Analysis of solar radiation changes in Chinese solar greenhouses with different roof structures based on a solar radiation model

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Abstract: Chinese solar greenhouses (CSGs) are important agricultural production facilities. Under non-artificial heating conditions, solar radiation is the only CSGs energy source. It is highly important to optimally obtain solar energy in greenhouse construction and production. In this study, a solar radiation model for solar greenhouses was adopted to explore the quantities of solar radiation in greenhouses considering different front roof forms and angles. Herein, the solar radiation amounts corresponding to five roof forms, namely, double-section arc, parabolic, oval, arc, and linear roofs, are compared and analyzed during the four solar periods (beginning of spring, vernal equinox, beginning of winter, and winter solstice). It was found that the solar radiation of oval roof greenhouses on the ground was the largest and was 4.44%-23.68% higher than that of parabolic roofs. In addition, the cumulative sum of light on the linear roof greenhouse wall is also the largest and was 6.02% to 12.08% higher than the parabolic roof greenhouse in the four solar terms. Moreover, the solar radiation in CSGs was compared with front roof angles of 25°, 30°, and 35°. It was observed that the solar radiation amount gradually increases with increasing angles. Notably, the variation at an angle of 35° influences the solar radiation of the paraboloidal CSGs ground and elliptical CSGs north wall to the greatest extent, which increased by 8.23% and 12.74%, respectively. This study confirms the role of front roof form and inclination angle in enhancing the greenhouse solar radiation level.

Keywords: Chinese solar greenhouse, roof structure, roof angle, solar radiation model
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1 Introduction

Chinese solar greenhouses (CSGs) are unique agriculture building facilities that are widely applied in northern China[1]. Composed of two side gables, a maintenance northern wall, a supporting skeleton, and covering material, the CSGs do not contain an indoor heating source (see Figure 1). Solar energy is absorbed through the north wall to achieve heat storage and release. Without any auxiliary heating, the greenhouse temperature can still be maintained, thus meeting the growth needs of fruit and vegetable crops[2-6].

Solar radiation is the only source of energy in the greenhouse under non-heating conditions. Cockshull et al.[7] found that light loss of 1% can lead to yield loss of 1%. The capture of incident energy by a solar greenhouse depends on the south-facing shape and the cover transmittance characteristics[8]. The front roof of a given greenhouse is the only channel for sunlight to enter. The solar radiation amount reaching the greenhouse interior is closely related to the solar radiation amount outside the greenhouse. Studies have indicated that the smaller the incidence angle is, the higher the transmittance, and vice versa[9]. To improve the greenhouse roof transmittance, the solar incidence angle should be reduced as much as possible, and the front roof should be accordingly increased. When the span and front roof angle are set, the shape of the CSGs front roof becomes a decisive factor in the solar energy amount captured by the greenhouse. The angle and shape of the front roof impose the greatest influence on the light reaching the greenhouse interior. Therefore, it is of great importance to achieve the maximum solar radiation accumulation via interception by adjusting the front roof angle and shape.

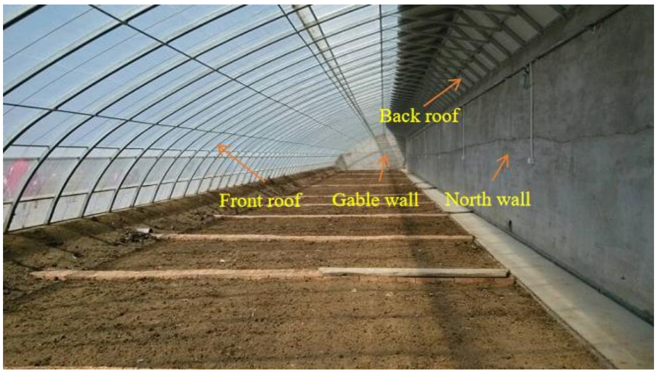

Figure 1 Chinese solar greenhouse internal structure image

Many experts and scholars have carried out extensive studies on the roof angle and roof form in front of greenhouses. A combined analysis of agricultural meteorology and optics has revealed that when the solar incidence angle is greater than or equal to 50°, the transmittance of transparent materials has little influence, and the Sun's incidence at the angle of 50° is the most reasonable

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lighting roof angle at noon on the winter solstice[10]. However, this conclusion is limited to theoretical analysis: practical problems exist in the production process, and the dip angle and the height of the north wall cannot be excessively increased. On this basis, an efficient solar greenhouse structure with a variable tilt angle is proposed. Compared with solar greenhouses with fixed lighting angles, the average illumination and average temperature of solar greenhouses with variable lighting angles are greatly improved on typical sunny and cloudy days[11,12]. Under the same span of the greenhouse, the average solar radiation of the greenhouse increases by 4.6% when the angle of the front roof increases by 2°. Appropriately increasing the angle of the front roof can greatly improve the internal illumination level of solar greenhouses[13,14].

In addition, the shape of the front roof also affects the light and temperature environment in the greenhouse[15]. To evaluate the internal illumination environments of single-section inclined solar greenhouses, paraboloidal greenhouses, and round paraboloidal greenhouses, a recent study[16] found that round paraboloidal greenhouses were notably better than the other two greenhouse types. Similarly, analyzing the internal light of the ellipse, circular arc, thrice spline, and parabola roof greenhouses revealed that the thrice spline roof is more practical than the parabola curvilinear roof[17]. Scholars have analyzed 1/7 power functions, 1/5 power functions, spline skeletons, and traditional greenhouses by using MATLAB software to simulate roofs. Through the evaluation of the three parameters of total sunshine transmittance, light distribution, and photosynthetically active radiation, it is found that the 1/7 power function roof is the best with respect to both daylight environments[18] and photosynthetically active radiation[19]. Using computational fluid dynamics (CFD) technology, the comparison and analysis of stringed roof greenhouses and bowstring roof greenhouses were carried out. Finally, considering the same calculation parameters, illumination, indoor temperature and soil temperature, wall temperature, and radiant heat flow, the bow roof solar greenhouse is superior to the string roof solar greenhouse and saves more energy[15,20]. However, the above studies only examine the variation law of the greenhouse roof type and a single tilt angle of the greenhouse front roof. Most studies were based on theoretical analysis, with the absence of actual control analysis. In addition, these studies were limited to a fixed geographical position and did not accurately explain the internal illumination variation inside solar greenhouses at different latitudes. The variation in solar radiation in greenhouses during the year was also not studied. Moreover, China occupies a vast territory, solar greenhouses are built and produced from 30° to 45° north latitude, and there are many forms of greenhouse construction, so it is impossible to use high-precision measurement equipment to collect solar radiation data in greenhouses in real-time. To solve the above problems, a solar radiation model was established in this study to test and analyze the sum of solar radiation of the greenhouse ground and wall with respect to different seasons, roof forms, and front roof inclinations. This can provide a theoretical basis for optimizing roof equations and roof inclination angles in different regions and seasons. In this study, an experiment was conducted in Urumqi, China, and a solar radiation model was adopted to establish solar greenhouse roof equations under five types of roof forms and three inclination angles. The solar radiation reaching the greenhouse interior was studied under different roof forms, and the change law of the greenhouse solar radiation amount was theoretically revealed considering various roof forms and roof inclination angles.

