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Research article

Heat transfer processes in ’Shine Muscat’ grapevine leaves in solar greenhouses under different irrigation treatments

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ABSTRACT

The use of solar greenhouses in China is increasing because they permit environmental conditions to be controlled. Studies of the heat transfer processes in the leaves of plants cultivated within solar greenhouses are needed. Here, we studied heat transfer processes in 'Shine Muscat' grapevine leaves under moderate deficit irrigation (MDI), severe deficit irrigation (SDI), and full irrigation (FI) treatments under varying weather conditions. The stomatal conductance, leaf temperature, and transpiration rate of both shade and sun grapevine leaves were measured, and the effects of ambient temperature and relative humidity on these variables were determined. A thermal physics model of the leaves was established to explore the heat dissipation process. On sunny days, the transpiration heat transfer of sun leaves in the MDI, SDI, and FI treatments was 2.62 MJ $m^{-2}\cdot day^{-1}$, 2.44 MJ $m^{-2}\cdot day^{-1}$, and 3.86 MJ $m^{-2}\cdot day^{-1}$and 0.818 MJ $m^{-2}\cdot day^{-1}$, 0.782 MJ $m^{-2}\cdot day^{-1}$, and 1.185 MJ $m^{-2}\cdot day^{-1}$ on rainy days, respectively. There was a significant difference in transpiration heat transfer under fully irrigated and deficit irrigation conditions under different weather conditions. Furthermore, transpiration heat transfer accounted for 41.49 % and 25.03 % of the total heat transfer of sun leaves in the FI treatment and 33.94 % and 29.43 % of the total heat transfer of shade leaves on rainy days, respectively, indicating that relative humidity plays a key role in determining transpiration heat transfer and leaf temperature and that its effect was greater on sun leaves than on shade leaves.

1. Introduction

In China, the use of solar greenhouses is increasing because they permit environmental parameters to be artificially and conveniently regulated. In light of differences in the growth of plants under greenhouse and natural conditions, more studies are needed to clarify heat transfer processes in the leaves of plants cultivated in solar greenhouses.

Studies of heat and mass transfer processes in leaves can provide new insights into plant growth and development. The heat and mass transfer processes in leaves have received much research attention [1–3]. A robust understanding of the heat and mass transfer processes in plant leaves can aid simulations of plant canopy temperature. Solar radiation is the main factor affecting leaf temperature.

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However, differences in leaf surface structure, intracellular stacking, and the chlorophyll content [4] affect the utilization of light by leaves and thus leaf temperature. Clarifying variation in canopy temperature can provide insights that can aid the formulation of plant irrigation regimes [5]. Studies of heat and mass transfer processes and leaf temperature thus have major implications for optimizing plant irrigation regimes.

Canopy temperature began to receive research attention in the 1960s. Variation in canopy temperature is a product of energy flow processes [6]. Gates [7] further studied the theory of energy exchange between organisms and the environment and discussed the relationship between energy flow and canopy temperature. This study examined various aspects of energy exchange, including radiation, conduction, convection, evaporation, and transpiration. Zhu et al. [8] proposed that energy flow resistance is a fundamental sign of ecological imbalance. Since then, few researchers have studied the mechanism underlying plant canopy temperature variation.

Canopy temperature is determined by plant thermal characteristics and the physiological responses of plants to the environment, which involves two main energy transfer processes: (1) heat transfer between plants and the environment through conduction, radiation, and the latent heat of evaporation and (2) internal heat transfer within biological tissues. Studies of the mechanism underlying variation in canopy temperature have focused on exploring these two processes [9]. This paper elaborates on the constitutive mechanism underlying variation in canopy temperature using plant leaves as an example.

In the natural environment, the temperature of plant leaves is influenced by physiological and non-physiological heat and mass transfer processes. Non-physiological processes include radiative heat exchange and convective heat exchange between leaves and the environment. Physiological processes include the photosynthesis, respiration, and transpiration of leaves. Solar radiation is a major factor contributing to increases in leaf temperature during the day. Incident solar radiation is divided into photosynthetically active radiation and shortwave infrared radiation based on the wavelength range. Photosynthetically active radiation is the main driver of plant photosynthesis, and plants typically utilize only 1–2% of absorbed solar radiation for photosynthesis [10]. Therefore, photosynthesis can be effectively ignored when considering leaf heat and mass transfer processes. Additionally, the heat generated by respiration has a negligible impact on leaf temperature [11].

An essential component of plant heat exchange is convective heat transfer, which refers to the heat exchange between leaves and the surrounding atmosphere. Wolpert [1] found that convective heat exchange is the primary mechanism of leaf cooling through studies of leaf heat transfer. Transpiration heat exchange leads to a decrease in leaf temperature [12], which affects convective heat exchange. He et al. [13] found that the evaporation from roof greening decreases and convective heat exchange increases when the soil moisture content decreases.

Plants and the soil emit long-wave radiation, which is related to the object's temperature. The emissivity of plant leaves is not highly correlated with the leaf water content and ranges from 0.90 to 0.98 [14]. Eumorfopoulou and Aravantinos [15] studied the heat transfer process of planted roofs. They found that when the soil emissivity is 0.3, the net photosynthesis of plants can mediate the transfer of 60 % of the radiant energy of the roof, return 27 % of this energy to the environment, and mediate the flow of 13 % of the radiant energy into the soil; the ratio of the three is related to the species, coverage, and leaf thickness of the plant.

Xu et al. [16] studied camphor leaves in the summer in different regions and found that radiant heat transfer was the second largest heat dissipation method in the summer. However, as the relative humidity in the environment increases, the proportion of radiant heat dissipation also increases. In Wuxi, the proportion of daytime leaf radiant heat exchange was 26.04 %, and in Xishuangbanna, the proportion of daytime leaf radiant heat exchange was 45.6 %. And light intensity and air velocity can also affect the thermal exchange [17].

Transpiration is the process by which water is lost from the inside of plants to the surrounding atmosphere in the form of water vapor; it is one of the important physiological processes in plants [18]. Transpiration creates tension that allows water and mineral transport within plants, which provides essential nutrients for plant growth and development. Plants absorb over 90 % of the water that is lost as water vapor through stomata on the leaf surface into the surrounding air from the soil [19]. Stomata, which are important structures on the surface of plant leaves, facilitate the entry and exit of gases, such as water vapor and carbon dioxide, in plant leaves. Plants can regulate the transfer rate of water vapor and carbon dioxide by controlling the opening and closing of the stomata, which regulates physiological processes such as transpiration and photosynthesis [20–22].

Transpiration has a significant effect on the temperature of leaves [23] on sunny days, the evaporative cooling has a significantly weaker effect on the temperature of bur oak leaves than on hypothetical non-evaporated leaves (David, 1964). When the solar irradiation intensity is 1000 $w \cdot m^{-2}$, the transpiration of roses in greenhouses can still make the leaf and indoor air temperature lower than the external ambient temperature [24]. Increasing in PAR, ambient temperature and air velocity promotes transpiration, and increasing in relative humidity decreases the transpiration rate [17,25].

Stomata play key roles in the control of carbon and water exchange between the leaves and atmosphere, and plant growth and survival depend on the regulation of carbon acquisition and water loss by leaf stomata [26]. Therefore, the opening and closing of the stomata affect plant transpiration, and the light intensity has a major effect on the opening and closing of the stomata. Excessive solar radiation increases canopy temperature, which promotes transpiration and water loss and results in stomatal closure [27]. Guo et al. [28] detected a positive correlation between transpiration, stomatal conductance, and solar radiation in tea leaves. Shen et al. [29] studied stomatal conductance in sun and shade cotton leaves and found that the stomatal conductance was consistently lower for shade leaves than for sun leaves at the same height due to differences in light intensity. Variation in stomatal conductance is associated with variation in light intensity, as high light intensity leads to increases in the environmental temperature, which accelerates transpiration, increases water loss, and reduces stomatal conductance [27].

Differences in irrigation regimes also affect the stomata [30,31]. The stomatal conductance and transpiration rate of lucerne are positively related under full irrigation and mild stress conditions. Under moderate and severe stress conditions, stomatal conductance increases as the transpiration rate increases; however, stomatal conductance decreases with the transpiration rate beyond a certain threshold [32].

