



Article

Performance of Reflective Film on the Light Environment of Chinese Solar Greenhouse

Wenbin Shi ^{1,2}, Yichao Zhang ², Yiming Li ³ , Xing'an Liu ², Sida Meng ^{2,*}, Tianlai Li ^{2,*} and Liping Zhao ²

¹ College of Life Engineering, Shenyang Institute of Technology, No. 1 East Part of Hebin Road, Shenfu District, Shenyang 113122, China; shiwenbin@situ.edu.cn

² College of Horticulture, Shenyang Agricultural University, No. 120 Dongling Road, Shenhe District, Shenyang 110866, China; zyc970310@gmail.com (Y.Z.); lxa10157@syau.edu.cn (X.L.); 2020101030@test.syau.edu.cn (L.Z.)

³ College of Engineering, Shenyang Agricultural University, No. 120 Dongling Road, Shenhe District, Shenyang 110866, China; liyiming@syau.edu.cn

* Correspondence: mengsida@syau.edu.cn (S.M.); ltl@syau.edu.cn (T.L.)

Abstract: To enhance the utilization of solar energy in Chinese solar greenhouses (CSGs), a new method for optimizing the internal lighting environment of CSGs using reflective films is proposed. The influence of different positions and angles of reflecting film on solar radiation in greenhouses was studied, using the solar radiation on the inside surface of the CSG as an evaluation index. According to the findings, total solar radiation increased by 5.33% when the reflective film was positioned on the north roof at an angle of 0°. The light interception on the north wall decreased from 7.91% to 10.54% when the angle was raised from 15° to 25°. The crop canopy was not significantly affected by the reflective film's various placements and angles, and the benefits of additional light were insufficient to compensate for the drawbacks of crop shading. This result provides a theoretical basis for the application of reflective films in relevant agricultural facilities. Reasonable installation of reflective film in the greenhouse can increase the light interception of plants inside the greenhouse and further increase the income of farmers.

Keywords: Chinese solar greenhouse; solar radiation; light environment; reflective film



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1. Introduction

The Chinese solar greenhouse (CSG) has been widely developed to produce vegetables in winter without utilizing auxiliary heating. These are completely passive greenhouses thanks to their one-sided structure, heat-storing thick walls, night curtains, and standard building materials [1,2]. CSGs offer Chinese farmers an effective and affordable production method that maximizes the effectiveness of vegetable planting overall, resolves the issue of difficult winter vegetable planting in northern China, and makes wintertime vegetable consumption more accessible to more people [3]. CSGs are mainly distributed in northern China (34° N–43° N). As of 2022, CSGs cover more than 0.5 million hectares in China, and their geographic scope is expanding annually. Solar radiation is the main energy source of greenhouses [4,5]. The three essential components of CSGs—lighting, heat preservation, and heat storage—allow them to survive winter without heating in frigid climates. The only energy source for CSGs is solar energy, which has a direct impact on the greenhouse's energy balance, as well as the conversion of organic matter during photosynthesis and the stimulation of crop development. Hence, raising the light energy level inside the CSG is crucial.

While the light entering the greenhouse may be reduced in intensity by 20–60% due to the structure of the solar greenhouse [6], only 30–70% of the natural light is present in the greenhouse. The primary emphasis of current research on enhancing the greenhouse light environment is on active light supplementation. Productivity and illumination in greenhouses can be increased with the use of additional lights. In recent years, light-emitting diodes (LEDs) have been rapidly introduced to provide supplemental lighting in

greenhouse cultivation systems [7–9]. However, the continuous illumination of the fill light increases the production cost of the greenhouse, and the profitability of vegetables is low. By installing solar technology in the greenhouse, the demands for energy production, land conservation, light propagation control, and temperature regulation may all be met [10]. When the area ratio of organic photovoltaic modules to greenhouse areas is 20%, incident radiation per unit area in a conventional greenhouse without photovoltaic modules is approximately twice as high as it is in a photovoltaic greenhouse [11]. Scientists have used Grasshopper (rhino 6) software for building light simulation analysis and photovoltaic power generation applications. In the photovoltaic greenhouse, the overall radiation and impact radiation for photosynthesis nearly declined by 30% and 20%, respectively [5]. The radiation intensity reflected by the ground has the same order of magnitude as that scattered by the ground, which means that the sunlight that is reflected back should not be disregarded [12]. During the growth process of grapes, due to the occlusion of the upper leaves, the photosynthesis of the leaves in the middle and lower parts of the tree crown is weak, which restricts the coloring of the fruits growing in the middle and lower parts of the tree. Laying reflective film can not only regulate the microenvironment of the tree canopy but also regulate the color of the fruit [13].

The utilization of reflected light provides a new idea for optimizing light conditions in a solar greenhouse. Therefore, light propagation control becomes the core problem of solar energy reutilization in solar greenhouses. The light environment of a greenhouse can be improved with reflective devices. Installing reflective materials in greenhouses, especially inclined greenhouses, is one of the most effective and economical solutions for improving light intensity [14,15]. Some literature reports have introduced the use of reflective materials on greenhouse benches to increase the amount of light for plants [16]. To increase the lighting for the greenhouse floor, a reflector was placed on the north wall of the Venlo greenhouse [4]. The reflector positioned in front of the north wall should be inclined between 75° and 85° [17]. In actuality, the best reflector height and angle should change depending on the time of day and the location of the particular greenhouse [18]. To optimize the reflector's height and angle parameters, Kun derived an equilibrium equation based on the theory of light reflection [19]. According to the derived governing formula, the most optimal temperature for setting reflectors at 32° – 42° latitude in China is between 0.5 m and 2.4 m [20]. Increasing the reflectivity of the north wall of the greenhouse can also increase the internal reflection of the greenhouse [4,21]. Additionally, the shining aluminized surface helps the greenhouse reflect sunlight. Moreover, a bright aluminized surface is conducive to reflecting sunlight in the greenhouse [14] to increase light interception in crop areas and modify the crop's flowering duration [22] and fruit quality [23]. In winter, the light intensity in the solar greenhouse is weakened, the level of light intensity is uneven, and the reflective curtain is hung on the north side of the cultivation bed of the solar greenhouse or near the back wall [24]. Several researchers have suggested using this inexpensive, easily reflective material. Some researchers have proposed using this low-cost material that easily reflects light and laying it on the ground to increase light interception in crop areas and adjust the flowering period, color, and fruit quality of the crop. The investigation of reflective film usage in China is also an initial exploratory study. The use of reflective film inside the greenhouse is very common; many farmers hang it, resulting in the internal light being more uneven inside the greenhouse. The link between the theoretical model and the application of the greenhouse reflective film at this stage has not been concluded. The first principle of reflective screens is reflection. When sunlight hits the surface of the reflective curtain, it reflects, thus changing the direction of the light. The choice of reflective material is crucial, and materials with high reflectivity, such as aluminum foil, are usually used. Aluminum foil has excellent reflection performance and durability, which can maximize the reflection of sunlight back to the interior of the greenhouse and reduce light loss. Because the angle of reflection is equal to the angle of incidence, when the light is reflected back from the reflective curtain, it will be closer to the vertical incident, thus improving the incident intensity and uniformity of the light.

