Brick-wall Solar Greenhouse Model and Its Temperature Analysis

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Abstract With brick-wall solar greenhouses in Changli area as the research object, using temperature dynamic monitoring and statistical methods, the greenhouse structure suitable for promoting early cultivation of local peach trees was selected by studying the temperature data of the solar greenhouses during the winter solstice, and a prediction model for daily average temperature was constructed. The results showed that greenhouse I had reasonable structural parameters and good daylight during the day. However, due to the low wall thickness and poor insulation material, the minimum temperature was significantly lower than other greenhouses. The thermal insulation performance of greenhouse II and III was better than that of greenhouse I, but the depth-span ratio and the front roof lighting angle were smaller. During the winter solstice, the average temperature of the three greenhouses was between 10 and 15 ℃, which was suitable for early cultivation of peach trees. The prediction model of daily average temperature was obtained: Daily average temperature = 1.02 + 0.69 × Daily average temperature of the previous day + 0.02 × Maximum temperature of the previous day - 0.01 × Minimum temperature of the previous day. To sum up, the structural parameters of brick-wall solar greenhouses suitable for early cultivation of peach trees in Changli area were as follows: span 6.5 - 8.5 m, depth-span ratio 0.47, front roof lighting angle 30° and wall thickness greater than 55 cm.

Key words Solar greenhouse; Brick wall structure; Temperature; Model construction

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Solar greenhouses are single-roof plastic film greenhouses for overwintering production that primarily utilize solar energy as their main power source and retain heat at night through three insulated walls and thermal blankets[1]. They serve as one of the most important agricultural facilities in China. The geometric parameters of solar greenhouses include ridge height, length, span, front roof shape and inclination angle, rear roof inclination angle, *etc.* These parameters are closely correlated and collectively influence the overall performance of greenhouses. However, issues such as the lack of scientific theoretical support in the design and construction of solar greenhouses have become increasingly prominent[2]. Many scholars in China have conducted extensive research on the daylighting, heat storage, structure, and micro-environment of solar greenhouses. Sun *et al.*[3] developed a computer simulation model for solar greenhouses based on the daylighting theory. They simulated the direct light environment inside greenhouses and obtained an optimized greenhouse daylighting structure. Song *et al.*[4] used mathematical models to optimize parameters such as the azimuth angle, daylighting roof angle, and rear roof elevation angle for energy-saving solar greenhouses in different regions of Gansu Province. Zhang *et al.*[5] analyzed variables such as light intensity and temperature, concluding that the new gravel heat-storage wall solar greenhouse provided better insulation than brick-wall solar greenhouses. Huang *et al.*[6] discussed issues with the north wall of solar greenhouses and summarized the physical properties of homogeneous walls as well as the insulation effects of various composite wall structures. Yu *et al.*[7] conducted tests on wall heat flux, indoor air temperature, and ground temperature, concluding that walls with polyurethane insulation material exhibited the best performance in heat storage, air temperature, and ground temperature, followed by XPS panels, while phenolic resin panels performed the worst in heat storage, air temperature, and ground temperature. Through extensive research by multiple scholars on solar greenhouses, it has been found that the structure of solar greenhouses is influenced by various factors such as latitude, season, and greenhouse location. Therefore, greenhouse design should align with local environmental conditions.

Changli County belongs to the eastern monsoon region of China, characterized by a warm temperate and semi-humid continental climate. This area has distinct seasons, abundant precipitation, a relatively long autumn, and an extended frost-free period, making it one of the main production regions for facility cultivation of peach trees in Hebei Province. As early as the 1990s, local growers began using greenhouses for early cultivation of peach trees. Since various types of greenhouses have been constructed locally, studying the most suitable greenhouse structure from the perspective of scientifically utilizing light and thermal resources is crucial for promoting the healthy development of the local facility peach industry. In this study, the indoor temperatures of three brick-wall solar greenhouses with different structures were investigated, providing a theoretical basis for structural optimization and temperature prediction of brick-wall solar greenhouses in Changli area. This study will promote the development of brick-wall solar greenhouses in Changli area.

