STUDY ON THE VARIATION OF THERMAL ENVIRONMENT AND PHOTOSYNTHESIS CHARACTERISTICS OF STRAWBERRY IN A SOLAR GREENHOUSE
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日光温室热环境变化规律及对植物光合特性的影响

Weiwei CHENG [1)], Yu WANG [2)], Changchao WANG [2)], Tao WANG [2)], Junlin HE [2)], Zhouhua LIU [*1)], Yue XU [1)]

[1)] Shanxi Agricultural University, College of Urban and Rural Construction, Taigu / China
[2)] Shanxi Agricultural University, College of Agricultural Engineering, Taigu / China
Tel: +86-0354-6287420; E-mail: lzh6175305@163.com
Corresponding author: Zhonghua LIU

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ABSTRACT
The sunken solar greenhouse is suitable for the development of vertical planting, which results in higher yield. In order to investigate the effect of temperature on photosynthesis of plants, an experimental study was conducted on the temperature and photosynthesis of strawberry plants at different heights in the sunken solar greenhouse. The study showed that when the indoor temperature was higher than 25.5ºC, the photosynthesis of plants was inhibited; the transpiration rate decreased by 3.89 μmol $m^{-2}s^{-1}$and photosynthesis rate decreased by 3.95 μmol $m^{-2}s^{-1}$ when the air temperature increased from 25.5 ºC to 33.3ºC and then decreased to 25.4ºC at a height of 1.8 m from the indoor floor; there were temperature differences in the vertical direction between the indoor temperatures of the sunken heliostat. The maximum temperatures at 0 m, 0.6 m, 1.0 m, 1.4 m, and 1.8 m height were 20.6°C, 24.1°C, 25.4°C, 25.4°C, 33, and 33.3°C, respectively, and different temperatures would have different photosynthetic characteristics of plants. This study can provide basic support for greenhouse regulation.

摘要
下沉式日光温室适宜于发展竖向种植，从而获得较高收益。温度对植物的光合作用有影响，为探究温度对植物光合作用的影响，对下沉式日光温室不同高度的温度和草莓植株的光合作用展开实验研究，研究显示：室内温度高于25.5℃时，会抑制植物的光合作用；与室内地面高度为1.8m处的空气温度由25.5℃升高到33.3℃，然后降低到25.4℃时，此时间段内蒸腾速率下降了3.89μmol $m^{-2}s^{-1}$光合速率下降了3.95μmol $m^{-2}s^{-1}$；下沉式日光温室室内温度在竖直方向存在温度差异，室内地面高度为0m、0.6m、1.0m、1.4m、1.8m位置处的最高温度分别为20.6℃、24.1℃、25.4℃、25.4℃、33、3℃，不同温度会对植物的光合特性产生差异。该研究可为温室调控提供基础支撑。

INTRODUCTION
The solar greenhouse is an important agricultural facility in China, supplying more than 30% of the total supply of fruits and vegetables of all facilities in winter, mainly due to the availability of a suitable microclimate in winter (*Chao et al., 2018*). Among the suitable microclimates, the thermal environment is the main reason why year-round cultivation can be achieved. Among the many thermal environment factors, plant body temperature is the most sensitive factor to the healthy growth status of plants, and air temperature is the most synergistic with plant body temperature, both of which have the same change pattern (*Yu, Ming-Han et al., 2015*), thus the temperature in the solar greenhouse can directly respond to the health status of plants. In greenhouse stereo culture, strawberry plants are more sensitive to environmental changes, especially temperature changes have a greater impact on strawberries (*Xu Chuan et al., 2015*).

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[1] *Weiwei Cheng, As Lec.Ph.D. Eng.; Yu Wang, M.S. Agr; Changchao Wang, M.S. Agr; Tao Wang, M.S. Eng.; Junlin He, Prof.Ph.D.Eng.; Zhonghua Liu, Aoc.Prof.Ph.D. Eng.*

Plant photosynthesis is also more sensitive to temperature changes, and temperature affects the photosynthetic rate of plants by changing the activity of enzymes (*Lv Huanhuan et al., 2021*), which is also an important factor affecting plant growth and secondary metabolite synthesis (*Zheng Youfeng et al., 2022*).