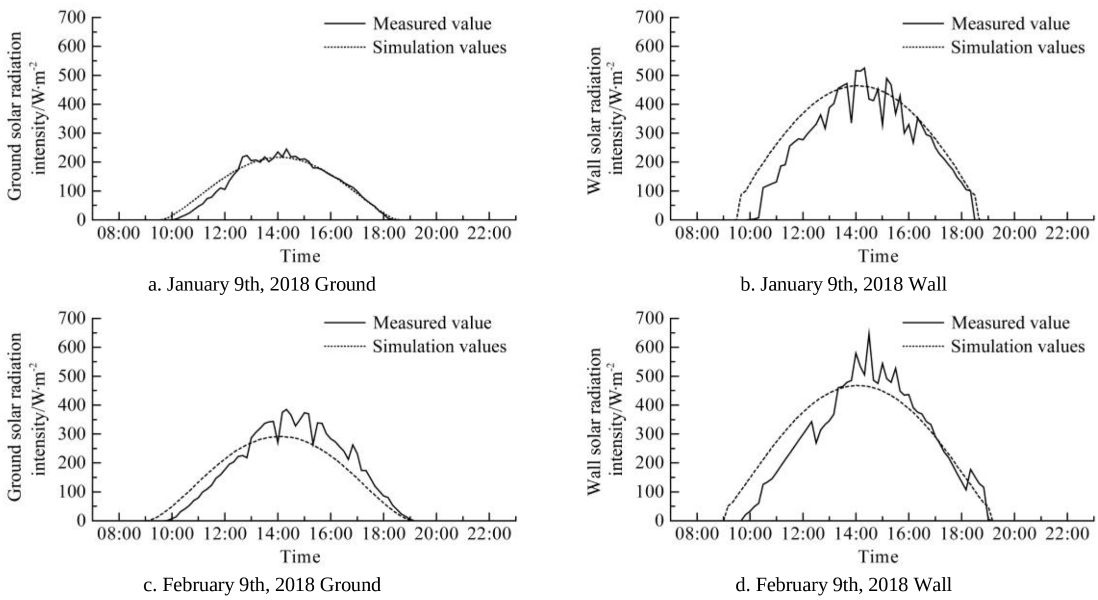
2 Materials and methods

2.1 Overview of the experiment

2.1.1 Theoretical foundation

This study is based on the solar radiation model for a solar greenhouse established by Xu et al.[21] In this model, the solar irradiance outside on a given date is obtained by consulting meteorological data, and the solar irradiance on the front roof of the greenhouse is obtained by comprehensively considering the influence of the atmosphere. Moreover, by establishing a physical relationship between solar irradiance and the greenhouse front roof, the incidence angle and light transmittance of the front roof at any position and time were determined. Finally, the solar irradiance at different positions on the ground and north wall surfaces was calculated.

The theoretical data were compared to actual test data, as shown in Figure 2. Four evaluation indexes were introduced, including the mean bias error (MBE), mean absolute bias error (MABE), root mean square error (RMSE), and determination coefficient (R^2), as listed in Table 1. A solar radiation model with a determination coefficient above 0.95 was obtained. The model predicts the solar radiation amount considering different areas, latitudes, and types of solar greenhouses.

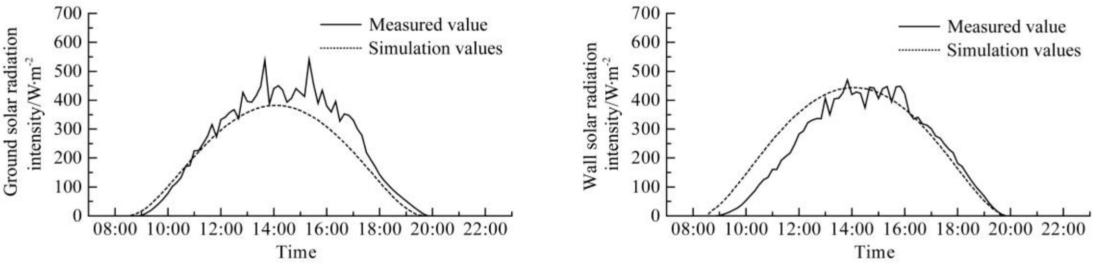


a. January 9th, 2018 Ground

b. January 9th, 2018 Wall

c. February 9th, 2018 Ground

d. February 9th, 2018 Wall



e. March 6th, 2018 Ground   f. March 6th, 2018 Wall

Figure 2 Comparison of the calculated and measured solar irradiation values of the ground and wall

Table 1 Greenhouse solar radiation model test data

Date	Position	MBE/W m^{-2}	MABE/W m^{-2}	RMSE/W m^{-2}	R^2
January 9, 2018	Ground	4.80	13.88	16.70	0.99
	Wall	51.72	62.94	72.84	0.95
January 9, 2018	Ground	−16.17	29.49	39.75	0.98
	Wall	24.23	54.09	65.06	0.95
March 6, 2018	Ground	−63.46	63.48	79.18	0.98
	Wall	35.94	39.94	50.19	0.97

Note: MBE: Mean bias error; MABE: Mean absolute bias error; RMSE: Root mean square error.

