

Diurnal Variation Characteristics of Root Zone Temperature in Embedded Substrate Cultivation with Ridging for Sweet Peppers in Solar Greenhouses (Postprint)

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Date: 2017-11-06T00:00:00+00:00

Abstract

To address problems such as low temperature stress in winter-spring seasons, soil continuous cropping obstacles, low yield per unit area, and low water and fertilizer resource use efficiency in solar greenhouses in northern China, this study designed a novel cultivation method—soil ridge substrate-embedded cultivation (SRSC), and investigated the diurnal variation characteristics of root zone temperature of sweet pepper seedlings under two SRSC patterns [slot-embedded ridge (SRSC-P) and mesh-embedded ridge (wire mesh slot support) (SRSC-W)], as well as soil ridge (SR) and single substrate trough ridge (NPG) cultivation in early spring. The results showed that the root zone temperature of cultivation ridges in solar greenhouse was significantly positively correlated with indoor and outdoor air temperature changes, with average indoor and ridge root zone temperatures increasing by 8.07 °C and 10.93 °C compared to outdoors, respectively, and by 9.90 °C and 14.81 °C during nighttime. During the nighttime low temperature period, SRSC-W showed superior performance in maintaining higher root zone temperatures compared to SR and SRSC-P, with its average root zone temperature being 1.34 °C and 0.52 °C higher than SR and SRSC-P, respectively; during the daytime high temperature period, the average maximum temperatures for SR, SRSC-P, NPG, and SRSC-W were 28.06 °C, 27.21 °C, 29.93 °C, and 26.05 °C, respectively, with SRSC-W exhibiting the best high temperature mitigation effect and NPG the poorest. Under overcast conditions, the heat storage and insulation performance of cultivation ridges was poorer than under sunny conditions. For SR, the average temperature of the central root zone was higher than the outer side during both day and night, whereas for SRSC-P and SRSC-W, the outer side temperature was higher during daytime while the central root zone temperature was higher during nighttime. The root zone temperature of the northern part of cultivation ridges was higher than that

of the southern part, exhibiting spatial heterogeneity, wherein the difference between southern and northern central root zone temperatures was smallest for the SRSC-W cultivation pattern compared to other treatments. Furthermore, SRSC-W had the longest lag time for central root zone temperature changes and strong temperature buffering capacity. In summary, the SRSC-W cultivation method exhibited the strongest ability to maintain sweet pepper root zone temperature during nighttime in early spring and the greatest buffering capacity against both low and high temperature stresses, with low cost, demonstrating promising application prospects for low temperature resistance production in solar greenhouses.

Full Text

Diurnal Change in Root Zone Temperature of Soil Ridge Substrate-Embedded Cultivation Method for Sweet Pepper in Solar Greenhouse

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Abstract

To address production challenges in solar greenhouses in northern China—including low temperature stress in winter and early spring, continuous cropping obstacles, low yields, and poor water and fertilizer use efficiency—this study designed a novel cultivation method called soil ridge substrate-embedded cultivation (SRSC). An experiment was conducted in early spring to investigate the diurnal variation characteristics of root zone temperature in sweet pepper seedlings under two SRSC patterns [SRSC-P (polyethylene groove embedded in soil ridge) and SRSC-W (plastic film with wire mesh support embedded in soil ridge)], compared with conventional soil ridge (SR) and naked polyethylene groove (NPG) cultivation. The results demonstrated that ridge root zone temperatures were significantly positively correlated with both indoor and outdoor air temperatures. The mean daily temperatures inside the greenhouse and in the ridge root zone were 8.07 °C and 10.93 °C higher, respectively, than outdoor temperatures. During nighttime, these differences increased to 9.90 °C and 14.81 °C, respectively. During low-temperature nighttime periods, SRSC-W maintained higher root zone temperatures more effectively than SR and SRSC-P, with average nighttime temperatures 1.34 °C and 0.52 °C higher, respectively. During high-temperature daytime periods, the mean maximum temperatures for SR, SRSC-P, NPG, and SRSC-W were 28.06 °C, 27.21 °C, 29.93 °C, and 26.05 °C, respectively, indicating that SRSC-W provided the best buffering against high temperatures while NPG performed worst. Under cloudy conditions, the

