Effects of different root zone heating systems on the microclimate and crop development in solar greenhouses

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Abstract: Heating greenhouse is indispensable for plant development particularly in winter when the air temperature is lower. In that sense, root zone heating is more energy-saving than traditional air heating. The current work was devoted to the study of the effect of two root zone heating systems based on carbon crystal electrothermal film and low temperature hot water pipe on the microclimate and tomato yield in solar greenhouse. And their performance was tested in the coldest period of winter in Yongqing County of Hebei Province. The results showed that the use of root zone heating system can improve the average substrate temperature by 6.8 ℃. This microclimate improvement had a positive impact on tomato production. The output per square meter has increased by 19% compared to the unheated. It was also noted that the presence of root zone heating leads to a decrease in the development of disease in heated areas. Based on these results, the root zone heating system can be an effective method of improving the environmental temperature of crop plant, which is of great significance for increasing crop yield.

Keywords: solar greenhouse, root zone heating, substrate temperature, air temperature, tomato trough cultivation

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1 Introduction

Solar greenhouse is a greenhouse type independently developed by China, which can realize the overwintering production of fruits and vegetables without auxiliary heating. By the end of 2020, Chinese solar greenhouse area has exceeded 5×10^5 hm^2. As an important way to solve the stable supply of vegetables in northern China in winter, it has played an important role in ensuring supply and increasing income. At the same time, it is also a key way for Chinese protected horticulture industry to achieve the goal of “double carbon”.

The solar greenhouse can carry out production without heating when the outside minimum temperature is –10℃ in North of China[1,2]. The main reason is that the wall and soil of solar greenhouse have the function of heat storage and release. The wall and soil store solar energy during the day, and release the energy at night. However, this heat storage and release structure has limited effect due to the slow heat transfer between the wall and soil. It is difficult to effectively collect and store the surplus solar energy in the daytime for improving inside temperature at night. Early researchers mainly used the solar energy absorbed by water and other media to heat the inside soil by building a ground heat exchange system. However, due to its large amount of work and limited heat storage and release effect, it has not been widely used[3]. Many researchers collect and store the solar heat energy in the water through internal or external heat collection devices, and release it into the greenhouse at night to improve the inside temperature[4-8], use rock-bed as heat storage[9-11], or make hot water and hot air into the inside underground to improve the inside ground temperature[12-16]. At the same time, the method of phase change latent heat storage in chemical industry has also been applied to solar greenhouse. Compared with water heat storage, this method can greatly reduce the volume of heat storage facilities[17,18]. These methods mostly use solar energy, and the heat storage and release are unstable. The main reason is that they rely too much on the changes of external environment. Therefore, the active heating system is another necessary choice.

The heating of greenhouse mainly includes air heating and soil heating. In the past, people often paid more attention to air temperature improvement and ignored the research on the root zone temperature. However, in the solar greenhouse, when it is sunny, the inside air temperature rises rapidly and soon reaches the appropriate temperature for crop growth, but the root zone temperature rises slowly. In winter mornings, after the heat preservation quilt is rolled up, the root zone temperature generally needs 2-3 h to enter the optimal range of root physiological activities. During severe cold time, it takes longer, so the aboveground part is in a high light and temperature environment, and the recovery of root function is slow, which cannot ensure the

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demand of crops for water and mineral nutrition, and is easy to cause physiological and biochemical metabolic disorders. In recent years, with the maturity of environmental control technology of solar greenhouse in China, more and more researchers also tend to control the temperature microenvironment of crop root zone. Root zone temperature significantly affects the growth of crop roots and the absorption, transportation and storage of water and mineral nutrients[19]. When the root zone temperature is higher or lower than the upper and lower limits of the optimal temperature for crop growth and metabolism, its growth and metabolism are easy to be inhibited or stressed. Generally, the temperature required by the root zone of crops is slightly lower than that of the aboveground part of crops, and the suitable temperature range required by the root zone is narrow, generally 15℃-25℃. This is a genetic feature formed by the root system living in the soil environment with small temperature variation for a long time, and it is also the reason why crops are more sensitive to the root zone temperature than the air temperature. Therefore, in a sense, controlling the root zone temperature is more important than air temperature.