This paper suggests a new technique for using reflective film to cover the internal maintenance structure of CSG in order to improve the light interception rate of crop areas and optimize the overall light distribution of the greenhouse to meet the requirements of energy-saving CSG for low energy consumption and high efficiency. Although the use of reflective film is simple, it is not the end of hanging. If the hanging angle is not right, the sun does not reflect on the vegetables, but reflects on the roof of the shed; the effect can be imagined. Especially when the winter is cloudy, the vegetables need light very much; if the hanging reflective curtain does not have the due effect, it will seriously affect the increase in vegetable production and income. To achieve this, first, a solar greenhouse was constructed to use as a light environment model. Next, the solar radiation of each surface was studied. A reflective film model was constructed based on this research. Finally, the effects of reflective film on the solar radiation of the indoor environment were studied. Ultimately, the reflective film's optimal configuration was obtained, which can offer fresh perspectives on how to improve the light environment in CSGs. Grasshopper, Ladybug, and Honeybee plug-ins were applied in Rhino. Ladybug mainly analyzes the motion trajectory of sun rays, and Honeybee mainly analyzes light intensity.

2. Materials and Methods

2.1. Experiment Environment

The experiment was carried out at a CSG in Shenyang Agricultural University, Liaoning Province, China ($41^{\circ}49'45''$ N, $123^{\circ}33'59''$ E, 75.0 m above sea level), as shown in Figure 1. The greenhouse is 60 m, facing south and east–west. It has a 7.5 m span. The height of the north wall is 2.3 m, and the length of the horizontal projection of the north roof is 1.5 m. The ridge height is 3.5 m. The south roof consists of two arcs, and the slope of the north roof is 42° .

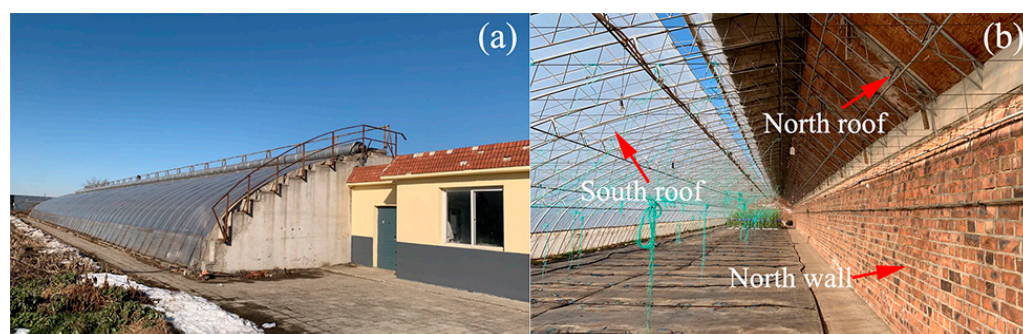


Figure 1. The experimental solar greenhouse: (a) the external views; (b) the internal views.

The north roof of the experimental greenhouse has a wooden panel covering the north and an earthen brick surface. Solar radiation in the greenhouse was measured and recorded using a TESS 1339 solar radiation logger. The measuring range is 0.01 Lux to 999,900 Lux, 0.001 fc to 99,990 fc, with 5 automatic shifts, a sampling rate of 2 s, high equipment accuracy, and an accuracy of $\pm 3\%$. The ES-1339 digital illuminometer is a professional-grade illuminometer that can be connected to a computer, providing a quick and accurate response. The automatic shutdown complies with CNS 5119: CHINA, 2011 Class A standards. It is mainly used in lighting production, environmental scientific research, classrooms, laboratories, indoor settings, agricultural greenhouses, and so on. There were 21 measuring points on the floor of the greenhouse (Figure 2). Figure 2A–C represents the three groups of experiments. The spacing of measuring points in the three groups was 6 m; each group of experiments had 7 groups of measuring points, and the spacing between each group of experimental measuring points was 1 m. Data were recorded at 60-min intervals and measured from 8 December 2021 to 9 December 2021.

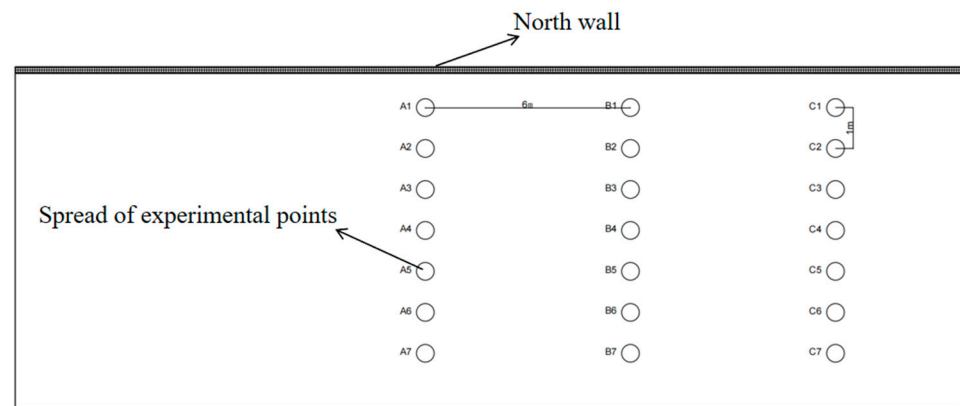


Figure 2. Arrangement of measurement points.

The reflective film (1×30 m, 70% reflectivity) was sourced from the market, a commonly available reflective film, and was applied to the north wall of the experimental greenhouse, as shown in Figure 3a. The control group is depicted in Figure 3b. The light radiation at noon was recorded at each measurement point when there was no shade outside.

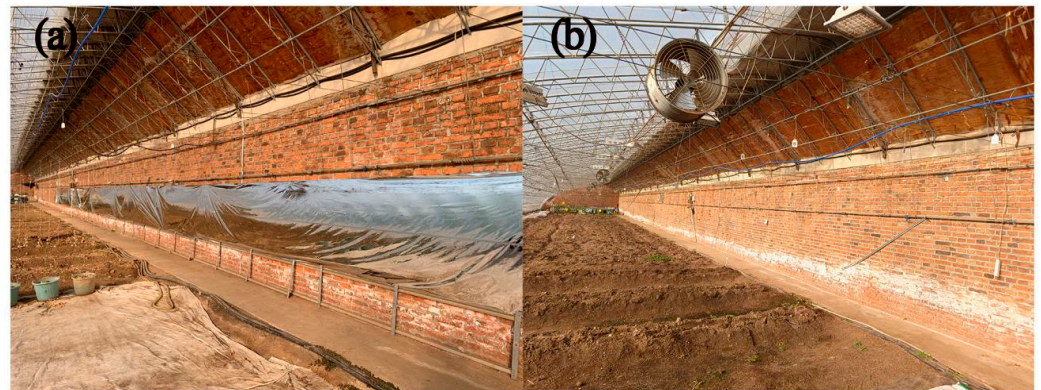


Figure 3. Photograph of experience: (a) with reflective film; (b) the control group.

2.2. Simulation Model and Calculation Method

The solar radiation intercepted by the south roof of the greenhouse is divided into two parts: direct radiation and scattered radiation. The radiation reflected by the outdoor ground and the environment can be ignored. The amount of direct solar radiation intercepted by the greenhouse is determined by the solar altitude angle, the Earth's dynamic diameter, the atmospheric transparency coefficient, the solar azimuth, the greenhouse azimuth, and the greenhouse roof angle. The sun's azimuth angle and altitude angle are time dependent in this section. The trajectory of the sun's movement during the day changes the solar radiation, which means that the angle of incidence into the south roof changes and directly affects the direct solar radiation received by the roof surface. Along the curved roof surface, the angle of incidence of sunlight can be expressed as [21]:

$$\delta_{(sr)}(t) = \cos^{-1}(\cos\gamma_{(sr)} \times \sinh_{(t)} + \sin\gamma_{(sr)} \times \cosh_{(t)} \times \cos(\beta_{(t)} - \beta_G)) \quad (1)$$

where δ is the angle of incidence ($^\circ$), h is the solar altitude angle of the south roof ($^\circ$), γ is the slope angle ($^\circ$), β is the solar azimuth angle ($^\circ$), and β_G is the greenhouse azimuth angle ($^\circ$). The subscript sr indicates the south roof ($^\circ$) and t indicates the change with time.

$$I_{b(sr)}(t) = I_{bt}(t) \times \cos\delta_{(sr)} / \sinh_{(t)} \quad (2)$$

The following equation can be used to calculate the direct radiation intensity I_b reaching any point on the south roof (W). I_{bt} represents the intensity of the solar beam radia-

tion reaching the external horizontal surface on a typical sunny day (W). The subscript *sr* indicates the south roof, and *t* indicates the change with time [25].

