SOIL–AIR THERMAL ENVIRONMENT IN CHINESE SOLAR GREENHOUSES WITH EARTHEN WALLS
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中国土墙日光温室土壤-空气热环境研究

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ABSTRACT
Chinese solar greenhouses with earthen walls can provide a suitable environment for crop production during winter. In this study, air and soil temperatures inside solar greenhouses in Shanxi Province, China, were monitored from January 1 to March 31, 2024. The results showed that, during nighttime, vertical air-temperature variation among the measurement points was greater than horizontal variation. Zones with approximately equal soil temperatures were also identified among the measurement points. The onset of the increase in weighted mean soil temperature occurred 4 h later than that of the weighted mean air temperature, whereas the onset of the decrease in weighted mean soil temperature occurred 5 h later. These findings provide a data-based foundation for regulating the thermal environment inside Chinese solar greenhouses with earthen walls.

摘要
中国土墙日光温室在冬季期间可为作物提供适宜的生长环境,本研究在 2024 年 1 月 1 日-2024 年 3 月 31 日期间对中国山西地区日光温室内空气温度与土壤温度进行测定，其结果显示：在夜间沿测点温度沿竖向的变化速率大于其沿横向的变化速率；土壤测点温度存在近似相等的区域；土壤加权温度升高界点比空气加权温度升高界点滞后 4 个小时，土壤加权温度下降界点比空气加权温度下降界点滞后 5 个小时。该研究可为日光温室内热环境调控提供数据支撑。

INTRODUCTION
Chinese solar greenhouse (CSG) are widely used for winter vegetable production in northern China, where solar energy collection, enclosure insulation and thermal storage help maintain a suitable crop-growing microclimate *(Wang et al., 2026; Sun et al., 2025; Liu et al., 2023)*. Their winter thermal environment is jointly affected by outdoor weather, covering materials, north walls, indoor air, crops and soil. Physical and transient models have shown that greenhouse air temperature is controlled by radiation, convection, conduction, ventilation or infiltration, ground heat exchange and heat storage processes *(Sun et al., 2026; Zhao et al., 2023; Xu et al., 2017; Joudi et al., 2015;)*. Therefore, understanding the internal thermal response of CSG remains important for winter environmental regulation and low-temperature risk management.

Indoor air and soil are two key thermal components with different functions. Air temperature directly affects the canopy-level environment, while soil temperature determines root-zone thermal conditions and influences root activity, water uptake and crop stress. Because greenhouse soil absorbs heat during the daytime and releases part of it during cooling periods, the air-soil temperature relationship is affected by heat storage and thermal inertia. Previous studies have reported significant air-soil temperature correlations *(Chang et al., 2010)* soil-temperature hysteresis under different moisture and fertilizer conditions *(Lin et al., 2010)* and the influence of soil moisture on soil thermal conductivity and heat capacity *(Al-Kayssi et al., 2010)*. Thus, this relationship should be viewed as a dynamic response rather than a simple synchronous correlation.

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Recent studies have shown that greenhouse soil temperature varies with depth and spatial position: fluctuations generally weaken with depth, peak or valley times may be delayed, and marginal effects or structural asymmetry can produce horizontal differences *(Jiao et al., 2025; Cheng et al., 2024; Cheng et al., 2014)*. Studies on ground thermal storage, soil-wall-air thermal environment and soil heat loss have further emphasized the role of soil in greenhouse heat exchange *(Li et al., 2024; Zhang et al., 2025; Luo et al.,2025)*. Meanwhile, mechanistic, transient and temperature-wave models have described CSG heat transfer processes *(Zhang et al., 2023)* and data-driven models such as LSTM, Attention-LSTM, RF-XGBoost and Transformer-BiLSTM have improved greenhouse air or soil temperature prediction *(Li et al., 2024; Liu et al., 2026; Yu et al., 2025)*. However, most studies still focus on distribution, zoning, heat-loss evaluation or prediction accuracy, with limited explanation of how indoor air temperature fluctuations propagate into multi-depth soil through time lag, phase delay, amplitude attenuation and hysteresis.