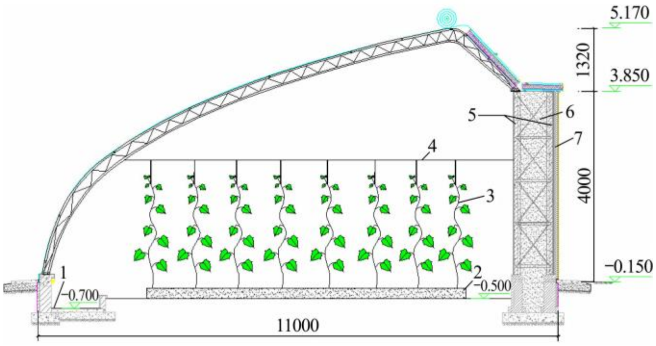
Root zone heating can reduce greenhouse air temperature required for crop growth by 5℃-15℃ and save energy consumption by 28% compared with traditional heating conditions[20]. At present, the way of root zone heating in crop production mainly adopts heating cable[21], capillary network through low temperature hot water[22], carbon crystal material[23-25] to heat the root zone directly, but it is mostly used in small-scale seedling production in winter of solar greenhouse. For substrate trough cultivation of fruits and vegetables, root zone heating is less used. Zhang et al.[26] built the burning cave hot water soil heating system of solar greenhouse, which can improve the soil average temperature 5℃-6℃. Ding et al.[27] designed a hot water heating system based on capillary pipe network, which can effectively improve the local temperature of solar greenhouse. Beyza et al.[28] and Llorach-Massana et al.[29] all used phase change materials (PCM) for root zone heating, but the temperature was difficult to control. Muhammad et al.[30,31] designed a nested double-layer cultivation pot in which silicone rubber heating plates was placed for root heating to solve the low temperature of Yangtze river delta region of China.

The purpose of this study is to explore the effects of two different root zone heating methods of carbon crystal electrothermal film and low temperature hot water pipe on tomato planting environment and yield, in order to provide practical basis for the design and application of heating system for large-scale soilless fruit and vegetable cultivation in solar greenhouse in the future.

2 Materials and methods

2.1 Experimental greenhouse description

The experiment was carried out in the solar greenhouse of Yongqing County, Hebei Province from October 2021 to April 2022 (39.32°N, 116.49°E, 11 m altitude). The solar greenhouse faces south, with a length of 60 m, a span of 10 m and a ridge height of 5.32 m. And the back wall was 4 m high and 950 mm thick. From inside to outside, it was 850 mm thick steel frame system prefabricated reinforced concrete slab fabricated wall and 100 mm thick extruded polystyrene board. The fabricated wall was a steel frame, the inner and outer layers were 80 mm thick precast concrete slabs, and the middle was 660 mm thick compacted soil, which needs to be compacted several times. The gable was 370 mm thick shale brick with 100 mm thick extruded polystyrene board outside. The film of front roof was polyolefin film with high light transmittance, aging resistance, fog elimination and good dripping performance, with a thickness of 0.12 mm. The front bottom of the greenhouse adopted electric film rolling ventilation, and the ridge adopted intelligent roof ventilation system to adjust the size of air outlet according to the inside air temperature feedback. The front roof was covered with composite insulation quilt, and the rolling time was 8:30-9:00 and 16:00-16:30. The air heating system was not installed in the greenhouse. Only the root zone heating system was installed in the foam planting trough, which section's width and height were 270 mm and 245 mm respectively. Figure 1 is the cross-sectional view of experimental greenhouse.



