EFFECTS OF INSULATION COVER MEASURES ON THE TEMPERATURE ENVIRONMENT OF CHINESE SOLAR GREENHOUSE
/
不同保温覆盖措施对日光温室温度环境的影响

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ABSTRACT
Chinese solar greenhouses (CSGs) are the important agricultural building facility with highly efficient and sustainable utilization of solar energy. In order to improve the thermal insulation performance and reduce the heat loss, different insulation cover measures were applied to Chinese solar greenhouses. In this study, a solar greenhouse with an internal insulation blanket (SG1), a greenhouse with an internal blanket and an internal plastic film (SG2) and a greenhouse with an external blanket, an internal blanket and an internal plastic film (SG3) were chosen as experimental objects to analyze their indoor temperature environment. The results indicated that the differences of solar radiation interior among three greenhouses were similar, which was not the main reason that caused the differences of the temperature environment in the three greenhouses. During the tests, the nighttime average temperature was increased by 2.1-3°C by adding the cover materials, and the duration of nighttime temperature greater than 8°C was increased by 33.5%-38.2%. In addition, the cost is increased by adding the insulation cover materials, but it will be beneficial for greenhouse production to reduce additional energy consumption.

摘要
日光温室是中国重要的农业设施，它能高效可持续的利用太阳能。为了改善温室保温性能从而减少热损失，研究了不同覆盖方式对日光温室温度环境的影响。该研究对单被内保温日光温室（SG1），单被双膜内保温日光温室（SG2）以及双被双膜内保温日光温室（SG3）进行了温度环境测试。研究结果表明：三座温室内太阳辐射的差异较小，而它们的温度环境的差异并非由所获得太阳辐射差异所造成。在测试期间，通过增加保温覆盖物，可使夜间平均温度增加 2.1～3° C，而且相较于 SG1，夜间温度大于 8° C 的持续时长也能够提升 33.5%～38.2%。此外，尽管增加保温覆盖使得成本上升，但是对于长期温室生产并减少额外供热是有利的。＊

INTRODUCTION
The greenhouse is an essential building facility for plant growth (*Irfan et al., 2021*). Under the situation that fossil energy is increasingly exhausting, and the environmental pollution caused by fossil fuel burning is inevitably getting worse, energy saving in agricultural greenhouses has become a key issue (*Gennadii et al., 2023*). The applications of solar energy in greenhouses have provided the renewable and clear energy for the needs of greenhouse heating (*Gorjian et al., 2021*). Chinese solar greenhouses (CSGs) are widely promoted in China because of their energy savings, improved efficiency, reduced energy consumption and low cost. Although frequently facing the harsh environmental conditions in cold winters, they had achieved notable economic and social benefits (*Tong et al., 2022)*.

CSGs are generally enveloped by the walls, the roof and its cover materials. The rear wall plays an important role to absorb and store solar energy projecting on it. The roof is covered with a fixed and transparent plastic film for lighting during daytime, and a rolled thermal insulation blanket covers the roof for heat preservation at night (*Cao et al., 2019; Tong et al., 2013*). However, there was approximately more than 60% of the total heat loss lost through the roof (*Xu et al., 2017*). In recent decades, multi-layered composite materials blankets were developed and widely used for the greenhouses to reduce the heat loss *(Qiao et al., 2008*).

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Hu et al., (2014), compared the insulation performance of three composite blankets having the same thickness, but the quality was different. The results showed that the insulation performance of the heaviest and porous blanket was the best than that of the compact blanket, and the lightweight blanket was not recommended to use in windy areas because of its poor windproof. *Liu et al., (2015),* analyzed the impact factors of the insulation performance by comparing various kinds of composite blankets. The insulation performance of blankets increased with their thickness in a certain weight. Although many materials, such as PE foam, spray-bonded cotton, waterproof fabric etc., have been used in blankets and the optimum applications need to be further investigated.

To improve the thermal environment performance of the greenhouses, different insulation cover measures was used for insulation. Thermal screens were drawn over the crop decreasing the heat loss by 35-60% at night (*Bailey, 1981*). Thermal curtains resulted in energy savings of about 28.7% in a double-layered plastic greenhouses at night (*Hyung-Kweon et al., 2018*). The external insulation system was applied to the multi-span greenhouse reducing by 36% of the glass roof heat loss (*Chen et al., 2023*).

Qu et al., (2004), designed and used a thin internal thermal screen in a solar greenhouse. The results showed that the nighttime air temperature inside the greenhouse covered with the screen increased by 0.7-1.0 °C. The energy saving effect of thermal screen used in solar greenhouse was poorer than that used in multi-span greenhouses. However, it was non-negligible that the internal insulation system had a significant impact on reducing the heat loss through the roof. In high latitude and cold regions, the insulation cover measures, represented by multi-cover system which integrated the internal insulation and the external insulation, could improve the thermal performance of solar greenhouses (*Liu et al., 2022*). The Chinese researchers' studies indicated that the insulation cover measures improved the thermal performance of solar greenhouses and decreased the energy consumption (*Bai et al., 2022; Wu et al., 2015*).