The penetration of solar light through the plastic trellis film caused an increase in the indoor temperature *(Ahemd et al., 2016*), which can still exceed 30°C for a period of time during midday in winter. Excessive temperatures are a problem in solar greenhouse (*Phunchok Angmo.et al., 2021*). While high temperature was one of the important limiting factors affecting plant physiological processes (*Raja, V. et al., 2020*), high temperature stress disrupted many physiological and biochemical processes, leading to inhibition of photosynthesis (*Mittler et al, 2022*).

The appropriate temperature for many greenhouse plants was 17-27°C (*Shamshiri et al, 2018*), and when the indoor temperature was higher than the maximum value of the appropriate temperature, plants showed to improve the efficiency of photosynthesis in greenhouse plants, the thermal environment of indoor crops should be prevented from being too high. The rate of change of indoor air temperature was in the descending order of: rate of horizontal change > rate of horizontal change > rate of longitudinal change (*Weiwei Cheng et al., 2022*), so the monitoring of vertical temperature is a priority. The greenhouse was a semi-enclosed facility system where the crop interacted with the environment through its own transpiration, respiration and photosynthesis (*Zheng, Rorin et al., 2023*).

The use of ventilation was an important tool for thermal environment regulation in the solar greenhouse (*Xie Di et al., 2010*), and therefore the management system for the regulation of the air outlet should be based on the indoor temperature values (*Ge Jiankun et al., 2021*). In order to investigate the pattern of changes in the thermal environment of the solar greenhouse and to define the effect of different temperatures on photosynthesis of plants, so as to achieve the goal of regulation according to the canopy temperature, the temperature at different heights of the sunken solar greenhouse and the factors related to photosynthesis of strawberries at different temperatures were measured.

MATERIALS AND METHODS

Indoor Environment

Outdoor weather conditions (wind level, temperature, light, carbon dioxide concentration, etc.) were measured using the outdoor weather meter of Shanxi Juxinweiye, and indoor light and temperature were measured using the Shanxi Juxinweiye indoor louvered box agricultural Internet system, with the collector located in the middle of the greenhouse at a height of 4 m from the indoor ground, and indoor and outdoor data stored in the cloud platform. The vertical heights of the upper surface of each layer of substrate and the indoor ground were 1.8 m, 1.4 m, 1 m and 0.6 m, as in Figure 1. Temperature and humidity sensors were arranged at the upper surface of each layer of substrate in the A-frame to record the temperature and humidity values at the corresponding heights.

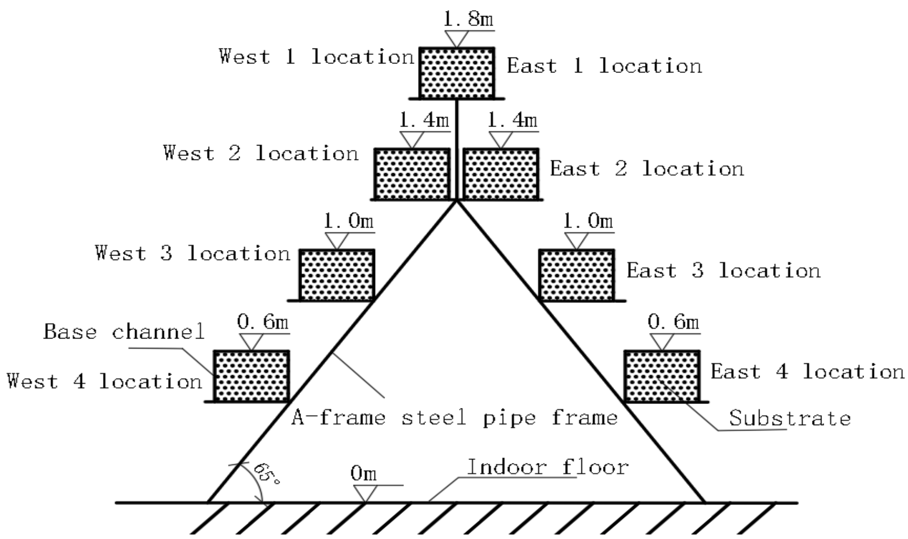

Fig. 1 - Substrates of different heights on A-frame

Experimental materials and methods

To determine the photosynthetic characteristics of strawberry leaves at different heights of strawberries and on the east and west sides of the A-frame, so as to establish the relationship between transpiration rate, photosynthetic rate and temperature at the corresponding heights inside the heliostat. The transpiration rate, photosynthetic rate and stomatal conductance of strawberry leaves in the sunken solar greenhouse were measured during 8:00-17:50 on December 29, 2019, using a portable photosynthesizer Li-6800.

