Combined Effects of Ventilation and Irrigation on Temperature, Humidity, Tomato Yield, and Quality in the Greenhouse

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Abstract. Ventilation and soil moisture influence greenhouse cultivation. Experiments were conducted at Xinxiang Irrigation Research Base of the Chinese Academy of Agricultural Sciences, Henan Province, China, to identify how ventilation and irrigation affected the greenhouse microenvironment. To develop ventilation and irrigation protocols that increase crop yield and improve the quality of drip-irrigated tomatoes grown in the greenhouse, three ventilation modes (T1, T2, and T3) were developed by opening vents in different locations in a completely randomized pattern. T1 had open vents on the north wall and roof of the greenhouse. T2 had open vents on the north and south walls and the roof. T3 had open vents on the north and south walls. Three irrigation treatments (W1, W2, and W3) were designed based on the accumulated water surface evaporation (E_p) of a standard 20-cm evaporation pan. The irrigation quantities were $0.9 \times E_p$ (W1), $0.7 \times E_p$ (W2), and $0.5 \times E_p$ (W3). The spatial and temporal distributions of temperature and humidity were analyzed for different combinations of ventilation and irrigation to identify their effects on tomato yield and fruit quality. Major results were as follows: 1) In addition to solar radiation, ventilation had an important influence on E_p and, on a daily scale, ventilation had a significant effect on E_p ($P < 0.05$). 2) Ventilation had a significant effect on indoor wind speed, but the effect varied during different growth stages. During the flowering and fruit setting stage, wind speed for T2 significantly differed from those of T1 and T3 ($P < 0.01$). During the harvest stage, the three ventilation treatments had significantly different effects ($P < 0.01$). A correlation analysis showed high correlation between T2 wind speed and T3 wind speed ($R = 0.831$), but low correlation between T2 wind speed and T1 wind speed ($R = 0.467$). 3) The effect of ventilation on greenhouse humidity and temperature was greater than the effect of irrigation. The differences in air temperature among various combined treatments of ventilation and irrigation were significant for the flowering and fruiting stages ($P < 0.05$), but they were not

Greenhouse cultivation is increasing in scale in line with other developments in modern agriculture that have made agriculture a major driver of economic development (Gong et al., 2020; Liu et al., 2018; Wang et al., 2020). Control of the greenhouse environment through management of the microclimate and controlled irrigation promotes healthy crop growth, increased crop yield, and increased fruit quality (Liu et al., 2019b; Shamshiri et al., 2018; Wang and Zhou, 2017). There is an urgent need for a science-based protocol to regulate the greenhouse environment and manage greenhouse irrigation to ensure the health and sustainability of greenhouse cultivation in China (Orgaz et al., 2005; Peng et al., 2018).

The greenhouse microenvironment has important effects on crop growth, crop yield, and fruit quality. For example, excessively high temperatures cause pollen damage and leaf wilting, thus reducing yield (Harel et al., 2014), whereas excessively low temperatures affect enzyme activity and inhibit plant growth (Vanthoor et al., 2011). Excessively high humidity in a greenhouse reduces plant transpiration and causes flower rot (Huang et al., 2011) and, over the long term, reduces fruit quality (Choi et al., 1997). Control of ventilation is critical to regulating the greenhouse environment because ventilation can affect temperature, humidity, wind speed, and other meteorological parameters in the greenhouse (Yuan et al., 2015), thereby affecting crop growth, fruit development, crop yield, and fruit quality (Traore et al., 2020; Zhang et al., 2019a). Chu et al. (2017) showed that different ventilation regimes cause different convection patterns that influence the indoor microenvironment. Benni et al. (2016) found that the spatial distributions of greenhouse temperature and humidity were greatly affected by ventilation. Indoor air was relatively still in an unvented greenhouse, and there were only small spatial differences in temperature and humidity. When the greenhouse was vented to increase airflow, the indoor temperature distribution showed a distinct gradient from higher temperatures in the south to lower temperatures in the north of the greenhouse, whereas the spatial distribution of relative humidity showed the inverse (a high–low gradient from north to south) (Su, 2016). Kong et al. (2009) showed that air movement at the seedling stage increased stem diameter, leaf thickness, plant dry weight, and chlorophyll content, all of which are critical to yield. However, some studies have shown that wind speed in a greenhouse can increase ineffective crop transpiration and reduce yield. For example, studies have shown that when wind speed in a greenhouse was 0.8 to 1.0 m/s, the leaf area index, stomatal conductance, transpiration rate, and photosynthesis increased significantly, resulting in earlier plant ripening by 2 d, an 11.1% increase in total sugar content, and a 24.4% increase in yield (Li et al., 2008; Yang et al., 2007). It is clear that the use of ventilation to regulate the internal greenhouse microclimate increases crop yield