The slope angle between the south roof and the horizontal surface can be used to calculate the intensity of the diffuse radiation that the south roof receives. The intensity of diffuse radiation *I_d* on the south roof is shown below:

$$I_{d(sr)(t)} = I_{dt(t)} \times \cos^2 \frac{\gamma(sr)}{2} \quad (3)$$

where *I_{d_h}*

 represents the diffuse solar radiation reaching the external horizontal surface on a typical sunny day (W). *λ* denotes the slope angle (°).

The external cumulative solar radiation reaching the outer surface of the south roof (SRR) during the day can be obtained by integration [26]:

$$SSR = \int_{t_1}^{t_2} \int_0^{L_{sr}} (I_{b(sr)(t)} + I_{d(sr)(t)}) dL dt \quad (4)$$

where *t₁* and *t₂* denote the start and end of the lighting time, respectively, *L_{sr}* is the length of the south roof (m), and SSR denotes the external cumulative solar radiation reaching the outer surface of the south roof during the day (W).

The direct light and scattered light transmittance of the north roof at the incident location are first determined before calculating the light radiation on each greenhouse surface. The impact of transparent materials on canopy coverage transmittance must be taken into account, as well as factors like water droplet adhesion, greenhouse film aging, and pollution [2,5].

$$\tau_Z = \tau_{Z_0} (1 - \gamma_1) (1 - \gamma_2) (1 - \gamma_3) \quad (5)$$

$$\tau_S = \tau_{Z_0} (1 - \gamma_1) (1 - \gamma_2) (1 - \gamma_3) \quad (6)$$

where *τ_Z* is the direct light transmission (%). *τ_s* is the transmittance of scattered light (%). *τ_z* indicates the transmittance of direct light (%). *τ_{z0}* is the light transmittance of the new covering material to direct optical emission (%) when the incidence angle is 0. *τ_{zθ}* is the light transmittance of the new covering material to direct light emission. *λ₁* is the shading loss of greenhouse structural materials (%). *λ₂* is the light transmission loss of covering material due to aging (%). *λ₃* is the loss of light transmission due to dust pollution and dewy drops (%).

The effects of light refraction through the greenhouse film on the direction of light and the effects of each surface in the greenhouse on the reflected irradiance can be disregarded when estimating the solar irradiance on each surface in the CSG. Initially, it was calculated and determined how much sunshine would shine on the interior floor, the north wall, and the plant layer surface (a horizontal surface 1.2 m above the greenhouse floor). As a result, it was possible to determine the direct sun irradiance's instantaneous and cumulative values. The following is the formula for determining the irradiance of direct light at any location within the greenhouse [27]:

$$I_{zp} = \tau_{zp} I_{bh} (1 - H_{aze}) \quad (7)$$

where *I_{zq}* is the direct light irradiance at a point (W). *τ_{zq}* is the direct transmittance of roof direct point p corresponding to any point (%). *H_{aze}* is the haze of the covering material. *I_{bh}* is the direct radiation intensity to any point on the south roof (W).

The direct solar irradiance of the soil surface, the surface of the north wall surface, and the surface of the plant layer surface were calculated as follows [28]:

$$I_{b,g} = \int_{t_1}^{t_2} \int_0^{L_g} I_{zp} \quad (8)$$

$$I_{b,w} = \int_{t_1}^{t_2} \int_0^{L_w} \frac{\cos \delta_w}{\cos \delta_z} I_{zp} \quad (9)$$

$$I_{b,pl} = \int_{t_1}^{t_2} \int_0^{L_{pl}} \frac{\cos \delta_p}{\cos \delta_z} I_{zp} \quad (10)$$

In the formula, $I_{b,g}$, $I_{b,w}$, and $I_{b,pl}$ represent the direct sunlight solar radiance of the ground surface, north wall surface, and plant layer surface in the greenhouse, respectively (W). δ_g , δ_w , and δ_{pl} represent the incident angle of light on the horizontal plane, the north wall, and the plant layer surface, respectively ($^\circ$).

In Figure 4, α represents the building lighting angle, h represents the sun height angle, and γ represents the sun incidence angle. The scattered radiation in a greenhouse is mainly affected by the gas molecules and water droplets, reaching each surface as a diffuse reflection. As a result, the dispersed radiation is diffuse box radiation with an algebraically calculated angular coefficient. The length of each line segment can be used to replace the area of the associated surface, as shown in Figure 4, regardless of how the greenhouse membrane affects its radiation. This is because the greenhouse's length is infinite, and each surface's length is the same. As a result, the following formula is used to compute the scattered solar radiance of the soil surface, north wall surface, and north slope surface in the greenhouse:

$$\varsigma_{ab,bc} = \frac{l_{ab} + l_{bc} - l_{ac}}{2l_{ab}} \quad (11)$$

$$\varsigma_{ab,ad} = \frac{l_{ab} + l_{ad} - l_{bd}}{2l_{ab}} \quad (12)$$

$$\varsigma_{ab,cd} = \frac{l_{bd} + l_{ac} - l_{bc} - l_{ad}}{2l_{ab}} \quad (13)$$

where $\varsigma_{ab,bc}$, $\varsigma_{ab,ad}$, and $\varsigma_{ab,cd}$ indicate the angle coefficients of the light to the soil surface, the north wall surface, and plant layer surfaces (W/m²), respectively.

$$I_{d,g} = \int_{t_1}^{t_2} \int_0^{L_g} (I_d \times \tau_s \times \varsigma_{ab,bc}) \quad (14)$$

$$I_{d,w} = \int_{t_1}^{t_2} \int_0^{L_w} (I_d \times \tau_s \times \varsigma_{ab,cd}) \quad (15)$$

$$I_{d,pl} = \int_{t_1}^{t_2} \int_0^{L_{pl}} (I_d \times \tau_s \times \varsigma_{ab,ad}) \quad (16)$$

where $I_{d,g}$, $I_{d,w}$, and $I_{d,pl}$ represent the scattered sunlight radiation of the soil surface (W), north wall surface, and plant layer surface in the greenhouse, respectively. According to Figure 4, the lengths of ab , bc , and ac can be obtained [13].

$$Q_g = I_{b,g} + I_{d,g} \quad (17)$$

$$Q_w = I_{b,w} + I_{d,w} \quad (18)$$

$$Q_{pl} = I_{b,pl} + I_{d,pl} \quad (19)$$

where Q_g , Q_w , and Q_{pl} represent the radiation amount of the soil surface, north wall surface, and plant layer surface in the greenhouse (W), respectively. $I_{b,g}$, $I_{d,w}$, and $I_{d,r}$ indicate the scattering on the surface of the main soil, the surface of the north wall, and the surface of the back slope in the greenhouse (W/m²), respectively [15].

