Design of an Air Blowing Device Above Seedbed: The Effect of Air Disturbance on the Microenvironment and Growth of Tomato Seedlings

Yang Li, Juanqi Li, Guoxiu Wu, and Yanman Li

College of Horticulture, Henan Agricultural University, Zhengzhou, China

Aimin Shen

Zhengzhou Vegetable Research Institute, Zhengzhou, China

Deli Ma and Shengli Li

College of Horticulture, Henan Agricultural University, Zhengzhou, China

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Abstract. In recent years, air circulation has been used in protected cultivation to improve the microenvironment around seedlings, which in turn enhances photosynthesis and seedling growth. However, a practical and precise air circulation device has not yet been reported, especially one for growing seedlings in a greenhouse. Considering the use of a seedbed in seedling cultivation, a blower that can move back and forth on the seedbed and accurately control the air velocity is designed. In this experiment, we take the nonblowing treatment as the control (CK); three air velocities (0.3, 0.6, and 0.9 m/s) were selected to investigate the effect of interval blowing on the microenvironment of the canopy, physiology of seedling growth, stomatal characteristics of leaves, and stem mechanics of tomato seedlings. The three air velocities were found to significantly reduce the canopy temperature by 0.44, 0.78, and 1.48 °C lower than the CK, respectively, and leaf temperature by 0.83, 1.57, and 2.27 °C lower than the CK, respectively, in cultivated seedlings during summer. The relative humidity of the tomato seedling canopy decreased by 2.7% to 7.0%. Compared with the CK, the plant height of tomato seedlings decreased by 13.54% and root dry mass, root-shoot ratio, and seedling quality index (SQI) increased by 34.63%, 21.43%, and 14.29%, respectively, at 0.6 m/s. In addition, mechanical indexes such as hardness and elasticity of the tomato seedling stem were higher under air disturbance than those of the CK. The best effect was seen in the treatment with the air velocity of 0.6 m/s, in which the hardness and elasticity of the stem base and the first node were significantly higher than that of the CK. In conclusion, air disturbance generated by the air blowing device we designed effectively improved the microenvironment around the plants, enhanced the physiological activity of the seedlings, and thereby promoted seedling growth.

In many parts of China, greenhouses are often not ventilated during winter and early spring to conserve heat. Hence, crops thus face unventilated conditions with the occlusion of air, resulting high humidity and low CO₂ concentration. As is known, moderate air circulation plays an important role in regulating the micrometeorological environment around plants, and subsequently the growth is improved (Shibuya et al., 2006).

Airflow movement improves the consistency of temperature, humidity, and CO₂ in greenhouses (Kuroyanagi, 2016).

In a study on the influence of air disturbance on the variation of canopy temperature in a double-span greenhouse, Ishii et al. (2012) found that the SD of canopy temperature under air disturbance with air velocity of 0.5 m/s was less than 0.6 °C, and the SD of canopy temperature without air disturbance was more than 1.1 °C. Stagnant air will form a boundary layer on the surface of plants, and as a result, the physiological processes of crops are suppressed (Kuroyanagi, 2013; Kuroyanagi et al., 2013; Takayama et al., 2014). Appropriate air disturbance can regulate the microenvironment of plant canopy leaves, promote energy exchange between the crop canopy and the surrounding environment, reduce CO₂ exchange resistance, increase CO₂ concentration in the microenvironment of leaves, and improve the transpiration rate and promote photosynthesis

(Elings et al., 2007). Shibuya et al. (2006) found that ventilation increased the exchange rate of CO₂ inside and outside the canopy and increased the dry matter accumulation of tomato plants. In a solar greenhouse, Yang et al. (2007) found that the optimal air velocity in the flowering and fruiting stage of muskmelon was ≈1.0 m/s, which increased the leaf area index and stomatal conductance (g_s) by 63.05% and 120.32%, respectively; the transpiration rate, photosynthetic rate, and fruit yield and quality were also significantly improved. A study performed in a single plastic greenhouse showed that the wetting time of the leaves is 1 h under ventilations and 5 h under no ventilation. Moreover, the reduction of the moisture condensation of leaves also inhibits the occurrence and spread of disease (Sekine et al., 2007).

A solar greenhouse is a common structure that is used for growing vegetable seedlings in northern China. To conserve heat in cold winter weather, the ventilation volume in these greenhouses is very small, and the airflow generated by the indoor temperature difference is extremely weak, so the indoor air is basically in a stagnant state (Bournet and Boulard, 2010; Kittas et al., 1996; Pérez-Parra et al., 2004; Wang et al., 1999). In addition, due to the use of the anti-insect netting, the airflow movement caused by natural ventilation inside and outside the facility in summer and autumn is greatly hindered (Fatnassi et al., 2002). At present, a horizontal fan is a type of air disturbance device that is widely used in greenhouses. Although turbulence fans can produce some air disturbance, the uniformity of air disturbance is insufficient, especially in solar greenhouses (smaller internal space). The coverage of the air velocity of 0.15 to 0.50 m/s at 1.5 m below the fan is only 73%, which results in poor uniformity of seedling growth (Zhang et al., 2016). Therefore, it is necessary to develop a controllable air disturbance device for growing seedlings in a solar greenhouse.

