Effects of Diffuse Light on Microclimate of Solar Greenhouse, and Photosynthesis and Yield of Greenhouse-grown Tomatoes

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Additional index words. Chinese solar greenhouse, diffuse light, light environment, tomato

Abstract. The application of diffuse light can potentially improve the homogeneity of light distribution and other microclimatic factors such as temperature inside greenhouses. In this study, diffuse light plastic films with different degrees of light diffuseness (20% and 29%) were used as the south roof cover of Chinese solar greenhouses to investigate the spatial distribution of microclimatic factors and their impacts on the growth and yield of tomato. The horizontal and vertical photosynthetic photon flux density (PPFD) distributions, air temperature distribution, and leaf temperature distribution inside the canopy, tomato leaf net photosynthesis (P_n), and fruit production during the growth period were determined. The results showed that diffuse light plastic film continuously improved the light distribution in the vertical and horizontal spaces of the crop canopy in terms of light interception and uniformity. A more diffuse light fraction also decreased the air and leaf temperatures of the middle canopy and upper canopy during the summer, thereby promoting the photosynthesis of the tomato plants. P_n of the middle and lower canopies with higher haze film were significantly greater than those with lower haze film (19.0% and 27.2%, respectively). The yields of higher stem density and lower stem density planted tomatoes in the 29% haze compartment were increased by 5.5% and 12.9% compared with 20% in the haze group, respectively. Diffuse light plastic films can improve the homogeneity of the canopy light distribution and increase crop production in Chinese solar greenhouses.

With the development of the greenhouse industry, vegetables can be grown locally year-round despite the restrictions of natural conditions. In northern China, the typical

Chinese-style solar greenhouses (CSGs) are east–west-oriented and constructed with a transparent south roof, opaque and insulated north wall, and north roof and side-walls; these are passive solar greenhouses without auxiliary heating (Tong et al., 2013). Therefore, solar radiation conditions inside CSGs comprise the most important determining factors of the creation of the greenhouse microclimate, which further influences the growth and yield of greenhouse-grown crops.

Generally, solar radiation inside a CSG is not evenly distributed due to its unique structure and the shading of the crop canopy (Zhang et al., 2020). The upper canopy intercepts more direct light, and leaves in the lower canopy receive limited incident light

as a result of canopy shading. Some of the upper leaves exposed to direct light may even experience excess light, eventually leading to photoinhibition, whereas the leaves beneath the greenhouse frameworks and upper canopy could suffer from a light energy deficit, which causes a dramatic decrease in the photosynthetic rate (Trouwborst et al., 2010).

Optimization of the greenhouse covering material provides a practical option for improving greenhouse meteorology, including light and thermal characteristics (Al-Mahdouri et al., 2013; Baeza et al., 2020; Lamnatou and Chemisana, 2013a), thereby achieving improvements in crop growth and quality (Hemming et al., 2008b). Diffuse light covering material was recently introduced mainly for conventional glass greenhouses (Hemming et al., 2008b; Li et al., 2016). Compared with regular greenhouse cover, light-diffusing cover scatters a certain fraction of the transmitted direct light into diffuse light, thus potentially improving the uniformity of spatial and temporal light distributions and increasing the radiation efficiency of the crops (Hemming et al., 2008a; Li and Yang, 2015). In the vertical direction of the canopy, diffuse light could penetrate deeper inside the canopy, thereby reducing the extinction coefficient and shading of the upper canopy (Lamnatou and Chemisana, 2013b). In the horizontal canopy, diffuse light also improves the homogeneity of light distribution by reducing the shadow of the greenhouse framework and local peaks in light intensity (Li and Yang, 2015).