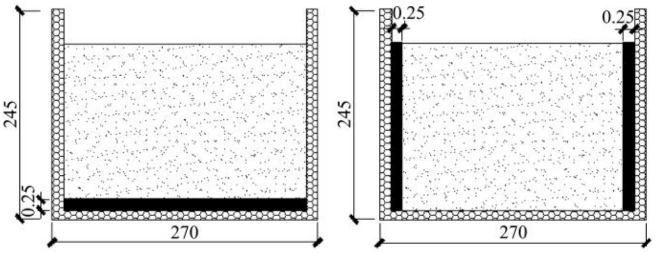
1. Front walkway 2. Cultivation trough and Substrate 3. Tomato plant 4. Hanging line 5. Reinforced concrete precast slab 6. Compacted soil 7. Extruded polystyrene board

Figure 1 Structure of experimental solar greenhouse

2.2 Root heating system description

2.2.1 Root zone heating system based on carbon crystal electrothermal film

The heating system was composed of carbon crystal electrothermal film, temperature control system and conductive circuit. The carbon crystal electric heating film is a surface heating material with heat dissipation on one side, which interior is carbon heating area, copper foil current carrying strip, silver slurry current carrying strip, base film, etc. Its surface temperature can reach 50℃, and the heating density is 120 W/m^2. It can directly convert electric energy into heat energy, and the conversion efficiency can reach more than 95%. The temperature control system is composed of substrate temperature sensor and liquid crystal control panel, and the carbon crystal electric heating film can be connected in parallel according to the width, which relates to the temperature control system by wires. The carbon crystal electrothermal film has various specifications. The thickness of the carbon crystal electrothermal film used in the experiment was 0.25 mm. It was cut into a long strip with a width of 0.15 m and a length of 8 m, which was laid in the cultivation trough in two different forms, as shown in Figure 2, in which the black rectangle in the figure represents the carbon crystal electrothermal film. Figure 2a shows that the carbon crystal electrothermal film was directly laid on the bottom of the cultivation trough, and Figure 2b shows that the carbon crystal electrothermal film was placed vertically on both sides of the cultivation trough. The substrate temperature was used as the control threshold, and the system was turned on when the substrate temperature was lower than (21±2)℃. When the substrate temperature was higher than the threshold, the heating system was turned off.

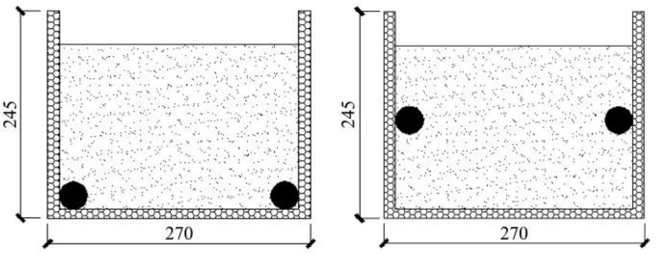


a. On the bottom b. On both sides

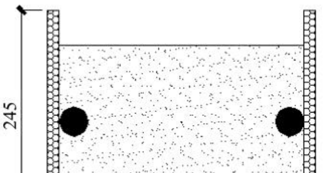
Figure 2 Different arrangement of carbon crystal electrothermal film

2.2.2 Root zone heating system based on low temperature hot water pipe

The heating system was composed of hot water boiler, hot water pipeline and valve. PVC pipe with nominal inner diameter of 32 mm, outer diameter of 40 mm and wall thickness of 3 mm was selected as the hot water pipe, and the outlet water temperature was set to 22℃. There were three different forms of hot water pipe layout, as shown in Figure 3. The black circle in the figure represented the hot water pipe. Figure 3a shows that one hot water pipe was set at both ends of the bottom of the cultivation trough, Figure 3b shows that one hot water pipe was set at both ends of the middle of the cultivation trough, and Figure 3c shows that one hot water pipe was set at both ends of the bottom and middle of the cultivation trough. The system also used the substrate temperature as the control threshold, and the control method was the same as the carbon crystal electrothermal film root zone heating system.