2.1.2 Overview of the CSG

This study adopted the San Ping Teaching Practice Base of the Xinjiang Agricultural University CSG, China (43.92 °N, 87.35 °E), as an example. This CSG faces south and is oriented 8 ° south by west, covering 60 m along the east-west direction, with a span of 8 m, a ridge height of 3.8 m, a north wall height of 2.8 m, and a front roof angle of 30 °. The front roof of the greenhouse relies on polyolefin (PO) plastic film. The light transmittance of the film base is 65%. The rear roof comprises 0.1-m colored polystyrene-covered steel plates, and the north wall of the solar greenhouse adopts a composite wall composed of a 0.01-m cement mortar plaster layer, a 0.5-m solid clay brick masonry layer, and a 0.1-m colored polystyrene-covered steel plate, as shown in Figure 3.

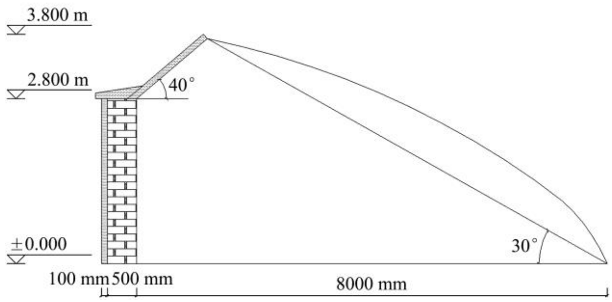


Figure 3 Schematic diagram of the solar greenhouse structure

Considering the intersection of the greenhouse wall and ground as the coordinate origin, the governing equation of the roof of the solar greenhouse section is obtained by fitting, as shown in Figure 4. The back roof of the greenhouse is a straight line, while the front roof comprises two arcs.

$$\begin{aligned} &5x-6y+16.8=0, && (0\le x<1.2)\\ &(x+1.72)^2+(y+10.6)^2=14.71^2, && (1.2\le x<7)\\ &(x-5.28)^2+(y+1.15)^2=2.95^2, && (7.0\le x\le 8)\end{aligned} \qquad (1)$$

where, x is the distance from the point on the roof to the north wall, m; y is the distance from the point on the roof to the ground, m.

2.1.3 Experiment processing

Selecting the greenhouse described in Section 2.1.2 as an example, roofs of different shapes were built considering the same greenhouse north wall, span, and back roof angle. Then, the tilt angle of the greenhouse front roof was varied with the same span. In this study, 30 ° was regarded as the control, and 25 ° and 35 ° were selected as the experimental groups. The maximum interval reached 10 °, and each gradient was 5 °, all within the normal range of actual production. Compared to previous studies, the span is larger, the corresponding radiation variation range is wider, and the variation is clearer.

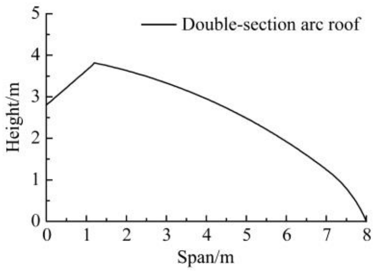


Figure 4 Schematic diagram of the front roof structure of the Chinese solar greenhouse

In this study, MATLAB 2016 was employed to simulate solar radiation data, and Origin 2017 was used to process the data and generate graphs.

2.2 Establishment of the roof equations considering the different roofs and dip angles

The front roof angle of the greenhouse is determined by the height of the roof and the span of the greenhouse. When the front roof is an arc, the roof slope is not constant. At present, greenhouse arcs mainly satisfy the following conditions: 1) the monotonous decrement function; 2) first-order guidance value between −90 ° and 0 °[16].

2.2.1 Roof equation at a roof dip angle of 30 °

On the basis of the original solar greenhouse, roof equations under the different forms are established with the same span, wall height, and north roof. The roof forms include parabolic roofs, oval roofs, circular roofs, and existing linear roof types. The angle of the front roof is the same as that of the original greenhouse front roof: approximately 30 ° (Figure 5).

Parabolic roof:

$$\left(-\frac{361}{170}\right)x-y^2+\frac{1444}{85}=0, \qquad (1.2\le x\le 8) \qquad (2)$$

oval roof:

$$\frac{x^2}{6.8^2}+\frac{y^2}{3.8^2}=1, \qquad (1.2\le x\le 8) \qquad (3)$$

circular roof:

$$(x-1.2)^2+\left(y+\frac{159}{38}\right)^2=\left(\frac{159}{38}+3.8\right)^2, \quad (1.2\le x\le 8) \qquad (4)$$

linear roof:

$$y=\begin{cases}\left(-\frac{4}{9}\right)x+\frac{13}{3}, & (1.2\le x\le 7.5)\\ -2x+16, & (7.5<x\le 8)\end{cases} \qquad (5)$$

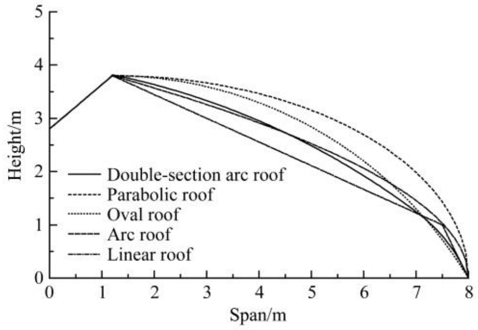


Figure 5 Roof curve when the roof angle is 30 °

2.2.2 Roof equation at a roof dip angle of 25 °

On the basis of the same span, the front roof angle of the greenhouse was changed by lowering the height of the CSG wall, and five roof equations were established with the front roof angle at 25 °(Figure 6).

double-section curved roof:

$$\begin{cases}(x-1.2)^2+(y+6.4)^2=9.6^2, & (1.2\le x\le 7.0)\\(x-5.28)^2+(y+1.15)^2=2.95^2, & (7.0<x\le 8)\end{cases} \tag{6}$$

parabolic roof:

$$\left(-\frac{128}{85}\right)x-y^2+\frac{1024}{85}=0, \quad (1.2<x<8) \tag{7}$$

oval roof:

$$\frac{x^2}{6.8^2}+\frac{y^2}{3.2^2}=1, \quad (1.2\le x\le 8) \tag{8}$$

circular roof:

$$(x-1.2)^2+(y+5.625)^2=8.825^2, \quad (1.2\le x\le 8) \tag{9}$$

linear roof:

$$y=\begin{cases}\left(-\frac{22}{63}\right)x+\frac{76}{21}, & (1.2\le x\le 7.5)\\-2x+16, & (7.5<x\le 8)\end{cases} \tag{10}$$

