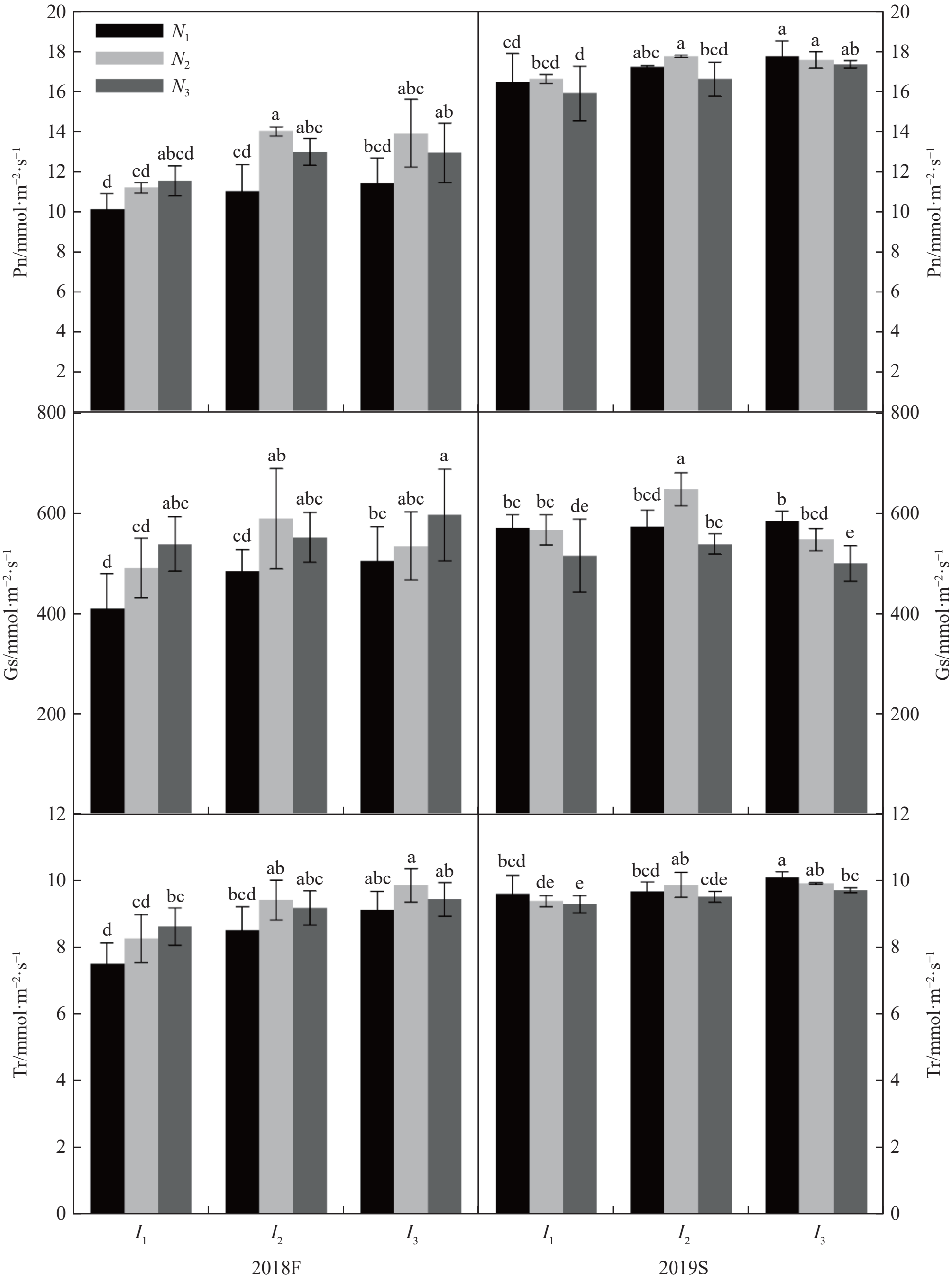
As a dependent variable, yield was influenced by the six yield components directly and indirectly. Path analysis revealed that SPFN and PDM had significant positive direct effects (0.648 and 1.159, respectively) on yield in 2018F, and LDM and Pn had highly positive indirect effects via SPFN and PDM (LDM via SPFN on yield: 0.258; LDM via PDM on yield: 0.986; Pn via SPFN on yield: 0.350; Pn via PDM on yield: 0.879) on yield. In 2019S, FDM and Pn had significant positive direct effects on yield with the values of 0.362 and 0.294, respectively (Figure 4).