significant for the late harvest stage ($P > 0.05$). There were significant differences in humidity on sunny days ($P < 0.01$), but no significant differences on cloudy or rainy days ($P > 0.05$). Air temperature at 2 m was greater than canopy temperature, but humidity at 2 m was less than that at canopy level. 4) Irrigation water quantity was positively correlated with tomato yield and negatively correlated with the fruit quality indicators total soluble solids, vitamin C content, organic acid content, and soluble sugars content. Ventilation had an effect primarily during the harvest period; it had no significant effect on yield ($P > 0.05$). However, it had a significant effect on vitamin C content and the sugar:acid ratio ($P < 0.01$). The combination treatment of T2W2 is recommended as the optimal treatment for greenhouse tomatoes using drip irrigation to produce an optimal combination of crop yield and fruit quality. This study provides theoretical and technical support for the improvement of greenhouse climate control by optimizing greenhouse ventilation and irrigation techniques to promote tomato yield and improve fruit quality.

and fruit quality. However, at present, natural ventilation of a greenhouse is based mainly on the farmer's experience, and the difficult task of developing a scientifically based effective ventilation management protocol remains incomplete.

Li et al. (2017) found that water was an important factor in determining crop growth, fruit development, crop yield, and fruit quality. A large quantity of irrigation water can promote plant growth and increase yield, but it will also increase water consumption and reduce fruit quality; a small irrigation quantity will constrain plant growth and yield, but it will also reduce water consumption and increase fruit quality. Liu et al. (2010) found that an excessive water deficit destroyed plant tissue by inhibiting stem flow, thus affecting the normal physiological processes of crop growth. Xie and Cai (2013) investigated the effects of drip irrigation under mulch on plant growth, crop yield, fruit quality, and water use efficiency for greenhouse muskmelon in Guanzhong. They found that using 75% of field capacity as the lower limit of the irrigation quantity increased the mass fractions of soluble solids, total soluble sugars, soluble proteins, and organic acids in fruit, and that this was the optimal irrigation quantity. Hooshmand et al. (2019) and Liu et al. (2019a) investigated irrigation protocols for greenhouse crops. During a preliminary study, they set different soil moisture levels and found that soil moisture had a significant effect on the crop yield and fruit quality of a greenhouse crop.

Tomato plants are sensitive to temperature and humidity as well as soil moisture. Thus

the effects of both ventilation and moisture must be fully considered in greenhouse cultivation. Most current studies consider only the effects of a single factor; therefore, there are few literatures concerning multifactor effects, particularly of ventilation and moisture, on the greenhouse microclimate, crop yield, and fruit quality. As a result, there is no widely accepted combination of ventilation and irrigation that optimizes greenhouse crop production. During this study, we combined water and ventilation treatments to investigate the spatial distributions of humidity and heat in a greenhouse as they affected crop yield and fruit quality for a commonly grown local tomato variety using drip irrigation. This research provides technical guidance for optimizing greenhouse ventilation and irrigation protocols to promote tomato yield and quality.

Materials and Methods

Experimental site

This study was conducted in a solar greenhouse at the Xinxiang Irrigation Research Base of the Chinese Academy of Agricultural Sciences (lat. 35°9'N, long. 113°47'E, 78.7 m above mean sea level) from March to July 2019. The average annual rainfall at the site is 548.3 mm. The average annual evaporation is 1908.7 mm. The average annual temperature is 14.1 °C. The average annual hours of sunshine are 2398.8 h. The frost-free period is 200.5 d. The climate is warm temperate continental monsoon. The greenhouse used for the experiment covered an area of 510 m² (60 m long and 8.5 m wide), and it was dug 0.5 m into the soil. The longitudinal axis was east–west. Soil in the greenhouse was covered with 0.2-mm-thick dripless polyethylene film, and a 5-cm-thick layer of thermal insulation was placed on top of that film. The side and rear foundation walls had 60 cm of insulation attached to ensure that the temperature in the greenhouse was $\geq 20^{\circ}\text{C}$. The soil in the experimental area was a chalk composite (10.49% clay, 80.76% powder, and 8.75% sand) with an average bulk weight of 1.6 g/cm³ in a layer 100 cm deep; the field capacity was 23.91% (water content $\times$ mass). There were three ventilation ports in the greenhouse located centrally at the top (60 m $\times$ 0.3 m) and in the south (60 m $\times$ 1.5 m) and north (20 cm $\times$ 20 cm) walls, resulting in a total of 19 adjustable vents.