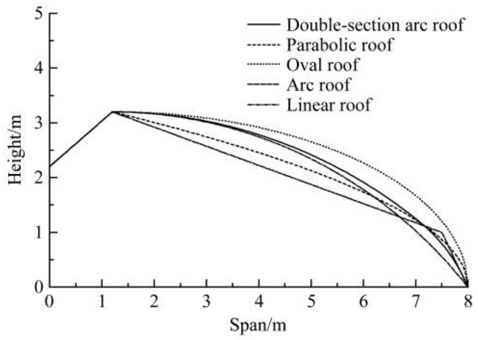


Figure 6 Roof curve when the roof angle is 25 °

2.2.3 Roof equation considering a roof dip angle of 35 °

On the basis of the same span, the front roof angle of the greenhouse was changed by adding the height of the CSG wall, and five roof equations were established with the front roof angle of 35 °(Figure 7).

double-section curved roof:

$$\begin{cases}(x-1.2)^2+(y+3.278)^2=7.978^2, & (1.2\le x\le 7.0)\\(x-5.08)^2+y^2=2.92^2, & (7.0<x\le 8)\end{cases} \tag{11}$$

parabolic roof:

$$\left(-\frac{2209}{680}\right)x-y^2+\frac{2209}{85}=0, \quad (1.2<x<8) \tag{12}$$

oval roof:

$$\frac{x^2}{6.8^2}+\frac{y^2}{4.7^2}=1, \quad (1.2\le x\le 8) \tag{13}$$

circular roof:

$$(x-1.2)^2+(y+2.567)^2=7.267^2, \quad (1.2\le x\le 8) \tag{14}$$

linear roof:

$$y=\begin{cases}\left(-\frac{37}{63}\right)x+\frac{227}{42}, & (1.2\le x\le 7.5)\\-2x+16, & (7.5<x\le 8)\end{cases} \tag{15}$$

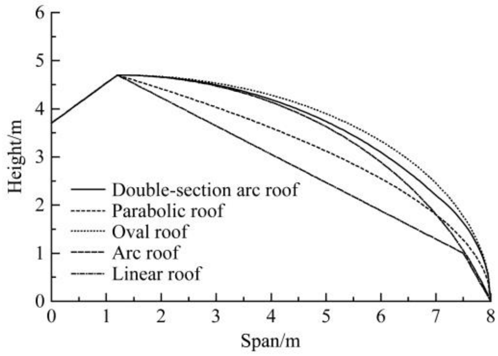
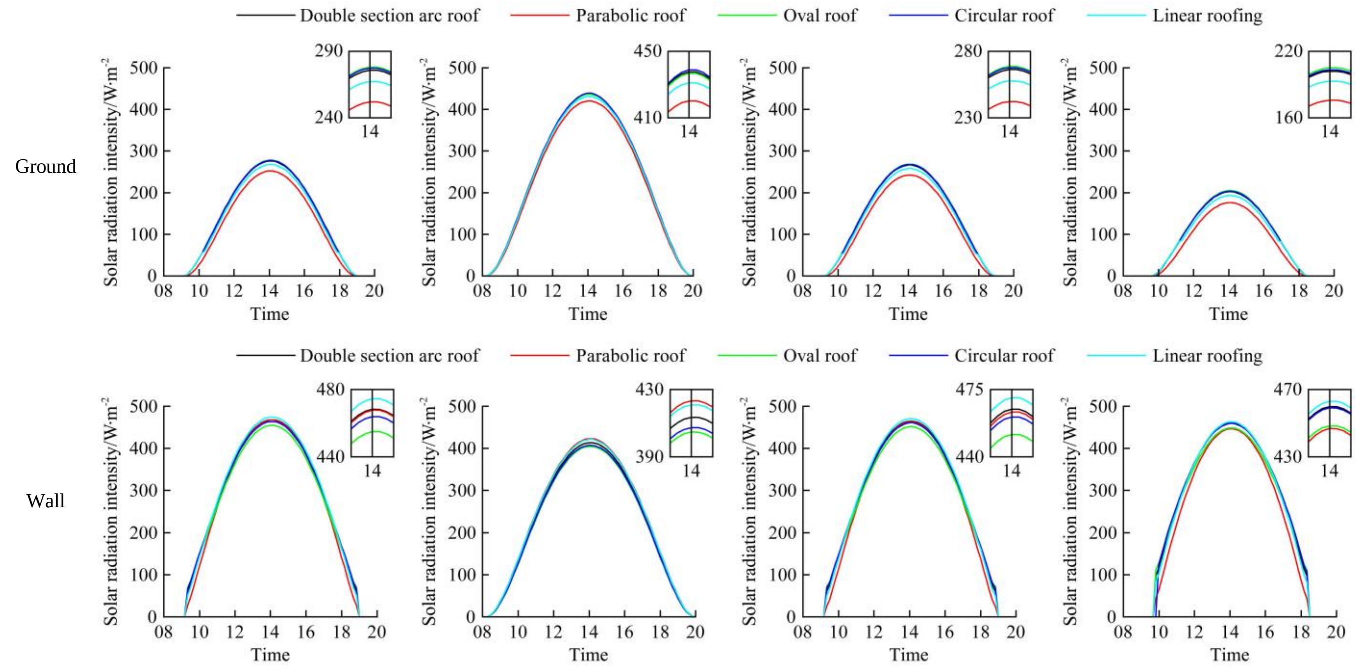