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Materials and Methods

The three tested solar greenhouses with peach trees cultivated inside were all located in Changli County (119.16°E, 39.72°N). Their specific structural parameters and insulation quilt materials are listed in Table 1. Indoor air temperatures were measured from December 22 to January 21 of the following year (around the winter solstice) in 2020, 2021, and 2022. In specific, three random sampling points were selected along the east-west direction inside each greenhouse, positioned 1.5 m above the ground and at the midpoint of the north-south span. Temperature and humidity data loggers (ZDR-20) were used to record indoor temperatures at 30 min intervals.

The daily average temperature was calculated as the average of recorded temperatures for that day. The average temperature was determined as the average of daily average temperatures over the measurement period. Accumulated temperature was defined as the sum of daily average temperatures during periods when they were ≥10 ℃ (or ≥15 ℃)[8].

Data statistics and comparison were performed using Excel spreadsheet software, while SPSS 25.0 statistical software was employed for difference analysis and multiple regression analysis of the experimental data.

Table 1 Structural parameters and insulation materials of solar greenhouses

No.	Span m	Ridge height//m	Depth-span ratio	Front roof lighting angle//°	Wall thickness//m	Wall material (from inside to outside)	Thermal insulation material (from inside to outside)
I	6.60	3.12	0.47	30.96	42.00	37 cm brick wall +5 cm high-density foam board	Black felt + tension adhesive + black felt
II	7.00	3.00	0.43	26.95	57.00	52 cm brick wall +5 cm high-density foam board	Tension adhesive + two layers of space cotton + tension adhesive
III	8.90	3.70	0.42	26.57	62.00	26 cm brick wall +10 cm high-density foam board + 26 cm brick wall	PE woven cloth + three layers of pearl cotton + PE woven cloth

Results and Analysis

Comparison of minimum, maximum and daily average temperatures in brick-wall solar greenhouses

The minimum temperature generally occurred in the morning before opening the insulation quilt, serving as a key indicator of greenhouses' thermal insulation performance. Analysis of the three-year temperature data showed that the minimum temperatures in all three greenhouses were below 10 ℃. Greenhouses II and III exhibited no significant difference in minimum temperatures, and both showed significantly higher values than greenhouse I in all three years. These results indicated that greenhouses II and III had superior insulation performance, while greenhouse I demonstrated poor thermal retention capacity.

The maximum temperature inside solar greenhouses is influenced by both outdoor weather conditions and indoor environmental control. Under sunny conditions with strong sunlight, temperatures rise rapidly after uncovering the insulation quilt. If the roof vents are not opened promptly, the maximum temperature can exceed 40 ℃, potentially causing heat stress. During cloudy days with weak sunlight and closed vents, the maximum temperature remains below 20 ℃. Analysis of the three-year temperature data showed no significant difference in maximum temperatures between greenhouses I and II. However, greenhouse III exhibited significantly lower maximum temperatures than both I and II in all three years. This difference was primarily attributed to the installation of intelligent temperature-controlled ventilation equipment in greenhouse III, which maintained indoor temperatures below 24 ℃ all the time. In contrast, greenhouses I and II relied on manually-operated vents. Under sunny conditions, delayed vent opening led to too-high temperatures in these greenhouses easily.

The daily average temperature was jointly affected by both minimum and maximum temperatures, and significant variations were observed among the three greenhouses over the three-year period. Greenhouse II exhibited the highest daily average temperature, reaching an extremely significant level (Table 2).