The interaction of the plant canopy with solar radiation results in both positive and negative shading effects. About 20–30% of the incident radiation is reflected and transferred between the canopies. Following the plant canopy, sunlight attenuates as it travels to the soil surface. Part of the light passing through the spaces between the leaves is unaffected and reaches the ground. Part of the light that is intercepted by the leaves is absorbed by the leaves, and part is reflected back into the surrounding environment. A portion of the radiation is reflected back to the blade from the environment.

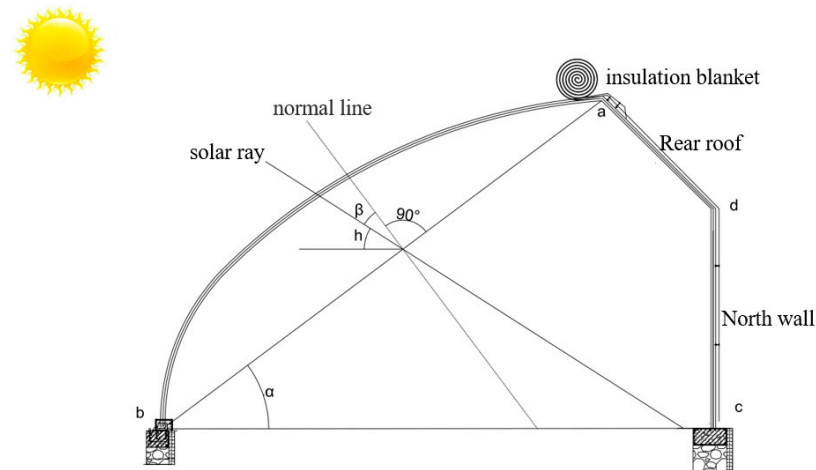


Figure 4. Profile sketch of the solar greenhouse (h ; solar altitude).

A crucial factor in determining the dynamic balance within the canopy, and expressing the degree of shading advantage of the plant, is the canopy's ability to intercept incident solar radiation, which can be represented in terms of canopy transmittance μ (%) for the solar radiation reaching the soil surface I_{gt} and the solar radiation reaching the top of the canopy I_p (W).

$$\mu = \frac{I_p}{I_{gt}} \quad (20)$$

Different plant species have different plant characteristic parameters. The effect of canopy structure factors on transmittance and extinction coefficients, leaf area index, and plant leaf inclination angle distribution are important parameters for studying plant canopy structure and calculating transmittance. In this study, the plants were made simple without considering the extinction coefficient, leaf area of the plants, or leaf inclination angle distribution. A simple cylinder was used to represent the plants, and only the shading of the plants themselves was considered [18].

In the humid environment of a greenhouse, the aluminum on the surface of the ordinary polyester-aluminized film tends to fall off. Therefore, it is necessary to use reflective film material covered with a protective plastic film on the outer layer, which is now the more commonly used polyester-aluminized film. Light is transmitted at an angle of incidence δ onto a polyester-aluminized film of thickness l . At the interface, most of the light is reflected. Some are refracted to the interior of the reflective film and then absorbed and secondarily reflected. The reflectance of the reflective film R_i is

$$R_i = t \times P \quad (21)$$

where P is the surface reflectance of the aluminized film (%), and r is the reflection ratio of the two media surfaces (%). The light transmittance of the protective film τ_i is

$$\tau_i = (1 - r_b)^2 a_b / (1 - r_b^2 a_d^2) \quad (22)$$

The surface reflectance P of the aluminized film is

$$P = r_d + r_d (1 - r_d^2) a_d^2 / (1 - r_d^2 a_d^2) \quad (23)$$

where R is the internal transmission ratio when the light proportion is absorbed as it advances through the material's interior (%) [26].

$$R = e^{-kl/\cos\theta} \quad (24)$$

where k is the extinction coefficient, taken as 0.16 to 0.18 cm, and l is the thickness of the material. R is the proportion of light that is absorbed as it advances through the interior of the material and becomes the internal transmission ratio (%).

In addition to the solar radiation and diffuse radiation absorbed by the inner surface of the solar greenhouse, the reflective film inside the heliostat reflects light in the surroundings. The amount of solar radiation in the reflective film is linearly proportional to the reflectivity of the film, which depends primarily on the smoothness of the surface. The model assumes that the surface of the reflective film is smooth and flat. Furthermore, the reflectance of the reflective film is uniform at all points on the surface. Therefore, the reflected light can be calculated as follows:

$$I_{rs} = I_{b(sr)(t)} \times R_i \quad (25)$$

where I_b is the direct sunlight solar radiance (W), and I_{rs} is reflected light radiation (W). When the reflected light reaches another surface, it is absorbed and reflected. Moreover, the above process is repeated several times in the greenhouse. Therefore, estimating the amount of reflected radiation from different surfaces is very complicated. After light is reflected four times, the intensity of the solar radiation received by the surface is too low to be ignored. Using the north wall as an example, the instantaneous total reflected radiation RE_w that reaches the surface inside the wall at the $i - th$ time is shown as follows (W):

$$RE_{w,i(t)} = \sum_{j=1}^5 \left(RE_{j,i-1(t)} \times r_j \times R_i \times \zeta_{ab,bc} \right) \quad (26)$$

$$RE_{j,i(t)} = \int_0^{L_j} \left(I_{zp(j)(t)} + I_{d,w(j)(t)} \right) dL \quad (27)$$

where j denotes internal surface, and r_j denotes the reflectance of the greenhouse surface (%) [26].

2.3. Software Introduction

The simulation tools used in this study were Rhino for the CSG geometry, Grasshopper for simulating the reflective film, which rotates based on the provided sun path, and “Ladybug & Honeybee” for evaluating daylight performance. In the software simulation process, the grid size is 0.01 m × 0.01 m. The CSG model with simple crops and the greenhouse model without crops established in Rhinoceros, and the influence of the reflective film on solar radiation in the greenhouse was simulated and calculated in Grasshopper.

3. Results

3.1. Validation of the Numerical Simulation

The north wall of the greenhouse was divided into east and west parts. The west part was covered with reflective film, while the east part remained without reflective film to measure the solar radiation received by the ground measuring points. The measured data were compared with the model calculation data (Figure 5). The numerical results for the entire simulation period were compared with the experimental results. The proposed error analysis method was used to evaluate the discrepancy between the experimental and theoretical results.

$$IA = 1 - \frac{\sum_{y=1}^N (X_{py} - X_{my})^2}{\sum_{y=1}^N (|X_{py} - X_{pave}| + |X_{my} - X_{mave}|)^2} \quad (28)$$

In error analysis Equation (28), X_{py} and X_{my} are numerical and experimental values, and X_{pave} and X_{mave} are numerical and experimental hourly mean values. The slight deviation may be because the test greenhouse floor is not flat, resulting in no uniform ground reflection. In the above, the range of IA can vary between 0 and 1. The IA value of 0 indicates complete inconsistency (numerical and experimental results do not match each other). An IA value of 1 means that the values of numerical and experimental results fully

match each other. In this study, the value of IA was 0.988, with a high level of accuracy (Figure 6).

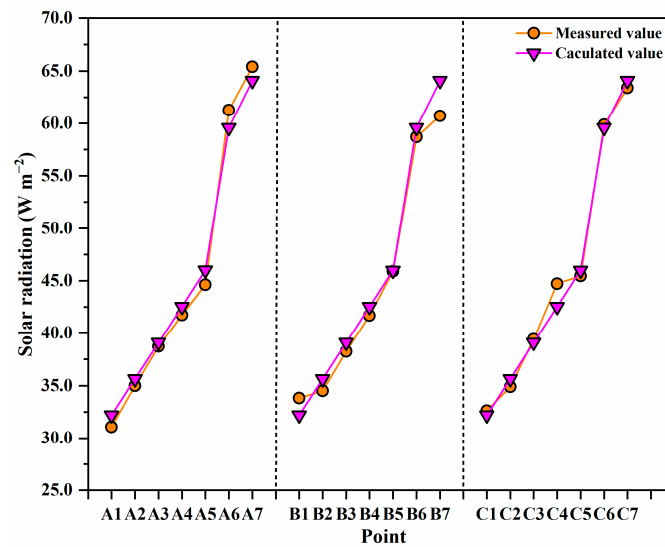


Figure 5. The light model verification of the solar greenhouse.