Figure 7 Roof curve when the roof angle is 35 °

3 Results

3.1 Solar radiation inside a greenhouse under the different roof forms

Based on the mathematical model, the solar radiation amount inside the greenhouse was analyzed considering the different roof forms at various times (Figure 8). Five roof forms, double-section arc, parabolic, oval, circular, and linear, were used to study the solar radiation changes in CSGs with different roof structures. Interestingly, excluding the day of the vernal equinox, the sum of solar radiation on the greenhouse ground descended in the order of oval, circular, double-section arc, linear, and parabolic roof greenhouses on the day of the start of spring, the start of winter and on the winter solstice (Figure 8a). In addition, the average solar radiation of oval roof greenhouses on the ground is the largest and is 4.44%-23.68% higher than that of parabolic greenhouses (the worst roof type in the context of this study). Similarly, the maximum daily solar radiation (at 14:00, GMT+8:00) also decreased in the same order for the five greenhouse types (Figure 8a, upper enlargement). However, during the day of the vernal equinox, the circular roof greenhouse had the best light conditions. The north wall is a site that can receive solar radiation and convert it into thermal energy to feed back to the plants in the greenhouse. Therefore, the solar radiation on the north wall was also examined to compare the influence of roof shape on the illumination environment in the greenhouse. The linear roof greenhouse has the highest solar radiation intensity and the strongest light (at 14:00, GMT+8:00) on the day of the start of spring, the start of winter, and the winter solstice (Figure 8b). The average solar radiation in the linear roof greenhouse is 6.02%-12.08% higher than that in the parabolic roof (the worst roof type in the context of this study). Interestingly, compared with other forms of greenhouses, the parabolic greenhouse has the lowest solar radiation in the morning (approximately 9:00-11:00, GMT+8:00) and afternoon (approximately 17:00-19:00, GMT+8:00), except on the day of the vernal equinox (Figure 8b). Together, these results suggest that roof forms can shift solar radiation on the ground and wall inside greenhouses. In addition, oval roofs are suitable for greenhouse ground to accept more solar radiation. However, the walls of greenhouses with linear roofs can store more thermal radiation.

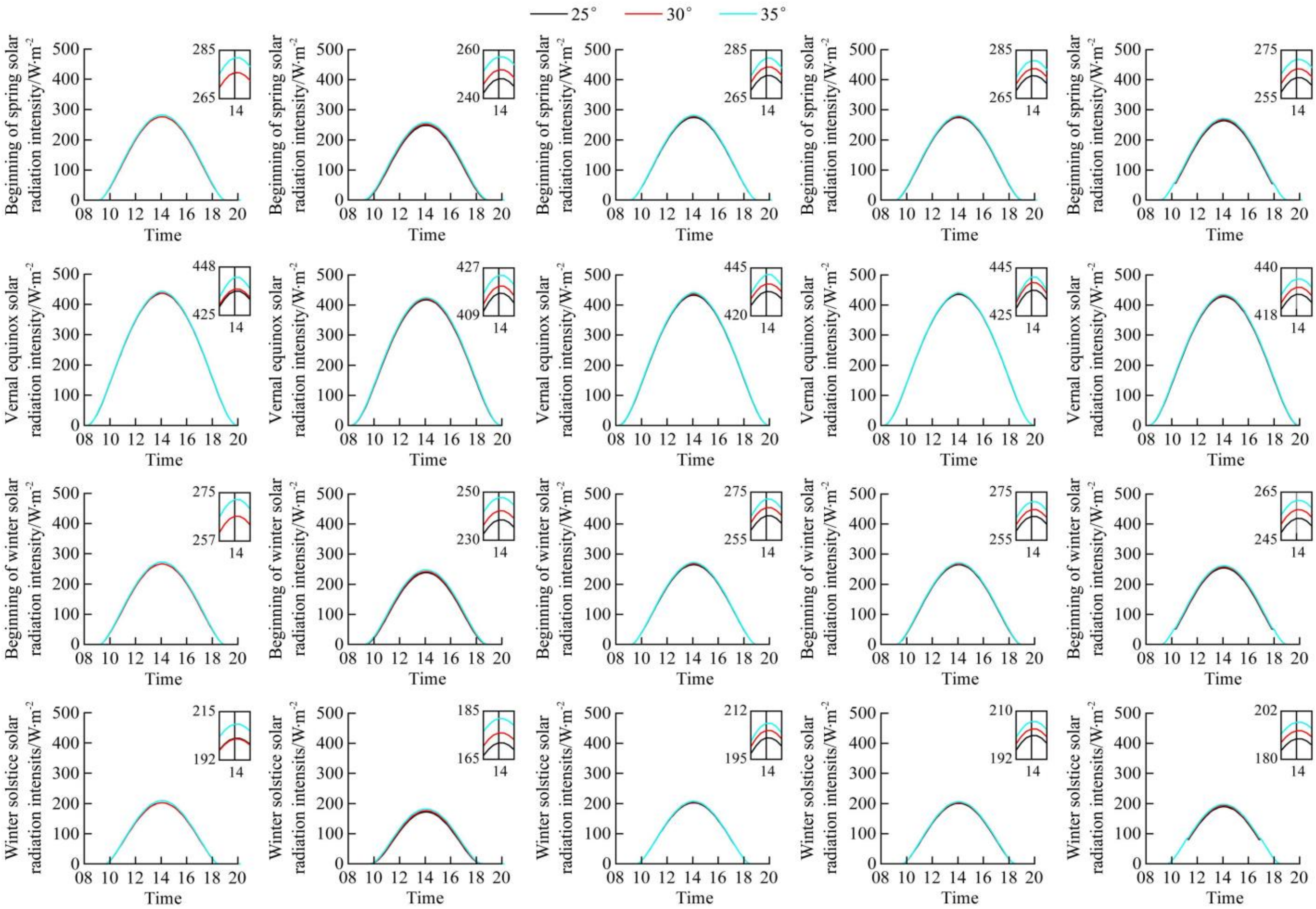


a. Beginning of Spring b. Vernal Equinox c. Beginning of Winter d. Winter Solstice

Figure 8 Solar radiation in five different front roof greenhouses during the four solar periods