Because of the complex and diverse climate conditions in different regions of China, which are many types of solar greenhouses, it is crucial to select a suitable type of solar greenhouse to ensure optimum light and thermal performance based on the local environment. In this study, three solar greenhouses with different insulation cover measures were tested to analyze the interior temperature environment in Baotou, Inner Mongolia, China (40.6°N, 110°E). Comparing the experimental results, their temperature performance was evaluated. The study can provide an effective choice for greenhouse producers to reduce energy consumption.

MATERIALS AND METHODS

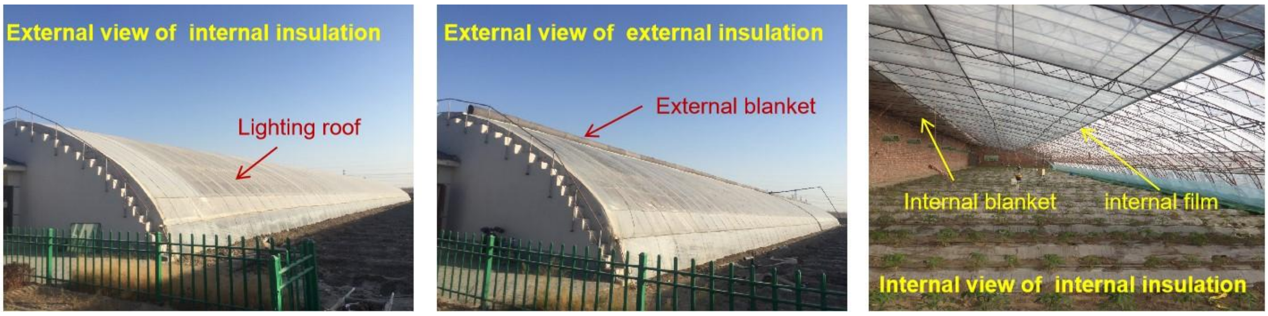
Tested solar greenhouses

In this study, SG1, SG2 and SG3 are chosen for testing. As shown in Figure 1, three solar greenhouses have basically the same structure which is double-layer steel frame structure. The orientation, the span, the length from east to west, the rear wall height, the ridge height and the wall thickness are 5° south to west, 10 m, 100 m, 4.2 m, 5.7 m and 1.5 m, respectively. SG1 is a greenhouse with single film and single internal thermal insulation. SG2 is a greenhouse with double film and single internal insulation. SG3 is a greenhouse with double film and double insulation. Other parameters are shown in Table 1. Moreover, both the air vents of SG1 and SG2 locate at the bottom of the south roof and the rear roof, and the air vent of SG3 locates at the bottom and top of the south roof due to the covered external insulation.

During the tested period, the opening and closing times of thermal blankets were 9:00 to 16:00. Tomato was cultivated in these greenhouses. Drop irrigation was used for improving the water efficiency. Other managements were consistent. To reduce the heat losses and energy consumption, there was no extra heating and ventilation in these greenhouses.

Experimental device and method

The data measurement planes were the 1/3 and 2/3 of east-west length direction of the greenhouse. Indoor temperature and solar radiation were measured by using the Farmland Microclimate Observation System (DZN1, Tianjin Meteorological Instrument Factory, China) which was placed in the middle of the span with the height of 1.5 m. Outdoor tested points were placed 1.5 m above the open ground. The measurement range of temperature was -40°C to 80°C with an uncertainty of 0.2°C, and the measurement range of solar radiation was 0 to 1400 W/m^2 with an uncertainty of 5%. The data collecting interval was 15 min.



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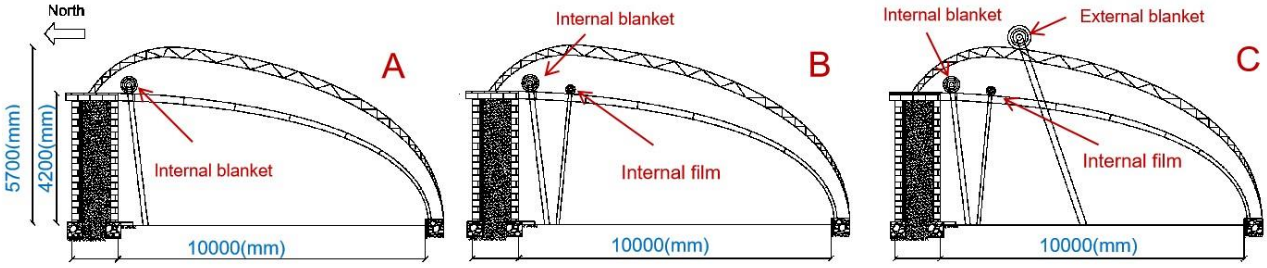

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Fig. 1 - Photo and schematic diagrams of tested solar greenhouses
(a) photos; (b) sectional view

A – a solar greenhouse with an internal blanket (SG1); B – a solar greenhouse with an internal blanket and an internal plastic film (SG2);
C – a solar greenhouse with an external blanket, an internal blanket and an internal plastic film (SG3).