Based on correlation analysis, Pn, LDM, FDM, PDM, PH, SPFN, and yield were selected to establish a comprehensive evaluation model. Table 8 lists the subjective and objective weight for all factors based on the AHP and entropy method, while Figure 5 illustrates the combined weights of yield and its main components. Among the factors, the highest weight value was recorded in yield in both years at 0.285 and 0.358, respectively. By contrast, PH recorded the smallest weight value at 0.075 in 2018F and 0.098 in 2019S. Based on the comprehensive evaluation of growth and yield by TOPSIS model, the comprehensive score and ranking were reported in Table 9. T_5 achieved the highest score followed by T_8 in both years, and the lowest scores were observed in T_7 of 2018F and T_1 of 2019S, which indicated that low nitrogen was unfavorable for the comprehensive growth of cherry tomatoes.

4 Discussion

4.1 Effects of water and nitrogen on the growth performance of cherry tomatoes

Cherry tomato growth data varied among different irrigation and nitrogen applications. TSD and HSD performed better in I_1 and I_2, which demonstrated that higher irrigation could inhibit the horizontal growth of plants. Although the effects of nitrogen on TSD and HSD were different in the two years, the greatest values were both found in N_2. This is because over-irrigation or excess nitrogen leaching to lower soil layers could reduce available nitrogen in the upper soil layer, thereby inhibiting the shoot growth



Note: Different lowercase letters indicate significant differences between treatments at p<0.05; Abbreviation: Pn is net photosynthetic rate; Gs is stomatal conductance; and Tr is transpiration rate.

Figure 2 Photosynthetic parameters under different irrigation and nitrogen treatments