Due to the mutual shading between plant canopy leaves, the intensity and quality of solar radiation received by the leaves vary at different canopy heights. Shade leaves (typically inside or at the lower part of the canopy) experience prolonged low solar radiation intensity conditions and are characterized by a single layer of palisade tissue. Leaves that experience prolonged high solar radiation intensity conditions (sun leaves) are usually at the top of the canopy and possess two nearly complete layers of palisade tissue [33].

The area of sun leaves is low, which limits increases in leaf temperature and slows premature aging. In contrast, the area of shade leaves is large, which enhances the absorption and utilization of solar radiation energy [34]. Shade leaves are less affected by wind-induced energy loss within the plant's internal and lower parts; thus, wind has a weak effect on water loss from shade leaves. Stomata are small and dense on sun leaves but sparse and large on shade leaves [35]. Sun leaves receive more solar radiation for longer periods, which results in rapid increases in temperature and accelerated water consumption. Jones et al. [36] found that sun leaf canopies experience larger and more varied changes in temperature than shade leaf canopies, and stomatal conductance could be estimated more accurately for the former than the latter. Under adequate irrigation, the temperature difference between illuminated and shaded canopies decreases [16].

In this study, a general thermal model was established for both shade and sun leaves of 'Shine Muscat' grapevine. The objectives of this research were to (1) determine the stomatal resistance and temperature of both shade and sun leaves through field experiments, (2) validate the thermal model, and (3) simulate leaf temperature and heat exchange between leaves and the environment under different irrigation treatments during the summer using measurements of stomatal resistance and meteorological data from YangLing District, Shaanxi Province.

2. Materials and methods

2.1. Study site

The study site was located in YangLing District, Shaanxi Province (34° 14′ 59.6256″ N, 08° 1 ′44.1752″ E). This region experiences a temperate semi-arid and semi-humid continental monsoon climate. All experiments were conducted in a SR-2 solar greenhouse shown Fig. 1 (The length of the SR-2 solar greenhouse is 93m, the span is 10m, the internal height of the greenhouse is 4.8m, and the height of the rear wall is 2.8m. It can increase the temperature by 3–5 °C compared with the same type greenhouse.); the average field moisture capacity and wilting coefficient were 27.6 % and 8.6 %, respectively (both based on the mass water content); and the soil dry bulk weight was 1.41 g cm^{-3}. The groundwater is located deep in the soil, and its upward recharge is negligible.

2.2. Experimental design

Five-year-old vines of 'Shine Muscat' grape were planted in a greenhouse. The experiment included three treatments: irrigation limits set at 50 % of the field water-holding capacity (SDI), 75 % of the field water-holding capacity (MDI), and 100 % of the field water-holding capacity (FI). Three replications of each treatment were performed, and there were a total of nine plots. The phenology of 'Shine Muscat' grapevine during the year of the experiment was as follows: budbreak (April 3); blooming (May 16); young fruit stage (July 10); the second berry expansion period (July 26); and berry mature stage (September 2). The experiments were conducted during the young fruit stage period and the second berry expansion period from July 15 to August 15. Irrigation cycles and amounts are shown in Table 1.

2.3. Data collection and analysis

Two experiments were conducted to determine the spectral response characteristics and stomatal resistance of 'Shine Muscat' grapevine leaves. In the greenhouse, measurements of stomatal resistance and temperature were taken; in another experiment, the spectral reflectance and solar absorption of 'Shine Muscat' grapevine leaves were measured. To determine the solar absorptance (α) of plant leaves, the solar spectral reflectance and transmittance of plant leaves in the 280–2500 nm wavelength range were measured using a Lambda 1050 near-ultraviolet, visible, and near-infrared spectrophotometer produced by KONICA MINOLTA. During various growth stages of the 'Shine Muscat', leaves with similar growth under different irrigation treatments were selected, aiming to maintain

Fig. 1. The internal and external environment of the study site.

Table 1
Irrigation amount in the different treatments between 7/15 and 8/15.

Irrigation date	Treatment	Irrigation water amount ($m^3 \cdot ha^{-1}$)
	SDI	49
7/16	MDI	72
	FI	96
	SDI	49
7/23	MDI	72
	FI	96
	SDI	30
7/25	MDI	30
	FI	30
	SDI	49
8/1	MDI	72
	FI	96
	SDI	49
8/9	MDI	72
	FI	96
	SDI	39.2
8/13	MDI	57.6
	FI	76.8

consistent leaf size and morphology. The AP4 instrument was used to measure stomatal resistance, temperature, and light quantum flux for both shade and sun leaves of 'Shine Muscat' grapevine every 30 min. Environmental air temperature and relative humidity near the selected leaves were measured at hourly intervals. An Agilent 34970A data logger was used to monitor the temperature of leaves and indoor conditions. The sampling interval was set to 1 min, and T-type thermocouples with a temperature range of −200 to 350 °C and an error of ±0.5 °C were used. Thermocouple probes were placed on leaves in the different irrigation treatments to measure leaf temperature (The thermocouple probes were tightly fitted to the leaves with a tinfoil-wrapped clip, avoiding direct sunlight on thermocouple probes and minimizing errors). In this paper, the leaves growing in the upper part of the canopy that can be completely exposed to direct sunlight are defined as sun leaves, and the leaves growing in the lower part of the canopy that cannot be completely exposed to direct sunlight are defined as shade leaves. Meteorological data, including atmospheric temperature, humidity, and total solar radiation, were be measure at 2m above ground by a miniature weather station, and the weather station sampling interval was set to 10 min. We used the cutting ring to measure water-holding capacity in the field, and used Multi-Layer Soil Parameter Monitor (RS-*-N01-TR-5) to measure soil moisture content at 10-min intervals. Instruments used in the experiments are listed in Table 2. The changes of ambient temperature, relative humidity, and solar radiation intensity in the solar greenhouse are shown in Figs. 2 and 3 during the experimental period from July 27 to August 3. Data processing was conducted using MATLAB, Excel, and SPSS.

2.4. Thermophysical model

The leaf thermal model was proposed by Ye(2013). They chose the camphor as their investigation object. Due to differences in test plant species, leaf morphology, and physiological parameters, we modified certain formula parameters to achieve optimal results.

According to the surface analysis of the leaf, the heat and mass transfer processes between the leaf and the environment are shown in Fig. 4, where Q_{rad} and Q'_{rad} represent the radiative heat transfer between the environment and the upper and bottom surface of leaves, respectively; Q_{conv} and Q'_{conv} represent the convective heat transfer between the ambient air and the upper and bottom surface of leaves, respectively; G_{sol} represents the solar irradiance; and Q_{evap} represents the latent heat of transpiration. The transient heat transfer equation can be expressed as follows [37]:

$$\rho_{leaf} c_{leaf} \delta_{leaf} \frac{dT_{leaf}}{dt} = \alpha_s G_{sol} - Q_{rad} - Q'_{rad} - Q_{conv} - Q'_{conv} - Q_{evap} \tag{1}$$

where T represents the temperature in Kelvin (K). ρ_{leaf}, c_{leaf}, δ_{leaf}, and α_s represent the density, specific heat capacity, thickness, and absorptivity of the leaf, respectively. The boundary layer resistances are equal for the two sides of the leaf; thus, Eq. (1) can be rewritten as:

Table 2
Instruments used in the experiments.

Instrument	Manufacturer	Parameters measured
AP4 porometer	Delta-T-corportion	r_s,G_{sol}
Lambda 1050	KONICA MINOLTA	a_s
RS-*-N01-TR-5	Shandong Renke Control Technology Co., Ltd.	Soil Moisture Content
RS-GZCO2WS-*-2-*	Shandong Renke Control Technology Co., Ltd.	T_a,lux,RH
Agilent 34970A	Agilent	T_{leaf},T_a,T_{ground}

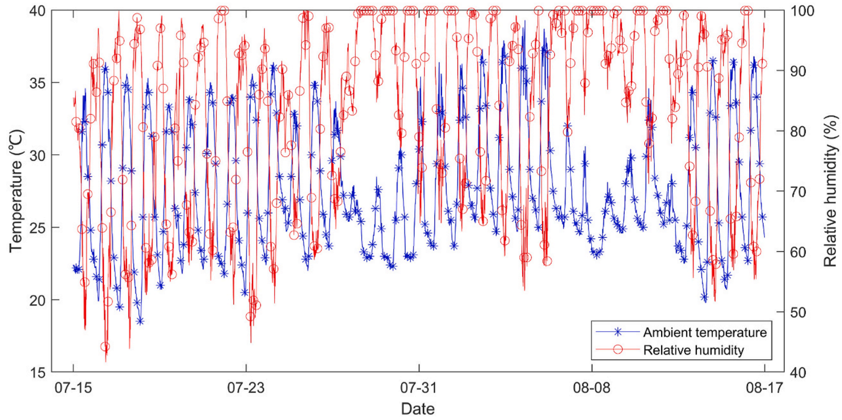

Fig. 2. Change in ambient temperature and relative humidity in the greenhouse from 7/15 to 8/15.