Although previous studies provide an important foundation, several issues remain insufficiently addressed. First, the time lag between indoor air temperature changes and soil-temperature responses at different depths is still not clearly quantified. Second, amplitude attenuation, phase delay and thermal hysteresis are often discussed separately or only qualitatively. Third, the effects of spatial position, soil depth, soil moisture and weather condition on air-soil thermal response have not been systematically compared. These gaps limit our understanding of how air temperature waves propagate into greenhouse soil.

In summary, existing research has provided an important foundation for understanding soil temperature distribution, heat transfer processes in greenhouses and temperature forecasting; however, there is still a lack of clear quantification of the patterns of co-variation between indoor air temperature fluctuations and soil temperatures at different depths. In light of the above issues, this paper utilises field-measured air temperature and soil temperature data from solar greenhouses across different spans to analyse the dynamic coupling relationship between indoor air temperature and soil temperature at multiple depths, thereby providing a reference for the analysis of air–soil thermal responses in solar greenhouses and for the management of root-zone temperatures during winter.

Soil temperature, compared with air temperature, exhibited time lags and complexity. Even a difference of just 1°C can have a significant impact on crop growth and development *(Sypka et al., 2016)*. The novelty of this study lies in the quantitative analysis of the thermal lag between indoor air and soil temperatures using multi-point measurements in a Chinese solar greenhouse with earthen walls. The obtained results provide engineering guidance for greenhouse thermal management, energy-saving strategies and intelligent environmental control.

MATERIALS AND METHODS

In this experiment, soil and air temperatures in the greenhouse were measured between 1 January 2024 and 30 March 2024, with measurements taken at 30-minute intervals.

Experimental Greenhouse

This experiment was conducted in the Taigu area of Jinzhong City, Shanxi Province, at 112.50° east longitude and 37.37° north latitude. The experimental greenhouse was a sun-heated structure with earthen walls; the southern side was covered with plastic sheeting, whilst the eastern, western and northern sides consisted of earthen walls. There were 1-metre-wide walkways along the southern and northern edges of the greenhouse, providing access for pedestrians and space for the laying of pipes. The sun-heated greenhouse faced south, with a length of 100 metres, a span of 10 metres and a ridge height of 4.5 metres.

Test Equipment

Indoor and outdoor air temperature: Measurements were taken using the RC-5 USB temperature logger manufactured by Jingchuang Electric Co., Ltd. (as shown in Figure 2.a). The instrument has a measurement range of –30 °C to 70 °C; within the range of –20 °C to 40 °C, the measurement accuracy is ±0.5 °C; outside this range, it is ±1 °C. The data-recording interval was set to 30 min.

Soil temperature and humidity: The Jingchuang GSP-6 was selected as the measuring instrument. The instrument has a temperature measurement range of –40 °C to 85 °C; within the temperature range of –20 °C to +40 °C, the temperature accuracy is ±0.5 °C; for other temperature ranges, the accuracy is ±1.0 °C. Data were recorded at 30-minute intervals.

a) RC-5 Temperature Logger *b) GSP-6 Temperature and Humidity Logger*

Fig. 1- Testing Equipment

Layout of measurement points

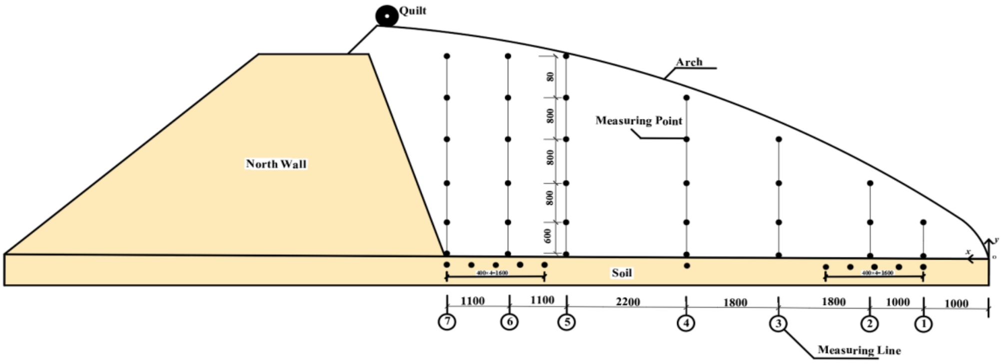


Fig. 2 - Layout of Testing Points

Soil measurement point layout: all measurement points situated at y = −150 mm and z = 0 mm; five measurement points arranged uniformly along the transverse direction at x = 1000–2600 mm and y = 8400–10000 mm, spaced 400 mm apart; a measurement point situated at x = 5600 mm in the centre of the greenhouse.