In this experiment, we designed an air blowing device that fastens to the seedbed and can move back and forth to provide accurate air velocity to the seedlings. This device was used to study the effect of airflow disturbance on the microenvironment of tomato seedlings during different seasons and its influence on seedling growth.

Materials and Methods

Design of blowing device for seedbed. The device includes an air blowing system, a moving bracket system, and a control system. The air blowing system is arranged on the moving bracket system through the fan suspension device, and the moving bracket system is arranged on the seedbed, which is controlled by the control system. The three systems are described as follows (Fig. 1):

- (1) The air blowing system includes the fan, the air supply tubing, and the air supply connecting pipe. The fan is

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S.L. is the corresponding author. E-mail: lsllhc@yeah.net.

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Fig. 1. The structure (A) and the motion simulation (B, C) of the air blowing device. 1, cross-flow fan; 2, controller; 3, microswitch; 4, telescopic sleeve; 5, switching power supply; 6, coupling; 7, DC geared motor.

fixed on the crossbar on the top of the gantry through the suspension device. The bottom of the fan has an air outlet, and the air supply pipeline is connected to the air outlet through the air supply connecting pipe. The air supply pipe is provided with an exit port that is inclined downward, and the angle between the axis of the inclined blowing mouth and the horizontal line is 60° .

- (2) The moving bracket system includes a portal frame, a roller, a drive motor, and a conical gear arranged on the main shaft of the drive motor. The roller and the drive motor are arranged at the bottom of the vertical poles on both sides of the gantry frame, and the moving bracket system travels along the seedbed.
- (3) The control system includes a controller and a micro switch arranged at the bottom of the gantry. Two blocks are arranged at both ends of the seedbed guide rail. The controller controls the forward rotation or reverse rotation of the drive motor according to the trigger signal of the microswitch.

Operation of blowing device for seedbed.

As shown in Fig. 2, the fan carried by the bracket is located above the seedbed and driven by the deceleration motor to move along the direction of the seedbed. When the microswitch that is connected to the electronic control unit (ECU) touches one of the two blocks, the ECU will automatically reverse the direction of motor rotation, which

result in the reciprocating motion of the portal frame between the two blocks. The moving speed of the support and the rotation speed of the fan are regulated by the control unit, which provides multistage speed regulation to meet the airflow demand of different seedlings. The width and height of the bracket can be adjusted within a certain range to meet the needs of different seedbed sizes.

Experimental site and design. The experiment was conducted in a solar greenhouse covered with polyethylene film (ground area $70 \text{ m} \times 6 \text{ m}$) without supplementary heating in Jinshui district, Zhengzhou, China (lat. $34^\circ 16' \text{ N}$, long. $112^\circ 42' \text{ E}$), from June to Dec. 2018. Three air velocity treatments were selected based on the air velocities measured in the canopy of seedlings below the fan outlet: T_1 (0.3 m/s), T_2 (0.6 m/s), and T_3 (0.9 m/s). The CK is defined as no blowing. The experiment was a randomized block design with four replications (seedbeds) and the size of each seedbed is 4 m long, and 1.6 m wide, for the total area of 6.4 m^2 . The moving speed of the air blowing device above each seedbed is 0.1 m/s, and it is started once every 30 min and can be blown back and forth five times every 5 min. Tomato seeds (*Solanum lycopersicum* cv. Fendu 77) were sown in 72-cell plastic plug trays that were filled with a mixture of peatmoss, perlite, and vermiculite (9:3:1, v/v/v). After sowing, tomato seedlings with two fully expanded true leaf and a small true leaf were transferred to the air blowing system. To avoid the influence of natural ventilation in the test area, thin films were

used to block the seedlings around the test area and between different treatments. The experiment was carried out in two seedling stages in both summer and winter.

Measurement of seedling canopy temperature, leaf temperature, and leaf humidity. The canopy temperature was measured by an automatic temperature recording tester (TRM-WD120; Jinzhou Sunshine Technology Co. Ltd., Jinzhou, China). Nine temperature measurement points were evenly distributed for each treatment. The probe was placed at the seedling canopy, and the recording interval was 1 min. The average temperature during air disturbance in each operating period of the blowing device was calculated, and then the average temperature during the blowing period was calculated hourly and daily. The leaf temperature of the tomato seedlings was measured by a thermocouple thermometer (OS136; Omega Engineering Inc., Norwalk, CT) on sunny and cloudy days, and the recording interval was 1 min. Five seedlings were randomly selected for each treatment, and the measurement site was the inner middle part of the main vein of the third true leaf. The leaf-air temperature difference was calculated from the measured leaf temperature and canopy temperature. The humidity was measured by a humidity automatic recorder (HE170; Jinzhou Sunshine Technology Co. Ltd.), and the distribution points, data collection, and analysis methods are the same as the canopy temperature.