a. On the bottom b. On the middle



c. On the bottom and middle

Figure 3 Different arrangement of low temperature hot water pipes

2.3 Crops

The crops planted in the experimental greenhouse were taste tomatoes. The seedlings were sown on September 15, 2021 and planted in the cultivation trough of the experimental greenhouse on October 21, 2021. The cultivation substrate was the mixed substrate of peat, vermiculite and perlite. The plant rows were oriented north-south. 12 rows of tomatoes were planted in the experimental greenhouse, of which 10 rows were heated, and the heating treatment of each 2 rows was the same; 2 rows were not heated. The plant rows with root zone heating were consistent with the production and management of unheated plant rows. All the plant rows were fertigated using the same system, and received the same amount of water and fertilizer.

2.4 Monitoring of physiological parameters of tomato

In order to evaluate the effect of different root zone heating modes on crop growth, some growth parameters of tomato need to be counted. Under five different heating treatments and unheated treatment, five plants were randomly selected to measure the growth indexes of tomato after 60 d and 90 d of planting separately, which included plant height, stem diameter, internode number and chlorophyll content. After 130 d of planting, the fruit yield and quality were counted. Since tomato diseases occurred in the late growth stage during the experiment, mainly epidemic diseases, the disease index 150 d after colonization was counted. All data were analyzed by SPSS software.

2.5 Test of tomato growth environment parameters

The parameters of outside meteorological conditions were monitored by the meteorological station, including outside temperature, relative humidity, solar radiation, wind speed, wind direction, rainfall, etc. Inside air temperature and humidity were measured by temperature and humidity recorder with model HOBO UX100-003, which is produced by American Onset Company, and the accuracy is ±0.21℃ and ±3.5%. The substrate temperature was measured by intelligent soil temperature recorder with model TJ1, which is produced by Beijing Hezhong Bopu Technology Development Co., Ltd, and the accuracy is ±0.2℃. The inside air temperature and humidity recorders were 1.5 m above the ground, and the soil temperature sensor was buried at the depth of 12 cm. The experimental planting and the distribution of environmental measuring points are shown in Figure 4, in which the same figure showed the same heating treatment. A-E are cultivation columns representing different root zone heating methods, which are also five treatments in test. A and B are consistent with Figures 2a and 2b respectively. C, D and E are consistent with Figures 3a-3c, while F stood for unheated cultivation column, which is taken as the control.

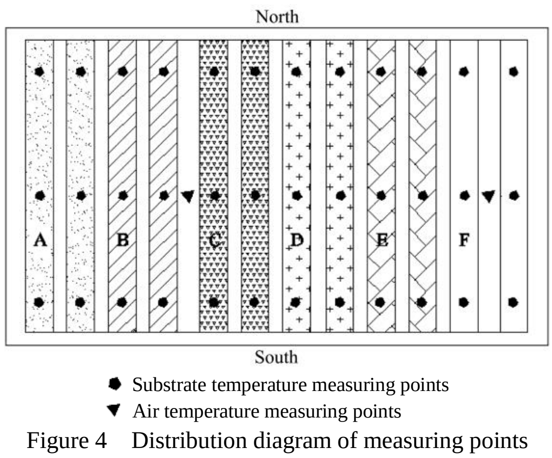


Figure 4 Distribution diagram of measuring points

3 Results and discussions

3.1 Climatic parameters

3.1.1 Changes of inside and outside environment during the test

For the temperature in the greenhouse is affected by many factors, there is non-uniformity in the horizontal and vertical distribution of inside temperature. In order to reduce the error, the measured values of the inside temperature were treated with the average values of the arranged measuring points. The test was carried out in the coldest period in Yongqing County of Hebei Province. Most of the periods were continuous sunny days, with occasional continuous overcast and snowy days. The outside temperature was –14.3℃-22.0℃, the relative humidity was 12%-100%, the maximum solar radiation was 628 W/m^2, and the maximum wind speed was 6.8 m/s, while the inside temperature was 6.8℃-42.9℃ without auxiliary heating, and the relative humidity was 16.2%-98.3%. Figure 5 shows the changes of temperature and relative humidity during the test period from November 5, 2021 to January 7, 2022. The variation range of inside and outside temperature difference is 2.6℃-33.9℃, which indicates that the thermal insulation effect of solar greenhouse is good.