Table 1

Coordinates for Soil Measurement point Layout

Measurement point number	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11
x	1.0	1.4	1.8	2.2	2.6	5.6	8.4	8.8	9.2	9.6	10.0
y	-0.15	-0.15	-0.15	-0.15	-0.15	-0.15	-0.15	-0.15	-0.15	-0.15	-0.15

Air sampling point layout: at RC-5, in an open outdoor area, at a height of 1.5 m, to record the outdoor air temperature. Indoor sampling points are as shown in Table 2.

Table 2

Air Measurement point Layout Coordinate Table (m)

Measuring line number			1	2	3	4	5	6	7
x			1.0	2.0	3.800	5.6	7.8	8.9	10.0
Measurement point number	1	y	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	2		0.6	0.6	0.6	0.6	0.6	0.6	0.6
	3			1.4	1.4	1.4	1.4	1.4	1.4
	4				2.2	2.2	2.2	2.2	2.2
	5					3.0	3.0	3.0	3.0
	6						3.8	3.8	3.8

RESULTS

As January was the coldest month of the year in Taigu, Jinzhong, Shanxi, in order to investigate the patterns of variation in air and soil temperatures during January and their mutual influence, the temperatures recorded at all monitoring stations in January 2024 were averaged on an hourly basis, and the hourly averages for all stations over the month were then calculated.