Growth characteristics. When tomato seedlings had four true leaves, 10 seedlings were randomly selected to measure the growth characteristics for each treatment. Plant height and hypocotyl length were measured with a ruler. Stem diameter was measured with a Vernier caliper. Plant dry weight was recorded after drying in an oven at 85°C for 48 h. The SQI was calculated according to the equation: $\text{SQI} = \text{stem diameter} / \text{plant height} \times \text{dry mass of whole plant}$. Chlorophyll was determined by the portable chlorophyll meter (SPAD-502; Minolta, Osaka, Japan). Root activity was measured by the TTC (triphenyl tetrazolium chloride) method (Joslin and Henderson, 1984). The net photosynthetic rate (P_n), transpiration rate (T_r), and g_s were measured with LI-6400 photosynthesis equipment (6400xt; LI-COR, Lincoln, NE) every 2 h from 0800 to 1600 HR.

For the observation of the tomato seedling stomata, five fully developed leaves (the third leaf) were cut into $3 \text{ mm} \times 3 \text{ mm}$ sections and fixed in a formalin-acetic acid-alcohol solution for 24 h. The leaf segments were washed three times with distilled water, stained for 15 min in 0.01% acridine orange, and stained for another 15 min in 0.01% romadin. Finally, they were thoroughly washed with distilled water (Kim et al., 2004). Stomatal size and frequency were determined by microscopic examination of 10 leaf segments using a specialized computer system (MICRO-C4-2200 microscope CX31; Olympus, Tokyo, Japan). Samples were observed with a $\times 40$ objective lens. Stomatal length is defined as the length of dumbbell-shaped guard cell, whereas the stomatal width is perpendicular

to the dumbbell-shaped guard cell the widest value. The stomatal aperture measurement was determined by measuring the aperture width of stomata. The stomatal aperture ratio is defined as the ratio of the opening stomatal number to the total stomatal number. The stomatal density measurement is calculated as the stomatal density per square millimeter.

Stem mechanics characteristics test of tomato seedlings. To estimate the lodging resistance of tomato seedlings, when tomato seedlings had four leaves, 10 seedlings were selected for each treatment to measure the hardness, brittleness, and gel elasticity of the stem base and first internode by using a texture analyzer (TA1; Ametek Inc, Wallingford, CT). The parameters set in the test were the following: preloading speed, 1.00 mm/s; downloading speed, 1.00 mm/s; uploading speed, 1.00 mm/s after pressing; pause 5 s between two compressions; specimen compression deformation 70%; and triggering force, 0.2 N.

Statistical analysis. The experimental data were analyzed by one-way analysis of

variance using an SPSS software package (Version 21.0; IBM Corp., Armonk, NY). Differences between means were compared in the same column or row for any significant differences using the Tukey's honestly significant difference post hoc test at a significance level of $P < 0.05$.

Results

Effects of different air velocities on canopy temperature of tomato seedlings. Table 1 and Fig. 3 show the canopy temperature characteristics of tomato seedlings disturbed by different air velocities. During seedling cultivation in summer, no matter if the day was sunny or cloudy, the temperature in the canopy of seedlings decreased under air disturbance. With the increase of air velocity, the cooling effect increased to different degrees, and the cooling effect in the day was better than that in the night. The periods with the greatest cooling effect were from 1600 to 1800 HR. For example, at 1800 HR, the canopy

temperature of tomato seedlings was decreased by 1.6, 2.3, and 4.2 °C, respectively, for the three treatments of 0.3, 0.6, and 0.9 m/s compared with the CK. During seedling cultivation in winter, the influence of air disturbance on canopy temperature was contrary to that in the summer. Under air disturbance, the canopy temperature of the seedlings increased slightly. With the increase of air velocity, the heating effect was strengthened, but the amplitude was very small.

Effects of different air velocities on the leaf-air temperature difference of tomato seedlings. As shown in Table 2, air disturbance has a significant influence on leaf temperature and the leaf-air temperature difference of tomato seedlings. Compared with the CK, air disturbance decreased leaf temperature and increased leaf-air temperature difference in summer. Within the range of the selected air velocities, with the increase of airflow movement, the daily leaf temperature cooling effect and leaf-air temperature difference gradually increased, and this trend was better on sunny days than on cloudy days. For the average leaf temperature of tomato seedlings, the three treatments (T_1 , T_2 , and T_3) were 0.83, 1.57, and 2.27 °C lower than that of the CK on sunny days. Compared with the CK, the leaf-air temperature difference was increased by 13.8%, 45.9%, and 47.8% respectively. However, air disturbances had no influence on the average leaf temperature in winter. Moreover, the leaf-air temperature difference varies at different air velocities. The T_1 treatment had a significantly lower leaf-air temperature difference compared with that of the CK; conversely, leaf-air temperature difference in the T_3 treatment was higher than that of the CK.