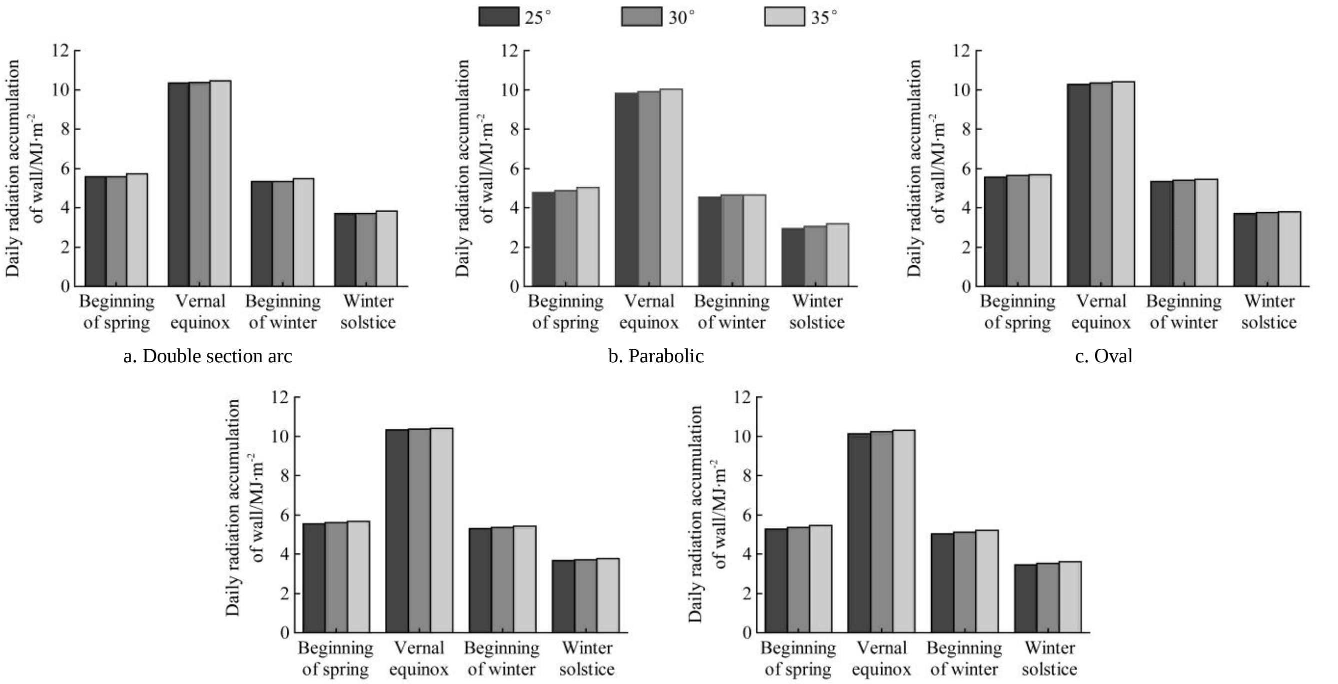
3.2 Solar radiation on the ground inside the CSGs with different roof inclination angles

Next, the influence of roof inclination angles on solar radiation was explored inside the CSGs. Therefore, three gradually changing angles (25°, 30°, and 35°) were set, and a solar radiation model was used to analyze the amount of solar radiation and variation rules inside the greenhouse according to roof angle changes in different periods. Both the change in roof form and roof angle can shift the solar radiation on the greenhouse ground in all seasons. The same variation law rose first and then decreased and reached the maximum value at approximately 14:00 (GMT+8:00) (Figure 9). To analyze the effects of solar radiation



a. Double section arc b. Parabolic c. Oval d. Circular e. Linear

Figure 9 Solar radiation on the ground inside the Chinese solar greenhouses with different roof forms and roof inclination angles caused by angle changes, when the roof angle is greater, there is a greater amount of solar radiation on the ground inside the greenhouse (Figure 10). In addition, among the five types of greenhouses, the maximum solar radiation of parabolic greenhouses increased the most at the winter solstice. This value increased by 10.05 W/m^2 and 5.95 W/m^2 for the greenhouse roof angle at 35° compared to those at 25° and 30°, respectively (Figure 9b). Similarly, the daily cumulative solar radiation of the parabolic greenhouse varied the most during the equinox, with values of 0.26 MJ/m^2 and 0.15 MJ/m^2, respectively (Figure 10). Although an increase in the inclination angle can increase the solar radiation on the greenhouse ground, it has little effect on the maximum solar radiation and daily accumulated solar radiation.



a. Double section arc b. Parabolic c. Oval d. Circular e. Linear

Figure 10 Total radiation received on the ground inside the Chinese solar greenhouses with different roof forms and roof inclination angles

3.3 Analysis of solar radiation on the CSG wall at different roof inclination angles

The north wall is an important part of the CSGs and offers excellent thermal insulation and heat storage performance. The same method was therefore used to analyze the effects of variations in the inclination of greenhouses with five different roofs on the solar radiation exposure of the walls. The pattern of solar radiation variation on the walls is consistent with that on the ground, and the overall performance of the greenhouse solar radiation is positively correlated with the roof inclination angle (Figure 10 and Figure 12). Among the five types of greenhouses, oval greenhouses have the largest value for both maximum solar radiation and daily accumulation at the winter solstice. Compared with the angles at 25° and 30°, the maximum solar radiation inside the oval greenhouse with the roof angle at 35° was increased by 40.98 W/m^2 and 20.66 W/m^2 (Figure 11), and the daily accumulation of solar radiation was increased by 1.20 MJ/m^2 and 0.58 MJ/m^2 (Figure 12). Together, these results suggest that the roof inclination angle can shift the intensity of solar radiation received on the north wall, regardless of the type of roof formed inside the greenhouse. In addition, when the roof angle was increased, more solar radiation illuminated the north wall.

3.4 Total solar radiation inside greenhouses with different roof forms and roof inclination angles

To investigate the variation in total solar radiation inside the different greenhouses, this study also analyzed the internal accumulated solar radiation (Figure 13). Parabolic greenhouses were found to be the worst of the five types of roofs in the seasons of spring, winter, and winter solstice. However, the linear greenhouses achieved the best solar radiation performance among greenhouses with three roof angles during the vernal equinox. Overall, a comparison of different inclination angles and the daily accumulation of solar radiation with respect to different roof forms showed that round roofs were more favorable for solar energy to enter the greenhouse at higher roof angles, while linear greenhouses were more favorable for greenhouses at low inclination angles.

4 Discussion

Using the solar radiation model to analyze the illuminance of solar radiation in the greenhouses with different roof forms, the change in roof variation in different seasons exerts a certain impact on the solar radiation in the CSG. The main reason for this is that the incident angles of the solar rays corresponding to the different Sun-roofing curves are different. However, this study did not further investigate the changing state of the incidence angle at different positions of different transparent roofs.