heat storage and insulation performance of cultivation ridges was inferior to that under sunny conditions. For SR, the central root zone temperature remained higher than the lateral zone during both day and night. However, for SRSC-P and SRSC-W, lateral temperatures were higher during the day while central temperatures were higher at night. Northern ridge positions consistently showed higher root zone temperatures than southern positions, demonstrating spatial heterogeneity. SRSC-W exhibited the smallest temperature difference between southern and northern central root zones among all treatments. Additionally, SRSC-W showed the longest lag time for temperature changes in the central root zone, indicating the strongest temperature buffering capacity. In conclusion, the SRSC-W cultivation method demonstrated superior ability to maintain root zone temperatures during low-temperature periods in early spring, with the strongest buffering capacity against both low and high temperature stress, low cost, and promising application prospects for low-temperature production in solar greenhouses.

Keywords: Solar greenhouse; Soil ridge substrate-embedded cultivation; Heat storage and preservation; Root zone temperature; Diurnal temperature

Protected cultivation plays a crucial role in off-season and cross-regional production of vegetables and other economically important crops in China. By the end of 2012, China's protected cultivation area reached approximately 4×10^6 hm², with protected vegetable and melon production totaling about 2.67×10^8 t, accounting for 34% of total vegetable and melon output. Due to its high yield and efficiency characteristics, protected cultivation has become one of the most dynamic emerging industries in Chinese agriculture. Solar greenhouses serve as the primary facility for winter and early spring vegetable cultivation in northern China, with cultivation area exceeding 1×10^6 hm², making them one of the most important forms of protected vegetable production in the region. However, low temperature stress during winter and spring has become a bottleneck affecting crop production in solar greenhouses in northern China. Temperature is a key ecological factor influencing plant yield and quality, determining aboveground growth and root water/nutrient uptake, and significantly affecting plant development, photosynthesis, and transpiration.

The low temperature stress problem in solar greenhouses primarily results from interactions between structural limitations of the greenhouses themselves and external low-temperature environments. Solar greenhouses have large areas and weak environmental control capabilities, relying mainly on passive solar absorption to increase soil and air temperatures. Their resistance to low temperatures is poor; when external temperatures are low, insufficient heat supplementation often leads to low temperature stress, consequently reducing crop yield and quality. In addition to low temperature stress during winter and spring, brief high temperature stress can also occur during midday periods. Current approaches to mitigate low temperature stress in solar greenhouses include: (1) optimizing greenhouse structures to improve heat storage and insulation perfor-

mance; (2) utilizing solar heating, such as active heat storage-release systems, to increase indoor air temperature; and (3) employing root zone electric heating or ridge mulching to elevate root zone temperature. Although these methods can effectively alleviate low temperature problems, practical applications suffer from drawbacks including high energy consumption, poor economic viability, and operational complexity. Both air temperature and root zone temperature are critical factors affecting crop growth in solar greenhouse production. Research indicates that plant growth and development are more sensitive to root zone temperature than air temperature. When air temperature is suitable for photosynthesis, low root zone temperature becomes the primary factor inhibiting root physiological activity and plant growth. Studies report that for greenhouse-grown cucumbers, seedling growth becomes significantly inhibited when root zone temperature falls below 12 °C, as low root zone temperature reduces root respiration, water and nutrient uptake, and root growth, affecting gas exchange and post-transplant survival. Gosselin et al. found that increasing root zone temperature could enhance pepper yield in low-temperature environments, while Jones et al. demonstrated that root zone heating could offset the effects of nighttime low temperature on tomato yield. These findings confirm that elevating root zone temperature is an effective approach to solving low temperature stress in solar greenhouses.