Table 2 Comparison of temperature differences among solar greenhouses from 2020 to 2022 ℃

No.	Minimum temperature	Maximum temperature	Daily average temperature
	2020		
I	4.74 ± 1.70 bB	26.63 ± 5.07 bA	11.19 ± 1.98 cC
II	9.16 ± 1.89 aA	29.60 ± 5.90 aA	14.65 ± 2.48 aA
III	8.97 ± 1.84 aA	22.07 ± 1.44 cB	13.03 ± 1.98 bB
	2021		
I	5.31 ± 1.06 bB	28.22 ± 5.04 aA	12.16 ± 1.46 cB
II	8.65 ± 0.93 aA	28.16 ± 4.16 aA	14.53 ± 1.32 aA
III	8.52 ± 0.87 aA	22.55 ± 1.51 bB	12.93 ± 1.32 bB
	2022		
I	4.91 ± 1.18 bB	29.91 ± 6.17 aA	12.07 ± 2.00 bB
II	7.20 ± 1.77 aA	31.22 ± 5.11 aA	13.80 ± 2.22 aA
III	7.15 ± 0.88 aA	22.15 ± 1.52 bB	12.51 ± 1.46 bB

Comparison of average temperature and accumulated temperature in the three brick-wall solar greenhouses

The average temperature in solar greenhouses represents the growing temperature provided for crops. As shown in Table 3, greenhouse II had the highest average temperature (14.33 ℃), which was significantly higher than those of greenhouses I and III. The average temperature in greenhouse III was also significantly higher than that of greenhouse I. During the winter solstice period, the average temperatures in all three greenhouses ranged between 10 and 15 ℃.

The accumulated temperature is essential for crop growth. Greenhouse II showed no significant difference in accumulated temperature (≥10 ℃) compared with greenhouse III, but was significantly higher than greenhouse I. For accumulated temperature (≥15 ℃), greenhouse II was significantly higher than both greenhouses I and III. Fruit trees generally require lower accumulated temperature compared with vegetables. As all three greenhouses were used for peach cultivation, and the peach trees cultivated in the greenhouses were in their flowering period during the investigation period, the temperature at that time adequately met their developmental needs. Too-high temperatures will adversely affect peach pollination and fertilization, which explains the relatively lower accumulated temperatures (≥15 ℃) observed.

Table 3 Comparison of average temperature and accumulated temperature in solar greenhouses ℃

No.	Average temperature	Accumulated temperature (≥10 ℃)	Accumulated temperature (≥15 ℃)
I	11.83 ± 0.55 cB	334.13 ± 56.50 bA	20.80 ± 18.01 bB
II	14.33 ± 0.47 aA	441.07 ± 19.63 aA	180.87 ± 29.11 aA
III	12.80 ± 0.26 bB	397.57 ± 8.50 abA	54.50 ± 26.29 bB

Thermal performance analysis of brick-wall solar greenhouses in Changli area

The main factors affecting daylighting in solar greenhouses include the front roof lighting angle, rear roof elevation angle, height, span, and depth-span ratio, while the key factors influencing thermal insulation consist of rear roof horizontal projection, wall material, wall thickness, and insulation quilt material. When designing solar greenhouse structures, both daytime lighting and nighttime insulation requirements must be comprehensively considered[9]. As shown in Table 1, the front roof lighting angles of the three greenhouses were all higher than the local reasonable roof angle (22.5°) but lower than the local roof angle during the reasonable daylighting period (33.45°). Additionally, greenhouses II and III both had relatively small depth-span ratios. It indicated that while maintaining the same greenhouse height, the spans of greenhouses II and III were increased during construction. The increased span not only reduced the front roof lighting angle (affecting light intake), but also expanded the front roof enclosure area, thereby indirectly impacting the overall thermal insulation performance of the greenhouses.

Comprehensive analysis of Tables 1, 2 and 3 showed that greenhouse I had the largest front roof lighting angle, small span and appropriate depth-span ratio, resulting in good daylighting performance. However, its poor nighttime insulation was mainly due to its wall thickness and the material of insulation quilt. Although greenhouses II and III differed in span and height, their similar depth-span ratios, front roof lighting angles and wall thicknesses led to comparable daylighting and insulation performance. All three greenhouses are suitable for peach cultivation in protected facilities, but for horticultural crops with high temperature requirements such as tomato and cucumber, it is necessary to strengthen the thermal insulation performance of greenhouses.

