

Effects of LED Supplemental Lighting and Root Zone Heating on Growth and Yield of Sweet Pepper in Ridge-Embedded Substrate Cultivation in Solar Greenhouses (Postprint)

Authors: FU Guohai, Yang Qichang, Liu Wenke

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Abstract

Under field conditions, using the soil ridged substrate-embedded cultivation (SRSC) method, the effects of LED canopy supplementary lighting and electric heating wire root-zone warming on sweet pepper growth and yield were studied in a solar greenhouse. The experiment consisted of six treatments: a control without warming or supplementary lighting (CK), root-zone warming at 15 °C treatment (T15), root-zone warming at 18 °C treatment (T18), supplementary lighting alone treatment (L), root-zone warming at 15 °C + supplementary lighting treatment (T15+L), and root-zone warming at 18 °C + supplementary lighting treatment (T18+L). The results showed that, compared with the control, root-zone warming could increase the root-zone temperature of SRSC sweet peppers, but the root-zone temperature still showed a trend of changing with ambient temperature, with T18 maintaining a higher root-zone temperature throughout the day. Changes in root-zone heat flux corresponded to changes in root-zone temperature. The diurnal variation of root-zone heat flux in T15 and T18 treatments was more intense than in CK, with heat transfer from the side of the root zone inward during the day being delayed, and heat transfer outward from the side at night being advanced with increased transfer amount; heat transfer in the vertical direction inward during the day was delayed with reduced transfer amount, while vertical outward heat transfer at night was advanced with increased transfer amount. Both T15 and T18 significantly increased plant height, canopy thickness, and canopy diameter of sweet peppers, with T18 showing more pronounced effects than T15. T15 had no significant enhancing effect on the aboveground and underground dry and fresh weights of sweet peppers, whereas T18 showed significant enhancement. The biomass of sweet peppers under combined root-zone warming and supplementary lighting treatments was generally higher than that under single root-zone

warming or supplementary lighting treatments, with the enhancement effect of T18+L treatment being significantly better than that of T15+L treatment. T15, T18, and L all increased the single-plant yield of sweet peppers compared with CK, with yield increases of 30.74%, 53.0%, and 14.81%, respectively. Furthermore, the synergistic effect of root-zone warming and LED supplementary lighting demonstrated better yield-increasing effects than single root-zone warming or canopy supplementary lighting alone, with T15+L and T18+L increasing yields by 32.86% and 15.50% compared with T15 and T18, respectively, and by 51.29% and 53.87% compared with L, respectively. In conclusion, root-zone warming and LED supplementary lighting are effective regulatory measures for increasing sweet pepper yield in solar greenhouses. The two treatments exhibit significant synergistic effects on increasing single-plant yield, with their combined application showing more pronounced effects than single applications. Moreover, root-zone warming demonstrates more significant promoting effects on sweet pepper growth and yield than canopy supplementary lighting, which has important guiding significance for practical production.

Full Text

Preamble

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Effect of LED supplemental lighting and root zone heating on growth and yield of soil ridged substrate-embedded sweet pepper in solar greenhouses in China

FU Guohai, YANG Qichang, LIU Wenke

(Institute of Environment and Sustainable Agricultural Development, Chinese Academy of Agricultural Sciences / Key Laboratory of Energy Conservation and Waste Management of Agricultural Structures, Ministry of Agriculture, Beijing 100081, China)

Abstract: To address resource and environmental issues associated with soil cultivation, sunlight deficiency, and low winter temperatures in Chinese solar greenhouses, a field study was conducted using the soil-ridged substrate-embedded cultivation (SRSC) method to investigate the effects of LED canopy supplemental lighting and electric root zone heating on sweet pepper growth and yield. Six treatments were designed: control without heating or lighting (CK), root zone heating at 15 °C (T15), root zone heating at 18 °C (T18), sole LED supplemental lighting (L), root zone heating at 15 °C plus LED lighting (T15+L), and root zone heating at 18 °C plus LED lighting (T18+L). Results showed that, compared with CK, root zone heating increased SRSC sweet pepper root zone temperature, though temperatures still fluctuated with ambient conditions, with T18 maintaining higher temperatures throughout the day. Root zone heat flux variations corresponded to temperature changes, with T15 and T18 exhibit-