Variation in air temperature

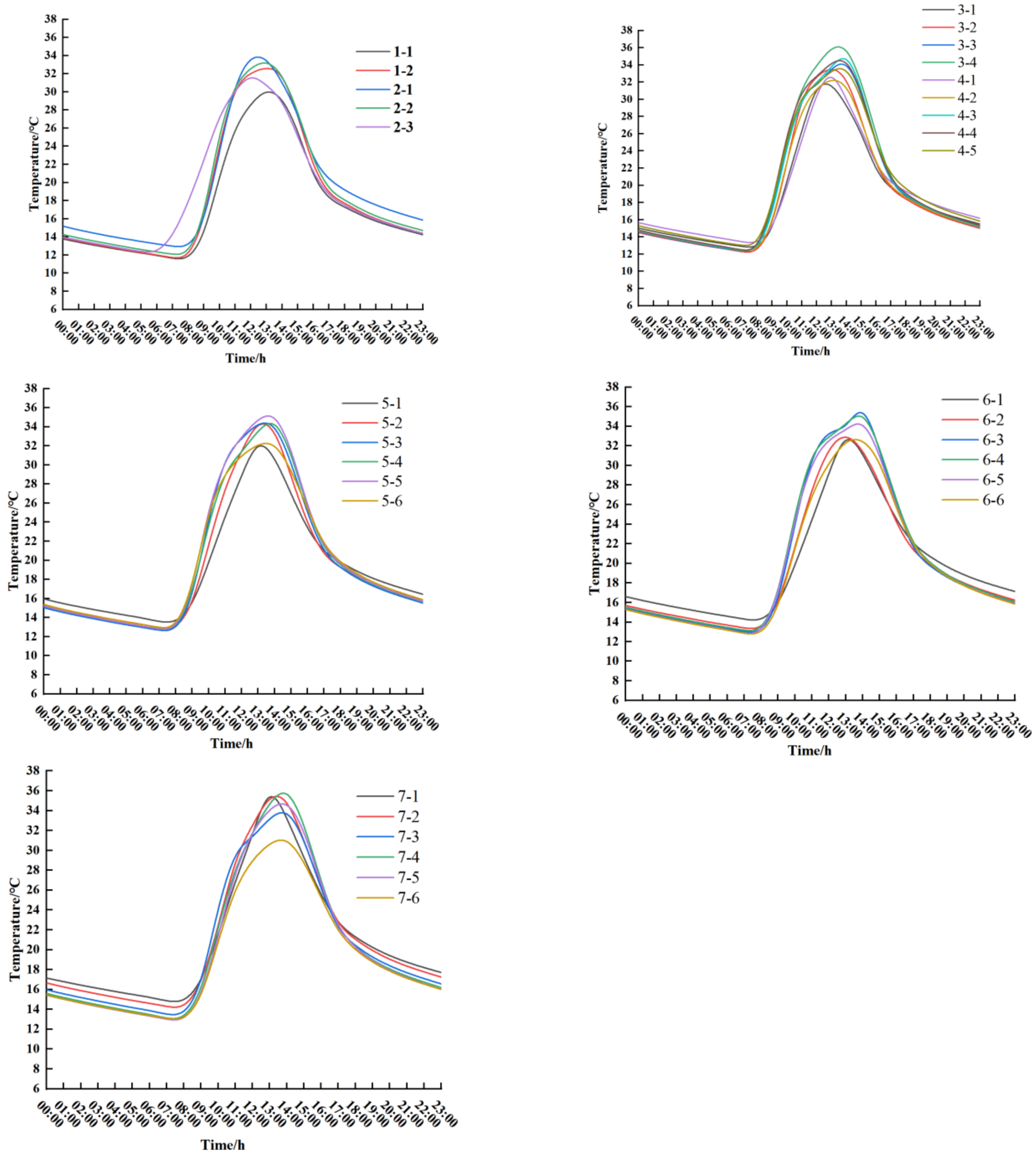


Fig. 3 - Graph of hourly averages at different measurement points in January 2024

As shown in Table 3, at all measurement points in January, temperatures gradually decreased over time during the night-time periods of 00:00–06:00 and 19:00–23:00, exhibiting a seasonal pattern. The average temperatures at all measurement points in January were above 10 °C; overall, the air temperatures at all measurement points met the requirements for plant growth. An analysis of the coldest days in January revealed that at measurement points 1 and 2—which were furthest from the wall and furthest from the soil, respectively—temperatures fell below 10 °C, with the lowest recorded temperature being 7.9 °C; these conditions still met the air temperature requirements for crop growth.

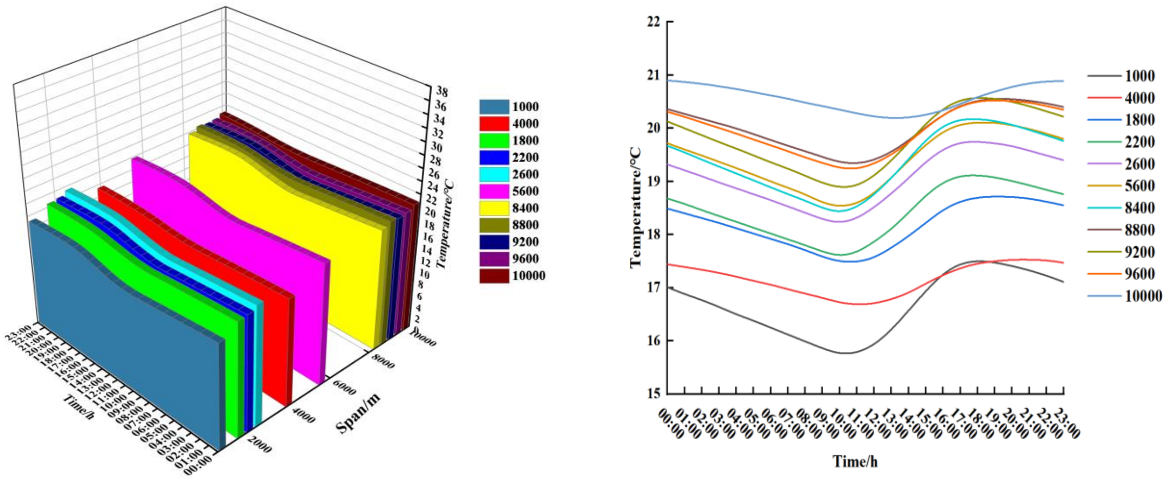
Between 0:00 and 6:00, temperatures were higher at measurement points closer to the ground. Excluding measurement point No. 1 from each measurement line, the maximum temperature difference among measurement points on the same line was 0.29 °C on measurement line No. 2, with a vertical distance of 600 mm; on measurement line No. 3, the maximum temperature difference was 0.18 °C, with a vertical distance of 1,600 mm; the maximum temperature difference between measurement points on Line 4 was 0.63 °C, with a vertical distance of 2,400 mm; on Line 5, the maximum temperature difference was 0.28 °C, with a vertical distance of 800 mm; on Line 6, the maximum temperature difference was 0.58 °C, with a vertical distance of 2,400 mm; the maximum temperature difference on measurement line 7 was 1.29 °C, with a vertical distance of 1,600 mm. Therefore, during the period from 00:00 to 06:00, the maximum rate of change in temperature difference across the same span at different heights was 0.81 °C/m, and the minimum rate of change was 0.11 °C/m.