The study found that with the increase in the inclination of roofs, the internal solar radiation in the greenhouse increased to some extent. This is consistent with the research results of Li et al.[13] regarding the relationship between the solar radiation amount and inclination. In this study, it is shown that the changes of 30° and 35° in double-section curved roof greenhouses are inconsistent with those of other types of greenhouses on the vernal equinox. That is, the quantity of solar radiation with an angle of 30° is greater than that at 35°. In the studies of Li et al.[13] , a temperature gradient increase step size of 2° was used, and in this study, a temperature gradient increase step size of 5° was utilized to highlight the effect of the change in roof inclination on the solar radiation inside the greenhouse. There is an optimal value in the range of 30°-35°. As the roof angle continues to increase, the incidence angle of the double-section circular arc front roof increases, which leads to a decrease in light transmittance and ultimately leads to a reduction in solar radiation in the greenhouse.

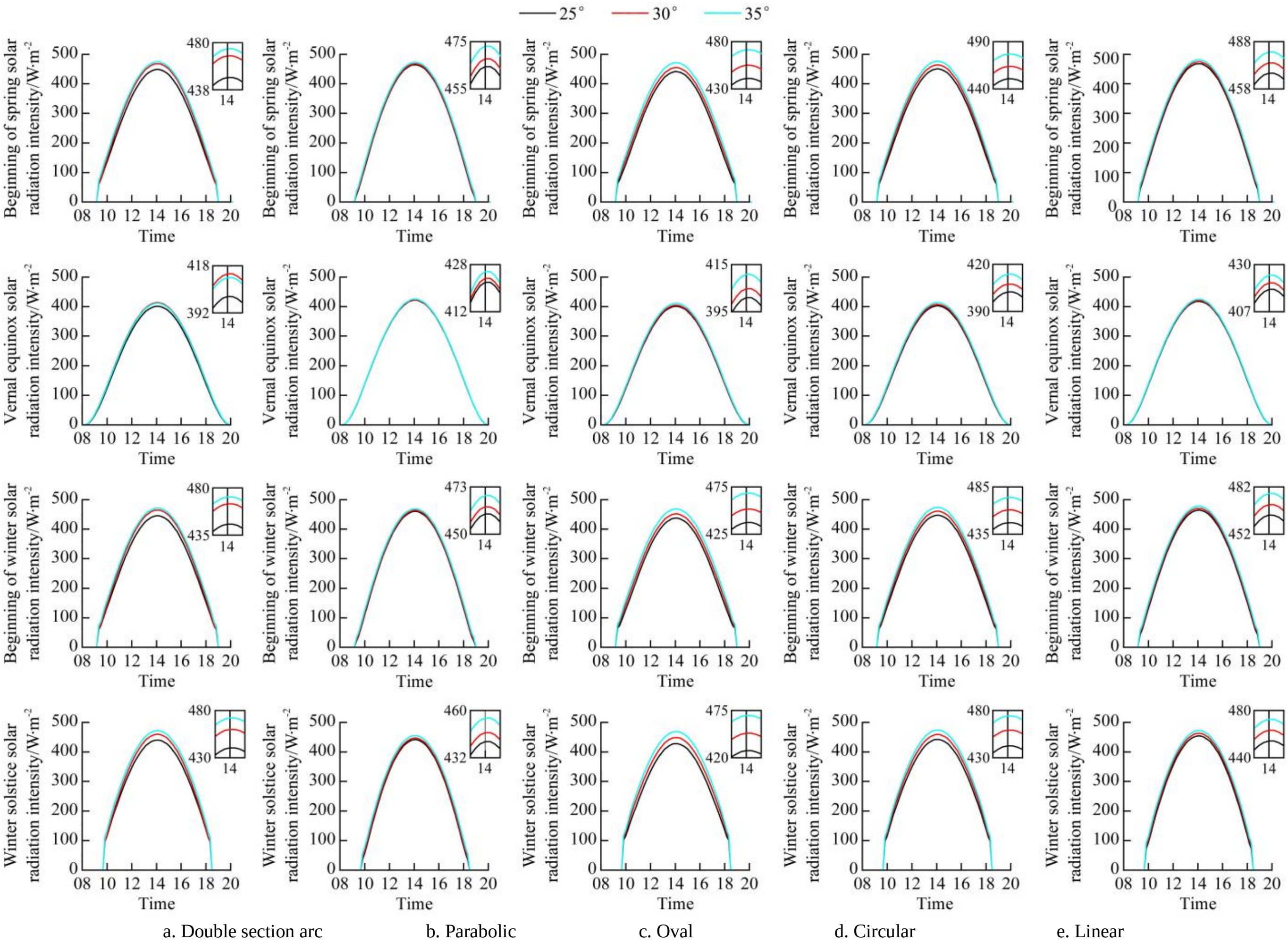


Figure 11 Solar radiation on the wall inside the Chinese solar greenhouses with different roof forms and roof inclination angles