Construction of indoor temperature prediction model for brick-wall solar greenhouses in Changli area

Using temperature data collected from greenhouse II, multiple linear regression analysis was conducted with the average temperature, maximum temperature, and minimum temperature of the previous day as independent variables, and the daily average temperature as the dependent variable (details in Table 4). Factors passing the 0.05 significance level test were selected to establish the final prediction model for daily average temperature: Daily average temperature = 1.02 + 0.69 × Average temperature of the previous day + 0.02 × Maximum temperature of the previous day − 0.01 × Minimum temperature of the previous day.

The adjusted R^2 value of the model was 0.49, which indicated that the daily average temperature of the previous day, the daily maximum temperature of the previous day and the lowest temperature of the previous day could explain 49% of the variation in average temperature. The F-test confirmed the model's validity (F = 33.49, $P = 0.00 < 0.05$). Multicollinearity tests showed all VIF values were below 5, confirming no multicollinearity issues. With a D-W value of 1.89, the model demonstrated no autocorrelation, indicating no correlation between sample data and confirming good model quality.

In this model, the regression coefficient for the previous day's average temperature was 0.69 ($t = 9.82$, $P = 0.00 < 0.01$), indicating that the average temperature of the previous day exerted a highly significant positive influence on the average temperature. Therefore, the average temperature of the previous day plays a meaningful role in temperature prediction for brick-wall solar greenhouses.

Table 4 Regression analysis for brick-wall solar greenhouses

	Non-standardized coefficient		Standardized coefficient	t	P	VIF
	B	Standard error	Beta			
Constant	1.02	0.38	–	2.68	0.00**	–
Daily average temperature of the previous day	0.69	0.07	0.71	9.82	0.00**	1.03
Daily maximum temperature of the previous day	0.02	0.08	0.02	0.27	0.78	1.04
Minimum temperature of the previous day	−0.01	0.07	−0.01	−0.12	0.90	1.02

The dependent variable is the average temperature; * $P < 0.05$; ** $P < 0.01$

Discussion and Conclusions

The daytime indoor temperature in solar greenhouses primarily derives from solar radiation, while nighttime temperature mainly depends on heat release from various structural components and soil. Luo *et al.*[10] analyzed the curvature, depth-span ratio, air temperature, and ground temperature of five different solar greenhouse structures in Turpan area, concluding that the 9 m-span steel-frame solar greenhouse demonstrated the best thermal insulation performance. Regarding thermal insulation, Song *et al.*[11] conducted detailed comparisons of rear roof structure, back wall configuration, span, ridge height, and low-temperature performance among five typical energy-efficient solar greenhouse designs in eastern Hebei, proposing multiple improvement suggestions for enhanced insulation. Jiang *et al.*[12] evaluated solar greenhouses with five different spans in Chifeng hilly areas by analyzing indicators including light transmittance, air temperature, humidity, soil temperature, crop yield, and construction costs, concluding that the 10 m-span solar greenhouse demonstrated optimal performance in all parameters. Generally, larger spans enhance the daylighting capacity of solar greenhouses, but the depth-span ratio should be determined based on local light conditions and geographical environment. According to the lighting conditions and geographical environment in Changli area, the optimal depth-span ratio for solar greenhouses falls within the range of 0.46 – 0.53[9].

Analysis of key indicators including minimum temperature, maximum temperature, average temperature and accumulated temperature revealed that although greenhouse I had reasonable structural parameters, its thin wall and inferior insulation quilt material resulted in significantly poorer thermal performance compared with other greenhouses. Greenhouses II and III demonstrated better insulation than greenhouse I, but had too-large spans and relatively small depth-span ratios and front roof lighting angles. Comprehensive evaluation of all three greenhouses' structural parameters and temperature data suggested following structural parameters for brick-wall solar greenhouses for early cultivation of peach trees in Changli: span 6.5 – 8.5 m, depth-span ratio 0.47, front roof lighting angle 30°, and wall thickness greater than 55 cm.

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