Fig. 2 - Li-6800 photosynthesizer measured in a sunken solar greenhouse

Since a quilt was spread in the middle of the greenhouse film, it was necessary to avoid its influence on indoor light and temperature. The strawberry A-frame in the middle of the greenhouse was selected at 5 m west of the cross-sectional position, and the transpiration rate, photosynthetic rate and stomatal conductance of strawberry leaves were measured in a fixed order: West 1 - West 2 - West 3 - West 4 - East 1 - East 2 - East 3 - East 4, with the strawberry plants at the upper east position and the upper west position were placed in the same basal tank with the distance between plants equal to 15 cm.

Outdoor weather condition

December 29, 2019, all day, sunny, maximum temperature 8°C, minimum temperature -9°C, wind northwest 1 to 2, relative humidity 29%, and the time of sunrise was 7:43 and sunset was 17:20. 8:13 opened the shed, the quilt rose to the full pressure upwind, 11:04 opened the upwind, 14:23 closed the upwind; 15:36 opened the upwind again, 16:00 to close the upwind opening, 17:20 to put down the quilt. Due to the low temperature in winter, the downwind vent was always closed.

RESULTS

Indoor light change and change in indoor carbon dioxide concentration

As can be seen from Figure 3, the indoor light intensity was less than 5000 lx during the time period from closing the shed and putting down the quilts to opening the shed and putting up the quilts the next day; the light intensity gradually increased during the time period from opening the shed to 13:00, and the highest value occurred at 13:00, which was 44440.4lx; the light intensity gradually decreased during 13:00-14:30, increased during 14:30-15:00, and increased after 15:00. After 15:00, the light intensity gradually decreased.

According to Figure 3, the CO_2 concentration of indoor environment decreased from 636 μmol $m^{-2}s^{-1}$ to 296 μmol $m^{-2}s^{-1}$ during 8:30-12:30, which was due to the photosynthesis of plants and CO_2 as the main material of photosynthesis, and the photosynthesis rate was greater than the respiration rate, and the indoor temperature did not inhibit the photosynthesis rate of plants during this period. It meant that the photosynthetic rate of plants decreased, which was due to the increase of indoor temperature between 12:00-13:00, and the increase of temperature to a certain value led to the decrease of enzyme activity in plants and the phenomenon of "lunch break" of the plants, and the highest temperature of 32.9^{o}C at 1.8 m height from the indoor ground in this time period occurred between 13:00-13:20.

The maximum value of CO_2 concentration was 369 during 12:00-15:00, and the temperature was 24.4^{o}C, which was 7^{o}C lower than the maximum temperature of the same measurement point in a day. The minimum value of CO_2 concentration was 340 μmol $m^{-2}s^{-1}$ during this time, and the temperature was 25.4^{o}C, the light intensity was higher during this time, but the CO_2 concentration increased, which indicated that the temperature had a greater influence on the enzyme activity, and Indoor temperatures between 24 and 25°C have a greater effect on the photosynthetic rate of plant. Therefore, the study of temperature stratification phenomenon in indoor stereoculture was conducted to avoid "lunch break" of strawberry leaves and to increase the yield of strawberry by taking appropriate measures.

The gradual increase of CO_2 concentration between 15:00 and 17:00 was due to the gradual decrease of light intensity, the decrease of photosynthesis, and the decrease of CO_2 consumption by photosynthesis, so that the indoor CO_2 concentration increased.