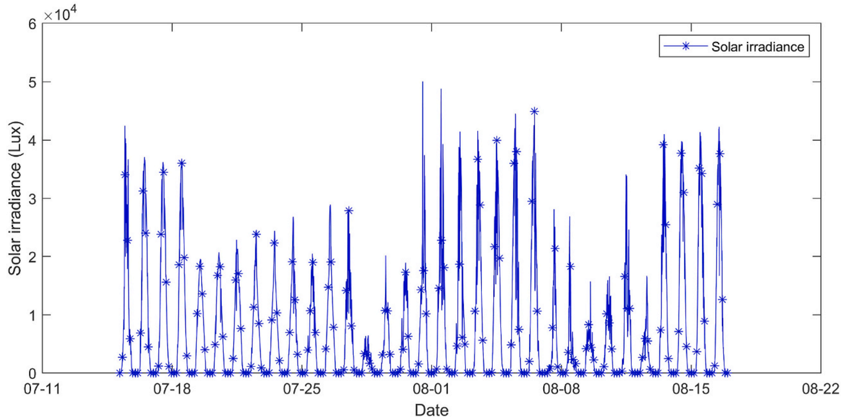

Fig. 3. Change in light intensity in the greenhouse from 7/15/to 8/15.

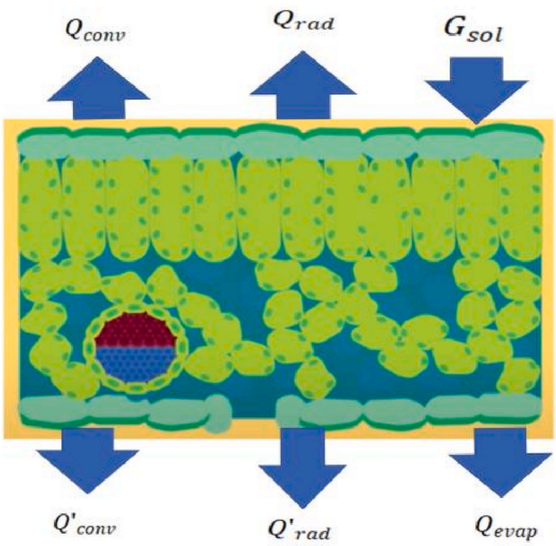

Fig. 4. Heat and mass transfer processes between the leaf and the environment.

$$\rho_{leaf}c_{leaf}\delta_{leaf}\frac{dT_{leaf}}{dt}=\alpha_s G_{sol}+\varepsilon\delta\left(T_{sky}^4-T_{leaf}^4\right)+\varepsilon\delta\left(T_{ground}^4-T_{leaf}^4\right)+2h\left(T_a-T_{leaf}\right)-E_C L_v \quad (2)$$

where ε represents the emissivity of the leaf; δ represents the Stefan-Boltzmann constant; T_{sky}, T_{leaf}, T_{ground}, and T_a represent the temperature (K) of the sky, leaf, ground, and ambient air, respectively; h represents the convective heat transfer coefficient; E_c represents the transpiration rate; and L_v represents the latent heat of vaporization. The density and specific heat capacity of the leaf can be regarded as equal to the density and specific heat capacity of water, respectively, because of the high-water content of the leaf.

Ye, (2013) proposed that leaf mesophyll cells have a large surface area, which facilitates the evaporation of water on the surface of leaf cells. Water vapor in the cell intercellular spaces reaches a saturated state, and saturated vapor diffuses through the leaf surface before escaping into the air. The transpiration rate is primarily determined by the escape of the saturated vapor through the leaf surface into the air. Therefore, the transpiration rate is the force driving the diffusion of water vapor outward divided by the total resistance encountered during the diffusion process, as shown in the following equation:

$$E_C=\frac{C_{leaf}-C_{\infty}}{r_s+r_a} \quad (3)$$

where C_{leaf} represents the saturated vapor concentration in the gaps among the mesophyll cells; C_{∞} represents the vapor concentration of the ambient air; r_s represents the stomatal resistance, which can be measured through a field experiment; and r_a represents the diffusion resistance of the vapor through the boundary layer. r_a can be expressed by the following formula [38] when the wind speed is less than 0.1 m s^{-1} (assuming that the wind speed inside the solar greenhouse is consistently below 0.1 m s^{-1}):

$$r_a=840\left\{\frac{d}{T_{leaf}-T_a}\right\}^{0.25} \quad (4)$$

where d represents the characteristic length of the leaf. Otherwise, r_a can be calculated as:

$$r_a=220\frac{d^{0.2}}{v^{0.8}} \quad (5)$$

The convective heat transfer coefficient in Equation (1) can be calculated using the boundary layer analogy, as shown in the following formula [39]:

$$\frac{h}{h_m}=\frac{k}{D_{AB}Le^n}=\rho C_p Le^{1-n} \quad (6)$$

In Equation (6), h_m represents the convective mass transfer coefficient in the boundary layer, which equals $1/r_a$; k (0.0263 W m^{-1} K) and C_p (1007 J kg^{-1} K) represent the thermal conductivity and specific heat capacity of air, respectively; D_{AB} (0.26×10^{-4} m^2 s^{-1}) represents the binary diffusion coefficient of water vapor in air; n is 1/3 and Le represents the Lewis number, which can be calculated using the following formula:

$$Le=\alpha\cdot D_{AB}^{-1} \quad (7)$$

where α (2.25×10^{-5} m^2 s^{-1}) represents the thermal diffusion coefficient of the air.

The photosynthetically active radiation PAR (μmol·m^{-2}·s) measured by AP4 can be converted to solar irradiance (W·m^{-2}) by :

$$G_{sol}=0.58PAR \quad (8)$$

The total reflectance of 'Shine Muscat' grape leaf in the solar spectrum can be determined as:

$$\rho=\frac{\int_{380}^{2500}E(\lambda,T)\rho(\lambda)d\lambda}{\int_{380}^{2500}E(\lambda,T)d\lambda}=0.228 \quad (9)$$

where $E(\lambda,T)$ represents the blackbody spectra emissive power. According to Planck's law, $E(\lambda,T)$ is expressed as:

$$E(\lambda,T)=\frac{C_1}{\lambda^5\left\{\exp\left(\frac{C_2}{\lambda T}\right)-1\right\}} \quad (10)$$

where C_1 and C_2 represent the first and second radiation constants, with values of 3.742×10^8 W μ m^4/m^2 and 1.439×10^4 μm^4·K, respectively. Assuming that the leaf is opaque, the solar absorptance of the 'Shine Muscat' grape leaf can be determined as:

$$\alpha_s=1-\rho=0.772 \quad (11)$$

The effective working wavelength range of the AP4 stomatal conductance meter is 400–700 nm. The original data recorded by the stomatal conductance meter is in terms of photon flux (mol·m^{-2}·s), which needs to be converted into irradiance data (W·m^{-2}) in the 400–700 nm range. The energy of a single photon is given by:

$$E_0 = hc \cdot \lambda^{-1} \tag{12}$$

where h is the Planck constant (6.63 × 10^{-34} J s), c is the speed of light in a vacuum (3 × 10^8 m s^{-1}), and λ is the wavelength of the photon. The recorded data of photon flux from the AP4 stomatal conductance meter can be converted into irradiance data in the 400–700 nm range:

$$Q_{PAR} = \int_{400}^{700} PAR \times M \times \frac{hc}{\lambda} \times \frac{E_{\lambda,b}(\lambda, T)}{ET} d\lambda = 0.22\text{PAR}(\text{W} \cdot \text{m}^{-2}) \tag{13}$$

where M is Avogadro's constant (6.02 × 10^{23} mol^{-1}), $E_{\lambda,b}(\lambda, T)$ is the spectral radiative power of a blackbody at temperature T, and ET is the integral value of $E_{\lambda,b}(\lambda, T)$ in the range of 400–700 nm. The solar radiation in the 400–700 nm range accounts for a certain proportion of the total solar radiation:

$$\eta = \frac{\int_{400}^{700} E_{\lambda,b}(\lambda, T) d\lambda}{\int_{280}^{2500} E_{\lambda,b}(\lambda, T) d\lambda} = 0.379 \tag{14}$$