ing more dramatic diurnal fluctuations than CK. These treatments showed delayed inward heat transfer during daytime and advanced outward heat transfer at night from the lateral root zone, with increased transfer amounts. Vertical heat transfer was similarly delayed during daytime with reduced transfer amounts, while nighttime vertical outward transfer occurred earlier with increased amounts. Both T15 and T18 significantly increased plant height, canopy thickness, and canopy diameter, with T18 showing more pronounced effects than T15. While T15 did not significantly increase above- or below-ground dry/fresh weights, T18 produced significant improvements. Biomass under combined root zone heating and LED lighting was generally higher than under single treatments, with T18+L showing significantly greater enhancement than T15+L. Compared with CK, T15, T18, and L increased yield by 30.74%, 53.0%, and 14.81%, respectively. The synergistic effect of root zone heating and LED lighting outperformed single treatments, with T15+L and T18+L yielding 32.86% and 15.50% more than T15 and T18 alone, and 51.29% and 53.87% more than L alone. In conclusion, root zone heating and LED supplemental lighting are effective agronomic measures for increasing sweet pepper yield in solar greenhouses, demonstrating significant synergistic effects on per-plant yield that exceed single interventions. Root zone heating showed more pronounced effects on growth and yield than canopy lighting, providing important guidance for practical production.

Keywords: Soil ridged substrate-embedded cultivation; Solar greenhouse; Root zone heating; LED supplemental lighting; Sweet pepper; Yield

Introduction

Solar greenhouses have been widely adopted in northern China due to their excellent heat retention, energy efficiency, and ability to support winter vegetable production. Currently, China's solar greenhouse area exceeds 1×10^6 hm², accounting for approximately 25% of protected horticulture area, making it the most important facility type for vegetable production in northern regions. Traditional soil cultivation dominates solar greenhouse production, but this approach suffers from low yield, severe continuous cropping obstacles, and numerous production problems. Excessive water, fertilizer, and pesticide inputs in soil cultivation lead to resource waste and environmental pollution. Furthermore, low temperature stress and insufficient light are critical environmental factors affecting crop growth during winter and spring production seasons.

Solar greenhouses typically lack temperature control equipment, and winter extreme low temperatures inhibit photosynthesis and other physiological activities, resulting in reduced growth and yield. Research indicates that root zone temperature affects crop growth more than air temperature. Reduced root zone temperature impacts root respiration, water and nutrient uptake, root growth, and transplant survival, severely hindering flowering and fruiting. Light is a crucial environmental factor regulating plant morphogenesis, physiological metabolism, photoperiodic responses, growth, and fruit quality. During winter and early

spring, low solar altitude and short daylight hours weaken photosynthesis and impair material synthesis, ultimately affecting yield and quality.

To address winter low temperature stress and environmental problems associated with soil cultivation, our research group developed a novel cultivation method—soil ridged substrate-embedded cultivation (SRSC)—aiming to improve nighttime root zone temperature and increase yield by combining the stable root environment of soil cultivation with the high yield advantages of substrate cultivation. Previous studies showed that compared with soil ridge cultivation, SRSC increased nighttime minimum root zone temperature by 2.15 °C and sweet pepper yield by over 50% under early spring low temperature conditions. However, SRSC has limitations in coping with low temperature stress. Research by Miao et al. demonstrated that while greenhouse air temperature can rapidly increase from 12 °C to 30 °C in the morning, root zone temperature remains around 10 °C, exhibiting a lag effect relative to air temperature changes. When air temperature becomes suitable for crop growth, low root zone temperature becomes the primary factor inhibiting root physiological activity and plant growth. Additionally, root zone heating allows crop growth at greenhouse temperatures 5–10 °C lower than conventional heating conditions. Qu et al. found that root zone heating saves approximately 28% energy compared with air heating through local regulation, with lower production input. Therefore, exogenous artificial root zone heating offers more pronounced growth promotion and yield improvement effects with greater energy efficiency, representing important research value for addressing winter low temperature stress and achieving sustainable agricultural development.