Effects of different air velocities on canopy humidity of tomato seedlings. Under air disturbance, the canopy humidity of tomato seedlings decreased to a certain extent, and the humidity reduction effect increased with the increase of air velocity. However, the blowing duration had no influence on the overall humidity reduction. In terms of the average humidity reduction within one day,

Fig. 2. The operating principle of device.

Table 1. The average daily canopy temperature of tomato seedlings at different air velocities.^z

Season	Weather Conditions	Treatment	Mean daily temp (°C)	Mean day temp (°C)	Mean night temp (°C)
Summer	Sunny day	T_1	27.94 ± 1.91 a	31.68 ± 2.11 a	24.21 ± 1.28 a
		T_2	27.60 ± 2.41 a	31.18 ± 1.87 a	24.02 ± 1.66 a
		T_3	26.90 ± 1.34 a	30.16 ± 0.97 a	23.63 ± 0.51 a
		CK	28.38 ± 1.54 a	32.46 ± 1.86 a	24.30 ± 1.17 a
	Cloudy day	T_1	30.01 ± 0.67 a	32.89 ± 2.11 a	27.13 ± 0.45 a
		T_2	29.57 ± 1.82 a	32.30 ± 1.97 a	26.83 ± 0.22 a
		T_3	29.13 ± 1.02 a	31.83 ± 0.65 a	26.43 ± 0.71 a
		CK	30.63 ± 1.57 a	33.68 ± 0.98 a	27.58 ± 1.06 a
Winter	Sunny day	T_1	17.05 ± 0.12 a	20.29 ± 1.12 a	13.80 ± 0.21 a
		T_2	17.53 ± 0.92 a	21.05 ± 0.65 a	14.00 ± 0.81 a
		T_3	17.73 ± 0.13 a	21.25 ± 0.81 a	14.20 ± 0.17 a
		CK	16.87 ± 1.05 a	20.11 ± 1.29 a	13.63 ± 0.54 a
	Cloudy day	T_1	13.55 ± 0.92 a	14.95 ± 1.01 a	12.16 ± 1.02 a
		T_2	13.65 ± 1.02 a	15.08 ± 0.84 a	12.22 ± 0.65 a
		T_3	13.80 ± 0.23 a	15.28 ± 0.25 a	12.32 ± 0.14 a
		CK	13.48 ± 0.55 a	14.89 ± 0.31 a	12.01 ± 0.65 a

^zValues are mean $\pm$ SE (n = 4). The same letter in the same data column in the same cropping season indicates no significant difference ($P = 0.05$).

the air disturbance velocity of 0.9 m/s (T_3) decreased by 7.0% and 5.9%, respectively, on sunny days and cloudy days in summer and 3.8% and 2.7%, respectively, on sunny days and cloudy days in winter (Fig. 4).

Effects of different airflow velocities on growth and physiological characteristics of tomato seedlings. As shown in Table 3, during seedling cultivation in summer, the plant height of tomato seedlings decreased significantly under air disturbance, while the root dry mass, root-shoot ratio, and SQI increased. In addition, the T_2 treatment had the best positive effect. Compared with the CK, the plant height decreased by 13.54%, the root dry mass, root-shoot ratio, and SQI increased by 34.63%, 21.43%, and 14.29%, respectively at 0.6 m/s. Conversely, air disturbance in winter had different effects than in summer. Under all air disturbance treatments, the plant height of tomato seedlings increased

significantly, and the trend of other morphological indexes of seedlings was the same as that in summer, which were better than that of the CK. The effect of air velocity was still 0.6 m/s (T_2), which was the best performance.

The physiological indexes of tomato seedlings were improved to different degrees under air disturbance (Table 4). Under the air disturbance with the air velocity of 0.6 m/s (T_2), all of the indexes were significantly higher compared with that of the CK. During seedling cultivation in the high temperature season (summer), chlorophyll, root activity, soluble sugar, P_n , T_r , and g_s of tomato seedlings treated with the air velocity of 0.6 m/s were increased by 18.7%, 75.3%, 12.0%, 10.4%, 32.8%, and 31.3%, respectively, compared with those of the CK; similarly, when seedlings were raised in the low temperature season, the above indexes increased by 16.6%, 14.5%, 49.0%, 22.9%, 28.2%, and 43.3%, respectively.

Effects of different airflow velocities on stomatal characteristics of tomato seedlings. During seedling cultivation in summer, the stomatal length and width, opening degree, stomatal density, and opening ratio of the leaves of tomato seedlings treated with the three air velocity were slightly higher than that of the control (Table 5). Under the treatment of the 0.6 m/s (T_2), the stomata length and width, opening degree, and opening ratio of tomato seedling leaves were increased by 19.6%, 32.4%, 12.7%, and 12.7%, respectively, compared with the those of the CK. During seedling cultivation in winter, for the 0.9 m/s (T_3) treatment, stomata length and width, stomata density, and opening ratio of tomato seedling leaves were all lower than that of the CK. Except for stomatal aperture, other indexes had no significant difference. At T_1 (0.3 m/s) and T_2 (0.6 m/s), stomata-related indexes were greater than those of the CK; stomatal width, opening degree, and opening ratio of T_1 were significantly higher than those of the CK, which increased by 9.3%, 9.6%, and 9.4%, respectively (Table 5).