Therefore, the photosynthetically active radiation PAR (μmol·m^{-2}·s) measured by AP4 can be converted to solar irradiance (W·m^{-2}) by :

$$G_{sol} = \frac{Q_{PAR}}{\eta} = 0.58PAR \tag{15}$$

The uncertainty of the leaf thermophysical model was estimated by:

$$U_v = VR_V \cdot \overline{d}_v \tag{16}$$

where U_v represents the uncertainty of the leaf thermophysical model; VR_V represents the sensitivity coefficient of the different meteorological variables, and $\overline{d}_v$ represents the self-uncertainty of the different meteorological variables. Self-uncertainty (the error) is obtained by calculating the average relative deviation from comparison.

3. Results

3.1. Stomatal changes in leaves under different weather conditions

Fig. 5 shows variation in the stomatal resistance of 'Shine Muscat' grapes leaves during sunny and rainy days. During clear days, particularly in the morning, the stomatal resistance gradually decreased as solar radiation increased. However, around noon, there was a discernible increase in leaf resistance due to the midday decrease in photosynthesis. During this period, stomata close to reduce transpiration, which increases leaf resistance. After 4 p.m., stomata gradually close as solar radiation decreases, and this leads to an increase in leaf resistance. Stomatal resistance is higher on rainy days when the solar radiation intensity is weak than on sunny days. Changes in stomatal resistance during rainy days mirrored those during sunny days, and there was a notable decrease around noon. This same pattern was observed on sunny days, with the stomatal resistance decreasing at noon.

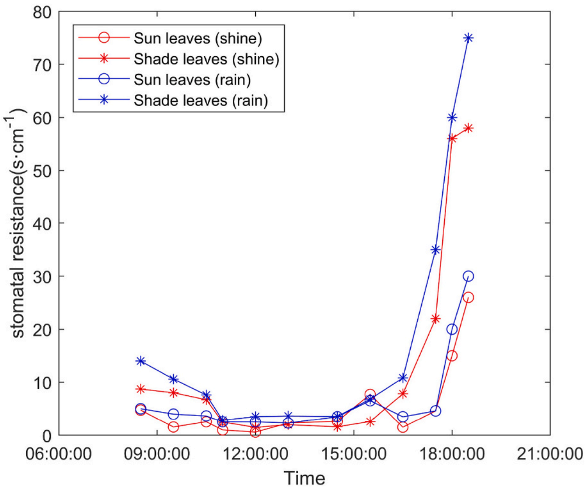

Fig. 5. Changes in stomatal resistance in sun and shade leaves under different weather conditions. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.2. Heat dissipation processes of sun and shade leaves on sunny day

We utilized the validated model to calculate variation in the leaf temperature of 'Shine Muscat' grape leaves during the summer. The a and d panels in Fig. 6 show changes in the actual leaf temperature, theoretically calculated leaf temperature, and environmental temperature during sunny days under MDI. The fit between the actual and calculated temperatures of sun leaves was high, and their trends were consistent. However, in the afternoon, the temperature of sun leaves rapidly decreased due to the application of foliar fertilizer. At same time, as the greenhouse solar radiation intensity gradually decreased and the sensitivity of stomatal conductance to light increased. This contributed to the low fit between the theoretically calculated leaf temperature and actual temperature values (the maximum temperature difference between the calculated leaf temperature and actual leaf temperature was 4.99 °C, which occurred at 4:30 p.m.). In contrast, shaded leaves showed minor temperature fluctuations and were closely aligned with changes in environmental temperature. The most substantial difference between theoretical and actual leaf temperatures (3.68 °C) occurred around 11:00 a.m.

The b and e panels in Fig. 6 show the effect of the SDI treatment; leaf temperatures were notably higher in this treatment than in the other treatments. In the sun leaf canopy, the maximum temperature difference between the calculated and actual leaf temperature was 4.46 °C during the rapid afternoon decrease in leaf temperature, which was driven by foliar fertilizer application. Temperature variation is lower in the shade leaf canopy than in the sun leaf canopy given that shade leaves receive less solar radiation than sun leaves. Therefore, when the ambient temperature was high, the calculated and actual leaf temperature differences were smaller for shade leaves than for sun leaves. However, the difference between the actual leaf temperature and calculated values increased as leaf temperature decreased.

The c and f panels in Fig. 6 show the effect of the FI treatment; the leaf temperature was lower and temperature stability was higher in the FI treatment than in the other treatments. The difference between the calculated and actual temperature of sun leaves was smaller in the FI treatment than in the other irrigation treatments. However, during the afternoon when leaf temperatures decrease, the disparity between the calculated and actual temperature increases; the maximum difference (2.79 °C) was observed at 5:30 p.m. For shade leaves, changes in calculated and actual leaf temperature were similar, and the maximum difference (3.74 °C) occurred at 11:00 a.m. A lag in the peak theoretical calculated leaf temperature compared with the actual leaf temperature was observed in both sun and shade leaves.

Across all three irrigation treatments, the maximum leaf temperature increased for sun and shade leaves on sunny days as the irrigation amount decreased. Differences between the theoretical and actual leaf temperature also increased under such conditions. Calculated and actual changes in temperature in the morning were generally consistent for sun leaves in the different irrigation treatments. However, in the afternoon, the change in the calculated temperature lagged behind the actual leaf temperature, and the lag

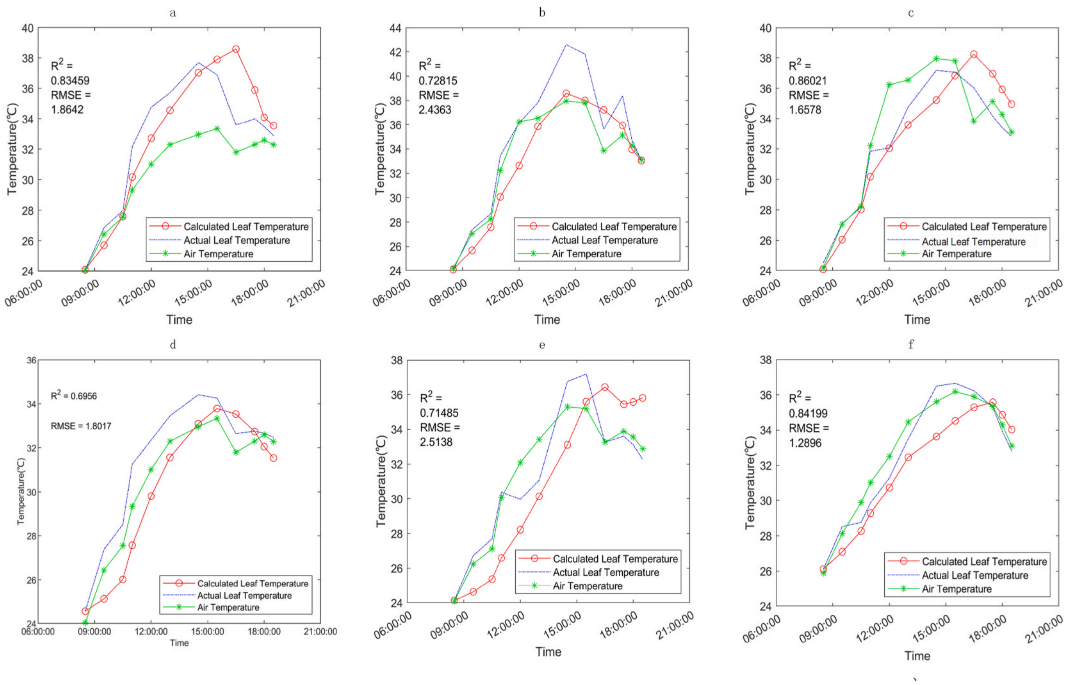

Fig. 6. Calculated temperature, actual leaf temperature and ambient temperature for sun and shade leaves under the MDI、SDI and FI treatments on clear days. (Panel from left to right corresponds to MDI、SDI and FI treatment, a,b,c show the temperature change of the sun leaf and d,e,f show the temperature change of the shade leaf respectively). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

time decreased as the irrigation amount increased. The temperature range of shade leaves was smaller than that of sun leaves in the different irrigation treatments. However, the correlation between calculated and actual leaf temperatures was generally lower for shade leaves than for sun leaves given the lower solar radiation intensity experienced by shade leaves, their lower variation in stomatal conductance, and other environmental factors. Suitable shading can reduce the damage of strong sunlight to the photosynthetic mechanism and reduce heat dissipation [40,41,42].