Table 1

Specific parameters of different greenhouses

Number	Type	Cover materials		Insulation materials	
		External film	Internal film	Internal blanket	External blanket
SG1	External film and internal insulation	PO film (0.15 mm)	N/A	Expandable PE foam (13 mm)	N/A
SG2	Double film and internal insulation	PO film (0.15 mm)	PE film (0.03 mm)	Expandable PE foam (13 mm)	N/A
SG3	Double film and double insulation	PO film (0.15 mm)	PE film (0.03 mm)	Expandable PE foam (13 mm)	Waterproof and recycled cotton (25 mm)

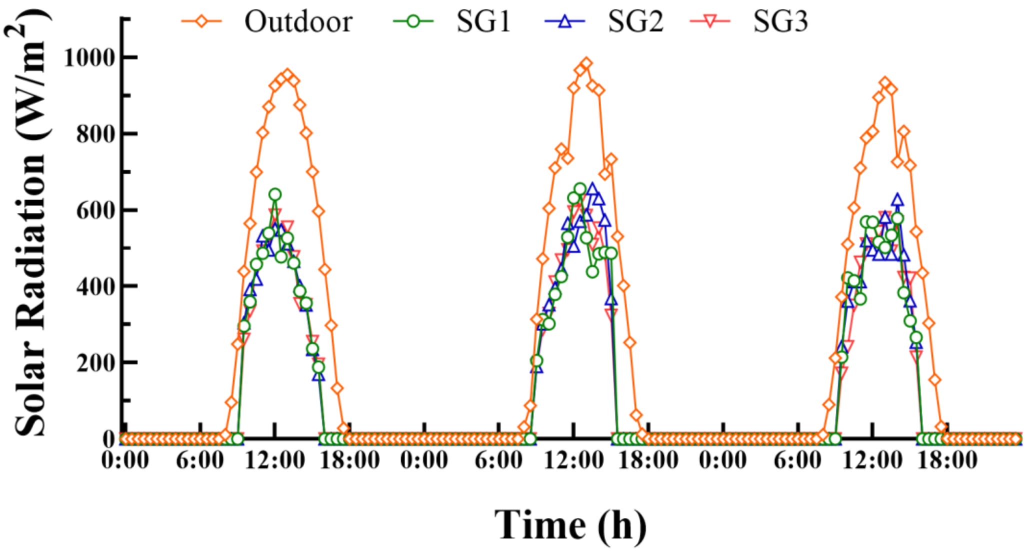
RESULTS AND DISCUSSION

Influence of solar greenhouse structure on the transmitted solar radiation

Solar radiation directly affects the light demand of crops and the heat demand in the solar greenhouse. During testing, December to February are the cold months for greenhouse production, and January is the coldest one with low temperature, freezing damage occurring frequently. Therefore, the transmitted solar radiation in January directly reflects the lighting and heat storage of the greenhouse, thereby affecting the thermal insulation performance. In order to describe the solar radiation of different greenhouses under different weather conditions more accurately, the solar radiation data of consecutive sunny days and consecutive cloudy days were selected to analyze (Jan 4 to 6 and Jan 20 to 22).

Figure 2 presents the solar radiation variations of three greenhouses under different weather conditions that vary with the solar radiation outdoor. In consecutive sunny days, the diurnal average solar radiation intensity of SG1, SG2 and SG3 were 428.3 W/m^2, 436.8 W/m^2 and 422.4 W/m^2 during lighting period, respectively. In consecutive cloudy days, the diurnal average solar radiation intensity of SG1, SG2 and SG3 were 212.9 W/m^2, 204.1 W/m^2 and 187.1 W/m^2, respectively. The solar radiation of three greenhouses on sunny and cloudy days presented consistent trends with minor differences. Therefore, the light performance of three greenhouses is consistent under same structure and weather conditions.

The differences of the temperature environment in three greenhouses are not mainly caused by the differences of transmitted solar radiation. However, they highly depend on the exterior solar radiation to ensure sufficient solar energy to provide a suitable environment for crop growth. Hence, it is crucial to take effective measures for thermal insulation to reduce the heat loss through the south roof in harsh winters.