Experimental design

The experiment was conducted in a solar greenhouse, which was subdivided laterally into three separate partitions of equal area using opaque polycarbonate panels. A different ventilation treatment was applied to each partition. Treatment T1 consisted of opening the north wall vents and the top window vents simultaneously; T2 consisted of opening the north wall vents, south wall vents, and top vents; and T3 consisted of opening the north wall vents and south wall vents. Three irrigation treatments, W1, W2, and W3, were applied to each partition. Each irrigation treatment consisted of three applications on three adjacent experimental plots. The irrigation time and water quantity were determined by the cumulative evaporation E_p using a 20-cm standard evaporation pan in each partition. Irrigation commenced when E_p reached 20 ± 2 mm. The irrigation quantities were $0.9 \times E_p$ (W1), $0.7 \times E_p$ (W2), and $0.5 \times E_p$ (W3). Each irrigation plot was surrounded by plastic film dug to a depth of 60 cm to prevent lateral water seepage.

The experiment used the greenhouse tomato cultivar Fire Phoenix. The plant seeds were sown on 5 Jan. 2019 and transplanted on 21 Mar.; fruit were picked eight times from 29 May onward. Ridge planting was used with ridges 8 m long and 0.5 m wide. Two rows were planted in each ridge. Row spacing was 50 cm, and plant spacing was 30 cm. Drip irrigation was applied under the mulch. Drip orifices were spaced at the same intervals as those used for plant spacing. A drip irrigation hose (designed flow rate 1.1 L/h) was laid out along each plant row.

The tomato plants were considered to have three growth stages: a seedling stage (21 Mar.–13 Apr.), a flowering and fruit setting stage (14 Apr.–29 May), and a harvest stage (30 May–6 July). All three partitions were uniformly irrigated with 20 mm of water after planting to ensure the survival of seedlings. There was no other irrigation during the first 3 weeks to avoid leggy tomato seedlings. Irrigation was withheld until soil moisture content in the upper 40 cm of the soil layer reached 60% of field capacity. Irrigation was ceased 1 week before the end of the experiment. The ventilation treatments were applied concurrently with the irrigation treatments. The vents were usually open from 08:00 HR to 18:00 HR, but this varied in cases of extreme weather, such as heavy rain or gales.

Experimental parameters and methods

Meteorological parameters. Meteorological factors inside the greenhouse were recorded by an automatic climate monitoring system. Data gathered included total radiation R_a (LI200X; Campbell Science Inc., Logan, UT), air temperature (T_i), and humidity (RH_i) (U23-002A; Onset Hobo Inc., Cape Cod, MA), and wind speed (u) (WindSonic; Gill Inc., Newcastle Upon Tyne, UK). All meteorological data were automatically recorded by a data logger (CR1000; Campbell Science Inc.) at 30-min intervals. The sensors were

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one air temperature and humidity sensor (2.0 m above the ground with resolution of 0.02 °C and 0.05%), one two-dimensional wind sensor (30 cm above the canopy, with resolution of 0.01 m/s), and one radiation sensor (30 cm above the canopy, with resolution of 0.001 MJ/m²/d). Sensors were placed at the center of each partition. In addition, three air temperature and humidity sensors were placed in each partition 30 cm above the crop canopy for each irrigation treatment. These sensors were adjusted as canopy height increased.

Surface evaporation. Surface evaporation in each partition was measured using a standard evaporating pan (ADM7; Zhonghuan Tig Inc., Tianjin, China) with a 20-cm diameter and 11-cm depth. The evaporating pan was placed at the center of the partition 30 cm above the canopy; its position was adjusted as canopy height changed. The evaporating pan was measured daily during the period from 0700 to 0800 HR. Distilled water in the evaporating pan was replaced to a depth of 20 mm after each measurement.