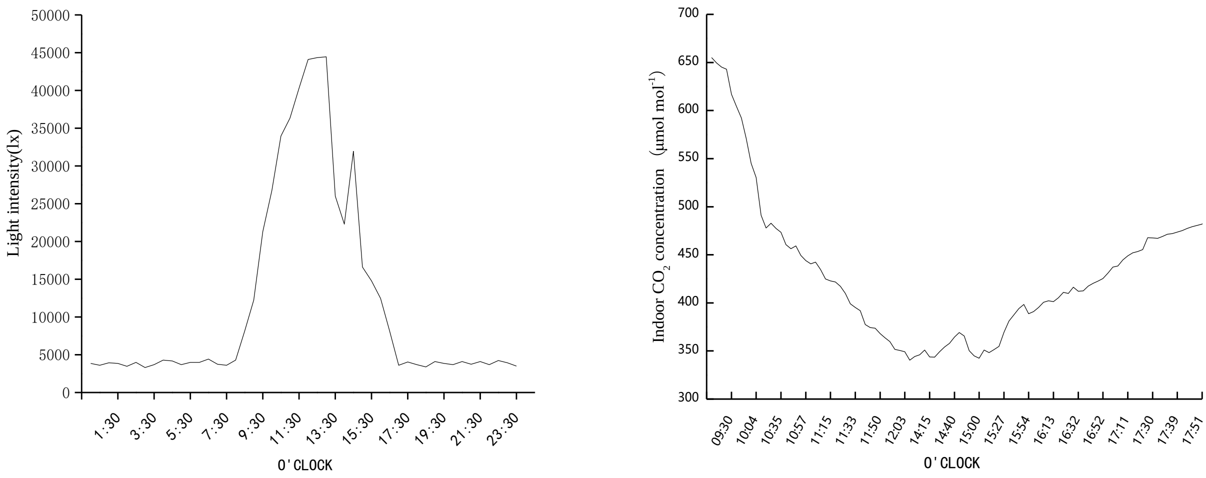

Fig. 3 - Indoor light and CO_2 content curves with time

Variation pattern of temperature with time at different heights

The photosynthetic rate, transpiration rate and stomatal conductance of strawberry leaves at different heights in the central section of the sunken solar greenhouse were measured from 8:54 to 16:54, and the relationship between the temperature values at different heights in this time period was $t_{1.8}>t_{1.4}\geqq t_1>t_{0.6}>t_0$ (t_0 represented the temperature value at the height of 0 m from the indoor floor, i.e., the temperature value at the upper surface of the indoor, the same below); the highest temperature at the height of 0 m, 0.6 m, 1.0 m, 1.4 m and 1.8 m from the indoor floor were 20.6ºC, 24.1ºC, 25.4ºC, 25.4ºC, 33.3ºC, the highest temperature value at each height did not appear at the same time, the time difference between the highest temperature value at each measurement point was less than 12 min; Within the measurement time period, the maximum temperature difference between t1.8 and t0 at the same time was 13.6ºC, the maximum temperature difference between t1.4 and t1 at the same time was 0.5ºC, the maximum temperature difference between t1.4 and t0.6 at the same time was 1.6ºC, and the maximum temperature difference between t0.6 and t0 at the same time was 3.8ºC. It could be seen that the air temperature distribution below 1.8 m from the indoor ground height is not uniform, and there is a large temperature gradient at the same moment. This was mainly due to the uneven solar radiation, which led to large temperature differences in the indoor air layer, i.e., the unevenness of indoor temperature distribution along the vertical space was larger.

During 17:00-18:00, the temperature difference between adjacent measurement points decreased, and the maximum temperature difference between adjacent measurement points was 0.4ºC. Due to the weakening of the sunlight intensity, the indoor air absorbed less heat, and the indoor and outdoor air conducted heat conduction due to the temperature difference, resulting in a larger amount of indoor heat loss, so the indoor air temperature value gradually decreased. This was due to the fact that the greenhouse gradually entered the exothermic state and the indoor ground soil, the substrate in the base tank and the indoor walls were gradually in the exothermic state, and the rate of heat gain was faster at the measurement points closer to the ground. Therefore, the study of the vertical distribution of indoor temperature and the maximum value of temperature in the greenhouse during winter could provide the accurate time period of ventilation and heat exchange for stereoculture and the temperature difference data for stereoculture in the vertical height.

Relationship between light intensity and indoor temperature at the same height during the time period of 10:00-14:00

During the period of strong daylight, the indoor ground and the north wall were in the state of heat absorption, while the indoor temperature and the outdoor temperature were exchanging heat due to the temperature difference, but the temperature rising was mainly related to the light intensity, using the light intensity and indoor temperature values collected by the louvered box type data collector at 4 m height of the greenhouse to draw a scatter plot and add a trend line.

To establish the relationship between light intensity and temperature during the period of strong light to provide theoretical data on the corresponding light intensities for temperature calculations in stereoculture.