During the period from 0:00 to 6:00, across different spans, the maximum temperature difference at Measurement Point 1 on each transect was 3.37 °C, with a horizontal distance of 9,000 mm; the maximum temperature difference at Measurement Point 2 on each transect was 2.74 °C, with a horizontal distance of 9,000 mm; and the maximum temperature difference at Measurement Point 3 on each transect was 1.99 °C, with a horizontal distance of 8,000 mm; the maximum temperature difference at measurement point 4 on each transect was 0.91 °C, with a horizontal distance of 6,200 mm. Therefore, within the growth height of the crop layer, the maximum rate of variation in temperature difference across the transects was 0.37 °C/m, and the minimum rate was 0.15 °C/m.

Between 06:00 and 18:00, temperatures at each measurement point rose gradually in a curvilinear pattern from 06:00 to 14:00, and fell gradually in a curvilinear pattern from 14:00 to 18:00. Between 06:00 and 14:00, temperatures rose gradually; measurement points near the greenhouse film showed a greater increase in temperature, whilst the peak values at points 6 and 7 were lower than those at the central measurement points due to the obstruction caused by the cotton blankets. Measurement line 1 recorded a maximum temperature rise of 20.26 °C; measurement line 2, 19.71 °C; measurement line 3, 23.6 °C; measurement line 4, 22.84 °C; measurement line 5, 22.48 °C; measurement line 6, 23.35 °C; and measurement line 7, 23.04 °C. Between 14:00 and 18:00, temperatures gradually decreased, with a more pronounced drop observed at measurement points close to the greenhouse film. Measurement line 1 recorded a maximum temperature decrease of 14.55 °C; measurement line 2, 11.7 °C; measurement line 3, 17.38 °C; measurement line 4, 15.86 °C; measurement line 5, 16 °C; measurement line 6, 15.84 °C; and measurement line 7, 16.33 °C.

Consequently, at night, the rate of vertical temperature variation at the measurement points is higher than the rate of horizontal variation; during the daytime, when maintaining the thermal environment in a solar greenhouse, attention should be paid to heat absorption in the morning and heat dissipation in the afternoon. Within the crop growth range, equipment can be used to absorb heat from the greenhouse, thereby maintaining the thermal conditions of the solar greenhouse at night. The pattern of air temperature variation was consistent with the findings of *Cheng et al. (2024)*, with relatively marked vertical variations in temperature.

The pattern of soil temperature variation



a) Figure of soil temperature variation with span and time b*) Graph of soil temperature over time for different span*

Fig. 4 - Soil temperature at measurement points over time and across different span