Many previous researchers have investigated the impact of diffuse light on plant growth and physiology. It is considered that plants could use diffuse light more efficiently than direct light, such as apple trees (Lakso and Musselman, 1976), spruce (Urban et al., 2012), and grass (Sheehy and Chapas, 1976). Such studies of diffuse light have been performed by comparing plant responses on clear days and cloudy days in natural conditions (Gu et al., 2002, 2003; Urban et al., 2007). Applying diffuse light in the greenhouse decreased the leaf temperature of tomato and resulted in a higher leaf area index and lower specific leaf area, which help regulate photosynthetic activities (Li et al., 2014a) and further benefit the yield at harvest (Adams et al., 2000).

In recent years, our research group has conducted a series of investigations of the effects of light diffuse plastic films on CSG microclimates and crop growth. The results showed that diffuse light improved the seedling index and accumulation of chlorophyll and increased the total leaf area of tomato, cucumber, and pepper as well as the quality and yield of tomato (Fan et al., 2016; Song et al., 2017; Sun et al., 2016). However, these studies have focused on the effects of diffuse light plastic films on plant growth and yield, but not environmental factors such as light and temperature distributions.

The main objective of the present study was to provide more comprehensive theoretical

Received for publication 19 June 2020. Accepted for publication 16 July 2020.

Published online 26 August 2020.

This research was funded by the Earmarked Fund for Modern Agro-industry Technology Research System (CARS-23-C02) and Borouge Sales and Marketing (Shanghai) Co., Ltd (201704810910196).

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Fig. 1. The structure of the experimental Chinese solar greenhouse (CSG) consisting of a transparent south roof covered with plastic film, a north wall, and an opaque and insulated north roof and sidewalls. The north wall is constructed with clay bricks (200 + 200 mm) insulated with polystyrene boards (70 mm) in the middle. The experimental greenhouse was divided into two compartments with heat insulation board. (A) Outside view of the CSG. (B) Inside view of the greenhouse (when seedlings were transplanted). (C) Schematic structure of the greenhouse.

knowledge regarding the introduction of diffuse light plastic films to CSGs by elaborating on microclimate factors including light and temperature of CSGs with different haze plastic films and investigating the effect of the greenhouse environment on tomato plant growth and yield.

Materials and Methods

Experimental setup. This experiment was conducted in an east–west-oriented Chinese solar greenhouse located in Beijing, China (lat. 39°48'N, long. 116°56'E). The greenhouse was divided into two equal compartments (328 m² and 41 m × 8 m for each compartment) with heat insulation board (Fig. 1). The greenhouse compartments were covered with two types of diffuse light plastic films (Borouge Co. Ltd., Shanghai, China) that are regularly used by local growers. The transmittance and haze factor of the plastic films were measured with a light transmittance and haze meter (WGT-2S; INESA Physico-Optical Instrument, Shanghai, China) according to the ASTM Committee (2013). Transmission was measured with the build-in light source with a wavelength range of 200 to 2500 nm. Haze is defined as the percentage of diffuse light from transmitted light that deviates more than 2.5 degrees from the direction of the incident light. Haze values of the two types of plastic films [ethylene-vinyl acetate (EVA)] were 20% and 29%, respectively, whereas the transmission of the plastic films was 89%. The experiment was conducted for year-round production of tomato (cv. Zhongshu 4) from 1 Oct. 2016. Tomato plants were cultivated in the greenhouse with peat-based substrate. Irrigation and fertilization were performed

according to good horticultural practices. Plant rows were south–north-orientated with a row distance of 70 cm. Two stem densities were set in each row; these were initially 6 and 5 stems/m², but they were reduced to 4.3 and 3.6 stems/m² at 66 d after planting.

Measurement of PPFD distribution within the canopy. The distribution of PPFD was measured with the S-LIA-M003 sensor (Onset Inc., Bourne, MA) in each compartment as shown in Fig. 2. The vertical PPFD distribution was recorded from Oct. 2016 to June 2017. It was measured at the top of the canopy, 10 cm below the top of the crop, the middle of the canopy, and the bottom of the canopy; measurements were replicated three times at each height. The vertical PPFD measuring height varied with the growth of the tomato plant. The horizontal PPFD distribution was measured at 1.5, 4.5, and 6.5 m to the north wall and 50 cm below the top of the canopy; measurements were replicated three times at each point from 2 Mar. 2017 to 27 Apr. 2017 at the main fruit stage of tomatoes.