Effects of different airflow velocities on mechanical properties of tomato seedlings. Hardness and elasticity can reflect the ability of the seedling stem to withstand pressure and return to the original state after bending. These mechanical properties are key data of seedlings suitable for mechanized transplanting and provide a basis for the design of related equipment. As shown in Table 6, mechanical indexes such as the hardness and elasticity of the tomato seedling stem under air disturbance were higher than those of the CK in the two seasons of seedling cultivation. Air disturbance with air velocity of 0.6 m/s (T_2) had the best effect.

Discussion

Leaf temperature is more accurate than air temperature for plant management. The difference between leaf temperature and air temperature, that is, the leaf-air temperature difference, is an index reflecting the water absorption capacity of crop roots and the

Fig. 3. Diurnal variation of canopy temperature in tomato seedlings at different air velocity. (A) Sunny day in summer. (B) Cloudy day in summer. (C) Sunny day in winter. (D) Cloudy day in winter. Bars represent standard errors ($n = 4$).

Table 2. Leaf temperature and leaf-air temperature difference of tomato seedlings at different air velocities.

Season	Time	Sunny day								Cloudy day							
		T ₁		T ₂		T ₃		CK		T ₁		T ₂		T ₃		CK	
		t_{leaf}	Δt	t_{leaf}	Δt	t_{leaf}	Δt	t_{leaf}	Δt	t_{leaf}	Δt	t_{leaf}	Δt	t_{leaf}	Δt	t_{leaf}	Δt
Summer	0400	21.07	-1.43	20.83	-1.57	20.11	-1.6	21.85	-1.25	25.18	-1.12	24.58	-1.32	24.12	-1.5	26.08	-0.82
	0800	26.03	-1.89	25.76	-2.16	25.07	-2.35	27.06	-1.56	27.11	-1.3	26.14	-1.86	25.27	-1.93	28.02	-0.98
	1200	31.72	-2.38	30.18	-3.72	29.42	-3.58	32.39	-1.87	33.85	-1.75	33.29	-2.01	32.13	-2.57	34.74	-1.56
	1600	33.08	-2.12	31.29	-3.01	30.78	-2.92	34.25	-1.75	32.52	-1.58	31.57	-1.68	31.08	-2.32	33.58	-1.12
	2000	23.05	-1.65	22.65	-1.95	22.09	-2.01	23.64	-1.76	26.64	-1.17	26.52	-1.26	25.85	-1.85	27.28	-0.97
	2400	22.29	-1.41	22.08	-1.52	21.15	-1.65	23.05	-1.35	27.03	-1.06	25.54	-1.71	25.03	-1.43	26.68	0.72
	Mean	26.21	-1.81	25.465	-2.32	24.77	-2.35	27.04	-1.59	28.72	-1.33	27.94	-1.64	27.25	-1.93	29.39	-1.03
Winter	0400	13.05	-0.65	12.94	-1.16	12.29	-1.41	12.38	-1.05	11.62	-0.05	11.78	-0.21	11.38	-0.39	11.2	-0.4
	0800	12.21	-0.89	12.11	-1.28	11.47	-1.83	11.24	-1.76	11.78	-0.16	11.32	-0.38	10.77	-0.57	10.67	-0.41
	1200	26.87	-1.56	26.63	-2.07	26.15	-2.62	27.02	-1.83	16.8	-0.52	16.74	-0.72	16.53	-1.23	16.04	-0.75
	1600	17.82	-1.01	17.35	-1.95	17.58	-2.35	17.52	-1.28	16.25	-0.12	16.12	-0.35	16.07	-0.87	15.95	-0.52
	2000	14.02	-0.75	13.67	-1.43	13.2	-1.9	13.35	-1.12	12.92	-0.06	12.7	-0.21	12.58	-0.65	12.57	-0.38
	2400	13.64	-0.68	13.55	-1.18	12.88	-1.52	12.91	-1.07	11.79	-0.07	11.64	-0.16	11.68	-0.51	11.82	-0.41
	Mean	16.27	-0.92	16.04	-1.51	15.59	-1.94	15.74	-1.35	13.53	-0.16	13.38	-0.34	13.17	-0.70	13.04	-0.48

t_{leaf} = surface temperature of tomato leaf; Δt = the difference between surface temperature and canopy temperature of tomato leaves.