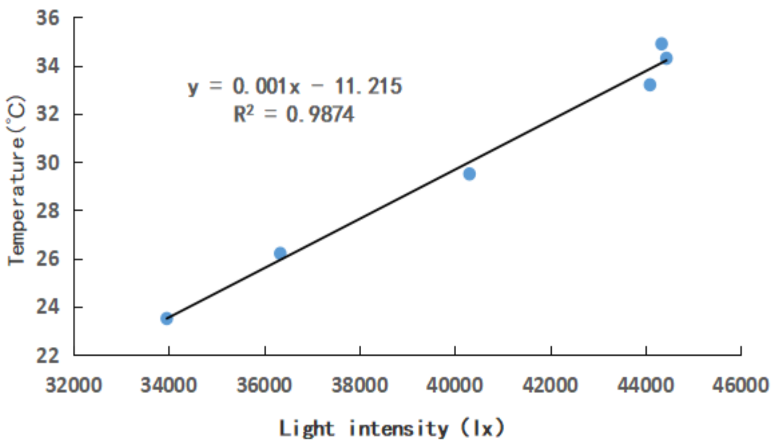

Fig. 4 - Relationship between temperature and light intensity above 30000 Lx

As shown in Figure 4, the temperature increased linearly with the increase of light intensity above 30,000 lx. Fitting with the light intensity and temperature values in the corresponding time period, R2 > 0.98, indicated that there was a significant linear relationship between the increase of indoor temperature and light in the sunken solar greenhouse. Temperature has a significant effect on plant photosynthetic enzyme activity, transpiration rate and stomatal conductance values. Establishing the relationship between indoor temperature and light intensity can reduce the effect of temperature on photosynthetic enzymes by setting automatic shading curtains at the highest part of the stereoculture planting in advance when the temperature was too high at noon and plant photosynthesis was reduced.

Variation of transpiration rate of plants with time

East 1 and West 1 positions refer to the height of 1.8 m from the indoor floor; East 2 and West 2, East 3 and West 3, East 4 and West 4 positions refer to the height of 1.4 m, 1.0 m and 0.6 m from the indoor floor. since the strawberries in East 1 and West 1 positions were located at the same A-frame height of 1.8 m, and the strawberry plants in East 1 and West 1 were spaced 15 cm apart. Therefore, the greenhouse temperature and light environment of strawberries in the east and west positions were the same.

From Figures 3 and 5, the transpiration rate and stomatal conductance of strawberry at 1.8 m height during 8:50-17:00 were as follows: from 8:30 to 12:00, the transpiration rate tended to increase, with the maximum transpiration rate of 0.0086 μmol $m^{-2}s^{-1}$, and the temperature of the corresponding measurement point in the greenhouse increased gradually with time in the form of a curve, with the maximum value of 27.6°C and the minimum value of 10.2°C.

The overall trend of transpiration rate in the time period of 12:00-14:00 was decreasing, and the maximum value of temperature at 1.8 m height in the greenhouse was 33°C and the minimum value was 25°C, and the value of stomatal conductance in this time period was also gradually decreasing, and the strawberry leaves appeared "lunch break" due to the high temperature.