3.1.2 Changes of cultivation substrate temperature

The changes of substrate temperature under two typical weather conditions were analyzed. Figure 6 shows the substrate temperature changes of five root zone heating treatments and unheated treatment in sunny and cloudy days. The substrate temperature of root zone heating was significantly higher than that of unheated. The fluctuation range of substrate temperature in cloudy and snowy days was not as large as that in sunny days. The main reason was that the temperature change of substrate was affected by solar radiation, while the solar radiation in cloudy and snowy days was weak and had little effect on substrate temperature. Among two heating treatments of carbon crystal electrothermal film, the heating effect of B was better than A, and the temperature fluctuation range was the smaller.

The extreme values of substrate temperature in different test areas during the whole test period and under two typical weather conditions were counted, as listed in Table 1. The average substrate temperature of heating areas was 6.8℃ higher than that of unheated area, and in five heating areas the maximum difference between average substrate temperature was 1.9℃. In two typical climates, the average substrate temperature of heating areas was 6.6℃ and 9.6℃ higher than that of unheated area, and the maximum difference of average substrate temperature between five heating areas was 1.8℃ and 7.7℃ respectively.

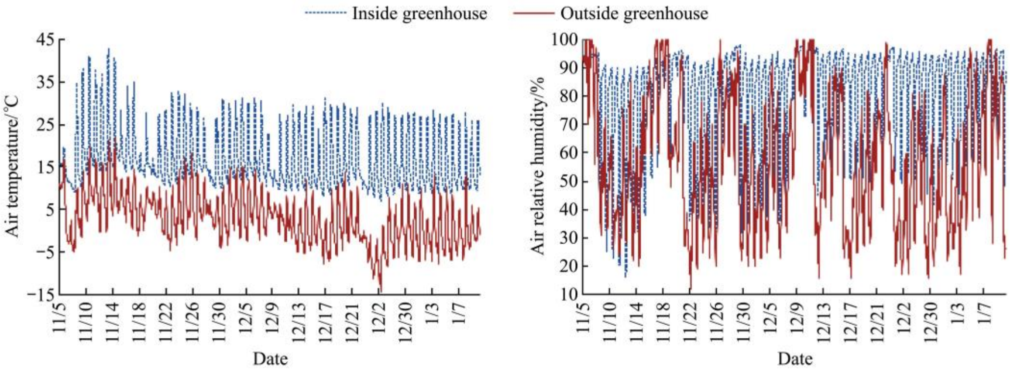
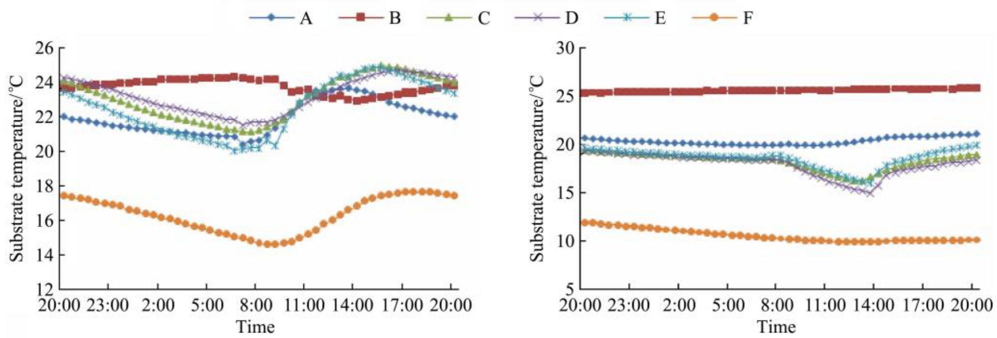