Since improving root zone temperature effectively addresses low temperature stress in solar greenhouses, we propose a novel cultivation method called soil ridge substrate-embedded cultivation (SRSC). This method integrates soil cultivation with soilless culture by embedding substrate cultivation grooves within soil ridges, covering with plastic film, and using drip irrigation for vegetable production. Soil's stable structure provides excellent heat storage, insulation, and temperature buffering properties, and soil temperature changes lag behind external environmental changes, providing plants with a more stable root zone temperature environment. By accumulating more solar energy, soil ridges increase root zone temperature and enhance substrate stability and buffering capacity. Soilless culture offers high yield advantages while replacing the root zone soil environment with substrate, resolving contradictions in water, air, and nutrient supply associated with traditional soil cultivation and mitigating soil continuous cropping obstacles. Additionally, the drip irrigation system reduces water and fertilizer waste while improving crop yield.

Based on two SRSC configurations—groove-embedded ridge (SRSC-P) and film-embedded (wire mesh-supported) ridge (SRSC-W)—this study used sweet pepper (*Capsicum annuum* L.) as the experimental crop to compare the heat storage and insulation capacities and diurnal root zone temperature characteristics of four different cultivation methods, providing theoretical and technical support for practical application of the SRSC method.

1.1 Experimental Design

The SRSC method combines soil cultivation with soilless culture. Unlike conventional above-ground substrate cultivation, it leverages the high yield and efficiency advantages of soilless culture while utilizing the heat storage and insulation properties of soil ridges, significantly reducing construction material costs and simplifying operations. The method involves embedding specially designed PE substrate cultivation grooves (with holes on lower side surfaces) or wire mesh grooves with film (also with lower side holes) into standardized soil ridges. Specifically, the PE substrate cultivation grooves or wire mesh grooves with film are first arranged in north-south orientation and filled with uniformly mixed cultivation substrate (peat:vermiculite:perlite = 1:1:1). Soil is then mounded around the grooves according to specific standards, embedding the cultivation grooves within the soil ridges to achieve integration. After ridge formation, plastic film mulching and drip irrigation installation significantly increase soil temperature and reduce water and fertilizer loss. The SRSC method integrates soil, substrate cultivation grooves, substrate, plastic film, and drip irrigation systems, combining the respective advantages of soil cultivation and soilless culture while achieving: (1) confined root space for efficient water and fertilizer utilization; (2) reduced substrate quantity for convenient disinfection; (3) sealed cultivation device bottoms to improve water and fertilizer use efficiency; (4) side openings to enhance aeration and soil nutrient utilization; and (5) integration with drip irrigation systems to reduce water and fertilizer inputs. The structure and parameters are shown in [Figure 1: see original paper].

This experiment designed two types of cultivation grooves: one using PE substrate cultivation groove embedding (SRSC-P) and another using wire mesh groove (with internal plastic film) embedding (SRSC-W), aiming to compare the effects of groove materials on heat storage and insulation capacity and to identify cost-effective practical materials. Based on practical production and experimental requirements (ensuring root growth while confining roots within a defined space to improve nutrient absorption efficiency), the PE substrate cultivation groove specifications for the SRSC method were set at length \times width \times height = 120 cm \times 12 cm \times 16 cm, with 2 mm thickness. Two rows of holes (1 cm diameter) were drilled on the sides 5 cm from the bottom, with 5 cm horizontal spacing and 2.5 cm vertical spacing in a staggered arrangement (see [Figure 1: see original paper]). The alternative groove was a wire mesh film-embedded substrate cultivation groove. The wire mesh reduced costs and facilitated heat conduction through its 2.5 cm mesh openings. With internal plastic film, its dimensions matched those of the PE substrate cultivation groove, with identical hole positions and specifications. SRSC cultivation ridges were spaced 67 cm apart, with bottom width of 42 cm, top width of 22 cm, and height of 15 cm. Additionally, soil ridge cultivation rows (SR) and single PE substrate groove cultivation rows (NPG) with identical specifications were established to investigate diurnal root zone temperature characteristics of sweet pepper under four different cultivation methods.