For both sun and shade leaves on sunny days, the difference between the calculated and actual leaf temperature increased in the afternoon when the solar radiation intensity and environmental temperature decreased rapidly. The deviation in the canopy temperature from the air temperature was positively related to long-wave radiation in the canopy layer and negatively related to the soil water content in the afternoon [43,44]. This might be attributed to rapid changes in environmental parameters that lead to delayed feedback in calculated leaf temperature values.

3.3. Heat dissipation processes of sun and shade leaves on rainy days

Changes in the daytime actual temperature, calculated temperature, and environmental temperature of sun leaves were consistent under MDI on rainy days (a and d panels in Fig. 7). Hence, the error between the calculated and the actual leaf temperature was low, indicating that they were highly correlated. The maximum difference between the calculated and actual temperature of sun leaves (2.57 °C) occurred at 2:30 p.m. The maximum

difference between the calculated and actual temperature of shade leaves (1.46 °C) occurred at noon.

Variation in leaf temperature was nearly identical in the MDI and SDI treatments (b and e panels in Fig. 7). The maximum disparity between the calculated and actual temperature of sun leaves (2.28 °C) was observed at 6:00 p.m. The maximum difference between the calculated and actual temperature of shade leaves (1.51 °C) was observed at noon.

During the daytime, the maximum temperature difference between the calculated and actual temperature of sun leaves was 2.29 °C, which was observed at 5:30 p.m. (c and f panels in Fig. 7). The maximum temperature difference between the calculated and actual temperature of shade leaves was 1.68 °C, which was observed at 12:00 p.m.

On rainy days, changes in temperature, including the calculated and actual leaf temperature, were generally consistent. As the leaf temperature began to drop in the afternoon, the fit between the calculated and actual leaf temperature was high, and the temperature difference between them did not increase significantly (in contrast to observations on sunny days). This could be attributed to the lower solar radiation intensity on rainy days, which maintains the stability in the stomatal conductance of both sun and shade leaves. Additionally, the change in environmental temperature was not as drastic on rainy days; thus, there was radiative and convective heat exchange between sun and shade leaves. Consequently, the temperature difference between sun and shade leaves under different irrigation amounts was not as pronounced on rainy days as on sunny days.

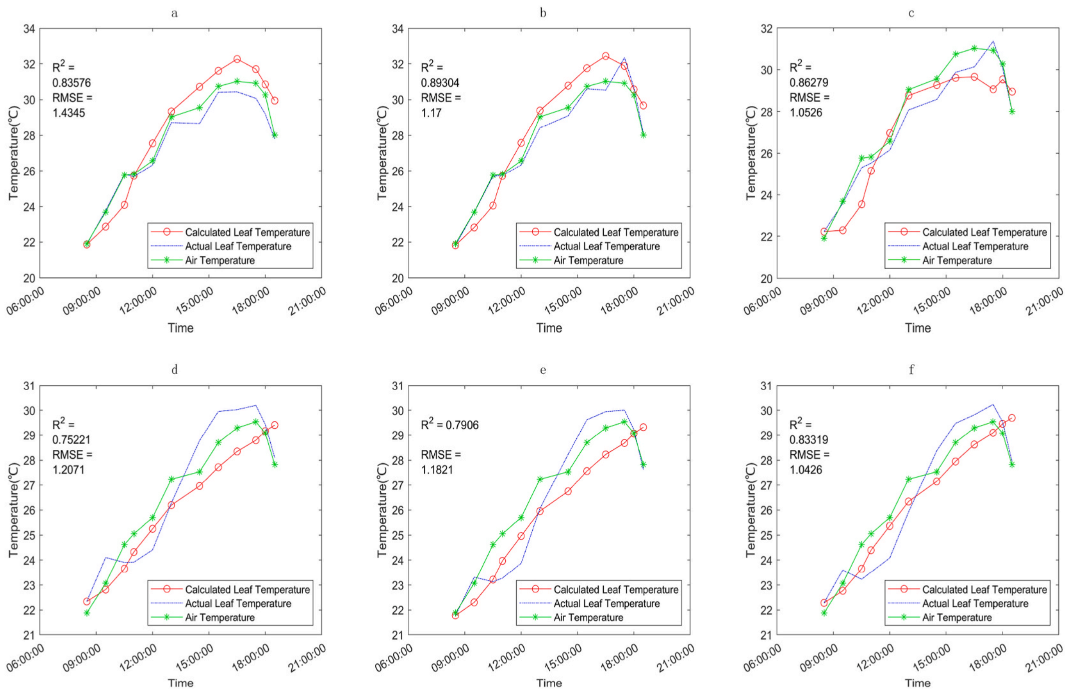

Fig. 7. Calculated temperature, actual leaf temperature and ambient temperature for sun and shade leaves under the MDI、SDI and FI treatments during the daytime on rainy days. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.4. Heat dissipation processes of leaves

Fig. 8 shows the daytime radiation, evaporation, and convection heat fluxes in the sun leaf canopy under different irrigation amounts from July 27th to August 3rd. The weather was rainy from July 27th to July 29th, and the heat fluxes and proportion of the three heat exchange processes under different treatments during these days were basically the same. On July 30th and July 31st, the weather transitioned from rainy to clear, and notable variation was observed in the radiation and evaporation heat fluxes in the SDI treatment; evaporation heat fluxes were higher in the SDI treatment than in the MDI and FI treatments. Rahman et al. [45] studied canopy temperature differences and the cooling ability of *Tilia cordata* trees in different urban regions; they observed that evapotranspiration can be affected by high temperature and humidity in the absence of wind. These environmental conditions were observed from July 30th to July 31st in our experiment, which might explain the significant fluctuations in the transpiration heat flux. In a few limited cases, high transpiration can occur without photosynthesis when T_{air} is high [46–49]. From August 1st to August 3rd, the weather was sunny, and irrigation was applied on August 1st. During these days, the evaporation heat flux was consistently higher in the FI treatment than in the other two treatments. For example, on August 2nd, the daytime evaporation heat flux was 2.16 MJ m^{-2}·day^{-1} under MDI, 2.36 MJ m^{-2}·day^{-1} under SDI, and 3.17 MJ m^{-2}·day^{-1} under FI, which stems from the greater use of water for evaporative cooling in the FI treatment. Consequently, as the soil moisture content decreased, the proportion of evaporation heat flux decreased. The daytime evaporation heat flux in the FI treatment was 3.86 MJ m^{-2}·day^{-1}, 3.17 MJ m^{-2}·day^{-1}, and 2.69 MJ m^{-2}·day^{-1} on August 1st, 2nd, and 3rd, respectively.

Overall, convection heat flux was basically the same in the different treatments during days with high solar radiation; given that the temperature difference between the leaf and the environment is decreased on such days, there was no difference in the radiation heat transfer among treatments. On sunny days, the irrigation amount differed among different treatments, and the maximum temperature of the blade increased, which resulted in differences in radiation heat exchange. Therefore, transpiration contributed more to leaf cooling than physical traits when water was not limiting. Plants reduce stomatal opening under drought to conserve water. Under such conditions, leaf cooling mainly depends on physical traits [50]. On rainy days, changes in stomatal conductivity and the solar radiation intensity were small, and the transpiration heat exchange was similar in the different treatments. On sunny days, when the solar radiation intensity increased, the stomatal conductivity changed greatly, and the heat exchange and proportion of transpiration increased. The irrigation amount varied among treatments, and the heat exchange and proportion of transpiration increased as the irrigation amount increased. In sum, the convection heat fluxes in different treatments in the sun leaf canopy during the day were generally consistent across various weather conditions. On rainy or overcast days with low solar radiation, the warming effect of solar radiation on the leaves weakened, which resulted in a small difference between the leaf temperature and environmental temperature. Therefore, differences in radiation heat fluxes among treatments were not significant. On sunny days, differences in the irrigation amount among treatments led to variation in maximum leaf temperature and radiation heat flux. During rainy days, the evaporation heat flux in the different treatments was relatively consistent when solar radiation was weak and changes in stomatal conductance were small. On sunny days characterized by intense solar radiation and significant changes in stomatal conductance, the evaporation heat flux increased, which reflects the effect of irrigation on the evaporation heat flux.