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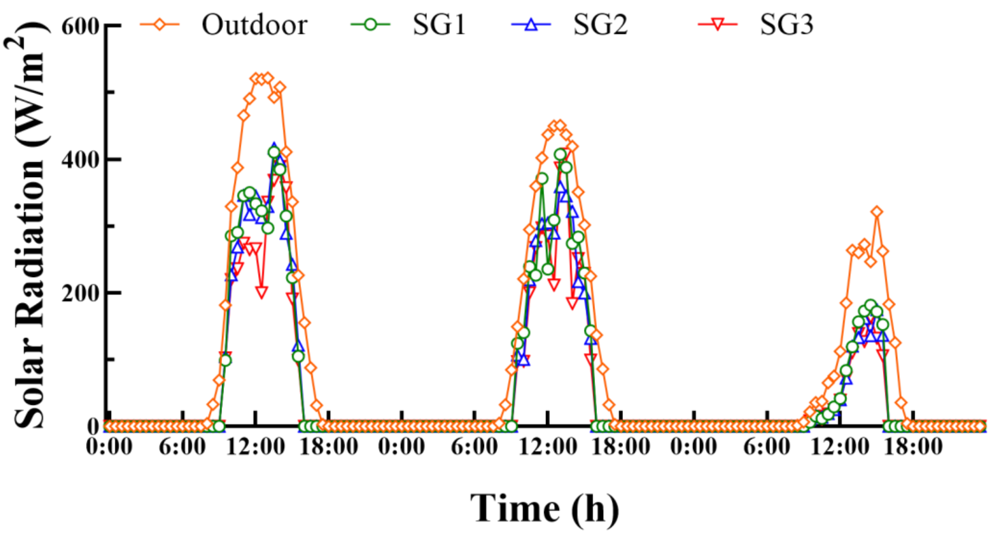

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Fig. 2 - Variations of indoor and outdoor solar radiation in different solar greenhouses

(a) consecutive sunny days; (b) consecutive cloudy days.

Influence of different insulation cover measures on the greenhouse temperature environment

Stability of the temperature environment

The crop growth relies on the congenial environment inside greenhouses. The temperature is significantly affected by greenhouse structures and heat preservation measures. The indoor and outdoor temperature variations of 31 days (December 15 to January 15) of three greenhouses were analyzed in Figure 3. During the period, the indoor temperature variations of three greenhouses indicated the insignificant differences at daytime (with the thermal insulation blankets rolled up at 9:00 a.m.) and its opposite at nighttime (with the thermal insulation blankets rolled down at 16:00 p.m.), while the nighttime outdoor temperature was lower. It was showed that effective insulation measures can ensure a relatively stable thermal environment with temperature changed sluggishly for the greenhouses during nighttime.

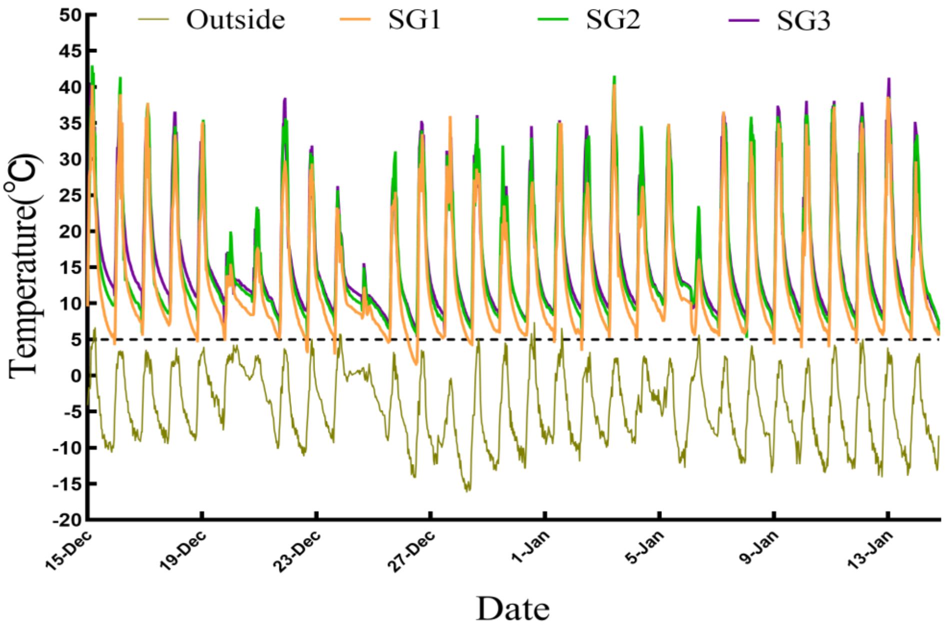


Fig. 3 - Variations of indoor and outdoor air temperature in different solar greenhouses for 31 days