As can be seen from Figure 4, the temperatures at each measurement point in the soil gradually decreased over time during the periods from 00:00 to 12:00 and from 18:00 to 23:00, whereas they gradually increased over time during the period from 12:00 to 18:00. During the 00:00–12:00 period, the temperature decreased by 1.09 °C, 0.74 °C, 0.93 °C, 0.82 °C, 0.81 °C, 0.95 °C, 0.92 °C, 0.96 °C, 1.03 °C, 0.98 °C and 0.68°C at measurement points S1 to S11, respectively. During the period from 12:00 to 18:00, the temperature at the measurement points increased by 1.59 °C, 0.76 °C, 1.14 °C, 1.26 °C, 1.24 °C, 1.34 °C, 1.43 °C, 1.14 °C, 1.48 °C, 1.18 °C and 0.37 °C respectively. During the period from 18:00 to 23:00, the temperature decreased at measurement points 1–11 by 0.4 °C, 0.01 °C, 0.15 °C, 0.36 °C, 0.35 °C, 0.31 °C, 0.42 °C, 0.12 °C, 0.36 °C, 0.16 °C and 0.3 °C respectively. Therefore, during January 2024, excluding the temperature at the measurement point at the base of the north wall (i.e. at y = 10,000 mm), the temperature decreased by approximately 1 °C between 00:00 and 12:00, whilst it increased by approximately 1.2 °C between 12:00 and 18:00, and a decrease of approximately 0.3°C between 18:00 and 23:00; the total temperature rise and fall over the course of the day were thus approximately equal.

At the same time, the temperature at each measurement point gradually increased with the span; compared with the temperature at measurement point S1 at y = 1000 mm, the maximum temperature difference between measurement points S2–S11 and S1 during the period from 00:00 to 12:00 was 0.97 °C , 1.74 °C, 1.94 °C, 2.59 °C, 2.85 °C, 2.83 °C, 3.61 °C, 3.18 °C, 3.5 °C and 4.6 °C; the maximum temperature differences between measurement points S2–S11 and S1 during the period from 12:00 to 18:00 were 0.58 °C, 1.55 °C, 1.90 °C, 2.57 °C, 2.87 °C, 2.86 °C, 3.35 °C, 3.19 °C, 3.3 °C and 3.99 °C; The maximum temperature differences between the S2–S11 measurement points and S1 during the period from 18:00 to 23:00 were 0.36 °C, 1.44 °C, 1.65 °C, 2.29 °C, 2.69 °C, 2.66 °C, 3.29 °C, 3.11 °C, 3.24 °C and 3.78 °C. It can therefore be seen that the temperatures at the soil measurement points are approximately equal. The variations in soil temperature were consistent with those reported in previous studies (*Li et al., 2024; Zhang et al., 2025*). Building on this prior research, the present study defined soil temperature ranges for different span lengths. Further research should be conducted on soil temperatures in solar greenhouses of different structural types and span lengths, in order to investigate the effects of span length and arch height on soil temperature.

The relationship between air temperature and soil temperature

As can be seen from Figure 3 and Figure 4, there was a certain temperature difference between air temperature and soil temperature. Air temperature gradually decreased over time between 18:00 and 06:00 the following day, and between 14:00 and 18:00, whilst it gradually increased between 06:00 and 14:00; soil temperature, on the other hand, gradually decreased with the passage of time between 18:00 and 12:00 the following day, whilst it gradually increased with the passage of time between 12:00 and 18:00. There was a certain discrepancy between the points at which soil temperature and air temperature began to rise. To investigate the relationship between air temperature at the measurement points and soil temperature, coordinate-weighted calculations were performed on the air temperatures from all measurement points in January and on the soil temperatures, and the two temperature series were analysed. The formulas for the coordinate-weighted soil temperature and the coordinate-weighted air temperature were as follows: $T = \frac{\sum T_i x_i y_i}{x_i y_i}$, where T is the weighted temperature, x_i, y_i was the coordinate value, and T_i is the temperature at the i-th measurement point.

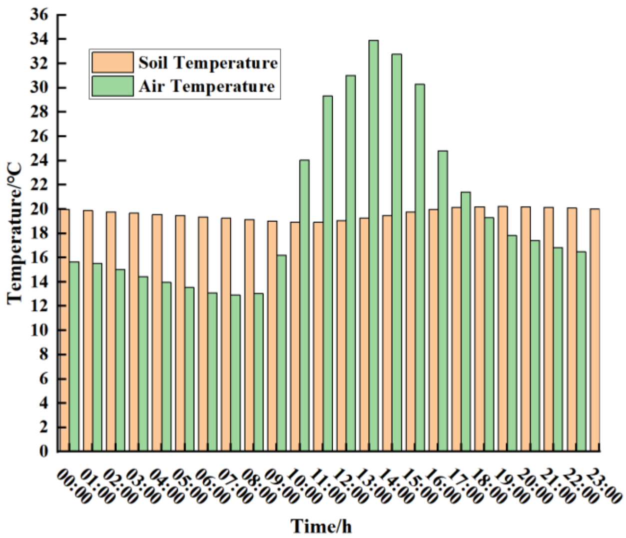


Fig. 5 - Curve of the ratio of air-weighted temperature to soil-weighted temperature in a solar greenhouse at the same time