Yield and quality. Fruit were picked eight times during the experiment. During the harvest stage, 20 tomato plants in the middle of each ridge were identified and marked as yield measurement plants. The tomato number per treatment was recorded for each fruit picking, and the tomato weight per treatment was measured and recorded using an electronic scale with an accuracy of 0.001 kg. Six fruits that had blossomed and set fruit on the same day were randomly selected from each treatment as quality-measurement plants. Fruit hardness was measured by a fruit hardness tester (FHM-5; Takemura Electric Works Ltd., Tokyo, Japan). The total soluble solids (TSS) content was measured with a handheld sugar meter. The vitamin C content (V_C) was determined by 2, 6-dichlorophenol indophenols titration. The organic acid (OA) content was measured by alkali titration. The soluble sugar content (SSC) was measured by anthrone colorimetry.

Data processing. Data were processed, analyzed, and charted using Excel software (Microsoft, Redmond, WA). An analysis of variance was performed using SPSS software

(IBM, Armonk, NY). Significance was determined using Duncan's new multiple range test.

Results

Solar radiation, surface evaporation, and wind speed

Figure 1 shows the R_a and E_p for different ventilation treatments during the growth period. Variations in E_p for the three ventilation treatments were consistent with the variations in R_a . There was no significant difference in evaporation among different treatments over the entire growth period ($P > 0.05$) (Fig. 1B). The E_p reached a maximum (5.9 mm) with T2 on 6 July, when R_a was 18.72 MJ/m²/d. The E_p reached a minimum (0.1 mm) with both T1 and T3 on 22 Apr., and R_a reached a minimum (0.59 MJ/m²/d) during the flowering and fruit setting stage (Fig. 1A). This showed that R_a was the main factor that influenced surface evaporation. The E_p was greater with T2 than with T1 or T3 in windy weather. For example, the E_p of T1 on 15 June was 4.5 mm, which was 18.4% greater than the E_p with T1 and 15.8% greater than the E_p with T3. This indicated that ventilation was also an important influence on surface evaporation and that, in the case of good ventilation, wind pressure outside the greenhouse made a significant difference in the E_p in the greenhouse with different ventilation treatments ($P < 0.05$).

Wind speed during different growth stages

Figure 2 shows wind speed, u , in the greenhouse for different growth stages. Overall, trends were consistent across the three partitions, but there were differences during the three growth stages. During the flowering and fruiting stage, u was as follows: T2 > T1 > T3 (Fig. 2A). There was no significant difference in u between T1 and T3, with respective mean values of 0.095 m/s and 0.091 m/s ($P > 0.05$). The mean value of u with T2 was 0.134 m/s, with a maximum value of 0.449 m/s, which was significantly different from the values of u with T1 and u with T2 ($P < 0.01$). During the harvest stage, u was as

follows: T2 > T3 > T1 (Fig. 2B). The mean value of u with T2 was 0.223 m/s, which was 79.8% greater than u with T3 and 123.1% greater than u with T1. There were also significant differences in u among the three ventilation treatments ($P < 0.01$).

A correlation analysis showed a high correlation between u with T2 and u with T3 ($R = 0.831$), and a low correlation between u with T2 and u with T1 ($R = 0.467$), which indicated that opening the horizontal vent on the south wall increased gas exchange more than opening the roof vent, and that in windy conditions, u could change suddenly with both T2 and T3.

Changes in air temperature and humidity under different ventilation treatments

Figure 3 shows crop canopy temperature, T_i , and relative humidity, RH_i , for each irrigation treatment under the three ventilation treatments. Both T_i and RH_i with W1 were as follows: T3 > T1 > T2. T_i for the entire growth period with W2 was ordered as T3 > T1 > T2, but RH_i for the flowering and fruiting stage was ordered as T1 > T3 > T2. T_i with W3 was ordered as T1 > T3 > T2, but RH_i with W3 was ordered as T3 > T1 > T2. For the entire growth period, T_i and RH_i were both lower with T2 than with T1 or T3. The lowest value of T_i was 15.983 °C for the combined treatment T2W1, which was 2.3% less than that for T2W2 and 3.1% lower than that for T2W3. The minimum value of RH_i was 43.7% for T2W2, which was 5.7% less than that for T2W1 and 6.2% less than that for T2W3. Over the entire growth period, both moisture and ventilation affected canopy T_i and RH_i , but the effect of humidity was less than the effect of ventilation.