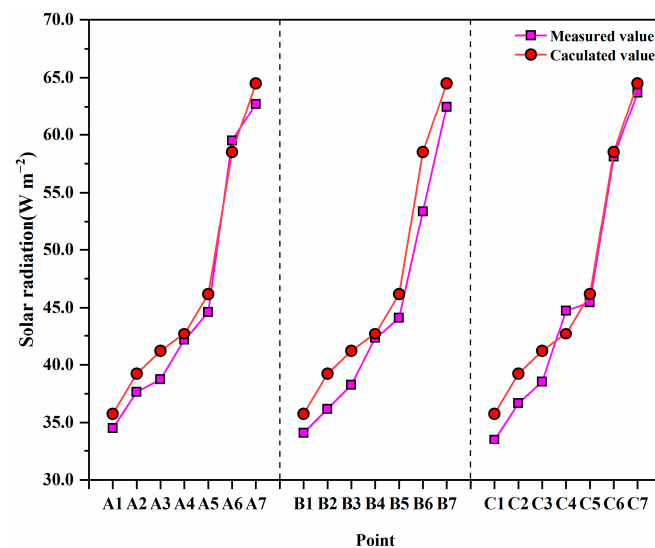


Figure 6. The reflective film model verification of a solar greenhouse.

The reasons for this deviation can be divided into three points. First, in winter, the significant temperature difference inside and outside the greenhouse often leads to the formation of a layer of water mist on the greenhouse film, affecting its light transmittance. Second, in the numerical simulation, the greenhouse film's transmittance is set to a fixed value, which does not account for variations in the greenhouse skeleton's curvature, thus impacting the light environment within the greenhouse. Third, the surface of the reflective film set in the modeling is simplified as flat, whereas in reality, reflective films can deform and have relatively uneven reflectivity, which affects their performance.

3.2. Analysis of Reflective Films at Different Positions

The reflective film can be arranged in one of five ways (Figure 7). Solar radiation on the inner surface of the CSG was monitored to analyze the impact of reflective film installation placement on the interior lighting environment. Figure 8 depicts the impact of the reflective film at various positions on the radiation of the north wall. When the

film was placed at the bottom end of the greenhouse's north roof, it achieved the highest acceptability rate for the north wall compared to the other reflective film placements in the CSG. When the film was positioned at the lower end of the north roof of the greenhouse, the cumulative radiation was 5.2% higher compared to the control group.

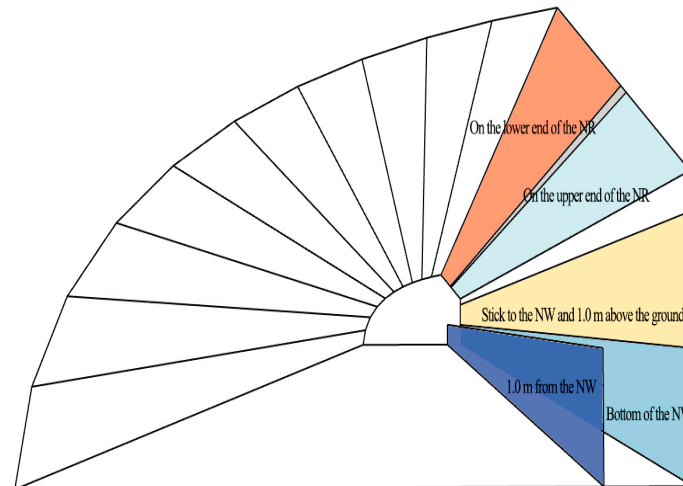


Figure 7. Five common reflective film placements.

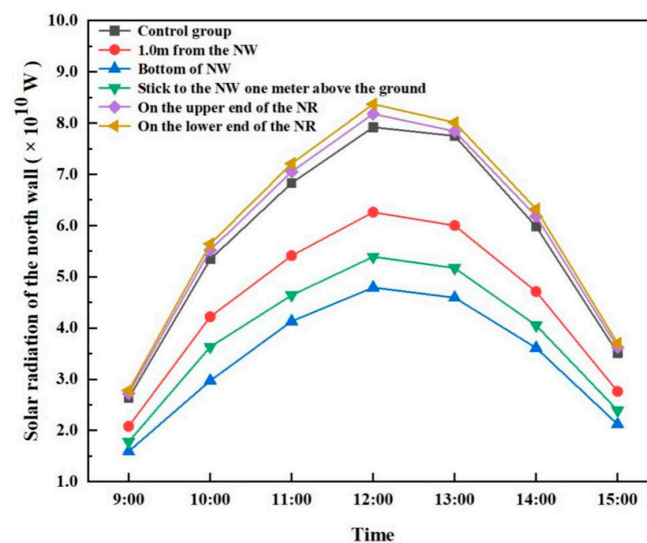


Figure 8. The influence of the reflective film at different positions on the total radiation of the north wall.

The greatest amount of light was intercepted on the ground when the reflective film was placed at the bottom of the north wall between 9:00 am and 15:00 pm. Additionally, the highest light interception at ground level occurred between 10:00 am and 14:00 pm. when the reflective film was positioned at the lower end of the north roof (Table 1). However, no significant difference was observed in the total radiation at different positions of the reflective film. The maximum light intensity increase was observed at the 1.2 m level when the reflective film was placed at the higher end of the north roof, as shown in Table 2. The difference in light intensity at the 1.2 m level was negligible when the reflective film was positioned in various locations.

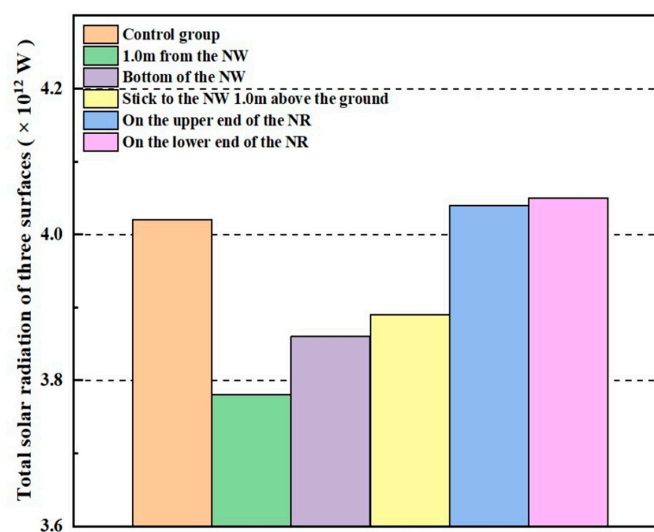
Table 1. Total radiation of the ground with different positions for the reflective film.