Weather adaptability of solar greenhouses with insulation cover measures

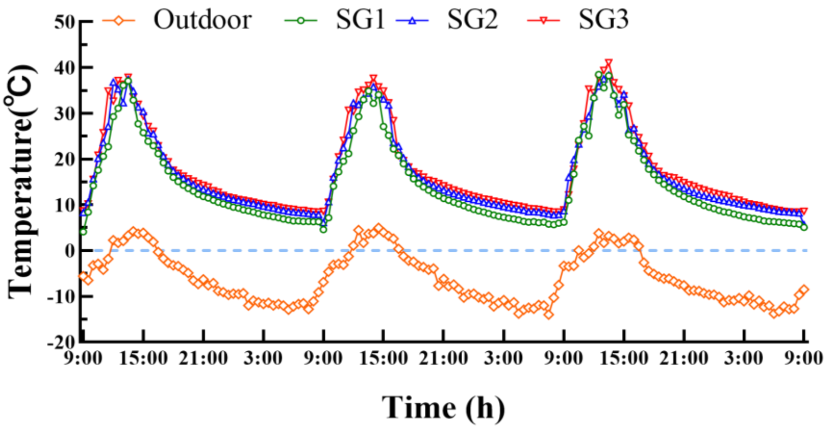
To further evaluate the temperature environment of three greenhouses, the representative continuous nice and bad days were selected, as shown in Figure 4.

On sunny days (January 11 to January 14), the indoor temperature increased rapidly with sunlight entering through the south roof of three greenhouses. When the indoor temperature reached the maximum temperature at 13:00 to 14:00, then it was gradually decreasing.

The average daytime indoor temperature of three greenhouses and the average daytime outdoor temperature were 14.6°C, 16.6°C, 17.4°C and -5.9°C, respectively, and the average temperature differences between indoor and outdoor were 20°C of SG1, 22.5°C of SG2 and 23.3°C of SG3, respectively.

The average nighttime indoor temperature of three greenhouses and the average nighttime outdoor temperature were 10.5°C, 12.4°C, 13.1°C and -8.5°C, respectively, and the average temperature differences between indoor and outdoor were 19°C of SG1, 20.9°C of SG2 and 21.6°C of SG3, respectively. On cloudy or overcast days, because of less solar radiation, the daytime indoor temperature rose slowly in three greenhouses, and this situation had not improved under bad weather conditions.

The average daytime indoor temperature of three greenhouses and the average daytime outdoor temperature were 10.4°C, 12.3°C, 13.1°C and -1.9°C, respectively, and the average temperature differences between indoor and outdoor were 12.3°C of SG1, 14.2°C of SG2 and 15°C of SG3, respectively. The average nighttime indoor temperature of three greenhouses and the average nighttime outdoor temperature were 8.5°C, 10.4°C, 11.1°C and -3.1°C, respectively, and the average temperature differences between indoor and outdoor were 11.6°C of SG1, 13.5°C of SG2 and 14.2°C of SG3, respectively.



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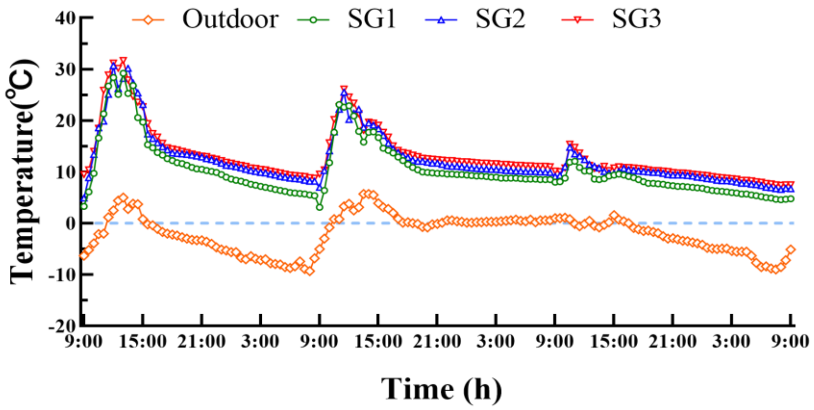
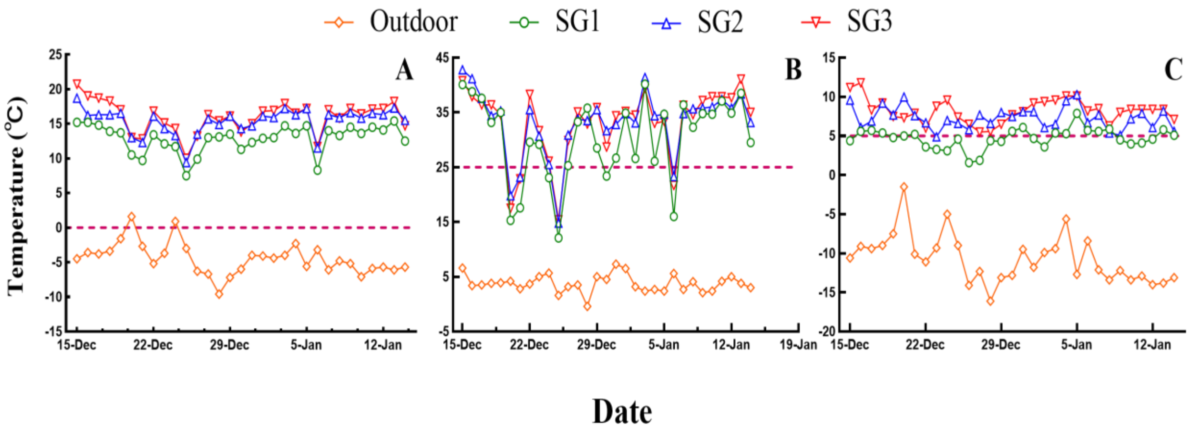