As can be seen from Figure 5, the soil-weighted temperature gradually decreases between 00:00 and 11:00, whilst the air temperature gradually decreases between 00:00 and 07:00 and gradually increases between 07:00 and 13:00. Between 00:00 and 07:00, the air-weighted temperature was lower than the soil-weighted temperature, with an initial temperature difference of 4.3 °C; at 07:00, the difference between the soil-weighted temperature and the air-weighted temperature was 6.33 °C. At some point between 09:00 and 10:00, the weighted air temperature gradually equalled the weighted soil temperature, and between 10:00 and 14:00, the weighted air temperature was gradually higher than the weighted soil temperature. Between 09:00 and 14:00, the difference between the air-weighted temperature and the soil-weighted temperature gradually increased, reaching a maximum of 14.66 °C at 13:00. Between 14:00 and 19:00, the soil temperature gradually increased while the air temperature gradually decreased; between 17:00 and 18:00, the air-weighted temperature gradually decreased until it equalled the soil-weighted temperature. Consequently, there was a certain lag effect in the transition points for the rise and fall of the air-weighted temperature and the soil-weighted temperature in the solar greenhouse: the transition point for the rise in soil-weighted temperature lagged behind that for the rise in air-weighted temperature by four hours, whilst the transition point for the fall in soil-weighted temperature lagged behind that for the fall in air-weighted temperature by five hours.

At 11:00, the soil temperature only began to rise gradually when the difference between the air-weighted temperature and the soil-weighted temperature was 10.38 °C; at 19:00, the soil temperature only began to fall gradually when the difference between the air-weighted temperature and the soil-weighted temperature was 2.39 °C. Consequently, for the soil-weighted temperature to rise in the morning, there must be a significant difference between the air-weighted temperature and the soil-weighted temperature; similarly, for the soil temperature to fall in the afternoon, there must be a small difference between the air-weighted temperature and the soil-weighted temperature.

Previous studies have examined the factors influencing soil temperature (*Tana et al., 2022*). However, there has been limited research on the lag times and temperature differences between air temperature and soil temperature. This section examines the lag times of air-weighted temperature and soil-weighted temperature in solar greenhouses. The correlation between air-weighted temperature and soil-weighted temperature, as measured by the Spearman coefficient, was low, with an R^2 value of less than 0.1.

CONCLUSIONS

This paper employed experimental equipment to measure air and soil temperatures in a solar greenhouse, and analysed the patterns of variation and interrelationships between air and soil temperatures. The main conclusions were as follows:

(1) During the night, the rate of vertical temperature variation at each measurement point was greater than the rate of horizontal variation; during the daytime, the maintenance of the thermal environment within the solar greenhouse should take into account heat absorption in the morning and heat dissipation in the afternoon; within the crop growth range, equipment can be used to absorb heat from the greenhouse, thereby maintaining the thermal environment of the solar greenhouse at night

(2) Soil temperatures at all measurement points gradually decreased over time between 00:00 and 12:00 and between 18:00 and 23:00, whilst they gradually increased over time between 12:00 and 18:00; there were areas where soil temperatures at the various measurement points were approximately equal.

(3) There was a certain lag effect in the transition points for the rise and fall of the weighted air temperature and weighted soil temperature within the solar greenhouse; the transition point for the rise in weighted soil temperature lagged behind that of the weighted air temperature by 4 hours, whilst the transition point for the fall in weighted soil temperature lagged behind that of the weighted air temperature by 5 hours. Heat can be stored during the day using equipment and thermal storage media to harness the high air temperatures, and then released at night using the same equipment, thereby raising the air temperature in solar greenhouses during winter nights.

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