Another major challenge in winter solar greenhouse production is weak light conditions. Canopy artificial supplemental lighting has been widely applied to address light deficiency in protected horticulture. Studies show that seedling-stage lighting promotes robust seedling formation and is important for improving crop quality and yield. However, few studies have reported on winter root zone heating and LED supplemental lighting in solar greenhouse production, and their synergistic mechanisms remain unclear. This study investigated the effects of root zone heating and canopy lighting on sweet pepper (*Capsicum annuum* L.) seedling growth and yield to provide scientific basis for root zone heating and LED supplemental lighting in solar greenhouses.

1.1 Experimental Materials

The experiment was conducted in a solar greenhouse located in Dasungezhuang Town, Shunyi District, Beijing (60 m long, 8 m span, 3.8 m ridge height). Experimental plots measured 15 m × 3 m, positioned 1 m from the greenhouse's southern end and 4 m from the western gable wall. Sweet pepper (*Capsicum annuum* L.) cultivar 'Haifeng 16' was used, with seedlings grown in plug trays and transplanted at the three-leaf-one-bud stage at 30 cm × 90 cm spacing on November 20, 2015. The SRSC method was employed, embedding specially designed substrate cultivation grooves (wire mesh grooves lined with plastic

film, 120 cm × 10 cm × 15 cm) into soil ridges filled with substrate mixture (peat:vermiculite:perlite = 1:1:1). After ridge formation, the surface was covered with plastic mulch (trapezoidal cross-section: 20 cm top width, 40 cm bottom width, 15 cm height). Full nutrient solution drip irrigation was used. Root zone heating was achieved by burying electric heating cables ($450 \text{ W} \cdot (30\text{m})^{-1}$) 2 cm underground, controlled by thermostats and timers. Canopy supplemental lighting used LED plant growth lights ($\text{PPFD} = 200 \text{ mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, R:B = 7:3, measured at seedling canopy top), arranged in strips 30 cm above the canopy, aligned with cultivation ridges, and controlled by timers. The experimental setup is shown in [Figure 1: see original paper].

1.2 Experimental Design

Six treatments were established to investigate effects of root zone heating and canopy lighting on sweet pepper seedlings. Root zone heating was set at 15 °C and 18 °C gradients, applied from 4:00-8:00. LED canopy lighting was also applied from 4:00-8:00, synchronized with heating. Treatments were: (1) Control (CK) without heating or lighting; (2) Root zone heating at 15 °C (T15); (3) Root zone heating at 18 °C (T18); (4) Sole LED lighting (L); (5) Root zone heating at 15 °C + LED lighting (T15+L); (6) Root zone heating at 18 °C + LED lighting (T18+L). Each treatment had three replicate rows with six plants per row, arranged from east to west in random order. Water and fertilizer management was consistent across treatments. Heating and lighting were applied from December 10, 2015, to February 25, 2016, with lighting treatments isolated from non-lighting treatments to avoid interference.

1.3 Harvest and Measurement Indicators

During the experiment, outdoor minimum temperature was approximately -5 °C, with low indoor air and root zone temperatures. Data collection began on December 10, 2015, during the seedling stage. Root zone temperature and indoor/outdoor air temperatures were recorded using YM-CJ intelligent soil temperature loggers ($\pm 0.05 \text{ °C}$ accuracy). Root zone temperature measurement points were located 10 cm deep at ridge center ([Figure 1: see original paper]). Indoor temperature points were 2 m above plots (shaded), and outdoor points were in ventilated, shaded locations, with 10-minute intervals. Data from December 12-14, 2015, were analyzed. YM-RT soil heat flux sensors measured lateral soil-substrate interface and vertical heat flux at root zone center (10 cm depth) ([Figure 1: see original paper]), with positive values indicating inward heat transfer. Data from January 30-February 1, 2016, and February 12-14, 2016, were analyzed. At harvest on March 20, 2016, growth and yield parameters were measured: stem diameter and fruit size with calipers, plant height and canopy dimensions with rulers, and biomass and yield with balances. Yield was measured twice (March 20 and 30).