Time	Control Group ($\times 10^{10}$ W)	1.0 m from the NW ($\times 10^{10}$ W)	Bottom of the NW ($\times 10^{10}$ W)	On the NW and 1.0 m above the Ground ($\times 10^{10}$ W)	The Upper End of the NR ($\times 10^{10}$ W)	The Lower End of the NR ($\times 10^{10}$ W)
9:00	17.304	16.088	17.377	17.336	17.333	17.362
10:00	28.731	26.377	28.743	28.717	28.735	28.789
11:00	35.580	32.635	35.547	35.543	35.574	35.632
12:00	36.850	33.763	36.806	36.806	36.847	36.906
13:00	32.385	29.666	32.376	32.348	32.389	32.441
14:00	22.954	21.156	22.989	22.963	22.968	23.003
15:00	9.286	8.769	9.431	9.383	9.354	9.360

Table 2. Total radiation of 1.2 m levels of different positions for the reflective film.

Time	CK ($\times 10^{10}$ W)	1.0 m from the NW ($\times 10^{10}$ W)	Bottom of the NW ($\times 10^{10}$ W)	On the NW and 1.0 m above the Ground ($\times 10^{10}$ W)	The Upper End of the NR ($\times 10^{10}$ W)	The Lower End of the NR ($\times 10^{10}$ W)
9:00	16.866	16.855	16.853	16.900	16.991	16.951
10:00	28.034	28.020	28.016	27.992	28.185	28.118
11:00	34.714	34.699	34.691	34.632	34.887	34.806
12:00	35.943	35.928	35.920	35.854	36.117	36.036
13:00	31.578	31.562	31.556	31.521	31.741	31.667
14:00	22.423	22.411	22.407	22.429	22.556	22.494
15:00	9.076	9.068	9.067	9.188	9.207	9.182

The greenhouse's heat storage capability was influenced by the attachment of the emitting film to the north wall. Therefore, the reflective film's optimal performance could only be evaluated with a combination of these factors. As shown in Figure 9, when the reflective coating was applied to the north roof, these three surfaces received more solar energy. In actual manufacturing, the south roof typically has a thermal blanket, which blocks light from reaching the top end of the north roof. Additionally, it is advisable to position the reflective film at the lower end of the CSG for optimal performance.

**Figure 9.** Total solar radiation of different positions for the reflective film.

The effect of reflective film on CSG light conditions was studied using 1.2 m tall tomato plants as a simulation model. The crop canopy blocked the transmission of light, and the reflective film at different positions had different effects on the light conditions of plants. When the reflective film was placed at the corner of the north wall compared to the control group, the greatest increase in ground solar radiation was 5.27–5.33% at 13:00 and 14:00 (Figure 10).

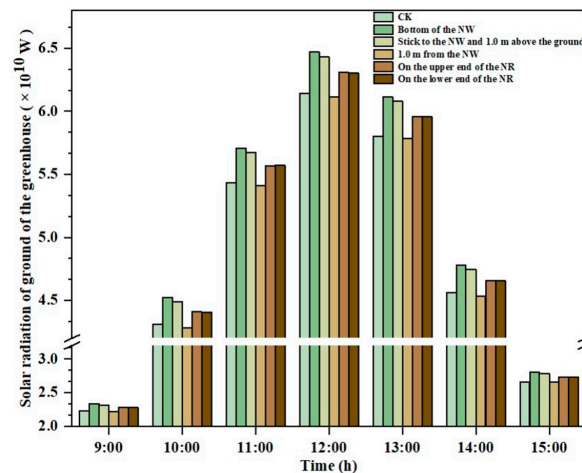


Figure 10. Effect of different angles of reflective film on ground radiation in a crop greenhouse.

This is attributed to the reflective film's close proximity to the ground and its effective reflectivity. The shaded area behind the crop receives more solar radiation. Solar radiation decreased when the reflective sheet was positioned one meter from the north wall, as the reflective sheet diminished solar radiation at ground level by blocking some light. Ground-level solar radiation increased by no more than 2.67% due to the reflective film installed at the top and bottom of the north roof. When the reflective film was applied to the corner of the north wall, the amount of solar radiation on the greenhouse floor and at the 1.2 m level increased the most (Figure 11). The overall amount of solar radiation increased globally by 2.28%. Solar radiation between the greenhouse canopies was significantly reduced by 3.49% when the reflective membrane was positioned 1 m above the ground on the north wall, indicating that more solar radiation was reflected in the plants. However, the 0.015–0.046% solar radiation from the 1.2 m plant canopy on the reflective membrane's north roof was insignificant. This is because the north roof is where the reflective membrane is situated, and as a result of the reflection process, the reflected light loses energy, with little solar radiation actually reaching the plant canopy.

When a reflective film was installed at the lower end of the north roof, the solar radiation on the north wall increased the most (Figure 12). The closer the reflector was to the surface of the object, the more solar radiation the surface received, and the less energy was lost in the air due to reflected light.

The ground and plant canopy intercept the majority of solar radiation when the reflective film was positioned at the corner of the north wall. The north wall experienced the largest increase in solar radiation when the reflective membrane was placed at the lower end of the north roof (Figure 13). It was evident that the total solar radiation reached its peak when the reflective film was installed on the north roof, considering the solar radiation reflected by the ground, the north wall, and the tree canopy.

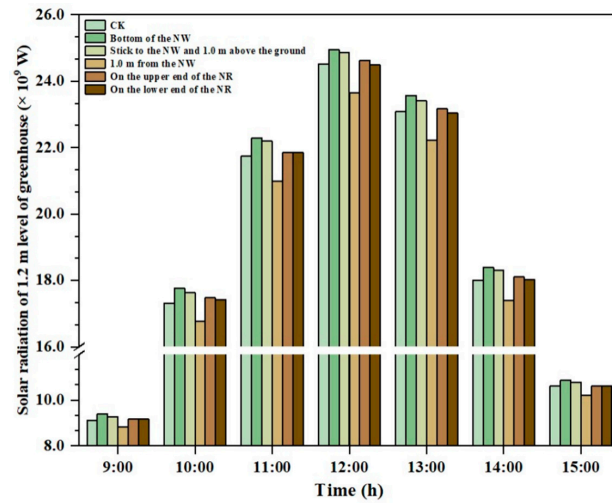


Figure 11. Effect of reflective film at different positions on the 1.2 m level of solar radiation in a crop greenhouse.

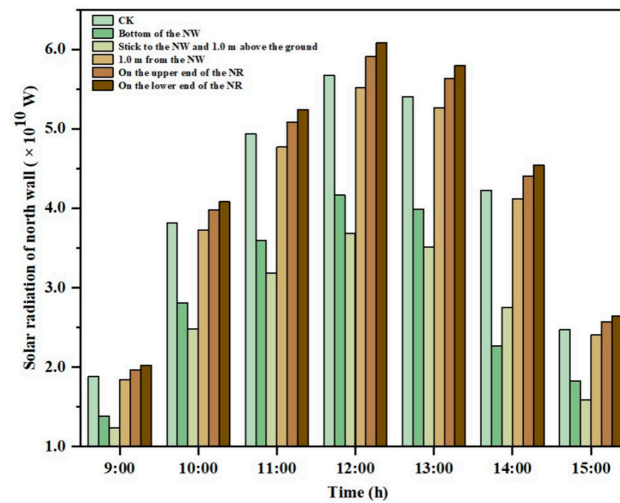


Figure 12. Influence of different angles for the reflective film on total radiation of the north wall in a crop greenhouse.

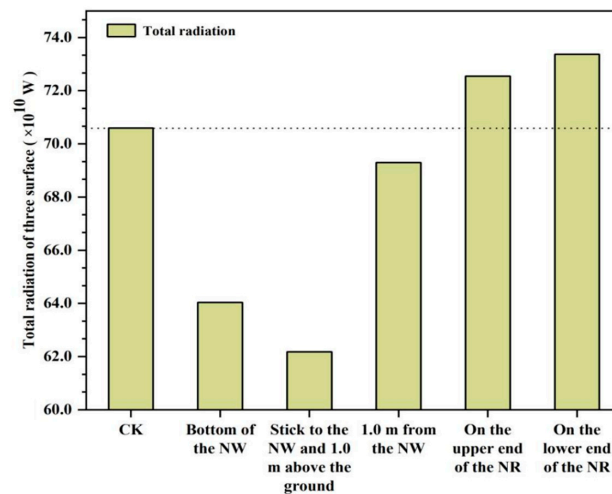


Figure 13. Effect of reflective film at different positions on the three surfaces in a crop greenhouse.