The experimental plot contained 14 cultivation ridges oriented north-south, with a length of 2.4 m. One protective row was established at each eastern and western end, with 12 treatment rows in between. Four treatments were arranged with three replications each, positioned from east to west as SR, SRSC-P, NPG, and SRSC-W.

1.2 Experimental Materials

The experiment was conducted from March 14-19, 2015, in a solar greenhouse at the experimental base in Dasungezhuang Town, Shunyi District, Beijing. The greenhouse measured 60 m in length, 8 m in span, and 3.8 m in ridge height. The experimental plot was 10 m long and 3 m wide, with its southernmost edge 1.5 m from the greenhouse's southern base. The solar greenhouse employed thermal insulation quilt coverage at night, with opening and closing times at 7:00 and 18:00, respectively. Sweet pepper (*Capsicum annuum* L.) cultivar 'Haifeng 16' was used as the experimental crop. Seedlings were raised in plug trays and transplanted at the three-leaf-one-heart stage on March 14, with 30 cm plant spacing.

A domestic intelligent multi-point soil temperature and moisture recorder (accuracy: ± 0.05 °C) was used to measure temperatures at all monitoring points.

1.3 Measurement Methods

A total of 44 temperature monitoring points were established. Two points measured indoor and outdoor air temperatures, positioned in ventilated, shaded locations to avoid solar radiation interference. Cultivation ridge temperature monitoring points were arranged as follows: For SR, SRSC-P, and SRSC-W, temperature sensors were placed at 10 cm depth in the ridge center, 0.6 m from the southernmost ridge end, and at a lateral position 7 cm from the center point (1 cm from the groove wall to minimize wall temperature interference). Each ridge contained 2 monitoring points, totaling 18 points. For NPG, only central root zone temperature was monitored at equivalent positions, with 1 point per ridge totaling 3 points. Data were collected at 20-minute intervals to investigate temporal temperature patterns. Additionally, to investigate spatial temperature variation, monitoring points were established at positions 1.8 m from each ridge's southern end, corresponding to the southern central root zone positions, totaling 21 points. Based on the insulation quilt schedule, daytime was defined as 7:00-18:00 and nighttime as 18:00-7:00 (next day). Representative temperature data from four diurnal cycles were selected for analysis of seedling root zone temperature temporal and spatial patterns. Data from 15:00 on March 14 to 15:00 on March 18 were analyzed for temporal patterns, while data from 17:00 on March 15 to 17:00 on March 19 were analyzed for spatial patterns. March 16 was cloudy, while other days were sunny.

Data were processed using Microsoft Excel 2003 and SAS 8.2 for graphing and statistical analysis.

2.1 Relationship Between Ridge Root Zone Temperature and Indoor/Outdoor Temperatures

As shown in [Figure 2: see original paper], the average root zone temperatures of the four cultivation ridges varied with indoor and outdoor temperatures. Correlation analysis using SAS software revealed identical correlation coefficients ($R^2 = 0.7$, $P < 0.0001$) between average root zone temperature and both indoor and outdoor greenhouse temperatures, indicating extremely significant positive correlations. Over the four diurnal cycles, average root zone, indoor, and outdoor temperatures were 20.77 °C, 17.91 °C, and 9.84 °C, respectively. The solar greenhouse increased indoor and root zone temperatures by 8.07 °C and 10.93 °C, respectively. Daytime indoor (21.11 °C) and root zone (21.64 °C) temperatures were 5.92 °C and 6.45 °C higher than outdoor temperature (15.19 °C), while nighttime indoor (15.03 °C) and root zone (19.94 °C) temperatures were 9.90 °C and 14.81 °C higher than outdoor temperature (5.13 °C). The greater nighttime temperature difference demonstrates that solar greenhouses significantly enhance ridge and indoor temperatures, with more pronounced effects during low-temperature nighttime conditions. During midday when external temperatures were high, the maximum root zone temperature (27.76 °C) remained lower than the maximum indoor temperature (29.83 °C), indicating that cultivation ridges provide certain buffering against high temperatures. Minimum and maximum indoor and outdoor temperatures occurred around 6:00 and 14:00, respectively, while minimum and maximum root zone temperatures occurred around 8:00 and 16:00, respectively. Root zone temperature changes lagged behind indoor and outdoor temperature changes by an average of 2 hours. [Figure 2: see original paper] also shows that during the cloudy day, indoor, outdoor, and ridge temperatures were lower and exhibited minimal variation, suggesting that heat storage and insulation effects of cultivation ridges were less pronounced under low-temperature, low-solar conditions.