1.4 Data Analysis

Data were processed and graphed using Microsoft Excel and analyzed using SAS 8.2 software.

Results

2.1 Temperature Variation Patterns Inside/Outside Solar Greenhouse and in Root Zone

During the experiment, solar greenhouse indoor and outdoor temperatures ranged from 6–30 °C and -11–12 °C, respectively. [Figure 2a: see original paper] shows that during heating periods, outdoor temperature varied from -7–8 °C, while indoor minimum temperature was only 8 °C, with an average of 12.7 °C. [Figure 2b: see original paper] demonstrates that root zone heating altered temperature patterns. Root zone temperature peaked around 15:00 and reached minimum around 10:00. The control showed regular diurnal fluctuations with one peak and one valley. T15 showed variable patterns across days—on day 1, no difference was observed likely because root zone temperature was above the heating threshold and the system didn't activate. On subsequent days, when temperature dropped below the setpoint, heating began at 4:00, peaked at 7:00, then decreased similarly to control but with slower decline and maintained higher temperatures. T18 showed consistent patterns, with temperature increasing from 4:00, peaking around 9:00 (later than the 8:00 heating cutoff, likely due to stored heat), then decreasing but remaining at higher levels.

2.2 Horizontal and Vertical Heat Flux Changes in Sweet Pepper Root Zone Under Single Heating

[Figure 3a: see original paper] shows differences in lateral root zone heat flux among treatments. Day 3 sunny-day data revealed that positive values indicated inward heat transfer and negative values outward transfer. All treatments showed regular patterns: daytime inward and nighttime outward transfer. As heating gradient increased, the temperature difference between root zone and environment increased, with maximum daytime inward heat flux increasing progressively (43.9, 49.1, and 54.9 $\text{W} \cdot \text{m}^{-2}$ for CK, T15, and T18, respectively). Nighttime maximum outward flux also increased (7.2, 11.8, and 12.6 $\text{W} \cdot \text{m}^{-2}$) due to greater temperature differentials.

[Figure 3b: see original paper] shows vertical heat flux differences. Using day 3 sunny data, positive values indicated inward transfer. As heating gradient increased, daytime maximum inward flux showed small differences, but heating treatments peaked 2 hours earlier than CK. Nighttime maximum outward flux increased slightly with heating gradient. With increasing heating gradient, lateral heat transfer timing showed consistent patterns: delayed inward transfer in morning and advanced outward transfer at night, likely due to differences

between ridge heat storage and air temperature changes. Higher heating gradients increased lateral daytime and nighttime heat transfer but decreased vertical daytime transfer while increasing vertical nighttime transfer.

2.3 Effects of Root Zone Heating and LED Lighting on Sweet Pepper Growth

shows morphological differences among treatments. Both T15 and T18 increased plant height, stem diameter, canopy thickness, and canopy diameter, with significant improvements in plant height, canopy thickness, and canopy diameter (canopy thickness = branch thickness; canopy diameter = branch diameter, representing photosynthetic area morphology). T18 effects were more pronounced than T15, with T18 significantly exceeding T15 in all parameters except stem diameter. Sole LED lighting significantly increased plant height and canopy diameter but not stem diameter or canopy thickness. Combined heating and lighting further improved morphological parameters, with both heating gradients significantly increasing canopy diameter. Under T18, lighting also significantly increased plant height and canopy thickness. Root zone heating effects were more significant than canopy lighting.

Biomass differed among treatments, with heating and lighting increasing above- and below-ground biomass. T15 did not significantly increase fresh/dry shoot and root weights, while T18 showed significant improvements. Sole LED lighting significantly increased shoot dry weight and root fresh weight, possibly due to imbalanced material transport. Combined treatments generally produced higher biomass than single treatments, with T18+L significantly outperforming T15+L.