Measurements of air temperature and leaf temperature. The air temperature was measured with the 175H1 sensor (Testo Inc., Lenzkirch Germany) with an accuracy of ±2%. Leaf temperature was measured with T-type fine-wire thermocouples (Omega Engineering, Norwalk, CT) at three canopy depths with three replicates. The measurement positions were adjusted with the growth of the plants (Fig. 2). The temperature was measured from 5 June 2017 to 10 July 2017.

Measurements of leaf photosynthesis and solar radiation transmittance. The P_n of leaf was determined with the CIRAS-2 portable gas exchange device (PP Systems, Amesbury, MA) at three canopy depths. Canopy depths were defined as leaf number 5, leaf

number 10, and leaf number 15 according to Li et al. (2014a). From 4 Apr. 2017 to 30 Apr. 2017, instantaneous P_n of three replicate leaves of different individual plants was measured on clear days at each canopy depth.

Canopy solar radiation transmittance (R_t) reflects the distribution of total solar radiation in crop communities in relation to the population structure:

$$R_t = Q_h / Q_0 \times 100\% \quad [1]$$

where R_t is the total solar radiation transmittance of crop communities (%), Q_h is the total solar radiation at the height of h from the ground (mol·m⁻²·d⁻¹), and Q₀ is the total solar radiation at the top of the population (mol·m⁻²·d⁻¹). The measurement positions were at three canopy depths from Jan. 2017 to June 2017.

Measurements of tomato fruit yield. During the harvest stage of the tomato plants, fruits were collected and weighed with an electronic scale balance (Meifu Electronics, Shenzhen, China) each week. The total yield was the sum of each week from 22 Jan. 2017 to 17 June 2017.

Statistical analysis. The significance analysis of data was evaluated by an analysis of variance and *t* test at *P* = 0.05 with SPSS 20.0 (IBM Inc., Armonk, NY). A linear correlation analysis was performed assuming that replications in the same greenhouse compartment were independent. The daily light integral (DLI) was obtained by integrating the value of PPFD with MATLAB (MathWorks Inc., Natick, MA). Sigmaplot 14.0 was used to perform the linear correlation analysis of the data and to plot all figures.

Results

PPFD distribution within the tomato canopy. Canopy PPFD of the two greenhouse compartments fluctuated on the example day, which was 19 Apr. 2017 (Fig. 3). The maximum fluctuation amplitude of PPFD in the upper canopy of the 29% haze compartment was 105.0 μmol·m⁻²·s⁻¹, with an average of 53.5 μmol·m⁻²·s⁻¹ (Fig. 3A); however, the maximum fluctuation amplitude of the 20% haze compartment was 233.5 μmol·m⁻²·s⁻¹, with an average of 101.2 μmol·m⁻²·s⁻¹ (Fig. 3B). In the 29% haze compartment, the lower canopy PPFD was kept above than 200 μmol·m⁻²·s⁻¹ for 4.7 h, which was longer than that of the 20% haze compartment, where that PPFD was kept for 2.0 h. PPFD above 600 μmol·m⁻²·s⁻¹ in the middle canopy of the 29% haze greenhouse lasted for 2.0 h, whereas that of the 20% haze compartment was kept for only 0.4 h. PPFD above 800 μmol·m⁻²·s⁻¹ in the upper canopy lasted for 1.3 h in the 29% haze compartment and 0.5 h in the 20% haze compartment.