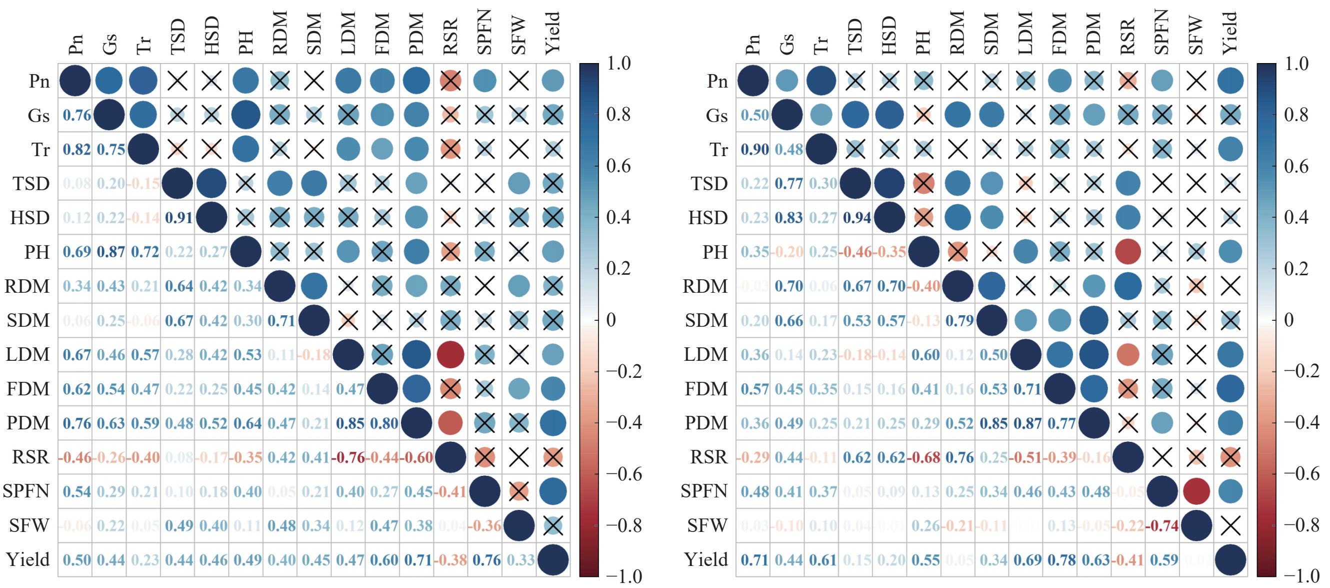
of tomatoes caused by insufficient nitrogen nutrition[31,32]. Also, based on correlation analysis, RDM and SDM were significantly correlated with TSD in both study years. It could be concluded that TSD was the performance indicator reflecting the growth of stem and root by promoting water and nutrient absorption and transplant action[33]. In this study, all photosynthetic parameters (except for Gs in 2019S) enhanced with the increase of irrigation, which indicated that I_3 could not represent a threshold for irrigation with regard to photosynthetic performance. The lowest value of all photosynthetic parameters was recorded under N_3 in 2019S, which may be because excessive nitrogen application could increase the osmotic potential of soil solution, thereby reducing the water potential gradient between soil and plant roots, reducing water absorption and transpiration of crops, and thus limiting photosynthesis[13]. Gs was lower in I_3 than in I_1 and I_2 of 2019S, which was different from the former study[34]. This result may indicate that high irrigation and high nitrogen input (particularly in T_9) increased the stomatal density of tomatoes, thereby decreasing Gs to maintain plant water status[35]. In correlation analysis, there was significant correlation between Pn and FDM, and also in Gs and PDM. In addition, FDM and PDM had significant correlation with yield in both growing seasons, which could support better photosynthetic status enabled dry matter accumulation and distribution to reproductive growth organs such as flower and fruit[36].

As nitrogen level increased, PDM and FDM did not increase in a similar pattern, which was consistent with the result reported by Kinoshita et al.[37]. Moreover, root growth (RDM) had a significant correlation with shoot growth (PDM) in two growing seasons (Figure 3). The I_3 irrigation level combined with N_2 or N_3 produced the lowest RDM and highest LDM proportion, which was similar to

Table 7 Effects of irrigation and nitrogen level on yield components of cherry tomatoes