Fig. 9 shows the daytime radiation, evaporation, and convection heat fluxes in the shade leaf canopy under different irrigation amounts from July 27th to August 3rd. Regardless of weather conditions, the heat fluxes for radiation and convection were relatively consistent among treatments. This stability is attributed to the shaded position of the leaves in the canopy, which decreases exposure to

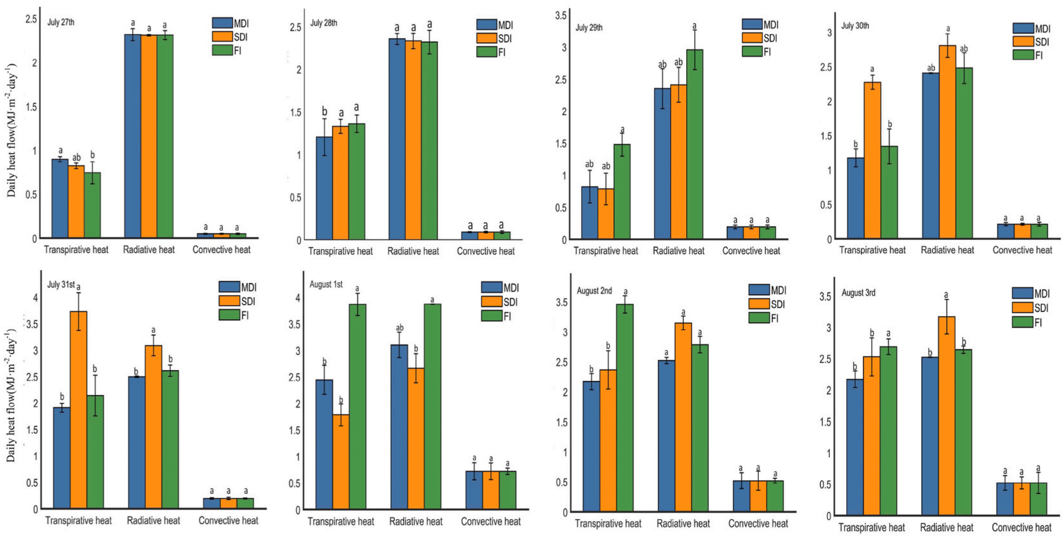

Fig. 8. Daily convection, radiation, and transpiration heat fluxes of the sun leaf canopy under different irrigation amounts from 7/27 to 8/3. Different lowercase letters indicate significant differences in daily heat flow at P = 0.05 (LSD; n = 6). Values are means ± standard errors.

solar radiation and variation in temperature. On rainy days, high relative humidity and low temperatures in the greenhouse affect leaf transpiration, which leads to a reduction in evaporation heat flux. Conversely, on sunny days with low relative humidity and high temperatures, evaporation heat flux increases to facilitate leaf cooling. The effects of different weather conditions on the radiation, convection, and evaporation heat flux were weaker in the shade leaf canopy than in the sun leaf canopy. Variation in leaf temperature was lower in the shade leaf canopy than in the sun leaf canopy.

Fig. 10 shows the radiation, convection, and evaporation heat fluxes throughout the daytime on sunny days under different irrigation treatments. When the irrigation amount varies, the radiation heat exchange is the primary cooling mechanism of the leaves. In the MDI treatment, the transpiration heat flux of the sun leaves was 2.62 MJ m^{-2}·day^{-1}, comprising 38.32 % of the total heat flux, and radiation and convection accounted for 47.33 % and 14.35 % of the total heat flux, respectively. Shade leaves in MDI had a transpiration heat flux of 1.53 MJ m^{-2}·day^{-1}, representing 32.36 % of the total heat flux, with radiation and convection comprising 58.55 % and 9.09 % of the total heat flux, respectively. Under the SDI treatment, the transpiration heat flux of sun leaves was 2.44 MJ m^{-2}·day^{-1}, accounting for 39.02 % of the total heat flux; radiation and convection accounted for 49.50 % and 11.47 % of the total heat flux, respectively. In SDI, the transpiration heat flux of shade leaves was 1.50 MJ m^{-2}·day^{-1}, comprising 33.17 % of the total heat flux, with radiation and convection comprising 57.44 % and 9.39 % of the total heat flux, respectively. Under the FI treatment, the transpiration heat flux of sun leaves was 3.86 MJ m^{-2}·day^{-1}, representing 41.49 % of the total heat flux; radiation and convection accounted for 41.55 % and 16.96 % of the total heat flux, respectively. In shade leaves in the FI treatment, the transpiration heat flux was 1.55 MJ m^{-2}·day^{-1}, which comprises 33.94 % of the total heat flux, with radiation and convection comprising 56.68 % and 9.38 % of the total heat flux, respectively.

On sunny days, there were significant differences in the proportion of the three heat exchange mechanisms for sun and shade leaves under different irrigation treatments. As the irrigation amount increased, the proportion of radiation heat exchange gradually decreased for sun leaves, which was consistent with the proportion of transpiration heat exchange. Shade leaves receive less solar radiation due to their position in the canopy; transpiration was thus lower in shade leaves than in sun leaves. The proportions of the three heat exchange fluxes were consistent for shade leaves across treatments, indicating that variation in the irrigation amount had a weak effect on shade leaves.

Fig. 11 shows the comprehensive radiation, convection, and evaporation heat fluxes throughout the day on rainy days under different irrigation treatments. Regardless of the irrigation amount, radiation heat exchange was the main cooling mechanism of the leaves. Under the MDI treatment, the transpiration heat flux of the sun leaves was 0.82 MJ m^{-2}·day^{-1}, which comprised 24.36 % of the total heat exchange, and radiation and convection accounted for 69.94 % and 5.70 % of the total heat exchange, respectively. Shade leaves in the MDI treatment had a transpiration heat flux of 0.96 MJ m^{-2}·day^{-1}, comprising 24.07 % of the total heat flux, and radiation and convection comprised 66.06 % and 9.87 % of the total heat flux, respectively. Under the SDI treatment, sun leaves had a transpiration heat flux of 0.78 MJ m^{-2}·day^{-1}, accounting for 27.30 % of the total heat flux, and radiation and convection accounted for 71.75 % and 4.94 % of the total heat flux, respectively. Shade leaves in the SDI treatment had a transpiration heat flux of 1.11 MJ m^{-2}·day^{-1}, comprising 29.40 % of the total heat flux, and radiation and convection comprised 65.48 % and 5.11 % of the total heat flux, respectively. Under the FI treatment, sun leaves had a transpiration heat flux of 1.19 MJ m^{-2}·day^{-1}, comprising 25.03 % of the total heat flux, and radiation and convection accounted for 59.83 % and 15.14 % of the total heat flux, respectively. Shade leaves in the FI treatment had a transpiration heat flux of 1.16 MJ m^{-2}·day^{-1}, comprising 29.43 % of the total heat flux, and radiation and