The DLI values of the middle and lower canopies of the 29% haze compartment were significantly greater than those of the 20% haze compartment (Table 1). The DLI values of the upper, middle, and lower canopies from January 2017 to June 2017 in the 29%

Fig. 2. Layout of the measuring points of a greenhouse compartment. Photosynthetic photon flux density was measured at the vertical and horizontal measuring points. Air and leaf temperatures were measured at the vertical measuring points. Each measurement point was recorded with three replicates. H represents the height of the crop canopy. Green bars represent the planting rows.

Fig. 3. Diurnal variations of photosynthetic photon flux density (PPFD) in the vertical canopy of the two greenhouse compartments. (A) The 29% haze compartment. (B) The 20% haze compartment. Data from 0700 to 1900 HR on 19 Apr. 2017 were selected to analyze the light distribution on clear days.

Table 1. Daily light integral (DLI) at different depths of the vertical canopy on 19 Apr. 2017.

Treatment	Lower canopy (mol·m ⁻² ·d ⁻¹)	Middle canopy (mol·m ⁻² ·d ⁻¹)	Upper canopy (mol·m ⁻² ·d ⁻¹)	Above canopy (mol·m ⁻² ·d ⁻¹)
29% haze compartment	10.58 ± 0.25	24.02 ± 0.29	30.19 ± 0.34	34.55 ± 0.32
20% haze compartment	8.47 ± 0.18	18.8 ± 0.20	29.91 ± 0.35	36.02 ± 0.50
Significance	*	*	NS	*

*Significant difference at $P = 0.05$. NS indicates the difference is not significant.

haze compartment were 0.7 to 1.6%, 5.7% to 23.6%, 4.5% to 16.9% greater than those in the greenhouse with 20% haze, respectively (data not shown). The DLI values at 2 m aboveground (above the canopy) in the 29% haze compartment were significantly lower than those in the 20% haze compartment.

The PPFD experienced three severe fluctuations in the horizontal canopy in the 20% haze greenhouse compartment between 900 and 1200 HR on 20 Mar. 2017 (Fig. 4). The maximum fluctuations were 512.3 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ at the south, 197.0 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ at the central, and 120.7 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ at the north areas of the greenhouse (Fig. 4B). However, the fluctuation frequency of the horizontal canopy in the 29% haze compartment was lower, and the fluctua-

tion value was lower than that of a different horizontal canopy (103.9 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) (Fig. 4A). In the 29% haze compartment, PPFD in the north canopy was maintained above 400 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ for 3.3 h (Fig. 4A), which was 2.3 h longer than that of the 20% haze compartment. PPFD in the central canopy was maintained above 600 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ for 4.0 h (Fig. 4A), which was 1.7 h longer than that of the 20% haze compartment. PPFD in the south canopy was maintained above 800 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ for 2.7 h (Fig. 4A), but only 1.1 h was recorded for the 20% haze compartment (Fig. 4B). The DLI of the central and north areas of the 29% haze compartment significantly increased ($P < 0.05$) by 29.3% and 40.6%, respectively,

compared with those in the 20% haze compartment (Table 2).

Temperature distribution during the summer period within the tomato canopy. From 15 to 17 June 2017, the temperature in both compartments increased rapidly in the morning and reached the highest value at approximately 1000 HR; then, the skylight was opened for ventilation and air temperature was kept relatively stable afterward. Except on June 18, no ventilation was performed in both compartments (Fig. 5).

In the upper canopy, under ventilation conditions (from 15 June to 17 June), the maximum temperatures in the 29% haze compartment were 3.1, 3.1, and 3.3 °C lower than those in the 20% haze compartment, and

Fig. 4. Diurnal variations of photosynthetic photon flux density (PPFD) in the horizontal canopy of the two greenhouses canopies. (A) The 29% haze compartment. (B) The 20% haze compartment. Data from 0700 to 1900 HR on 28 Mar. 2017 were selected to analyze the light distribution on clear days.