Treatments		2018F			2019S		
		SFW/g	SPFN/plant^{-1}	Yield/t·hm^{-2}	SFW/g	SPFN/plant^{-1}	Yield/t·hm^{-2}
Irrigation	I_1	18.80±0.33	101.28±3.87	57.06±1.52^{ab}	19.21±1.18	122.41±8.99	69.11±0.72^{b}
	I_2	18.94±0.82	103.57±3.63	58.80±3.63^{a}	19.39±0.67	129.86±8.84	72.93±3.22^{a}
	I_3	18.78±0.62	98.77±6.07	55.49±2.01^{b}	20.15±1.52	125.86±6.09	73.16±1.47^{a}
Nitrogen	N_1	18.55±0.41	99.81±5.94	55.42±2.26^{b}	19.92±1.48	122.59±8.10	71.19±2.50
	N_2	19.17±0.74	103.62±5.13	59.52±3.21^{a}	19.42±0.82	129.60±9.18	73.45±3.50
	N_3	18.80±0.53	100.19±2.45	56.40±0.76^{b}	19.41±1.26	125.93±7.02	71.10±1.60
Irrigation× Nitrogen	T_1	18.57±0.95	101.86±17.80	56.64±7.01^{bc}	19.02±3.62	123.54±30.52	68.85±3.05^{c}
	T_2	18.93±0.57	101.54±6.43	57.60±1.82^{b}	19.20±3.34	122.63±24.86	69.13±1.59^{c}
	T_3	18.91±0.91	100.43±2.70	56.94±1.22^{bc}	19.42±3.15	121.05±21.07	69.35±0.27^{c}
	T_4	18.35±0.41	102.68±4.66	56.35±1.77^{bc}	19.70±2.89	122.53±22.46	70.40±4.11^{bc}
	T_5	19.87±0.58	107.30±4.24	63.99±0.78^{a}	19.05±0.03	140.22±8.57	76.82±7.47^{a}
	T_6	18.58±2.38	100.74±10.40	56.05±1.39^{bc}	19.42±1.06	126.84±3.94	71.57±0.60^{bc}
	T_7	18.75±1.58	94.89±15.86	53.26±4.43^{c}	21.05±4.05	121.72±13.81	72.68±3.11^{abc}
	T_8	18.69±0.05	100.02±20.83	56.97±3.59^{bc}	20.01±1.25	125.96±4.12	74.41±1.31^{ab}
	T_9	18.89±2.64	99.41±5.18	56.22±2.71^{bc}	19.39±5.37	129.9±21.21	72.39±4.87^{bc}
Irrigation		ns	ns	*	ns	ns	**
Nitrogen		ns	ns	**	ns	ns	ns
Irrigation× Nitrogen		ns	ns	*	ns	ns	ns

Note: Abbreviation: SFW is single fruit weight; SPFN is single plant fruit number; yield is yield per hectare.



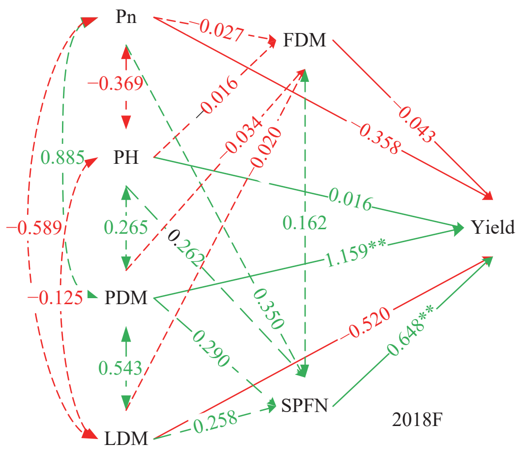
a. 2018F b. 2019S

Note: Gs, stomatal conductance; Tr, transpiration rate; growth data, including PH, plant height; TSD, transverse stem diameter; HSD, horizontal stem diameter; dry matter accumulation, including RDM, root dry matter; SDM, stem dry matter; LDM, leaf dry matter; FDM, fruit dry matter; PDM, plant dry matter; and RSR, root dry matter/shoot dry matter ratio; yield indicators, including SPFN, single plant fruit number; SFW, single fruit weight; and yield, yield per hectare. The circular area and color in the upper right panels represent the value of correlation coefficient. Low left panels show the Pearson correlation coefficients. Symbol × indicates significant level of p>0.05. A: 2018F; B: 2019S.

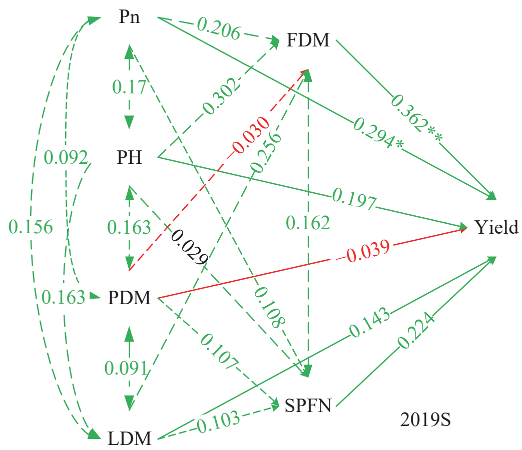
Figure 3 Circular and correlation coefficient plots of photosynthetic parameters, including Pn net photosynthetic rate