(b)

Fig. 4 - Variations of temperature in different solar greenhouses in different weather condition (a) sunny days; (b) cloudy or overcast days.

Nighttime temperature enhancement and time distribution

During the 31 days, as shown in Figure 5(a), the average daily temperature of SG1, SG2 and SG3 were 12.9°C, 15.3°C and 16°C, respectively, which were greater than 5°C. The average daily maximum temperature of SG1, SG2 and SG3 were 30.4°C, 33.2°C and 33.2°C, respectively. The average daily minimum temperature of SG1, SG2 and SG3 were 4.7°C, 7.3°C and 8.2°C, respectively. The nighttime minimum outdoor temperature ranged from -0.81°C to -15.9°C, and there were 18 days which the nighttime minimum outdoor temperature was below -10°C. And the days were 28 that the nighttime minimum outdoor temperature was below -5°C.



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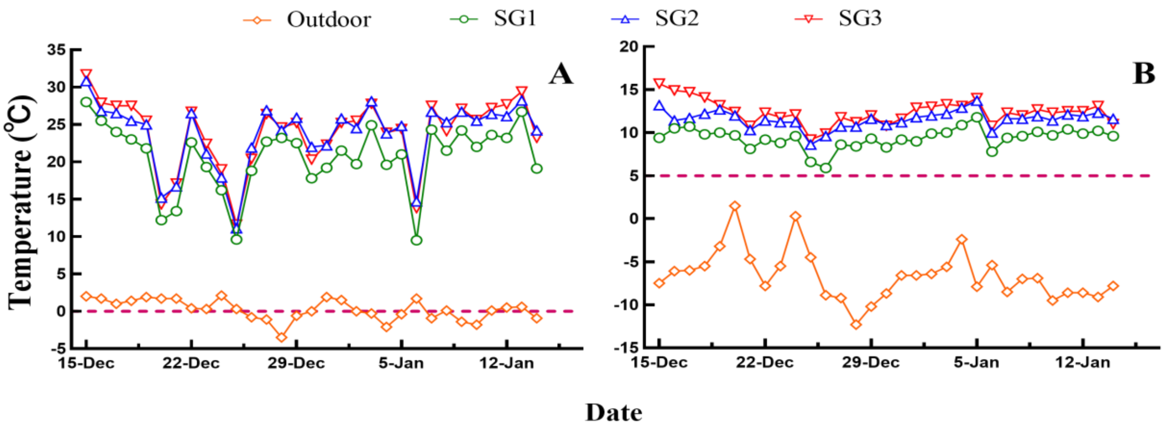

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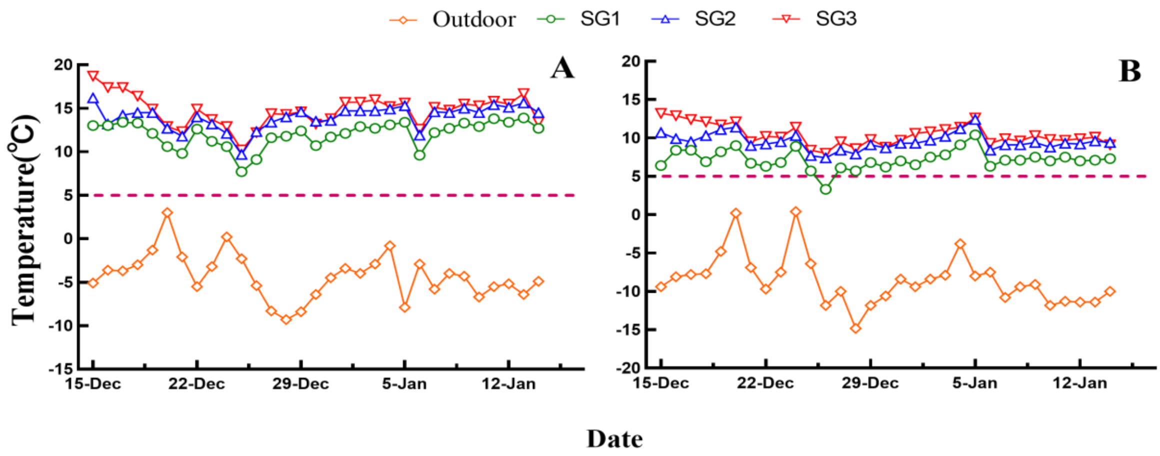