Table 2. Light distribution within the horizontal canopy of the two greenhouse compartments.²

Treatment	Area	DLI (mol·m ⁻² ·d ⁻¹)	Avg PPFD (μmol·m ⁻² ·s ⁻¹)
29% haze compartment	South	26.91 ± 6.13 a	400.23 ± 65.28 a
	Central	18.55 ± 5.09 a	310.85 ± 30.70 a
	North	16.02 ± 3.31 a	247.17 ± 21.21 a
20% haze compartment	South	27.15 ± 6.31 a	411.40 ± 69.93 a
	Central	14.78 ± 5.62 b	183.64 ± 35.55 b
	North	9.76 ± 4.01 b	126.43 ± 26.92 b

²The same lowercase letter indicates that the difference is not significant ($P = 0.05$). Data from 2 Mar. 2017 to 27 Apr. 2017 were selected to analyze the light distribution.

PPFD = photosynthetic photon flux density.

the upper canopy temperature in the 29% haze compartment stayed below 40 °C; however, it was higher than 40 °C in the 20% haze compartment at the same time (Fig. 5A). In addition to the similar temperatures during the ventilation period at 1200 HR, the 29% haze compartment temperatures were 1.9, 3.0, and 1.0 °C lower than those in the 20% haze compartment before ventilation. However, the 29% haze compartment temperatures were 1.2, 0.8, and 0.5 °C lower than those in the 20% haze compartment after ventilation, respectively. Under unventilated conditions (18 June), the air temperature of the two compartments increased to 36.7 °C at approximately 1300 HR, which was 5.9 °C lower than that of the 20% haze compartment (42.6 °C). The duration of temperatures above 40 °C in the 20% haze compartment was ≈4.3 h. During the period of normal ventilation from 1100 to 1800 HR, the average air temperature of the 29% haze compartment was 32.7 °C, which was 3.1 °C lower than that of the 20% haze compartment.

The maximum daily air temperature in the upper canopy of the 29% haze compartment was significantly lower than that in the 20% haze compartment. The air temperatures in the middle and lower canopies of the 29% haze compartment were slightly higher than those in the 20% haze compartment (Fig. 5B and C). Mean differences in the highest air temperature in the middle and lower canopies of the two compartments were 1.3 and 0.6 °C, respectively, and the differences were not significant ($P > 0.05$).

Under ventilation conditions, the leaf temperature in the upper canopy of the 20%

haze compartment was higher than that with higher haze film (Fig. 6). From 1000 to 1500 HR, the average leaf temperature in the upper canopy in the 29% haze compartment was 35.1 °C, which was 4.9 °C lower than that in the 20% haze compartment (40.0 °C). Leaf temperature reached the highest value at 1400 HR; in the 29% haze compartment it was 37.3 °C and in the 20% haze compartment it was 42.6 °C. Leaf temperature above 40 °C in the 20% haze compartment lasted for 4.6 h. After 1200 HR, except for a slight increase in leaf temperature in the upper canopy, the leaf temperatures in the middle and lower canopies were stable.

From 1000 to 1500 HR, the average leaf temperature in the middle canopy in the 29% haze compartment was 37.9 °C, which was 2.3 °C lower than that in the lower haze compartment (40.2 °C). At approximately 1400 HR, the leaf temperature in the middle canopy reached the highest value; in the 29% haze compartment it was 40.2 °C and in the 20% haze compartment it was 43.1 °C. There was no significant difference in leaf temperature in the lower canopy in the two compartments. From 1000 to 1500 HR, the average leaf temperatures in the lower canopy in the two compartments were both 35.8 °C. The maximum temperatures in the lower canopy were 38.7 °C in the 29% haze compartment and 38.8 °C in the 20% haze compartment.

During the experimental stage (35 d), the daily maximum leaf temperature in the upper canopy in the 29% haze compartment was significantly lower than that in the compartment with lower haze. The leaf temperature

in the middle canopy in the 29% haze compartment was, on average, 0.4 °C lower than that in the 20% haze compartment for 23 d. The leaf temperature in the lower canopy in the 29% haze compartment was lower than that in the 20% haze compartment for 3 d, and the two compartments had the same maximum value for 11 d.