Figure 5 Changes of inside and outside environment



a. Sunny day (December 21, 2021) b. Cloudy and snowy day (January 21, 2022)

Figure 6 Day change of substrate temperature

Table 1 Extreme value of substrate temperature in different test areas (℃)

Statistical period	Statistical indicators	A	B	C	D	E	F
Throughout the test period	Minimum	19.2	20.9	18.3	19.3	15.8	10.6
	Maximum	25.4	26.1	28.7	28.6	29.5	22.2
	Average	21.7	23.6	22.3	22.6	22.5	15.7
The sunny day	Minimum	20.4	22.9	21.1	21.5	20.0	14.6
	Maximum	23.6	24.3	24.9	24.7	24.9	17.6
	Average	21.9	23.7	23.1	23.2	22.5	16.3
The cloudy and snowy day	Minimum	19.8	25.2	16.2	14.9	16.0	9.9
	Maximum	21.0	25.8	19.4	19.3	19.9	11.9
	Average	20.3	25.5	18.3	17.8	18.5	10.5

3.2 Tomato growth parameters

3.2.1 Plant height, stem diameter, internode number and chlorophyll content

The effects of different heating treatments on plant growth are shown in Figure 7. Compared with the control, the various root zone heating methods promoted plant elongation to varying degrees, and the differences between B, C, D and F were significant. The effects of treatment for 60 d and 90 d were slightly different. Treatment D was the best at 60 d and treatment C was the best at 90 d. Meanwhile, compared with the control, all kinds of heating methods were conducive to increase the stem diameter of the plant. When treated for 60 d, the effects of treatment B and E seemed to be more obvious. When treated for 90 d, the effect of heating on the increase of stem diameter was more significant, but there was little difference in the positive effect of different heating methods. Interestingly, the control has more nodes than all heating methods, and its plant height was the lowest, indicating that the node spacing was also the shortest. When treated for 60 d, there was no difference between different heating methods. When treated for 90 d, among the five heating treatments, the number of nodes of A was the most and the number of nodes of D was the least, and there was no significant difference among other treatments. The effect of heating treatment on leaf chlorophyll content was not significant. Only treatment B and treatment E promoted the increase of chlorophyll content at 60 d and 90 d.