transpiration capacity of leaves. It is generally considered that a leaf-air temperature difference trending to zero benefits plants (O'Shaughnessy and Evett, 2010; Zhang et al., 2019a). Leaf temperature is mainly affected by solar radiation, crop transpiration, and heat exchange intensity with surrounding air (Greer, 2019). Moreover, airflow movement influences leaf temperature through transpiration and convection exchange, thus regulating the leaf-air temperature difference (Zhang and Zhang, 2019b). In summer, the leaf or canopy temperature was much higher than air temperature due to solar radiation. However, flow of air can take away a lot of heat and reduce the temperature of the leaf and canopy. Addi-

tionally, air disturbance at the appropriate air velocity also enhances the transpiration of the leaves. In this experiment, the transpiration rate was 32.8% higher at the air velocity of 0.6 m/s than that of the CK (Table 4), which could decrease the leaf temperature through vigorous transpiration, which was consistent with the research results of Moon et al. (2007) on cucumber. The leaf temperature of tomato seedlings decreased, and the leaf-air temperature difference increased when the air current was disturbed in summer. At night or on cloudy days, the ability of airflow movement to influence blade temperature through transpiration was greatly reduced; the leaf-air temperature difference also showed a trend of decrease. However, air disturbance has a

multiplicative effect on leaf temperature and leaf-air temperature difference in winter. When the solar radiation is weak or during night (without radiation), the self-radiation and transpiration of seedling can make the blade temperature lower than the surrounding air temperature. Appropriate air disturbance can eliminate the differences in temperature, so as to avoid excessive blade temperature decline. High air velocity (0.9 m/s) will aggravate the decrease of the blade temperature. It can be seen from the above that air disturbance is the key to achieving temperature and environmental regulation of seedlings, which needs to determine the appropriate air velocity according to solar radiation and seedling growth.

As is known, stomata morphology is a limiting factor that affects plant transpiration and photosynthesis (Chaerle et al., 2005; Wu et al., 2014). To reduce transpiration and improve the water utilization rate, plants will close stomata and constraint the diffusion of CO₂. Uneven stomatal closure reduces intercellular CO₂ concentration and thus affects the photosynthetic rate of plants (Franks and Farquhar, 2007). In this experiment, the two treatments with the air velocity of 0.3 m/s (T₁) and 0.6 m/s (T₂) significantly increased stomatal length and width, opening degree, stomatal density, and opening ratio of tomato seedling leaves (Table 5), thus improving the *g_s* and *P_n* of leaves (Table 4). Air disturbance was characterized by the same effect as the CO₂ fertilization, but a CO₂ concentration increase should not be a direct result of the disturbance of airflow. Air disturbance promoted the seedling groups inside and outside of air exchange, but CO₂ concentration in a solar greenhouse is basically consistent, so the air disturbance does not cause the difference of CO₂ concentration. We had hypothesized that the improvement of stomatal morphology of leaves was the main factor to promote photosynthesis.

Fig. 4. Variation characteristics of canopy humidity of tomato seedlings at different air velocity. (A) Sunny day in summer. (B) Cloudy day in summer. (C) Sunny day in winter. (D) Cloudy day in winter. Bars represent standard errors (*n* = 4).

Table 3. Growth characteristics of tomato seedlings at different air velocities.^z

	Treatment	Plant ht (cm)	Stem diam (mm)	Dry mass of shoot (mg)	Dry mass of root (mg)	Root/shoot	Seedling index
Summer	T ₁	15.76 ± 0.20 c	3.49 ± 0.09 a	262.2 ± 19.5 c	45.7 ± 2.6 b	0.18 ± 0.01 a	0.122 ± 0.007 a
	T ₂	17.72 ± 0.55 b	3.52 ± 0.11 a	298.6 ± 14.6 ab	50.1 ± 3.5 a	0.17 ± 0.01 a	0.128 ± 0.005 a
	T ₃	16.82 ± 0.38 bc	3.42 ± 0.58 a	284.0 ± 20.8 bc	48.7 ± 2.5 ab	0.17 ± 0.02 a	0.124 ± 0.004 a
	CK	20.12 ± 0.22 a	3.37 ± 0.03 a	317.2 ± 22.6 a	45.1 ± 3.7 b	0.14 ± 0.01 b	0.112 ± 0.08 b
Winter	T ₁	11.52 ± 0.16 b	3.06 ± 0.09 b	235.1 ± 14.2 b	42.8 ± 2.1 ab	0.18 ± 0.02 a	0.124 ± 0.002 b
	T ₂	12.56 ± 0.36 a	3.47 ± 0.08 a	257.2 ± 18.3 a	45.1 ± 1.9 a	0.18 ± 0.01 a	0.138 ± 0.007 a
	T ₃	11.31 ± 0.27 b	3.00 ± 0.10 b	232.1 ± 22.1 b	40.2 ± 3.9 b	0.17 ± 0.01 a	0.118 ± 0.004 bc
	CK	9.46 ± 0.31 c	2.85 ± 0.03 b	216.8 ± 27.8 b	33.5 ± 3.6 c	0.15 ± 0.01 b	0.118 ± 0.004 bc

^zValues are mean ± SE (*n* = 10). The same letter in the same data column in the same cropping season indicates no significant difference (*P* = 0.05).