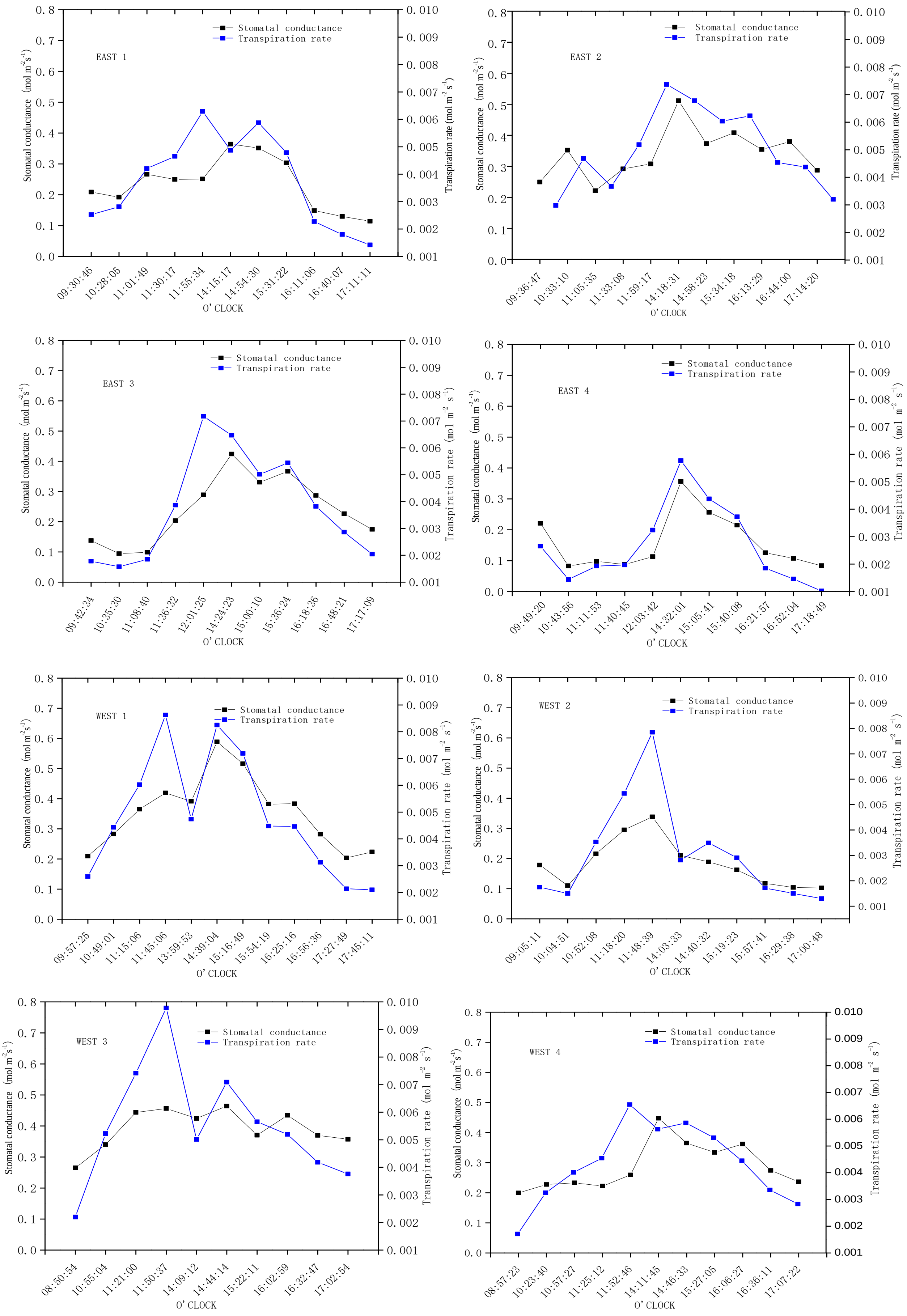

Fig. 5 - Variation curves of transpiration rate and stomatal conductance of strawberry leaves at different heights with time

As it can be seen, the period from 14:00 to 17:09 marked the decrease of the temperature curve in the greenhouse room, and this is caused by the gradual weakening of solar radiation, the heat exchanged between indoor air and outdoor was greater than the heat absorbed by solar radiation, and the transpiration rate and stomatal conductance values of plants gradually decreased during this period; after 17:30, the transpiration rate was maintained at about 0.002 μmol $m^{-2}s^{-1}$, which was more than 40 times different from the maximum transpiration rate, and the difference between the temperature value at this time and the highest temperature value of the same measurement point in a day was 14.3 times. The difference between the temperature value and the highest temperature value of the day at the same measurement point was 14.3ºC.

The transpiration rates of strawberry leaves at 0.6 m (West 4), 1.0 m and 1.4 m heights from the indoor floor were the same as those at 1.8 m, but the transpiration rate of strawberry leaves at 0.6 m (West 4) decreased less during the 12:00-14:30 time period, with a maximum of 0.006 μmol $m^{-2}s^{-1}$ and a minimum of 0.003 μmol $m^{-2}s^{-1}$, while the transpiration rate of strawberry leaves at 1.8 m was 0.009 μmol $m^{-2}s^{-1}$ and 0.004 μmol $m^{-2}s^{-1}$. This was due to the fact that the maximum temperature at 0.6 m (West 4) was 24°C and the stomatal conductance did not decrease, so the indoor temperature at this height did not exceed the suitable temperature for photosynthesis of strawberry and the plant did not take a "lunch break", so the transpiration rate at 0.6 m (West 4) was less variable.