There were fewer differences between leaf temperature and air temperature in the upper canopy in the 29% haze compartment than in 20% haze compartment (Fig. 7). In the 20% haze compartment, the maximum difference was 2.3 °C and the average difference was 0.6 °C, and the leaf temperature was lower than the air temperature at 76.9% of the measurement points (Fig. 7). The maximum temperature difference between the leaf and air in the 20% haze compartment was 5.2 °C, the average temperature difference was 1.2 °C, and the leaf temperature was higher than the air temperature at 98.3% of the measurement points.

R_t and leaf photosynthesis. From Jan. to June 2017, the R_t values in the middle and lower canopies of the 29% haze compartment were significantly greater than those in the 20% haze compartment (Table 3), except for the lower canopy in January, when there was no significant differences between the two greenhouse compartments.

The P_n rates of the lower and middle canopies of the 29% haze compartment were significantly greater than those of the 20% haze compartment, but there was no statistical difference recorded for the upper canopy (Table 4). R_t and P_n rates decreased with the

Fig. 5. Air temperature in the vertical canopy of the two greenhouse compartments. (A) Upper canopy. (B) Middle canopy. (C) Lower canopy. The data from 15 June 2017 to 18 June 2017 were selected to analyze the air temperature distribution.

decrease in canopy height in the two compartments (Fig. 8). The slope of P_n from the upper canopy to the middle canopy in the 29% haze compartment was significantly lower than that in 20% haze compartment. From the middle canopy to the lower canopy, the decline rate of P_n in the 29% haze compartment was higher than that in the 20%

haze compartment, but the P_n and R_t of the lower canopy in the 29% haze compartment were higher than those in the 20% haze compartment.

Yield of tomato. Fruit production is an important indicator of crop growth status. The final yields of high and low stem density in greenhouses compartments with 29% haze

were 4.1 and 4.4 kg·m⁻², respectively, and those of greenhouse compartments with 20% haze were 3.6 and 4.2 kg·m⁻² (Fig. 9). The yields of the 29% haze treatment-cultivated tomatoes with high and low stem density were 5.5% and 12.9% higher than those of the lower haze treatment-cultivated tomatoes, respectively.

Fig. 6. Diurnal changes in the leaf temperature of the vertical canopy in the two greenhouse compartments from 0600 to 1800 HR on 18 June 2017. (A) Upper canopy. (B) Middle canopy. (C) Lower canopy.

Fig. 7. Diurnal changes in the differences between leaf and air temperatures of the upper canopy in the two greenhouse compartments on 18 June 2017.

Discussion

In this study, the canopy light distribution, air temperature, leaf temperature, and net photosynthetic rate of tomato leaves in the

CSG with different haze plastic film covers were determined. We focused on the environmental parameters related to crop growth and evaluated the influence of the environment on plant photosynthesis and yield. The

results show that plastic film with higher haze (29%) increased the uniformity of light spatial and temporal distributions and cooled the air temperature and leaf temperature during the summer period in the top canopy compared with the lower haze film (20%), thus resulting in increased leaf photosynthesis and, eventually, increased plant yield, which is consistent with the results of previous reports (Hemming et al., 2008a; Li et al., 2016). Therefore, increasing the diffuse light fraction by applying diffuse plastic film is a potential solution that can optimize CSG production.