the results of Wang et al.[8], which indicated that excessive irrigation and nitrogen input induced unreasonable dry matter distribution of different organs[31,38]. Adequate water and nitrogen status can promote root-to-shoot signaling to regulate vegetative growth[39]. With the reduction of root growth, aboveground growth will be inhibited, particularly fruit growth. Insufficient water and nitrogen input can reduce vegetative growth and cause imbalances in dry matter partitioning[6]. This result may explain why the lowest irrigation and nitrogen treatment (T_1) had the highest proportions of RDM and SDM in 2019S. Adequate irrigation and nitrogen application amount (T_5) produced the highest FDM and PDM in both years. Moderate irrigation and nitrogen levels could promote efficient water and nitrogen usage and vegetative and reproductive growth through the contribution of enzymes involved in nitrogen metabolism, and induce the growth of the lateral roots and increase root quality, which improved the absorption of water and nutrient in the root zone, thereby increasing tomato FDM[40,41].

For dry matter accumulation indicators, interestingly, LDM had significantly positive correlation with PH, and had significantly negative correlation with RSR in both growing seasons. PH was the aboveground performance of tomato growth, and better PH could produce more truss to construct fruit and yield formation[42]. And



a. 2018F



b. 2019S

Note: Abbreviation: Pn, net photosynthetic rate; PH, plant height; PDM, plant dry matter; LDM, leaf dry matter; FDM, fruit dry matter; SPFN, single plant fruit number; Yield, yield per hectare. *, **=Significance of the direct path coefficients at 0.05, 0.01 probability levels. The solid line represents a direct path effect on the yield, the dotted line represents an indirect path effect on the yield

Figure 4 Path analysis diagram illustrating the interrelationships among six yield components contributing to yield in the two growing seasons

Table 8 Objective and subjective weight for all factors

Type	Yield	Pn	PH	LDM	FDM	PDM	SPFN
Subjective	0.366	0.125	0.065	0.126	0.115	0.101	0.104
Objective-2018F	0.118	0.191	0.097	0.189	0.111	0.203	0.090
Objective-2019S	0.207	0.094	0.147	0.097	0.141	0.096	0.218

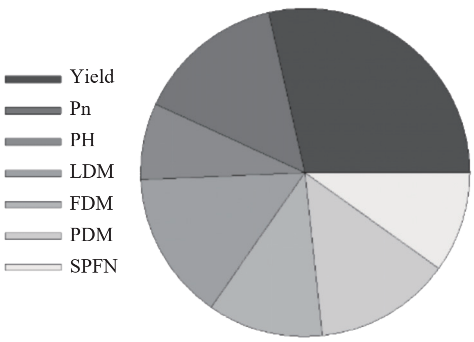
Note: Pn, net photosynthetic rate; PH, plant height; PDM, plant dry matter; LDM, leaf dry matter; FDM, fruit dry matter; SPFN, single plant fruit number; Yield, yield per hectare.

LDM was negatively correlated with RSR which indicated that LDM accounted the highest proportion of PDM. It explained the LDM could be used as performance indicator of tomato growth[14].

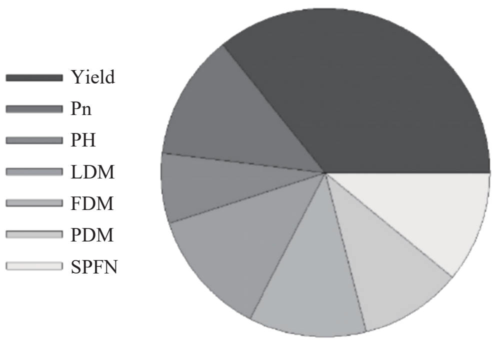
4.2 Effects of water and nitrogen on yield components of cherry tomatoes

Tomato yields decrease with the decrease of irrigation[43-45]. In the experiment, the yield under I_1 was significantly lower than that in I_2 and I_3 of 2019S primarily because low irrigation accelerated flowering and fruit developmental stage and decreased fruit numbers, thereby reducing yield[11]. By contrast, high relative humidity during the fruit ripening stage could cause fruit loss because of the cracking of tomatoes[46], which explained the lowest yield in I_3 of 2018F because of high relative humidity in November and December.