2.4 Effects of Root Zone Heating and LED Lighting on Sweet Pepper Yield

shows that both root zone heating and canopy lighting increased yield. T15 and T18 did not significantly improve fruit size, number, or single fruit weight but significantly increased per-plant yield, with T18 outperforming T15. T15 and T18 increased yield by 30.74% and 53.00% compared with CK, respectively. Sole LED lighting did not significantly improve yield parameters but increased yield by 14.81% over CK. Combined treatments further enhanced yield, with synergistic effects outperforming single treatments. T15+L and T18+L increased yield by 32.86% and 15.50% compared with T15 and T18 alone, and by 51.29% and 53.87% compared with L alone. T18+L yielded only 1.7% more than T15+L, showing minimal additional benefit.

Discussion and Conclusion

Sweet pepper cultivated via SRSC in solar greenhouses has high yield potential but suffers from low-temperature and weak-light stress. This study demonstrates that under low temperature conditions, root zone heating and LED

red-blue light supplementation promote SRSC sweet pepper growth and increase yield, indicating these measures can further enhance production efficiency. SRSC root zone heating altered thermal patterns, with higher heating temperatures producing greater effects on root zone temperature and heat flux. Research shows that winter solar greenhouse minimum air temperature occurs around 6:00, while soil or cultivation ridge temperature changes lag behind air temperature. Greenhouse air temperature rises rapidly in morning, but root zone temperature increases slowly, making low root zone temperature a key limiting factor for plant growth and physiological activity during cold seasons. We selected 4:00-8:00 for heating, when root zone temperature is lowest, to achieve energy efficiency and effectiveness. T18 maintained higher temperatures throughout the day, likely due to greater heat accumulation, while T15 improved temperatures during low-temperature periods and daytime warming phases but with weaker effects, indicating less heat storage. Both heating treatments showed temperature decreases during heating periods, possibly because extreme low ambient temperatures affected root zone temperature, causing relatively large drops before daytime warming resumed.

Root zone temperature changes are directly affected by heat transfer, but different heat transfer rates between lateral soil and vertical substrate caused timing differences in heat exchange between day and night. The delayed morning inward heat transfer and advanced nighttime outward transfer likely resulted from high ridge temperatures and rapid indoor air temperature changes, creating temporal differences in heat balance. Higher heating gradients increased internal heat, requiring greater inward and outward heat transfer to achieve balance. The smaller vertical daytime inward transfer may be due to faster substrate heat transfer rates, preventing significant temperature gradients across the ridge.

Both SRSC root zone heating and canopy lighting affected sweet pepper growth. Root zone heating influences root and canopy physiological activities by altering root zone environment, thereby affecting crop growth. Studies show that low-temperature root zone heating promotes root respiration, enhances metabolic activity, and improves water and nutrient uptake. Root zone heating also promotes canopy photosynthesis and facilitates material transport. Canopy lighting benefits photosynthesis—winter's short days and insufficient light reduce photosynthesis, affecting dry matter formation and yield. Artificial lighting effectively increases light and promotes photosynthesis. Like root zone heating in low-temperature environments, lighting 4 hours before uncovering thermal blankets allows early photosynthesis, and combined with heating produces better effects than single treatments. Root zone heating effects exceeded lighting effects, likely because root zone temperature is more critical for growth.

SRSC root zone heating and canopy lighting increased yield, demonstrating their effectiveness for improving production. Combined heating and lighting during heating periods enhanced nutrient uptake and photosynthetic capacity under low temperatures while extending photosynthesis duration. Research indicates

root zone heating saves approximately 28% energy compared with air heating through local regulation, making it more energy-efficient. This study shows yield increased with heating gradient, and combined treatments outperformed single treatments. However, T18+L yielded only 1.7% more than T15+L without proportional energy efficiency gains. Therefore, considering economic benefits, the combination of 15 °C root zone heating with LED lighting is optimal.

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