The *PPFD* reflects the effective light energy attributed to tomato photosynthesis. Tomato plants grew under 29% haze film experienced less *PPFD* fluctuation than those under 20% haze film (Fig. 3), indicating that increased diffuse light fractions provided a more homogeneous temporal light environment for greenhouse crops. Compared with the lower haze group, *PPFD* distribution was more uniform with the 29% haze treatment in both the vertical canopy and horizontal canopy (Fig. 3). Li et al. (2014a) analyzed the *PPFD* spatial distribution in greenhouses with glass covering and found that 71% haze covering provided more uniform horizontal and vertical *PPFD* distributions within the crop canopy and resulted in increased crop photosynthesis by 7.2%. The improvement effects of higher haze film on the light distribution within the canopy was greater in the middle canopy compared with the lower canopy in the vertical direction, but it was also greater in the north canopy compared with the central canopy in the horizontal direction. *DLI* is an important parameter that reflects the total photosynthetically active radiation (*PAR*) for plant growth (Li et al., 2016). Properly increasing the haze factor of the greenhouse covering film could potentially improve the light environment of the entire vertical canopy, thereby increasing the *PAR* intercepted at each depth of the canopy (Table 1). Above the canopy level, the *DLI* value of the 29% haze compartment was 4.1% lower than that of the 20% haze compartment (Table 1). This could have been caused by the higher degree of light diffusion in this greenhouse that increased the light attribution to each canopy level, which would be helpful for avoiding photoinhibition of the top canopy leaves from excessive direct light. Our results are consistent with those of a previous study (Li et al., 2014b). Higher diffuse light not only slows the attenuation trend of horizontal *DLI* in the greenhouse from south to north but also increases the *DLI* in the central and north canopies (Table 2).

The improved light distribution also provides other environmental factors that are better for promoting leaf photosynthesis and crop growth, such as temperature. Diffuse glass has been suggested to be able to reduce direct light on the top crop canopy in the greenhouse during summer with fewer sunflecks and shades, thus avoiding photoinhibition (Li et al., 2014a; Long et al., 1994). One of the causes of photoinhibition and

Table 3. Mean solar radiation transmittance (R_t) of the canopy of each month from Jan. 2017 to June 2017.^z

Month	R_t of the middle canopy (%)		R_t of the lower canopy (%)	
	29% haze	20% haze	29% haze	20% haze
Jan.	59.80 ± 5.91 a	56.00 ± 5.87 b	8.42 ± 0.72 a	8.09 ± 0.76 a
Feb.	63.18 ± 4.11 a	56.51 ± 4.04 b	10.77 ± 1.44 a	10.01 ± 1.03 b
Mar.	68.25 ± 4.90 a	59.41 ± 4.48 b	11.37 ± 1.05 a	9.98 ± 0.80 b
Apr.	70.27 ± 6.75 a	58.82 ± 7.63 b	13.24 ± 1.56 a	11.38 ± 1.89 b
May	71.03 ± 8.97 a	59.14 ± 7.72 b	13.96 ± 1.83 a	11.79 ± 1.74 b
June	74.85 ± 10.21 a	60.17 ± 9.77 b	15.72 ± 1.67 a	13.27 ± 1.55 b

^zThe same lowercase letter indicates that the difference is not significant ($P = 0.05$).Table 4. Net photosynthetic rate (P_n) of the tomato leaves on sunny days during the experiment period.

	Lower canopy P_n (mmol·m ⁻² ·s ⁻¹)	Middle canopy P_n (mmol·m ⁻² ·s ⁻¹)	Upper canopy P_n (mmol·m ⁻² ·s ⁻¹)
29% haze compartment	8.07 ± 0.60	13.38 ± 0.92	15.02 ± 1.23
20% haze compartment	5.67 ± 0.54	9.04 ± 0.96	14.18 ± 1.17
Significance	*	*	NS

*Significant difference at $P < 0.05$. NS indicates that the difference is not significant. Fig. 8. Relationship between radiation transmittance (R_t) and net photosynthesis (P_n) at different canopy depths of the two greenhouse compartments. (A) The 29% haze compartment. (B) The 20% haze compartment. To further analyze the effect of light intensity on the P_n rate, correlation analyses of R_t and P_n at different canopy heights were performed using the data from April.

photodamage is the closure of stomatal pores due to unfavorable temperatures (Kirschbaum, 2004). The application of diffuse light in the greenhouses can decrease the leaf temperature with less *PPFD* of the top canopy leaves (Li et al., 2014a), which is in agreement with the results of our study of the plastic greenhouse. The air temperature at the upper canopy level in the higher haze greenhouse compartment was lower than that in the lower haze compartment. However, the air temperatures of the middle and lower canopies were in contrast to that of the upper canopy. This phenomenon might be induced by the application of higher haze film that delivers a certain fraction of light energy to the middle and lower canopies by scattering the incident direct light while the top natural ventilation has less influence on the middle and lower canopies, thus leading to the increased air temperatures at these canopy levels.