(c)

Fig. 5 - Comparison of air temperature in different solar greenhouses

(a) variations of average daily air temperature (A), average maximum air temperature (B) and average minimum air temperature(C); (b) variations of average daytime air temperature (A, 9:00-16:00) and average night air temperature (B, 16:00- next 9:00); (c) variations of night air temperature in different solar greenhouses (A, the first half of the night 16:00-0:00; B, the second half of the night 0:00-next 9:00).

At that time, there were 16 days in SG1 with the average daily minimum temperature below 5°C, while there were 1 day and 0 days in SG2 and SG3, respectively. Comparing with SG2 and SG3, the thermal environment stability of SG1 was worse than that of SG2 and SG3, which the insulation measure was not well meet the thermal insulation demand to effectively reduce heat loss through the south roof.

The nighttime average temperature is one of crucial factors to evaluate the thermal performance indoor. In Figure 5(b), the nighttime average temperature of SG1, SG2 and SG3 were 9.4°C, 11.5°C, and 12.4°C, respectively, which were greater than 5°C. The nighttime average temperature in SG2 and SG3 was increased by 2.1-3°C at least, comparing with SG1. It means that these three greenhouses can provide a suitable thermal environment for warm vegetables without auxiliary heating, while the thermal environment of SG3 is better than SG1 and SG2.

Figure 5(c) presented the variation of the nighttime temperature in the three greenhouses. The nighttime average temperature of SG1, SG2 and SG3 from 16:00 to 0:00 (the first half of the night) were 7.3°C, 9.4°C and 9.1°C, respectively, which were greater than 5°C. The nighttime average temperature of SG1, SG2 and SG3 from 0:00 to 9:00 (the second half of the night) were 7.1°C, 9.5°C and 10.4°C, respectively, which were greater than 5°C except that there was 1 day below 5°C in SG1.

Vegetables (such as tomato) are extremely affected by low-temperature, though they can bear for a short time. If the low-temperature environment continues for a long time, the growth of vegetables will suffer the cold damage. In Table 2, the duration of nighttime indoor temperatures less than 5°C was a total of 17 hours during 31 days in SG1, while it was only 1 hour in SG2 and 0 hour in SG3. The duration of nighttime indoor temperatures between 5°C and 8°C was a total of 204.25 hours during 31 days in SG1, while it was 43.5 hours in SG2 and 20.25 hours in SG3.

The temperatures less than 5°C was mainly distributed from 6:00 to 9:00 in SG1, which was defined as nighttime because the thermal blankets being not rolled up. The duration of nighttime temperatures greater than 8°C accounts for 58% in SG1, 91.5% in SG2 and 96.2% in SG3, respectively. At that times, with no heating supplement, a pure internal insulation blanket was not enough to meet the demands of heating preservation in harsh weather conditions. The decline of nighttime indoor temperature was reduced in SG1, but not obvious than that in SG2 and SG3. The internal plastic film under the internal blanket has effectively reduced the convection through the crevices of blanket which reduced the heat loss through the internal insulation in SG2. However, the air between external plastic film and internal blanket inside the greenhouse was irregularly disturbed by wind exterior. To achieve optimum insulation effect, the combination of external and internal insulation was used as insulation measure in SG3, reducing the heat loss caused by air flow between external plastic film and internal blanket. During 31 days, the nighttime indoor temperatures were greater than 5°C. Therefore, different insulation cover measures can improve the thermal performance of the solar greenhouse, and the combination of external and internal insulation was a more-effective measure than the others.