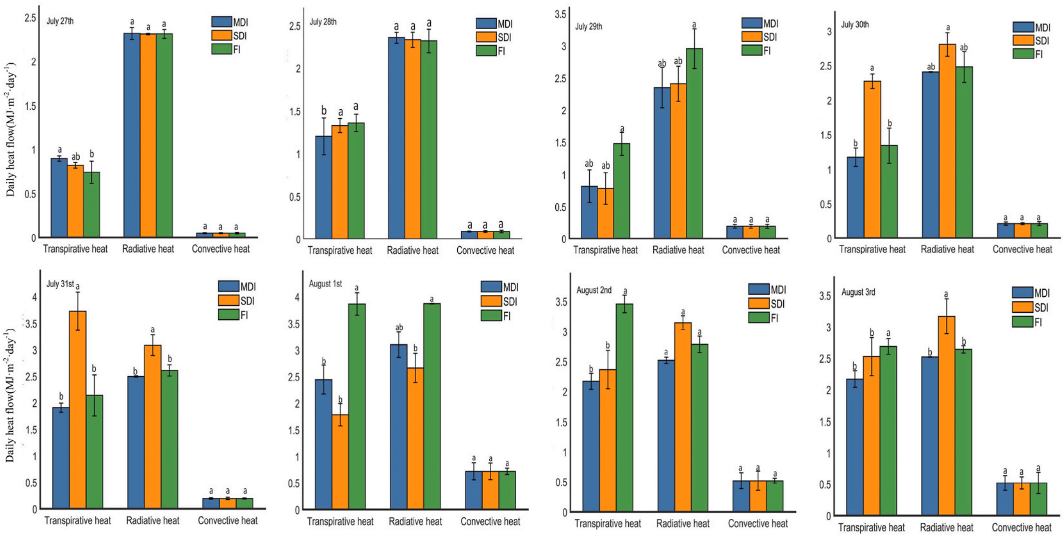

Fig. 9. Daily convection, radiation, and transpiration heat fluxes of the shade leaf canopy under different irrigation amounts from 7/27 to 8/3. Different lowercase letters indicate significant differences in daily heat flow at P = 0.05 (LSD; n = 6). Values are means ± standard errors. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

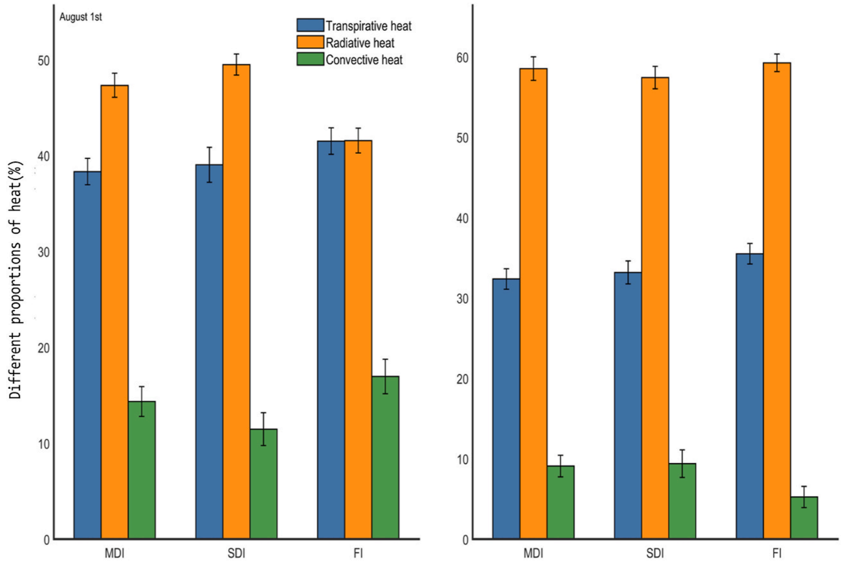

Fig. 10. The proportion of convective, radiative, and transpiration heat fluxes for sun and shade leaves on 8/1 under different treatments on a sunny day (figure a show sun leaves, and figure b show shade leaves). Different lowercase letters indicate significant differences in different proportions of heat at P = 0.05 (LSD; n = 6). Values are means ± standard errors. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

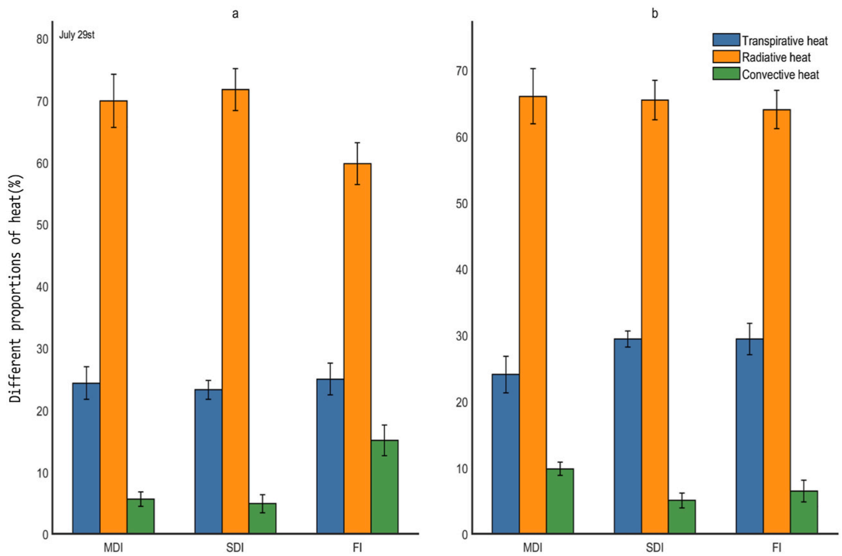

Fig. 11. The proportion of convective, radiative, and transpiration heat fluxes for sun and shade leaves under different treatments on 7/29, a sunny day figure a show sun leaves, and figure b show shade leaves). Different lowercase letters indicate significant differences in different proportions of heat at P = 0.05 (LSD; n = 6). Values are means ± standard errors. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

convection comprised 64.06 % and 6.51 % of the total heat flux, respectively.

The average relative humidity is higher on rainy days than on sunny days, and the proportions of the three heat exchange fluxes differed on rainy days and sunny days. The transpiration heat flux of sun and shade leaves was similar on rainy days. Leaves need to increase the proportion of transpiration heat exchange to maintain an appropriate temperature on sunny days when temperatures are higher and humidity is lower. Therefore, the proportion of transpiration heat exchange was higher on sunny days than on rainy days. Xu et al. [16] also concluded that relative humidity affects transpiration heat exchange. The proportion of radiation heat exchange varies because variation in the amount of irrigation affects leaf temperatures. Greater irrigation amounts reduce the average leaf temperature, and the main factors affecting radiation heat exchange include leaf temperature and environmental temperature. On rainy days, sun leaves receive more sunlight than shade leaves, which leads to large variation in the temperature of sun leaves;

however, variation in temperature was lower on rainy days than on sunny days.

From Tables 3 and 4 we can see that Ta, RH and T_{ground} contribute less to the model uncertainty on cloudy days than on sunny days. And G_{sol} is the core driving variable of the model, which contributes much to the model uncertainty.

3.5. Physiological status of sun and shaded leaves

Fig. 12 illustrates the contents of chlorophyll *a*, chlorophyll *b*, total chlorophyll, and MDA (malondialdehyde) in sun and shade leaves. The difference in chlorophyll content between sun leaves in MDI and FI is not significant, while there is a pronounced difference in chlorophyll content between SDI and the other two. These illustrate that severe water deficiency significantly affects chlorophyll content in sun leaves. In comparison to the chlorophyll content in shade leaves of the three, the impact of different irrigation levels on shade leaf chlorophyll content is relatively minor.

The difference in MDA content in sun leaves between MDI and FI is not significant, while the MDA content in sun leaves of SDI is significantly higher than the former two. There is no significant difference in MDA content among the shade leaves of the three. This indirectly indicates that different irrigation treatments have a greater impact on the three heat exchange parameters in sun leaves, while the effect on shade leaves is relatively smaller. Under the same heat exchange conditions, there are significant differences between sun leaves with different irrigation levels, while the differences in shade leaves are much smaller.

4. Discussion

In this study, we analyzed the variation of radiative, convective, and transpiration heat fluxes in sun and shade leaves under different weather conditions for different irrigation treatments in a solar greenhouse. First, we observed that the percentage of radiative heat fluxes was consistently highest under different weather conditions. Second, the percentage of transpiration heat exchange of the sun and shade leaves gradually increased with increasing irrigation amount, which was similar to the results observed by Xu et al. [16] in Xishuangbanna. This situation could be due to the fact that the environment in the Xishuangbanna region was similar to that in the solar greenhouse during the summer.

Heat stress is one of the main factors influencing crop evapotranspiration [51]. Heat stress caused by drought stress can also decrease the leaf area and directly reduce the plant evaporative surface [52]. In addition, it also damages leaf function, accelerating leaf senescence, and indirectly limiting transpiration [53]. The contents of total chlorophyll and MDA of sun leaves under SDI treatment were significantly different from MDI and FI treatments due to drought, so irrigation amount and leaf morphology jointly influenced transpiration heat dissipation [13].