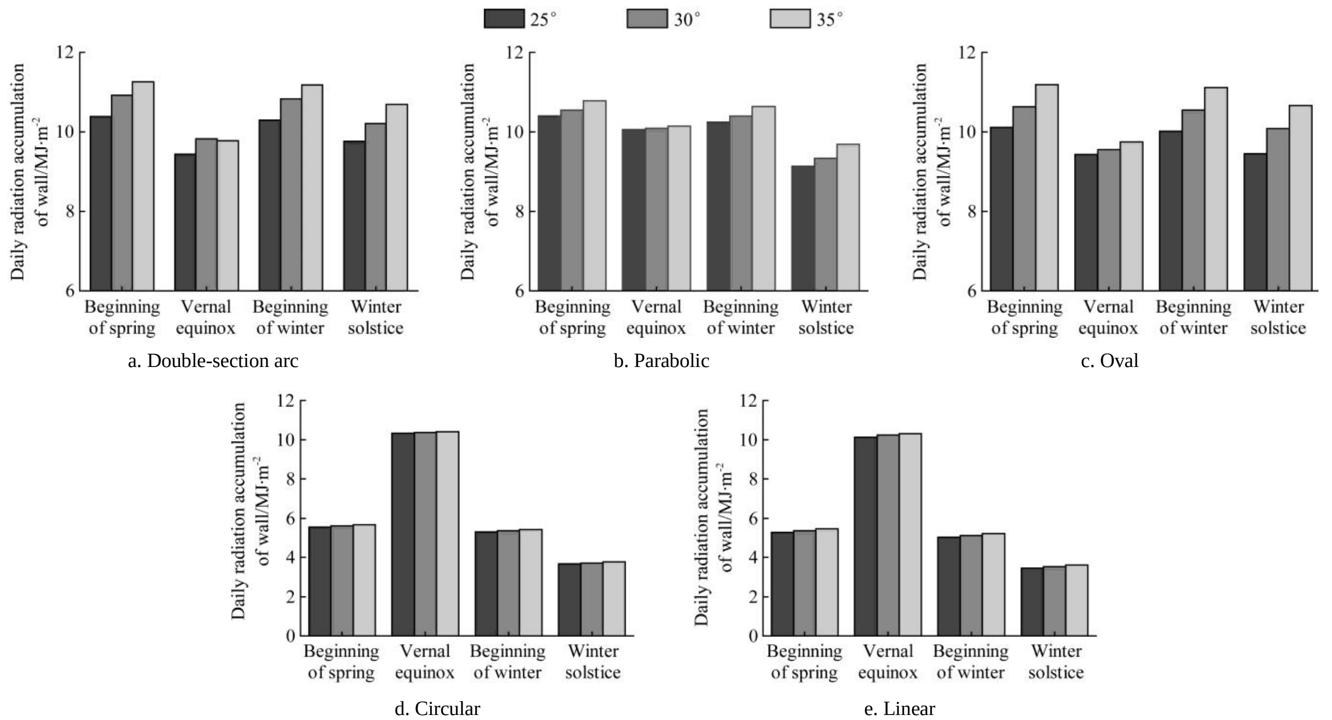
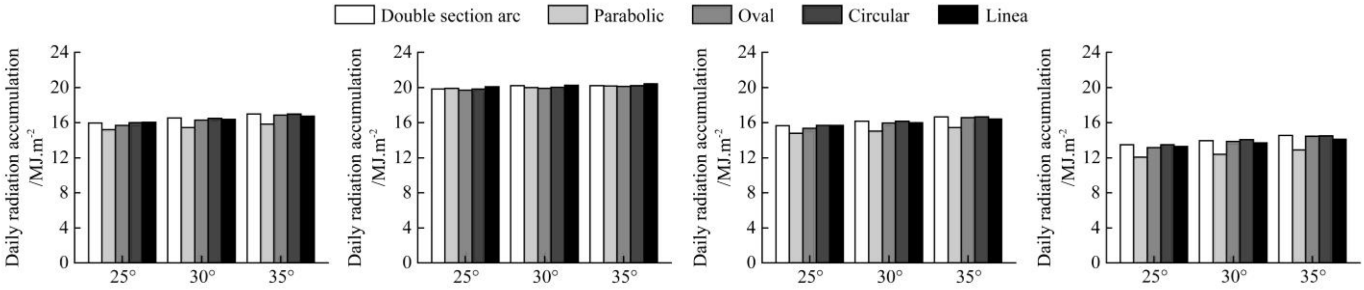


Figure 12 Total radiation received on the wall inside the Chinese solar greenhouses with different roof forms and roof inclination angles



a. Beginning of Spring b. Vernal Equinox c. Beginning of Winter d. Winter Solstice

Figure 13 Cumulative solar radiation amount in greenhouses with different roof forms and roof inclination angles

The angle between the plastic film roof on the sunny side of the greenhouse and the ground plane is referred to as the front roof angle[22]. The front roof angle here is different from the actual roof angle. Due to the solar elevation angle continuously changing throughout the day, the incidence angle corresponding to a certain point on the front roof was also constantly changed. The roof dip angle differs across the entire arc roof and remains the same across the entire straight roof. The solar incidence angle is related to the roof shape, i.e., to the slope of the tangent line of the roof at the point of solar incidence.

Regardless of whether the roofing angle or the shape of the roof changed, the primary effect was the modulation of the incident relationship between the roof and solar rays. Different roofing forms are combined in different seasons to establish the corresponding relationship between the best roof and solar rays and to maximize the use of solar energy. Further research and exploration are needed.

This comprehensive study found that the change in greenhouse roofs has little effect on the total solar radiation inside the greenhouse, while the change in wall envelope is required to change the roof inclination, which is time-consuming and laborious. Therefore, new methods are needed to improve the light and temperature environments of greenhouses without changing the structure and roof form; however, there is a contradiction between the lighting and insulation of greenhouses. The next step will be to continue to explore the factors affecting the light-temperature balance of the greenhouse, summarize the balanced relationship between light and temperature, maximize the use of solar energy, and optimize the light-temperature environment of the greenhouse.

5 Conclusions

The solar model for solar greenhouses adopted in this study has been verified and attains high accuracy. In addition, the change in the roof shape of solar greenhouses exerts a certain influence on solar irradiance. The solar irradiation of the ground and wall of the parabolic roof greenhouse represents the worst among the five kinds of greenhouse roofs. The ground solar radiation of elliptic greenhouses is the largest, 4.44%-23.68% higher than that of elliptic greenhouses in the four solar terms. The rectilinear greenhouse wall has the largest solar radiation, which is 6.02% to 12.08% higher than the ellipse in the four solar terms.

In the case of a constant roof form and different inclinations of the front roof, the solar radiation of double-section circular, parabolic, elliptical, circular, and linear roofs increase with increasing roof inclination. For ground-level solar radiation, parabolic roofs showed the greatest variation (8.23%), while elliptical roofs showed the greatest variation in solar radiation at the north wall (12.74%). The adjustment of roof angle among the five greenhouses during the equinox has a small effect on the solar radiation of the walls, while the angle variations during the spring, winter, and winter solstice seasons impose a certain effect on the solar radiation of the greenhouse walls.

In general, the change in roof shape exerts a certain influence on the total amount of solar radiation in the greenhouse under the same front roof angle, but the influence is not significant. The double-section circular greenhouse exhibited good performance in all seasons, and the linear greenhouse achieved good performance on the Spring Equinox. It is can improve the solar radiation inside the greenhouse when the angle of the roof was increased properly. Usually, under the same front roof angle condition, the change in roof shape exerts some effect on the total solar radiation in the greenhouse, but the effect is not obvious. The two-section circular greenhouse performed well in all seasons, and the linear greenhouse performed well in the equinox season. The parabolic greenhouse performed the worst in all three seasons except for the Vernal Equinox. Solar radiation in the greenhouse can be improved by appropriately increasing the roof angle.

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