Figure 4 shows T_i and RH_i at a height of 2 m in the greenhouse over the course of the growth period. The variation in T_i at 2 m was consistent across the three ventilation treatments and was ordered as T3 > T1 > T2. There was a significant difference in T_i at 2 m among the three ventilation treatments ($P < 0.05$) during the flowering and fruiting stage. The average T_i

Fig. 1. Changes in solar radiation (A) and water surface evaporation (B).

Fig. 2. Changes in the greenhouse wind speed during the flowering and fruiting stage (A) and the mature and picking stage (B).

with T2 was 22.0 °C, which was 7.0% less than that with T1 and 7.2% less than that with T3. During the harvest stage, when temperature increased, ventilation had little cooling effect. The difference was not significant ($P > 0.05$), and T_i was ordered as $T3 > T1 > T2$.

RH_i at 2 m in the three partitions was also ordered as $T3 > T1 > T2$. The maximum RH_i

occurred with T3 (57.73%), and the minimum RH_i occurred with T2 (46.71%); there was no significant difference among treatments over the course of the entire growth period ($P > 0.05$). Cooling caused by ventilation was greatly affected by weather conditions. For example, during an unbroken period of sunny days (6 June–16 June), the average RH_i with

T2 was 49.6%, which was 7.5% less than that with T1 and 10.1% less than that with T3. The differences were significant ($P < 0.01$). However, on cloudy or rainy days (such as 20 June), RH_i at 2 m inside the greenhouse and outdoor relative humidity were both more than 85%; therefore, ventilation did not reduce humidity.

Fig. 3. Changes in canopy temperature and humidity with T1 (A), T2 (B), and T3 (C).

Fig. 4. Temperature and humidity changes at 2 m with different ventilation modes.

Changes in vertical air temperature and humidity for different ventilation modes

Figure 5 shows T_i at canopy height and RH_i at 2 m for the three ventilation treatments. It could be seen that the variation in T_i at canopy height over the entire growth period was consistent with the variation in T_i at 2 m, and that T_i at 2 m was always greater than T_i at canopy height. Differences between the two were greatest with treatment T2. For example, during the period 7 June to 11 June

(Fig. 5B), the average T_i at 2 m was 4.8% greater than the average T_i at canopy height, and the difference in temperature reached a maximum of 1.5°C. This difference in vertical temperature was significant ($P < 0.05$). When there was little effective ventilation, there was no significant difference in the vertical temperatures with T1 and T3 ($P > 0.05$) (Figs. 5A and C).

RH_i at canopy height was consistent with RH_i at 2 m with all three ventilation treatments,

and RH_i at canopy height was greater than RH_i at 2 m. The difference among them was greatest with treatment T2. For example, during the period 9 June to 22 June (Fig. 5B), the average RH_i at canopy height was 12.1% greater than the RH_i at 2 m. The difference in relative humidity in the greenhouse was significant ($P < 0.01$). There were no significant differences in relative humidity with treatments T1 and T3 over the course of the entire growth period ($P > 0.05$) (Figs. 5A and C). Ventilation clearly had a great effect on the vertical distribution of humidity and temperature in the greenhouse.

Variations in air temperature and humidity with different irrigation treatments

Figure 6 shows T_i at canopy height and RH_i at canopy height with different irrigation treatments. T_i for the three ventilation treatments was ordered as $W3 > W1 > W2$ for the entire growth period. RH_i with treatment T1 was ordered as $W2 > W3 > W1$ for the entire growth period (Fig. 6A). RH_i with treatment T2 was ordered as $W1 > W2 > W3$ during the flowering and fruiting stage and as $W2 > W1 > W3$ during the harvest stage (Fig. 6B). RH_i with the T3 treatment was ordered as $W1 > W2 > W3$ (Fig. 6C). The effects of the irrigation treatment on temperature at canopy height

Fig. 5. Comparison of temperature and humidity between the canopy and 2 m with T1 (A), T2 (B), and T3 (C).

Fig. 6. Temperature and humidity with different water treatments with T1 (A), T2 (B), and T3 (C).

and relative humidity at canopy height were small, and differences were not significant ($P > 0.05$).