The values of transpiration rate and stomatal conductance of strawberry measured at 0.6 m (East 4) did not decrease in the time period of 12:00-13:30, which was due to the change of solar azimuth in this time period, while the strawberry leaves at the lower east position of 0.6 m were in the shade position due to the shading of the adjacent A-frame plants at this time, and the actual temperature was lower, and the temperature values did not make the stomatal conductance decrease, and the strawberry leaves did not show the phenomenon of "lunch break".

It could be seen that: the transpiration rate of strawberry leaves in stereo planting had a greater relationship with the temperature at the corresponding height in the same time period, while the vertical temperature gradient difference in the greenhouse was larger, which had a greater effect on the transpiration of plants.

Variation of stomatal conductance and photosynthetic rate of plants with time

In Figs. 3 and 6, it is showed that the air temperature at different heights increased curvilinearly with time from 8:00 to 12:00, and the photosynthetic rate of strawberry leaves at different heights increased with stomatal conductance from 8:30 to 11:30, which was due to the increase of stomatal conductance, which increased the transport of CO_2, the raw material of photosynthesis, and the photosynthetic rate of each measurement point gradually increased as the light intensity gradually increased. However, between 11:30-12:00, the photosynthetic rate of strawberry leaves at both the East 1 and West 1 positions were 1.8 m from the indoor ground height, and the photosynthetic rate of strawberry leaves at both the upper east and west positions showed a decreasing trend, and the lowest value of air temperature at the indoor stereoscopic planting height of 1.8 m during this time was 27ºC, and the high temperature would inhibit the activity of plant photosynthetic enzymes, so the photosynthetic rate decreased. During 12:00-15:00, the photosynthetic rate of strawberry leaves at different heights decreased during some time, and the outdoor light intensity gradually increased and the stomatal conductance increased, but the photosynthetic rate decreased, because the photosynthetic enzyme activity was affected by the high temperature and the photosynthetic rate decreased.

At 11:45, the air temperature at 1.8 m from the indoor floor height was 25.5ºC, at 11:55, the air temperature at 1.8 m from the indoor floor height was 26.5ºC, at this time the temperature increased by 1ºC, while the transpiration rate decreased by 2.33 μmol $m^{-2}s^{-1}$ and photosynthesis decreased by 1.41 μmol $m^{-2}s^{-1}$; when the indoor temperature was higher than 25.5°C, it would inhibit the photosynthesis of the plant. From 11:45 to 14:00, the air temperature at a height of 1.8 m from the indoor floor increased from 25.5°C to 33.3°C and then decreased to 25.4°C, but the transpiration rate and photosynthesis rate of strawberry leaves at the same height during this time period showed a decreasing trend, with transpiration rate decreasing by 3.89 μmol $m^{-2}s^{-1}$ and photosynthesis rate decreasing by 3.95 μmol $m^{-2}s^{-1}$. Different temperatures affected the quality of strawberry plants, and the photosynthetic and transpiration rates of the plants were inhibited at temperatures above 25.5ºC.