The canopy can block the heat exchange of air temperatures above and below the canopy, and lower the rates of convective heat exchange [54–56]. And in our study, we found that the temperature difference between the upper and lower part of the grape canopy could reach a maximum of 4.65 °C on sunny days, which had a significant effect on the microclimate changes in the greenhouse.

From Tables 3 and 4, the uncertainty analysis of the leaf mass and heat transfer model showed that there were significant differences in the effects of environmental factors on the model simulation accuracy under different weather conditions. During sunny days, the four environmental factors had an impact on the uncertainty of model, and Ta and Gsol had a greater impact than other factors. We observed that the accuracy of model simulation of leaf temperature was generally lower on sunny days than on rainy days. Analyzing the model uncertainty under different weather conditions, we found that the effect of the four environmental factors on model uncertainty analysis were significantly higher on sunny days than on rainy days, which could be the reason for the decrease in the simulation accuracy on sunny days. In addition, the model exhibited higher R^2 values when simulating sun and shaded leaf temperature under the FI treatment. Therefore, we noted variations in soil moisture and soil temperature due to different irrigation amounts, and these factors also affected the accuracy of the model. In the future study, we need to further quantify the effect of soil moisture changes on the model to improve the simulation accuracy of the model under different weather and treatment conditions.

In conclusion, this study illustrates the variation of radiation, convection, and transpiration heat transfer in the solar greenhouse during the daytime in different weather conditions, and clarifies the process of heat fluxes in the plant canopy in the fluctuation of greenhouse energy flow.

5. Conclusions

Weather conditions can affect greenhouse environmental parameters. On sunny days, the transpiration rates of sun leaves in the MDI, SDI, and FI treatments were 2.62 MJ m^{-2}·day^{-1}, 2.44 MJ m^{-2}·day^{-1}, and 3.86 MJ m^{-2}·day^{-1}, respectively, indicating that the irrigation amount has a significant effect on transpiration. In contrast, temperature variation and heat exchange fluxes in the canopy of shade leaves were comparatively modest. On rainy days, the transpiration rates of sun leaves in the MDI, SDI, and FI treatments were 0.818 MJ m^{-2}·day^{-1}, 0.782 MJ m^{-2}·day^{-1}, and 1.185 MJ m^{-2}·day^{-1}, respectively, which indicates that ambient temperature and humidity have a major effect on transpiration. The canopy temperature of shade leaves was closely tied to greenhouse ambient conditions, and minimal variation in the canopy temperature of shade leaves was observed among the different irrigation treatments.

In sum, sun leaves show high sensitivity to fluctuations in greenhouse environmental parameters and the soil moisture content. The transpiration process, which is affected by the irrigation amount and weather conditions, plays a key role in regulating leaf temperatures and heat exchange dynamics. Understanding these interactions is crucial for optimizing greenhouse management strategies and improving crop performance and resource utilization.

In this paper, we focused on the heat transfer of summer mature sun and shade leaves under different irrigation treatments.

Table 3
Uncertainties of meteorological variables for leaf thermophysical model on rainy days (%).

	T_a	RH	G_{sol}	T_{ground}
MDI	0.61	1.27	7.88	0.29
SDI	0.61	0.18	12.63	0.25
FI	0.57	0.19	10.90	0.28

Table 4
Uncertainties of meteorological variables for leaf thermophysical model on sunny days (%).

	T_a	RH	G_{sol}	T_{ground}
MDI	6.20	2.07	5.57	4.87
SDI	5.88	2.03	8.27	3.94
FI	5.65	2.07	13.63	3.56

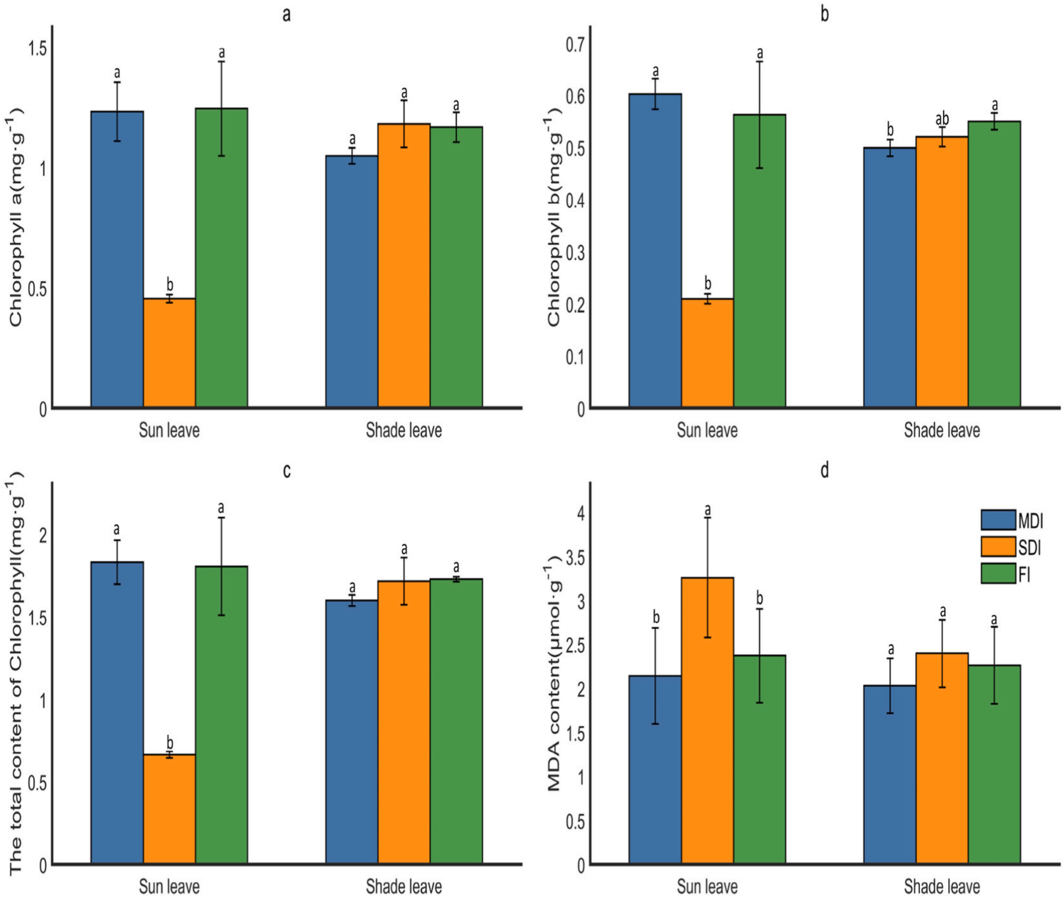

Fig. 12. The contents of chlorophyll *a*, chlorophyll *b*, total chlorophyll, and MDA (malondialdehyde) in sun and shade leaves. (a panel presents the contents of chlorophyll *a*, the b panel presents the contents of chlorophyll *b*, the c panel presents the total contents of chlorophyll, and the d panel illustrates the contents of MDA). Different letters in the same column indicate significant difference at P = 0.05 level (LSD; n = 6). Values are means ± standard errors. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

However, in order to construct a more comprehensive and accurate thermophysical model of leaves, the future research should consider the heat transfer process of leaves at different growth stages and incorporate both the effects of leaf conformation and physiological parameters on leaf heat transfer.

Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Kaiwen Wang: Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Guangyue Xie:** Visualization, Validation, Methodology, Investigation, Data curation. **Da Wang:** Validation, Supervision, Project administration, Methodology, Investigation. **Ziteng Wang:** Validation, Investigation, Formal analysis, Data curation. **Ziyan Li:** Validation, Formal analysis, Data curation, Conceptualization. **Letian Wu:** Methodology, Funding acquisition, Data curation, Conceptualization. **Yingtao Zhang:** Validation, Investigation, Data curation. **Danting Yang:** Validation, Investigation, Data curation. **Xianpeng Sun:** Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Xianpeng Sun reports financial support was provided by Shaanxi Key Research and Development Program Fund(2023-YBNY-051). Xianpeng Sun reports was provided by Xingjiang Uighur Autonomous Region Major Science and Technology project (2022A02005-5). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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