Effects of different ventilation and moisture combinations on tomato yield and quality

Tomatoes were harvested eight times during the harvest period. The harvested fruit count and yield were both low during the early (29 May–13 June) and late (27 June–15 July) pickings, and both were high during the middle period (14 June–26 June). The yields with T1, T2, and T3 during the middle period were 53.2%, 58.2%, and 65.5%, respectively, of the total yield.

Different combinations of ventilation and irrigation treatments had significant effects on tomato yield. Figure 7 shows that for the same irrigation treatment, picking during the early period of the harvest stage with T1 produced 48.6% of the total yield, but yields from the middle and late harvest periods with T1 were significantly lower than those with T2 and T3 ($P < 0.05$). During the middle and late harvest periods, the average yield of tomatoes was 117.6 t/ha with T2; this was 21.0% greater than that with T1 and 3.0% greater than that

with T3. Among them, the yields in the middle and late harvest periods with treatment T2W1 were 83.8 t/ha and 47.2 t/ha, respectively, which were significantly greater than the yields with other treatments ($P < 0.05$). Figure 8 shows that across all three ventilation treatments, tomato yields with irrigation treatments W1, W2, and W3 were in the ranges of 140 to 145.4, 130.1 to 135, and 122.7 to 124.7 t/ha, respectively, and in all three partitions were ordered as $W1 > W2 > W3$. The difference in total yield of the three irrigation treatments was most significant with T2 ($P < 0.05$). Overall, the irrigation treatment had a significant effect on tomato yield, whereas the ventilation mode mainly affected the number of tomatoes picked at each picking but had no significant effect on total yield ($P > 0.05$).

Effects of ventilation and irrigation combinations on tomato quality

Table 2 shows the values of the quality indexes TSS, VC, OA, SSC, and SAR for tomato fruits under different ventilation and irrigation treatments. For the same ventilation mode, irrigation quantity had no significant effect on SAR ($P > 0.05$) but was significantly negatively correlated with TSS, VC,

OA, and SSC ($P < 0.01$). The values of TSS, VC, OA, and SSC with treatment W3 were 8% to 14%, 11.7% to 18.1%, 16.2% to 20.5%, and 10.9% to 16.7%, respectively, greater than those with treatment W1. For the same irrigation treatment, the values of TSS, OA, and SSC in the three partitions were similar, but there were significant differences in VC and SAR among the partitions ($P < 0.01$). The VC and SAR values with T1 were 6% to 17.7% and 17% to 24.3%, respectively, greater than those with T2 and T3. Overall, the ventilation treatments were ordered as $T1 > T2 > T3$ for VC and as $T1 > T3 > T2$ for SAR. These results indicate that both ventilation and irrigation treatments affected the tomato quality indexes. An analysis of all the yield and quality results showed that the yield and quality of greenhouse tomatoes with T2W2 were relatively optimal; therefore, we recommend T2W2 as the optimal combination of irrigation and greenhouse ventilation.

Discussion

Effects of ventilation on surface evaporation and wind speed

Surface evaporation in the greenhouse was influenced by solar radiation and ventilation.

Fig. 7. Harvest and harvest date distribution of greenhouse tomato with W1 (A), W2 (B), and W3 (C).

Fig. 8. Yield and harvest date distribution of greenhouse tomato with T1 (A), T2 (B), and T3 (C).

We found that variation in greenhouse E_p for different ventilation modes matched the variation in R_a . There were no significant differences in E_p for different treatments ($P > 0.05$) over the entire growth period. Thus R_a was the factor that had the greatest effect on E_p (Li, 2017; Su and Fan, 2020; Zhang et al., 2019b). E_p reached a maximum value for the entire growth period with treatment T2, and that value of E_p was much greater than the E_p values with the other two ventilation treatments in windy weather. Using a daily time scale, with good ventilation, external wind pressure

caused significant differences in surface evaporation in the greenhouse with different ventilation treatments ($P < 0.05$). This result indicated that ventilation was an important influence on E_p (He et al., 2017). This result was similar to that found by Li et al. (2020), and similar conclusions have been found during studies of greenhouse cucumbers (Gong et al., 2015; Zou et al., 2005) and cantaloupes (Wang et al., 2011).