2.2 Temperature Variation and Differences Among Four Cultivation Ridges

As shown in [Figure 3: see original paper], central root zone temperatures varied among the four cultivation ridges. Over four diurnal cycles, the average minimum temperatures for SR, SRSC-P, NPG, and SRSC-W were 16.33 °C, 17.03 °C, 17.25 °C, and 17.40 °C, respectively ($SRSC-W > NPG > SRSC-P > SR$), indicating that SRSC-W had the strongest capacity to resist extremely low temperatures, while SR was weakest. The average maximum temperatures were 28.06 °C, 27.21 °C, 29.93 °C, and 26.05 °C, respectively ($NPG > SR > SRSC-P > SRSC-W$), demonstrating that SRSC-W provided the best high-temperature buffering, while NPG was poorest. Average root zone temperatures were 20.32 °C, 20.53 °C, 21.54 °C, and 20.7 °C, respectively. Daytime averages were 21.71 °C, 21.27 °C, 22.57 °C, and 21.03 °C, while nighttime averages were 19.01 °C, 19.83 °C, 20.57 °C, and 20.35 °C. Although NPG showed superior heat storage and insulation capacity, its high-temperature buffering was poor, with root zone

temperatures exceeding 30 °C during daytime peaks on days 2 and 4, which inhibits root growth. SR demonstrated good heat storage but poor insulation capacity. SRSC-W exhibited better insulation performance, with nighttime temperatures 1.34 °C and 0.52 °C higher than SR and SRSC-P, respectively, effectively buffering nighttime low-temperature conditions. Minimum central root zone temperatures occurred around 8:00, while maximum temperatures occurred around 17:00. Temperatures from 6:00–8:00 and 15:00–17:00 were averaged to represent low- and high-temperature conditions for difference analysis. Under low-temperature conditions, root zone temperatures differed significantly among treatments, with SRSC-W significantly higher than others. Under high-temperature conditions, NPG was significantly higher than other treatments, indicating poor high-temperature buffering, while SRSC-W was significantly lower, demonstrating strong high-temperature buffering capacity.

As shown in [Figure 4: see original paper], under sunny conditions, nighttime temperature differences between cultivation ridges and indoor air were positive, indicating ridges were in heat release phase. This demonstrates that cultivation ridges effectively maintained higher root zone temperatures and buffered low-temperature stress during nighttime, with SRSC-W performing better than SR and SRSC-P, showing larger nighttime temperature differences. Daytime temperature differences were negative, as indoor air temperature rose rapidly while ridge buffering slowed temperature increase, placing ridges in heat absorption phase. SRSC-W maintained relatively lower root zone temperatures during daytime high-temperature periods with smaller temperature differences, indicating strong temperature buffering capacity. Comparison of heat release and absorption periods revealed longer heat release than absorption duration. Under cloudy conditions, ridge root zone temperatures remained consistently higher than indoor temperature, indicating that while indoor temperature could not be effectively increased during cloudy days, cultivation ridges still maintained root zone temperature effectively during nighttime.