Table 4. Physiological characteristics of tomato seedlings at different air velocities.^z

Season	Treatment	Chlorophyll (SPAD)	Root vigor (mg·g ⁻¹ ·h ⁻¹)	Soluble sugar (mg·g ⁻¹)	<i>P_n</i> (μmol·m ⁻² ·s ⁻¹)	<i>T_r</i> (mmol·m ⁻² ·s ⁻¹)	<i>g_s</i> (mmol·m ⁻² ·s ⁻¹)
Summer	T ₁	48.02 ± 2.96 a	2.39 ± 0.12 b	20.25 ± 0.67 a	23.62 ± 1.04 ab	4.26 ± 0.06 b	18.78 ± 0.46 ab
	T ₂	47.78 ± 1.26 a	3.40 ± 0.26 a	19.20 ± 1.01 a	24.18 ± 1.11 a	4.78 ± 0.01 a	19.85 ± 0.78 a
	T ₃	42.38 ± 2.47 b	3.24 ± 0.27 a	19.98 ± 0.89 a	23.36 ± 0.85 ab	3.85 ± 0.05 c	17.23 ± 1.01 b
	CK	40.26 ± 1.77 b	1.94 ± 0.13 c	17.14 ± 0.65 b	21.91 ± 0.72 b	3.60 ± 0.11 c	15.12 ± 0.62 c
Winter	T ₁	39.62 ± 0.86 ab	2.41 ± 0.09 a	15.63 ± 0.86 b	17.25 ± 1.13 b	1.34 ± 0.07 b	10.67 ± 1.12 b
	T ₂	42.50 ± 0.53 a	2.53 ± 0.11 a	17.93 ± 1.02 a	19.52 ± 0.67 a	1.50 ± 0.06 a	12.28 ± 1.02 a
	T ₃	40.96 ± 0.73 a	2.33 ± 0.20 ab	13.33 ± 1.39 c	15.93 ± 0.68 c	1.12 ± 0.04 c	8.96 ± 0.88 c
	CK	36.44 ± 0.70 b	2.21 ± 0.15 b	12.03 ± 0.78 d	15.88 ± 1.03 c	1.17 ± 0.09 c	8.57 ± 0.59 c

^zValues are mean ± SE (*n* = 10). The same letter in the same data column in the same cropping season indicates no significant difference (*P* = 0.05).

P_n = net photosynthetic rate; *T_r* = transpiration rate; *g_s* = stomatal conductance.

Table 5. Stomatal characteristics of tomato seedlings at different air velocities.^z

Season	Treatment	Stomatal length (μm)	Stomatal width (μm)	Stomatal aperture (μm)	Stomatal density (number/ mm^2)	Stomatal aperture ratio (%)
Summer	T ₁	11.8 $\pm$ 0.49 b	8.6 $\pm$ 0.40 b	1.38 $\pm$ 0.28 ab	368.2 $\pm$ 18.1 a	78.2% $\pm$ 1.5% ab
	T ₂	13.4 $\pm$ 0.51 a	9.8 $\pm$ 0.37 a	1.51 $\pm$ 0.03 a	373.2 $\pm$ 19.4 a	80.5% $\pm$ 1.5% a
	T ₃	11.6 $\pm$ 0.41 b	8.3 $\pm$ 0.32 b	1.35 $\pm$ 0.02 b	361.6 $\pm$ 13.8 a	77.3% $\pm$ 1.3% bc
	CK	11.2 $\pm$ 0.32 b	7.4 $\pm$ 0.39 c	1.34 $\pm$ 0.01 b	360.3 $\pm$ 23.5 a	71.4% $\pm$ 2.4% c
Winter	T ₁	11.2 $\pm$ 0.21 ab	9.4 $\pm$ 0.24 a	1.49 $\pm$ 0.03 a	364.0 $\pm$ 21.8 a	76.0% $\pm$ 1.1% a
	T ₂	11.5 $\pm$ 0.41 a	8.8 $\pm$ 0.37 ab	1.47 $\pm$ 0.03 ab	368.0 $\pm$ 13.6 a	74.8% $\pm$ 0.9% a
	T ₃	10.2 $\pm$ 0.42 c	7.0 $\pm$ 0.32 c	1.32 $\pm$ 0.01 c	365.2 $\pm$ 24.0 a	67.2% $\pm$ 1.2% b
	CK	10.4 $\pm$ 0.24 bc	8.6 $\pm$ 0.24 b	1.36 $\pm$ 0.01 bc	355.6 $\pm$ 16.7 a	69.5% $\pm$ 0.4% ab

^zValues are mean $\pm$ SE (n = 5). The same letter in the same data column in the same cropping season indicates no significant difference ($P = 0.05$).