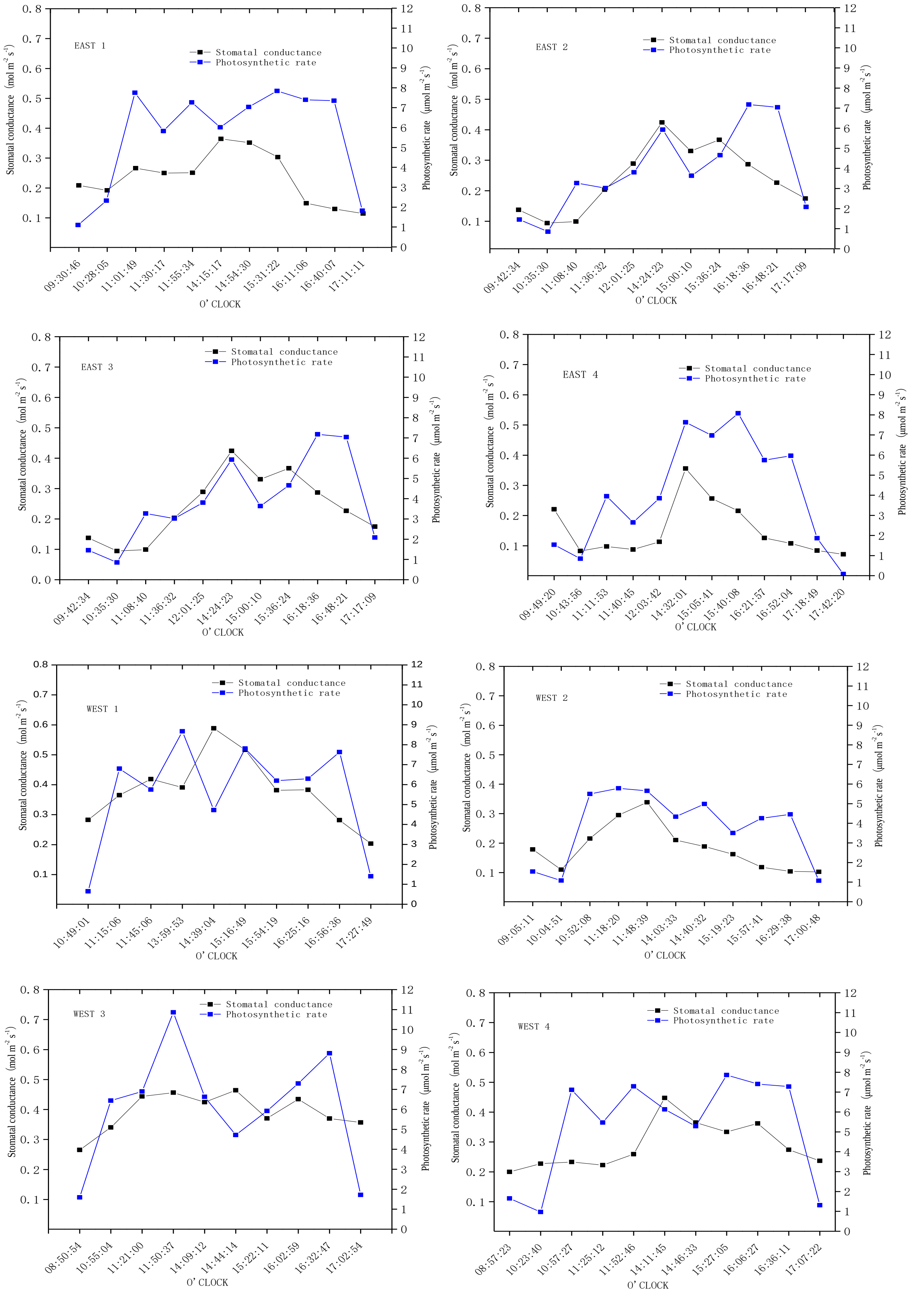

Fig. 6 - Variation curves of photosynthetic rate and stomatal conductance of strawberry leaves at different heights with time

Between 15:00 and 16:00, the photosynthetic rate increased briefly because the enzyme activity was not affected by the high temperature when the indoor temperature was below 25°C and the enzyme activity was not affected by the high CO_2 concentration outside, which led to an increase in photosynthetic material. The photosynthetic rate decreased between 16:00 and 17:30 because the intensity of outdoor light decreased, resulting in lower photosynthetic rate. Strawberry plants at East 1 and West 1 locations were at the same height with a horizontal plant spacing of 15 cm, approximating the same light conditions and the same temperature conditions.

When the outdoor weather was sunny in winter, the indoor air temperature values at different heights showed a trend of rising and then falling with time, and the temperature change was related to the light intensity, while the photosynthetic rate, transpiration rate and stomatal conductance values of strawberry leaves at different heights in the same time period were related to the temperature, and when the temperature was higher than 25.5ºC, it would reduce the transpiration rate and photosynthetic rate of strawberry leaves. Therefore, the study of indoor temperature can provide timely information about the photosynthetic properties of plants.

CONCLUSIONS

The transpiration rate and photosynthesis rate of strawberry leaves were different in different time periods, and were related to the indoor light and temperature. The following conclusions were drawn:

1) When the temperature value at a certain height in the room was above 25.5°C for a certain period of time, the photosynthetic characteristics of the plant were suppressed regardless of the change in the temperature value during this time period.

2) There was variability in temperature at different heights, and when indoor light reached a certain value, there was a linear relationship between indoor light and temperature at different heights.

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