2.3 Spatial Temperature Differences in Root Zone Under Different Cultivation Patterns

2.3.1 Temperature Differences Between Center and Lateral Positions

As shown in [Figure 5: see original paper], temperature variations between center (C) and lateral (L) positions were observed for SR, SRSC-P, and SRSC-W. Average minimum temperatures at lateral positions were 16.06 °C, 16.79 °C, and 17.15 °C, respectively, while central minimum temperatures were 16.60 °C, 17.19 °C, and 17.78 °C. SRSC-W exhibited the highest minimum temperatures at both positions, with central minimum temperatures higher than lateral minimum temperatures for all treatments. Average maximum temperatures at lateral positions were 27.74 °C, 26.80 °C, and 26.53 °C, respectively, while central maximum temperatures were 28.50 °C, 26.76 °C, and 26.94 °C. Both lateral and central maximum temperatures of SRSC treatments were significantly lower than SR, with central maximum temperatures higher than or similar to lateral

maximum temperatures. Daytime average temperatures at lateral positions were 22.08 °C, 21.79 °C, and 21.86 °C, respectively, while central daytime averages were 22.21 °C, 21.06 °C, and 21.27 °C. Nighttime average temperatures at lateral positions were 18.56 °C, 19.12 °C, and 19.49 °C, respectively, while central nighttime averages were 19.34 °C, 20.20 °C, and 20.92 °C. For SR, central temperature remained higher than lateral temperature during both day and night. However, for SRSC-P and SRSC-W, lateral temperatures were higher during daytime while central temperatures were higher at nighttime, indicating that lateral soil in SRSC treatments stored heat during daytime. Additionally, based on the timing of maximum and minimum temperatures, central temperature changes lagged behind lateral temperature changes by 1 hour, 2 hours, and 3 hours for SR, SRSC-P, and SRSC-W, respectively, with SRSC-W showing the longest lag time and thus the strongest temperature buffering capacity.

2.3.2 North-South Temperature Differences in Root Zone As shown in [Figure 6: see original paper], temperature differences between southern and northern central positions were analyzed, with differences >1 °C considered significant. Average minimum temperatures in southern central root zones for SR, SRSC-P, NPG, and SRSC-W were 16.60 °C, 17.19 °C, 17.71 °C, and 17.78 °C, respectively, while northern central root zone minimum temperatures were 16.78 °C, 18.10 °C, 18.73 °C, and 18.58 °C. Northern central root zone temperatures were 0.18 °C, 0.91 °C, 1.02 °C, and 0.84 °C higher than southern positions, respectively. Northern central minimum temperatures were generally higher than southern, with substantial north-south differences observed in all treatments except SR. The small SR temperature difference likely resulted from its lower temperatures being closer to indoor air temperature. Larger differences in other treatments indicated both capacity to maintain high root zone temperatures and inherent greenhouse north-south temperature gradients. Average maximum temperatures in southern central root zones were 28.50 °C, 26.76 °C, 30.65 °C, and 26.94 °C, respectively, while northern central maximum temperatures were 30.65 °C, 28.38 °C, 30.98 °C, and 26.58 °C. Northern maximum temperatures exceeded southern by 2.15 °C, 1.62 °C, 0.33 °C, and -0.36 °C, respectively. SR and SRSC-P showed large north-south maximum temperature differences, indicating poor production stability. While NPG showed small temperature differences, both north and south temperatures were high and close to air temperature, demonstrating poorest high-temperature buffering. SRSC-W exhibited small north-south high-temperature differences, indicating stable performance. Daytime average temperatures in southern central root zones were 22.21 °C, 21.06 °C, 22.76 °C, and 21.27 °C, respectively, while northern central daytime averages were 22.28 °C, 22.06 °C, 23.12 °C, and 21.28 °C, showing north-south differences of 0.07 °C, 1.00 °C, 0.36 °C, and 0.01 °C. Nighttime average temperatures in southern central root zones were 19.34 °C, 20.20 °C, 21.27 °C, and 20.92 °C, respectively, while northern central nighttime averages were 20.15 °C, 21.87 °C, 22.45 °C, and 21.06 °C, showing north-south differences of 0.81 °C, 1.67 °C, 1.18 °C, and 0.14 °C. SRSC-W exhibited the smallest aver-

age temperature differences between northern and southern central root zones during both day and night, indicating more stable temperatures throughout the day that would benefit crop growth.