Table 6. Mechanical properties of tomato seedlings at different air velocities.^z

Season	Treatment	Hardness		Elasticity	
		Basal part of stem	First internode	Basal part of stem	First internode
Summer	T ₁	19.775 $\pm$ 1.373 a	17.467 $\pm$ 0.865 ab	8.256 $\pm$ 0.788 b	6.265 $\pm$ 0.788 ab
	T ₂	20.427 $\pm$ 0.751 a	17.598 $\pm$ 0.762 ab	9.987 $\pm$ 0.762 a	6.646 $\pm$ 0.601 a
	T ₃	19.892 $\pm$ 1.473 a	18.960 $\pm$ 0.670 a	8.070 $\pm$ 0.982 b	6.629 $\pm$ 0.732 a
	CK	15.191 $\pm$ 0.372 b	16.042 $\pm$ 0.634 b	6.646 $\pm$ 0.601 c	5.924 $\pm$ 0.276 b
Winter	T ₁	11.811 $\pm$ 0.796 c	9.138 $\pm$ 0.525 b	3.102 $\pm$ 0.142 a	1.302 $\pm$ 0.058 ab
	T ₂	15.684 $\pm$ 0.995 a	10.850 $\pm$ 0.362 a	3.213 $\pm$ 0.156 a	1.365 $\pm$ 0.074 a
	T ₃	13.756 $\pm$ 0.473 b	9.603 $\pm$ 0.270 b	3.070 $\pm$ 0.531 a	1.229 $\pm$ 0.081 b
	CK	9.853 $\pm$ 0.675 d	7.743 $\pm$ 0.478 c	2.959 $\pm$ 0.126 a	1.103 $\pm$ 0.031 c

^zValues are mean $\pm$ SE (n = 10). The same letter in the same data column in the same cropping season indicates no significant difference ($P = 0.05$).

Mechanized transplanting is the current trend in vegetable cultivation. In addition to the traditional indexes to measure seedling quality, more attention is paid to plant height, root-shoot ratio, stem hardness, and flexibility. The air disturbance improved the temperature characteristics of seedling leaves and promoted the physiological activity; thus, the accumulation of dry matter in seedlings increased. In addition, wind causes the base of the stem to bend, and to maintain its own growth balance, the root system must provide an anchoring force to offset the pull of the wind and maintain its mechanical stability (Hodge et al., 2009; Tamasi et al., 2005). Previous studies have shown that under the action of long-term natural strong wind, plant stability can be promoted by increasing the root-shoot ratio thus reducing the wind pressure on the plant (Sayed, 1996). Due to the limitation of the distribution of root system in seedling cultivation, the number and diameter of lateral roots of seedlings under air disturbance were higher than that of the CK during sampling. The seedlings adapted to the air disturbance through these changes in root morphology, thus showing an increase in the root-shoot ratio of seedlings.

Another effect of air disturbance on seedlings cultivation in summer was a significant reduction in plant height. Plant height elongation depends on cell elongation and division, and cell elongation plays a decisive role in plant height (Downes et al., 2001); continuous turgor pressure provides the power needed for cell elongation and growth (Yamaguchi and Kamiya, 2000). The change in plant height is inhibited by the environment, which stimulates the production of hormones. Huang and Lin (2003) believed that low temperature stimulated the production of ethylene, which inhibited the plant height of tomato seedlings. Sun et al. (2010) revealed that the dwarf effect induced by cold

shock was related to the change of GA₃ content. The synthesis rate and content of internode ethephon increased after a mechanical scrub treatment. The induced synthesis of ethephon could inhibit auxin transmission to the base, thus delaying elongation growth and accelerating transverse growth (Latimer, 1998). Mechanical brushing gives the seedlings a bending force and caused mechanical damage; air disturbance had a similar effect, but this force was much softer and could not cause mechanical damage to the seedlings. However, air disturbance inhibited seedling height in summer but promoted seedling height in winter. The mechanism may be different from low temperature stimulation and mechanical scrubbing, which needs further study. Hardness and elasticity reflect the mechanical properties of the seedling stem after compression and bending. They are also important indicators to evaluate whether it is suitable for mechanized transplanting. In this experiment, both the hardness and elasticity of tomato seedling stems were higher under air disturbance in summer and winter. Under the disturbance of airflow with the air velocity of 0.6 m/s, the temperature and leaf-air difference of seedling leaves can be effectively improved, the canopy air humidity can be reduced, the photosynthesis and dry matter accumulation of seedlings can be promoted, and the hardness and elasticity of seedlings can be enhanced (Tables 2–4 and 6; Fig. 4).

Air disturbance is an important way to regulate the microclimate in seedling cultivation. In this experiment, a blowing device with constant airflow velocity was designed to regulate the microclimate around the seedlings. However, seedlings may need a multiple airflow velocity under different environmental conditions (solar radiation, humidity, and temperature). Further study is needed to obtain a proper airflow velocity based on other environmental factors and seedling growth

conditions. In addition, integrating the air disturbance device with the mobile water and fertilizer integration equipment and the truss-type mobile light compensation equipment to reduce equipment investment is also a key problem to be solved from the perspective of engineering.

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