Based on the knowledge we gained, increased fractions of diffuse light in our ex-

periment decreased air and leaf temperatures of the top canopy thus providing more suitable temperatures for tomato growth during the summer season. Photosynthetic activity is sensitive to many environmental factors such as light intensity (Sarlikioti et al., 2011) and temperature (Lin et al., 2012). Light is the sole energy source for photosynthesis of higher plants. Due to the shading of upper leaves, the distribution of sunlight in the vertical direction within the crop canopy is not uniform. At the same time, the horizontal light distribution is not uniform due to the shading of greenhouse frameworks. The leaves under the light irradiation intercept more light, and the leaves under the shadow intercept less light, resulting in decreased leaf photosynthesis. In this study, diffuse light in the 29% haze compartment provided more uniform *PPFD* in the vertical and horizontal directions (Figs. 3 and 4). This indicates that the lower and north canopies could have

more *PPFD* and beneficial leaf photosynthesis. Temperature affects the growth and development of plants. The leaf stomata closes when the temperature is too high to prevent water loss by transpiration. In our study, the increased diffuse light fraction cooled the air temperature and leaf temperature during summer (Figs. 5 and 6), thereby providing a more suitable temperature environment, which resulted in increased leaf photosynthetic rates. The homogeneous *PPFD* and suitable temperature of the tomato canopy under higher haze treatment contribute to increased leaf photosynthetic rates. In our study, the net photosynthetic rate with higher haze was greater than that with the 20% haze treatment within the middle and lower canopies, consistent with the results of previous studies of tomato and cucumber (Li et al., 2016; Fan et al., 2016; Sun et al., 2016).

Diffuse light plastic film enhanced the uniformity of light distribution within the

Fig. 9. Tomato fruit yields of two greenhouse compartments with high and low stem density. Columns with different letters indicate significant difference at $P < 0.05$.

tomato canopy and increased the *PPFD* in the middle and lower canopies. Because of the increased light interception in the middle and lower canopies, the net photosynthetic rates of the middle and lower canopies also increased compared with the 20% haze compartment. The average air temperature under 29% haze film was lower than that under 20% haze film. The leaf temperatures in the upper and middle canopies decreased in more diffuse light environments. The changed temperature environment under the increased diffuse light film improved the net photosynthetic rate of tomato leaves. Therefore, more homogeneous *PPFD* and more appropriate temperature environments promote leaf photosynthesis and eventually increase the fruit yield.

Conclusion

In this study, the plastic film with higher haze (29%) homogenized the light variation in the vertical and horizontal directions of the canopy. The DLI in the greenhouse with 29% haze was higher than that with 20% haze in the upper, middle, and lower canopies. The DLI of the central and north canopies in the 29% haze compartment were higher than that in the lower haze compartment. Compared with the 20% haze compartment, the 29% haze compartment decreased the leaf temperature in summer by 29.7%, 32.4%, and 5.6% in the lower canopy, middle canopy, and upper canopy, respectively. An increased fraction of diffuse light improves the uniformity of the light environment in CSGs, thus benefitting the photosynthetic activity and eventually increasing the yield of

greenhouse-grown tomato. Based on these findings, introducing diffuse plastic film into CSGs can improve environmental factors that influence crop production. Further increases in the haze factor of plastic film need to be evaluated to determine the most suitable haze range for CSGs.

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