3.3. Analysis of Reflective Film at Different Angles

As mentioned previously, when the reflective film was installed on the north roof, the illumination within the room increased significantly. A light study was conducted to determine the optimal angle for the reflective film. Since the CSG's north slope angle was greater than its solar height angle, solar radiation directly struck the north roof. The north wall was positioned at a 0° angle with respect to the reflective film. Additionally, for clarity, the film rotated counterclockwise. It is essential to investigate how the various angles of the reflective film affect the interior lighting of the greenhouse.

When the reflective membrane is placed at the bottom of the north roof of the CSG, maximum light absorption was achieved on all sides, making it the ideal location. The absorption rate of the north wall decreased as the angle of the reflective membrane moved from 0° to 25° , as shown in Figure 14. This is because the reflective film is an opaque material, and as its angle increases, its surface reflects more light into the air inside the greenhouse. Additionally, due to the higher angle, less light reached the north wall of the greenhouse and was prevented from reaching it.

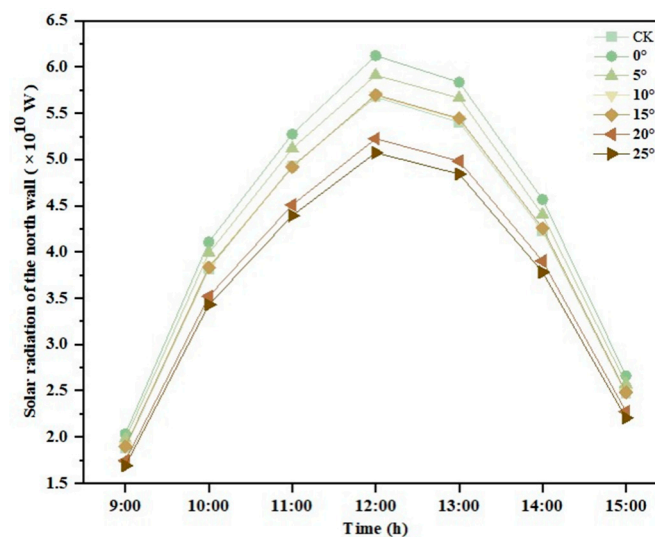


Figure 14. Solar radiation of the north wall at different angles for the reflective film.

The overall ground acceptance rate increased from 0° to 10° as the angle of the film increased. The low-angle reflective film enhanced illumination in low-light areas near the back wall by reflecting light from the north roof onto the rear ground. However, as the angle of the reflective film continued to increase to 20° , the ground light interception began to decrease. On the south side of the greenhouse, light was reflected on the ground because the angle of the reflective film was too steep. When the reflective film was too far from the ground, the amount of reflected light lost in the air reduced the solar energy received at the ground level (Table 3).

By analyzing the light interception at 1.2 m, it was found that the light interception was maximum between 9:00 and 13:00 when the reflective film was 0° (Table 4). The light interception at the 1.2 m horizontal plane reached its optimum at 14:00 when the reflective film was 5° . At 10° , the maximum light interception at the 1.2 m level was 15:00 p.m. By modifying the reflective film's angle, it was possible to change the light intensity as the plants grew in order to satisfy their lighting needs. The total interception of the reflective film on the three surfaces from 9:00 to 15:00 was compared (Figure 15). As shown in the figure, the total interception in the CSG reached a maximum of 0° of the reflective film.

To maximize the reflection of solar energy received from the north roof onto the crops, the reflective film rotated on the north roof. The greatest increase at ground level was 3.94% when the rotation angle of the reflective membrane at the lower end of the north roof was 20° (Figure 16).

Table 3. Effect of different angles of reflective film on total ground radiation in a crop greenhouse.

Time	CK ($\times 10^{10}$ W)	0° ($\times 10^{10}$ W)	5° ($\times 10^{10}$ W)	10° ($\times 10^{10}$ W)	15° ($\times 10^{10}$ W)	20° ($\times 10^{10}$ W)	25° ($\times 10^{10}$ W)
9:00	17.304	17.362	17.301	17.424	17.304	17.401	17.305
10:00	28.731	28.789	28.731	28.824	28.734	28.817	28.732
11:00	35.580	35.632	35.579	35.666	35.569	35.448	35.580
12:00	36.850	36.906	36.849	36.939	36.854	36.877	36.856
13:00	32.385	32.441	32.381	32.479	32.382	32.369	32.386
14:00	22.954	23.003	22.955	23.064	22.961	22.990	22.958
15:00	9.286	9.360	9.287	9.440	9.286	9.452	9.285

The second highest increase was 3.82% at 10°. The lowest increase at ground level was 2.44% when the reflective membrane was positioned at 0° on the north roof. The total radiation increased from 0.15% to 1.03% as the angle increased, with a progressive increase in the amount of solar energy intercepted at the 1.2 m level. However, the additional light provided by the roof reflective film to the 1.2 m horizontal plane was insufficient to completely eliminate the shadows caused by crop shading (Figure 17).

Table 4. Effect of different angles of reflective film on the total radiation at 1.2 m level in a crop greenhouse.

Time	CK ($\times 10^{10}$ W)	0° ($\times 10^{10}$ W)	5° ($\times 10^{10}$ W)	10° ($\times 10^{10}$ W)	15° ($\times 10^{10}$ W)	20° ($\times 10^{10}$ W)	25° ($\times 10^{10}$ W)
9:00	16.866	16.951	16.866	16.867	16.868	16.898	16.872
10:00	28.034	28.118	27.983	28.078	28.034	27.983	27.939
11:00	34.714	34.806	34.642	34.748	34.692	34.634	34.576
12:00	35.943	36.036	36.016	35.980	35.918	35.856	35.803
13:00	31.578	31.667	31.648	31.618	31.563	31.514	31.466
14:00	22.423	22.494	22.495	22.479	22.445	22.416	22.382
15:00	9.076	9.182	9.200	9.205	9.203	9.196	9.183

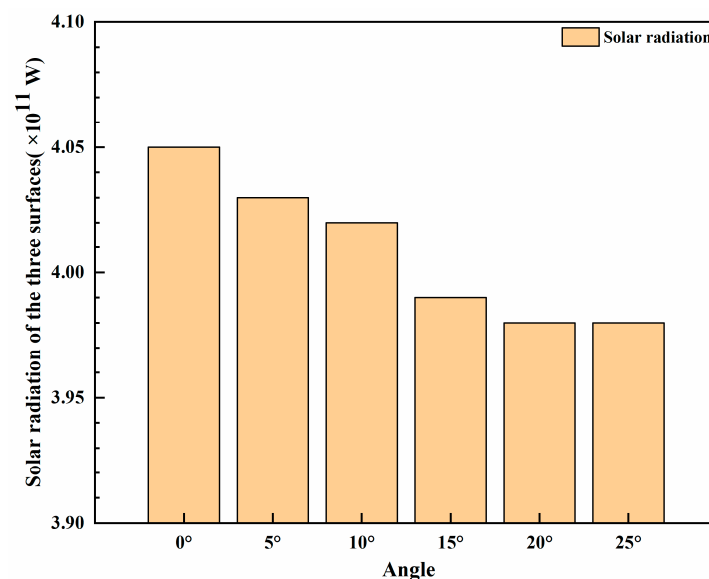


Figure 15. Effect of reflective film at different angles on the three surfaces.