3 Discussion and Conclusion

This study proposed and established a novel solar greenhouse cultivation method—soil ridge substrate-embedded cultivation (SRSC)—that embeds substrate cultivation grooves or films within soil ridges, fills the internal space with cultivation substrate, covers ridges with plastic film, and employs drip irrigation for soilless vegetable production. This method leverages the strong heat storage, insulation, and temperature buffering properties of soil to effectively maintain root zone temperatures during low-temperature conditions while enhancing substrate temperature stability. Using cultivation grooves or plastic film to isolate substrate from soil prevents continuous cropping obstacles and soil salinization, offering ecological benefits. The integrated water-fertilizer irrigation approach combines the high yield and efficiency advantages of substrate cultivation and drip irrigation while conserving water and fertilizer.

The results demonstrate that solar greenhouses significantly increase both indoor air and ridge root zone temperatures, particularly during nighttime low-temperature conditions, consistent with findings by Qiang et al. Additionally, ridge temperature changes lagged behind indoor and outdoor temperatures, confirming that soil's large specific heat capacity results in slower heating and cooling, consistent with Chang et al. These findings provide important guidance for timing root zone heating applications.

Although NPG exhibited good heat storage and insulation capacity, its high-temperature buffering was poor, with excessive root zone temperatures during midday periods that can inhibit root growth, with even greater impacts during summer high temperatures. In contrast, SRSC-W demonstrated strong buffering capacity against both low and high temperatures. Compared with conventional soil ridge cultivation, SRSC-W showed superior root zone temperature maintenance, which is highly beneficial for maintaining higher root zone temperatures during winter and spring low-temperature conditions. Furthermore, SRSC-W also provided good buffering against summer high temperatures, warranting further investigation. During nighttime low-temperature periods, SRSC-W root zone temperatures were significantly higher than SR and also higher than SRSC-P, demonstrating its important role in maintaining root zone temperatures during low-temperature conditions and promoting crop growth under such stress.

The superior temperature maintenance and buffering capacity of SRSC-W likely results from the soil ridge's angled structure and favorable characteristics, enabling greater solar radiation absorption. During daytime, both soil and substrate accumulated more solar energy, particularly the substrate with certain moisture content that could absorb more heat. During nighttime, heat stored

in the soil ridge was gradually released, while heat in the substrate was slowly released due to soil coating and film coverage, maintaining relatively higher central temperatures. Under cloudy conditions, ridge root zone temperatures remained higher than indoor temperature but lower than temperatures during sunny periods at equivalent times, indicating that inadequate indoor temperature increase during cloudy conditions affected ridge heat storage.

Liu et al. reported spatial heterogeneity in temperature distribution within solar greenhouses. This study found that northern ridge positions consistently showed higher root zone temperatures than southern positions, providing guidance for crop cultivation and root zone temperature management. While SR central root zone temperatures remained higher than lateral positions during both day and night, SRSC-P and SRSC-W showed higher lateral temperatures during daytime and higher central temperatures at nighttime, indicating that lateral soil in SRSC treatments stored heat during daytime and provided insulation at nighttime—key mechanisms for maintaining higher root zone temperatures. Furthermore, SRSC-W exhibited the smallest north-south central root zone temperature differences among treatments, providing a more stable root zone temperature environment for crop root development. The longest lag time between central and lateral temperature changes in SRSC-W further confirmed its strongest temperature buffering capacity.

In summary, solar greenhouses significantly improve crop root zone temperatures during winter and spring, making substantial contributions to vegetable production in northern China. To address low temperature stress in solar greenhouse production, the SRSC-W cultivation method demonstrated the strongest capacity to maintain higher root zone temperatures during low-temperature periods and the strongest buffering against high temperatures when they occur. This method enhances heat storage, insulation, and temperature buffering performance in the crop root zone, offering advantages over other cultivation patterns with lower-cost support materials compared to PE substrate grooves and greater practical applicability. Additionally, SRSC-W combines the high yield, efficiency, and environmental benefits of soilless cultivation with water and fertilizer savings from drip irrigation, effectively addressing resource and environmental issues such as soil quality degradation and low water/fertilizer use efficiency, thereby delivering outstanding comprehensive benefits.

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Note: Figure translations are in progress. See original paper for figures.

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