Based on correlation analysis, the significant correlations of PH and SPFN with yield were consistent with the results in African eggplant and chili pepper[47,48]. Considering the increase of photosynthetic parameters, PDM production achieved better values under proper water and nitrogen conditions[44]. High PDM accumulation is consistently linked to higher yields in vegetable production[12,49]. The correlations of performance parameters were significant for guiding the water-nitrogen schemes in tomato production. However, with the augmentation of independent parameters affecting a dependent character, some interdependence among attributes existed. In this complex situation, correlation was inadequate to describe the inter-parameter relationships[50]. Therefore, the path analysis was used to calculate the direct and indirect effects of the parameters on cherry tomato yield. The path coefficient analysis showed that SPFN and PDM of 2018F, as well as FDM and Pn of 2019S, had significant direct path coefficients to the yield, which were consistent with correlation analysis. LDM achieved the highest combined weight of all the six yield components in both study years. PDM and FDM had the highest direct path coefficients to yield in 2018F and 2019S, respectively. It showed that dry matter allocation of different organs could improve yield in different growing seasons due to the influence of climate condition[37,51]. Moreover, Pn and LDM of 2018F obtained yields via SPFN and PDM based on the path analysis result. Based on correlation analysis of yield components and comprehensive evaluation, the irrigation and nitrogen levels were determined more adequate and reasonable.



a. 2018F



b. 2019S

Note: Abbreviation: Pn, net photosynthetic rate; PH, plant height; PDM, plant dry matter; LDM, leaf dry matter; FDM, fruit dry matter; SPFN, single plant fruit number; Yield, yield per hectare.

Figure 5 Weights of yield and its main components in the two years

Table 9 Comprehensive evaluation score based on TOPSIS in the two years

Treatment	2018F		2019S	
	Score	Rank	Score	Rank
T_1	0.300	8	0.154	9
T_2	0.374	5	0.285	8
T_3	0.343	6	0.288	7
T_4	0.338	7	0.370	6
T_5	0.848	1	0.828	1
T_6	0.463	4	0.448	5
T_7	0.179	9	0.516	4
T_8	0.621	2	0.597	2
T_9	0.523	3	0.548	3

5 Conclusions

All apparent growth parameters of cherry tomatoes were significantly affected by nitrogen, with better performance in intermediate and high irrigation level during the two growing seasons. Nitrogen significantly affected all dry matter accumulation indicators except for FDM of 2018F. LDM increased with the increase of irrigation and nitrogen. Low nitrogen level impacted PDM growth and triggered imbalanced distribution of dry matter on different organs in cherry tomatoes. Intermediate irrigation and nitrogen levels significantly increased PDM and achieved the highest FDM proportion in 2018F (24.9%). All photosynthetic parameters performed better in intermediate and high irrigation levels, but the effect of nitrogen was inconsistent during the two growing seasons. Yield increased with the increase of irrigation, but the highest yield was achieved in intermediate irrigation level coupled with moderate nitrogen level in both years, with 63.99 t/hm^2 in 2018F and 76.82 t/hm^2 in 2019S.

Yield had significantly positive correlations with SPFN, PDM, FDM, PH, Pn, and LDM in both growing seasons. In particular, SPFN and PDM of 2018F, as well as FDM and Pn of 2019S, had significant positive direct effects on yield based on path analysis. Based on the TOPSIS comprehensive evaluation of yield and yield components, the highest score was recorded in T_5 for both years. Therefore, the irrigation level of 75% E_p combined medium nitrogen application could improve the yield formation of cherry tomatoes in northwestern China because it could comprehensively promote growth and photosynthesis.

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