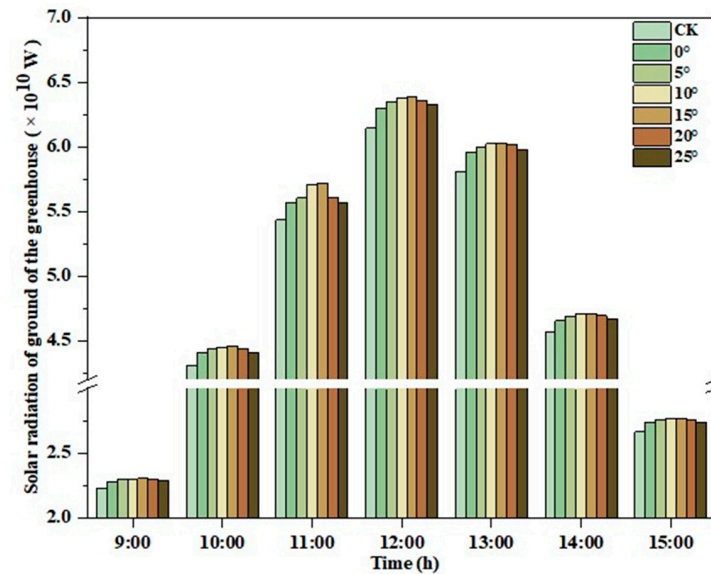


Figure 16. Effect of different angles of reflective film on ground radiation in the crop greenhouse.

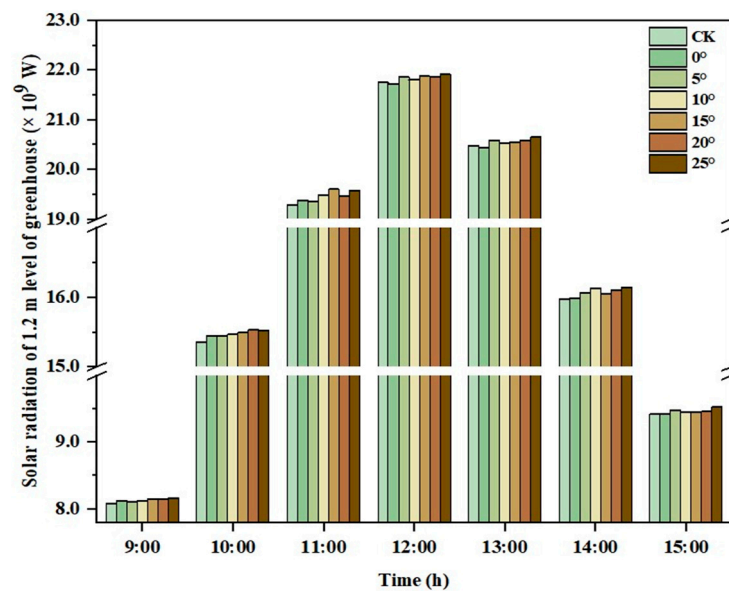


Figure 17. Effect of different angles of reflective film on the total radiation at 1.2 m level in a crop greenhouse.

The reflective membrane enhanced the north wall's light interception ability when the rotation angles were 0° and 5°, with overall increases of 7.74% and 4.43%, respectively. Even when turned at extreme angles, such as 20° and 25°, the reflective film reflected light into the air, including onto the plastic film of the front roof. However, this led to an increase in light loss, resulting in a higher light interception loss on the north wall, from 7.91% to 10.54%. The maximum total solar radiation was achieved when the reflective film was placed on the north roof at an angle of 0° (Figure 18), increasing the total solar radiation by 4.39% compared to the control group. This calculation considered the solar radiation intercepted by the ground, the north wall, and the 1.2 m level of the inner surface of the CSG.

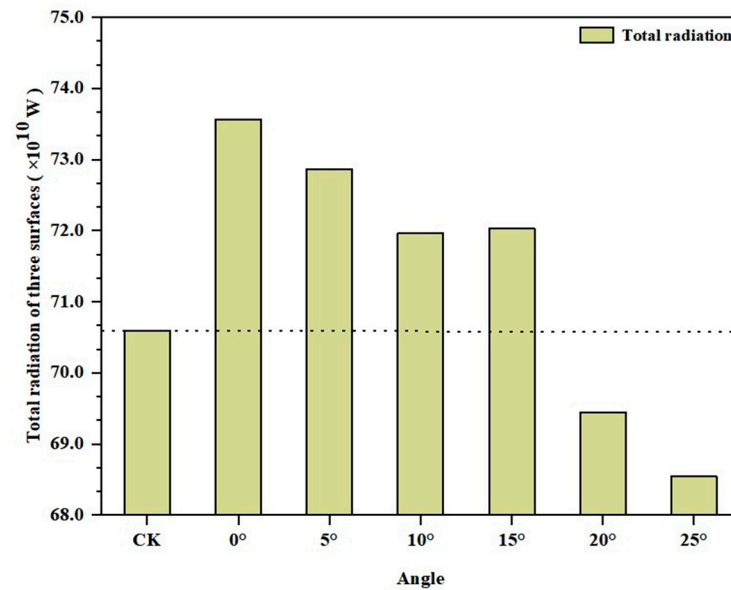


Figure 18. Effect of reflective film at different angles on the three surfaces in a crop greenhouse.

4. Conclusions

In this study, the CSG light environment simulation model was used to simulate and analyze the different positions and angles of the reflective film. By calculating the level of solar radiation on the inner surface of the greenhouse between hours 9 and 15 on the winter solstice, the optimal location for the reflective membrane was determined. The closer the plant was to the reflector, the more reflected light it received. Using 1.2 m tomatoes as an example, according to the simulated data, the light intensity of the 1.2 m horizontal position measurement point is 45,000 lx, and the suitable light intensity of tomato is 30,000–50,000 lx; thus, this study is reasonable to filter the light of crops through reflective film. The best light environment for crops was achieved when the reflector film was placed at a 0° angle on the north roof, as the total solar radiation increased by 5.33%. When the selected reflecting film angle was between 0° and 15°, the surface solar radiation rose. When the angle was expanded to 15°–25°, the light was reflected back into the air, the solar radiation of the ground and the north wall was reduced, and the light intercepting amount of the rear wall was reduced by 7.91–10.54%. Therefore, with the internal planting of tomatoes and other fruits and vegetables crops, the production process can be installed on the back of the roof to achieve the best light filling effect inside the greenhouse. The light intensity is required to be 30,000–70,000 lux; if it is too high or too low, the growth and development of melon vegetables will be affected. In addition, melon vegetables need more balanced light conditions during the growth period, so it is necessary to have good light regulation and control. In this study, the light distribution in the greenhouse was optimized, and this study can be applied to various crops.

In greenhouse production, a rotating reflective film can be installed and the angle of the film adjusted over time to meet the light needs of the different growth stages of the crop. In the production process, different reflective films can also be placed inside the greenhouse according to the planting of different types of vegetables. In a future study, we will focus on the study of different materials, different thicknesses of reflective film on the greenhouse, and plant light interception, which has great research value.

Author Contributions: W.S. and Y.Z. performed the analytic calculations and contributed to the interpretation of the results. Y.L. and X.L. took the lead in writing the manuscript. S.M. and T.L. conceived of the presented idea. L.Z. checked and revised the format of the paper. All authors have read and agreed to the published version of the manuscript.

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