Variations in indoor wind speed were similar for all three ventilation treatments across the entire growth period, but there were differences during different growth stages. During the flowering and fruiting stage, u was similar with T1 and T3, but there was a significant difference between these two treatments and T2 ($P < 0.01$). During

the harvest stage, there were significant differences in u among all three ventilation modes ($P < 0.01$); this result was consistent with the results obtained by Yan et al. (2020). The correlation between values of u with T2 and T3 was high ($R = 0.831$), and the correlation between values of u with T2 and T1 was low ($R = 0.467$). This was mainly because of the pressure differential across the horizontal vent, which increased ventilation over ventilation from the roof vents only.

Effects of ventilation and irrigation on the spatial distribution of air temperature and humidity

Ventilation and irrigation had a combined effect on the greenhouse microclimate. We

Table 1. Comprehensive experimental scheme under different ventilation and water conditions.

No.	Factors	
	Ventilation mode	Water treatment
1	T1	W1 (0.9 E_p)
2	T1	W2 (0.7 E_p)
3	T1	W3 (0.5 E_p)
4	T2	W1 (0.9 E_p)
5	T2	W2 (0.7 E_p)
6	T2	W3 (0.5 E_p)
7	T3	W1 (0.9 E_p)
8	T3	W2 (0.7 E_p)
9	T3	W3 (0.5 E_p)

T1 had open vents on the north wall and roof of the greenhouse. T2 had open vents on the north and south walls and the roof. T3 had open vents on the north and south walls. E_p is the cumulative evaporation of the 20-cm standard evaporation pan.

Table 2. Total soluble solid (TSS), vitamin C (V_c), organic acid (OA), and soluble sugar content (SSC) of drip-irrigated greenhouse tomato under different ventilation and water conditions.

Treatment	TSS (%)	V_c (mg·kg ⁻¹)	OA (%)	SSC (%)	SAR
T1W1	4.49 ± 0.01 g	157.11 ± 3.53 cde	0.36 ± 0.03 e	2.67 ± 0.09 b	7.58 ± 0.84 a
T1W2	4.81 ± 0.01 e	180.33 ± 11.07 ab	0.38 ± 0.03 cde	2.78 ± 0.06 ab	7.43 ± 0.52 ab
T1W3	5.12 ± 0.01 a	185.48 ± 5.05 a	0.42 ± 0.02 abc	2.96 ± 0.14 a	7.04 ± 0.65 abc
T2W1	4.48 ± 0.02 h	149.95 ± 5.81 e	0.37 ± 0.01 de	2.33 ± 0.14 d	6.31 ± 0.20 cd
T2W2	4.79 ± 0.01 f	153.25 ± 8.74 de	0.40 ± 0.02 bcde	2.59 ± 0.10 bc	6.52 ± 0.59 abcd
T2W3	4.84 ± 0.01 d	167.54 ± 5.59 bc	0.43 ± 0.00 ab	2.72 ± 0.03 b	6.34 ± 0.12 bcd
T3W1	4.47 ± 0.01 h	148.11 ± 5.45 e	0.39 ± 0.01 bcde	2.40 ± 0.07 cd	6.10 ± 0.28 cd
T3W2	4.88 ± 0.01 c	164.56 ± 6.80 cd	0.42 ± 0.01 bcd	2.64 ± 0.07 b	6.35 ± 0.15 bcd
T3W3	4.97 ± 0.02 b	169.35 ± 6.97 bc	0.47 ± 0.05 a	2.80 ± 0.16 ab	5.94 ± 0.52 d

Different letters in the same column indicate significant differences at $P = 0.05$.

found that variations in T_i and RH_i over the entire growth period were similar with all three ventilation treatments; however, there were differences with different growth stages and different weather conditions. During the flowering and fruiting stage, there were significant differences in T_i among all three ventilation modes. During the later part of the harvest period, there were no significant differences in temperature among the three partitions because of a gradual increase in external air temperature and a decrease in cooling by ventilation. The effect of ventilation on reducing humidity was also greatly influenced by weather conditions. RH_i differed significantly among partitions for different ventilation modes when there was a period of continuous sunshine ($P < 0.01$); however, on cloudy or rainy days, there were no significant differences among partitions, and humidity was close to the saturation point.

We also found that ventilation mode greatly affected the vertical distributions of humidity and temperature in the greenhouse. T_i at 2 m was generally greater than T_i at canopy height, but RH_i was generally greater at canopy height than RH_i at 2 m. The difference between T_i at 2 m and T_i at canopy height with treatment T2 was significant ($P < 0.05$), and the difference in relative humidity was more significant ($P < 0.01$). There were no significant differences in the vertical distributions of temperature or relative humidity across the entire growth period with treatments T1 and T3.