Table 2

Time distribution of low temperature in the greenhouses during 31 days

Duration	SG1			SG2			SG3		
	>8°C	5-8°C	<5°C	>8°C	5-8°C	<5°C	>8°C	5-8°C	<5°C
	[hour]			[hour]			[hour]		
16:00 -17:00	31	0	0	31	0	0	31	0	0
17:00-18:00	31	0	0	31	0	0	31	0	0
18:00-19:00	29	2	0	31	0	0	31	0	0
19:00-20:00	29	2	0	31	0	0	31	0	0
20:00-21:00	28.5	2.5	0	31	0	0	31	0	0
21:00-22:00	28	3	0	31	0	0	31	0	0
22:00-23:00	27.25	3.75	0	31	0	0	31	0	0
23:00-0:00	24.5	6.5	0	31	0	0	31	0	0
0:00-1:00	20.5	10.5	0	31	0	0	31	0	0
1:00-2:00	17.25	13	0.75	31	0	0	31	0	0
2:00-3:00	10.75	19.25	1	30.75	0.25	0	31	0	0
3:00-4:00	7.5	22.5	1	29.25	1.75	0	31	0	0
4:00-5:00	7	23	1	28	3	0	30	1	0
5:00-6:00	4.75	25.25	1	27.5	3.5	0	29.5	1.5	0
6:00-7:00	4	24.75	2.25	24	7	0	27.25	3.75	0
7:00-8:00	3	24	3	20.25	10.75	0	25.5	5.5	0
8:00-9:00	2.75	21.25	7	12.75	17.25	1	22.5	8.5	0

Cost evaluation

As shown in Table 3, the total cost of SG1, SG2 and SG3 were 284.7 RMB/m^2, 293.4 RMB/m^2 and 317.7 RMB/m^2, respectively. The total cost mainly includes basic construction cost and cover materials cost. The basic construction cost was the same for the three greenhouses. The cost of cover materials in SG2 increased by 8.7 RMB/m^2, which represented the internal plastic film and its control system. The internal plastic film, external blanket and their control system increased by 33 RMB/m^2 in SG3. For the long-term perspective in greenhouse production, the increasing cost of cover materials maintained the average nighttime temperature above 10°C, ensuring the suitable thermal environment for promoting vegetables maturation. Besides, compared with SG1, the tomato yield per unit area in SG2 and SG3 increased by 0.71 Kg/m^2 and 1.09 Kg/m^2, respectively. Considering that the wholesale price of tomatoes will rise to 14.0 RMB/Kg in winter, SG2 and SG3 can increase income by 9.94 RMB/m^2 and 15.26 RMB/m^2, respectively. Therefore, choosing SG2 or SG3 to plant vegetables can both generate significant benefits for farmers.

Table 3

Expenses of different solar greenhouses

Greenhouse	Construction		Cover materials				Other costs [RMB/m^2]	Total [RMB/m^2]	The increase of tomato yield [Kg/m^2]
	Steel frame [RMB/m^2]	Walls [RMB/m^2]	Internal blanket [RMB/m^2]	External blanket [RMB/m^2]	External film [RMB/m^2]	Internal film [RMB/m^2]			
SG1	55.0	180.9	27.0	0.0	3.5	0.0	18.3	284.7	--
SG2	55.0	180.9	27.0	0.0	3.5	2.0	25.0	293.4	0.71
SG3	55.0	180.9	27.0	16.0	3.5	2.0	33.3	317.7	1.09

DISCUSSIONS

The enhancement of the thermal insulation performance in solar greenhouse is mainly attribute to effective insulation cover measures, because the coverings reduce the convection and radiation heat transfer between the greenhouse interior and exterior. However, under the continuous and extreme cold weather conditions, with no sufficient heat supplement, it is crucial to optimize the insulation cover measures. In addition, to meet the heat demand, it is essential to optimize the passive or active heating system. The combination of insulation measures and heating system will benefit to improve the thermal performance of the greenhouses.

CONCLUSIONS

In this study, three different insulation coverage measures solar greenhouses were designed and built in Baotou area. To evaluate the thermal insulation performance inside the greenhouses, the indoor temperatures under different weather conditions were experimentally measured. Based on the experimental results, the conclusions were as follows:

(1) The average transmitted solar radiation through SG1, SG2 and SG3 were 428.3 W/m^2, 436.8 W/m^2 and 422.4 W/m^2 during lighting period in consecutive sunny days, and those were 212.9 W/m^2, 204.1 W/m^2 and 187.1 W/m^2 in consecutive cloudy days. Therefore, the differences of the temperature environment in three greenhouses are not mainly caused by the differences of transmitted solar radiation.

(2) During 31 days, the nighttime average temperature of SG1, SG2 and SG3 were greater than 5°C. By adding insulation coverage materials, the nighttime average temperature was increased by 2.1-3°C, and the duration of nighttime temperature greater than 8°C was increased by 33.5%-38.2%. The insulation cover measures have effectively improved the thermal insulation performance of the greenhouses.

(3) The increase of cost was mainly ascribable to the insulation cover materials, however, the greenhouse will benefit from improving the indoor environment and reducing energy consumption in long term production. Meanwhile, it is beneficial for greenhouse production to increase yield and income.

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