Irrigation had some effect on T_i and RH_i over the entire growth period. This was observed primarily for the behavior of RH_i during different growth stages. However, the effect of irrigation was not as great as the effect of ventilation. This result was similar to the results obtained by Meng et al. (2016). We found that both ventilation and irrigation affected crop growth, and that regulating the combination of ventilation and irrigation can increase the beneficial effects of the greenhouse microenvironment on crop growth.

Combined effects of ventilation and irrigation on crop yield and fruit quality

Both ventilation mode and irrigation treatment had significant effects on crop yield and tomato fruit quality. This finding is consistent with the results of Yuan et al. (2003) and Zheng et al. (2011). There was a positive correlation between fruit yield and irrigation amount with each ventilation mode. This was because both the plant canopy and the maturing fruit require a large quantity of water during the middle and late growth stages; a high soil water content will satisfy the water requirements in the root zone and support movement of water through the plant and the accumulation of water and nutrients in the fruit, thus promoting fruit ripening and obtaining higher yield (Harel et al., 2014). Ventilation mode mainly affected environmental factors inside the greenhouse. Wind speed was greatest with treatment T2. This increased the rates of indoor and outdoor air exchange

and reduced air temperature more rapidly than with treatments T1 and T3. The reduced air temperature, in turn, reduced the accumulated degree days, which are necessary for fruit ripening, thereby reducing the quantity of early ripening fruit available for picking during the initial period of the harvest stage.

A comparison of fruit quality indexes showed that ventilation primarily affected VC and SAR. Values of VC and SAR with T1 were significantly greater than those with T2 and T3 because the higher temperature in partition T1 increased the rate of synthesis of enzymes in fruit (Hooshmand et al., 2019; Liu et al., 2019a). Irrigation had a significant effect on TSS, VC, OA, and SSC; the values of all four indexes decreased as irrigation quantity increased. In contrast, yield increased as irrigation quantity increased. These results indicated that irrigation increases fruit yield and affects fruit quality, which is consistent with the findings of Li et al. (2012), who studied greenhouse melons. However, we observe that water deficit was proportional to fruit quality only within a certain range. When the soil water content in the root zone decreased below a certain level, the ability of the plant to synthesize carbohydrates was reduced, thus reducing fruit quality and decreasing crop yield.

Conclusion

We investigated the effects of different ventilation and irrigation treatments on the greenhouse microclimate, crop yield, and fruit quality of tomatoes. On a daily scale, ventilation had a significant effect on E_p ($P < 0.05$). The maximum value of E_p over the entire growth period occurred with treatment T2. Evaporation with T2 was much greater than that with T1 or T3 in windy weather. Ventilation had a significant effect on indoor wind speed, but there were differences at different growth stages. During the flowering and fruiting stage, there was no significant difference between T1 and T3 ($P > 0.05$), but there was a significant difference between T2 and both T1 and T3 ($P < 0.01$). During the harvest stage, there were significant differences in wind speed among the three ventilation treatments ($P < 0.01$). Ventilation had a greater effect on the spatial distribution of both greenhouse humidity and temperature than irrigation. Air temperature and humidity over the entire growing period were ordered as $T3 > T1 > T2$. There were significant differences in T_i among treatments during the flowering and fruiting stage ($P < 0.05$) but not during the harvest stage ($P > 0.05$). During periods of successive sunny days, there were significant differences in RH_i among treatments ($P < 0.01$), but this was not the case for cloudy and rainy days ($P > 0.05$). T_i at 2 m was greater than that at canopy height, whereas RH_i at 2 m was less than that at canopy height. Ventilation and moisture combined had a great effect on crop yield and fruit quality. Irrigation amount was significantly positively correlated with yield ($P < 0.05$) and significantly negatively correlated with the fruit quality indexes TSS, VC, OA,

and SSC ($P < 0.05$). Ventilation primarily affected the temporal distribution of fruit picked (i.e., tomato ripening) but had no significant effect on total yield ($P > 0.05$); the effect of ventilation on the indexes VC and SAR was significant ($P < 0.01$). In terms of optimizing both crop yield and fruit quality, we recommend T2W2 as the optimal combination of ventilation and drip irrigation for greenhouse tomatoes.

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