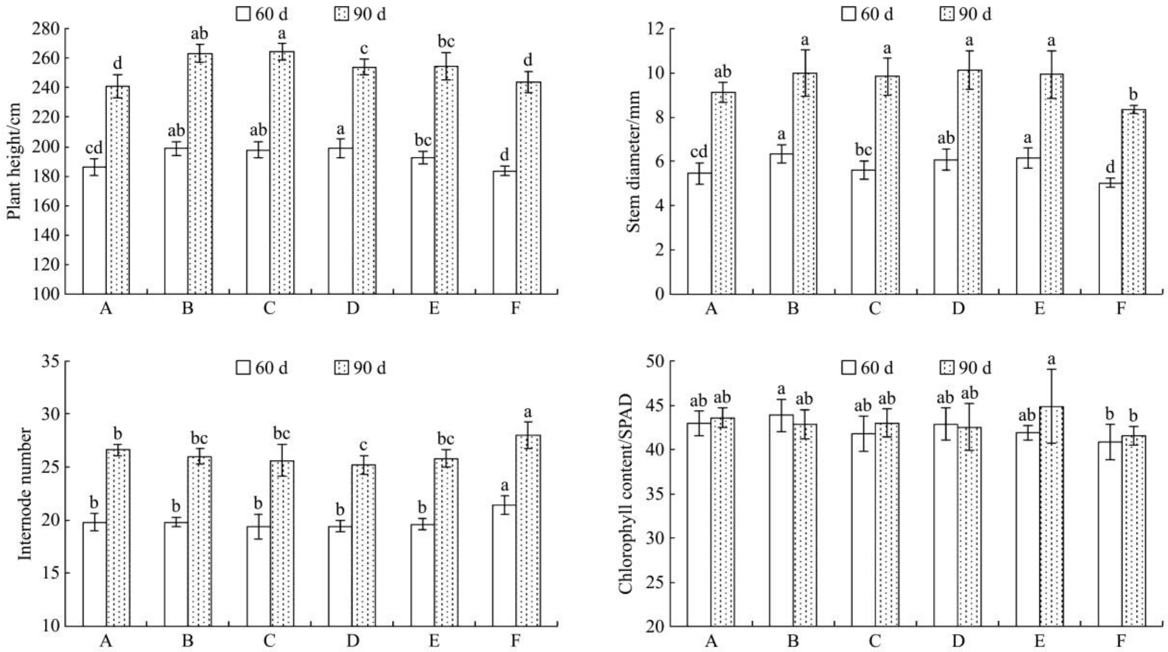


Figure 7 Effects of different heating treatments on plant height, stem diameter, internode number and chlorophyll content of tomato plants 60 and 90 d after transplanting

3.2.2 Tomato production and soluble solid content (SSC)

The effects of different heating treatments on yield and SSC are shown in Figure 8. As of 130 d after planting, the cumulative yield of tomato under the three heating treatments of B, C, and D reached more than 10 kg/m^2, significantly higher than the control by 8.1 kg/m^2. The yield of treatment E and treatment A was slightly higher or lower than the control, but the difference was not significant. Soluble solid was the general name of all compounds dissolved in water in the sample, including sugar, acid, vitamins and minerals. It was the most important quality index to reflect the taste of tomato. We determined the content of soluble solids in tomato fruit, and the result was almost the opposite of the yield. The highest SSC was treatment A and treatment E, which indicated that the plant may have experienced some water deficit. There was no significant difference between SSC and control in treatment B and C with the highest yield. Combining these two indicators, treatment D seemed to have a better balance, higher yield and higher SSC.

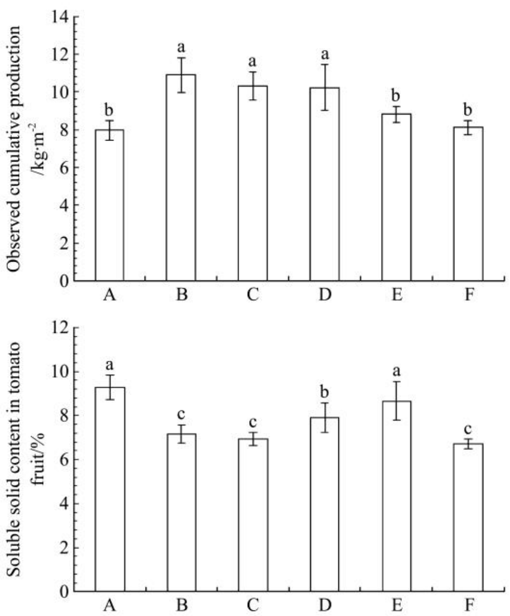


Figure 8 Effects of different heating treatments on cumulative yield and soluble solid content of tomato fruit 130 d after transplanting

3.2.3 Disease index

Serious diseases occurred in the later stage of cultivation, and seedling pulling ended the cultivation cycle in advance. The disease index was counted 150 d after planting before seedling pulling. Effects of different heating treatments on disease index are shown in Figure 9. Compared with the control, the incidence of all heated tomato plants was significantly reduced. Among the five heating treatments, treatment A was the most serious, treatment E was the lightest, C and D were in the middle, and there was no significant difference with B or E. From the above two indexes, the plants of treatment A were subjected to obvious abiotic and biological stress, but compared with the control, heating still had a positive effect.

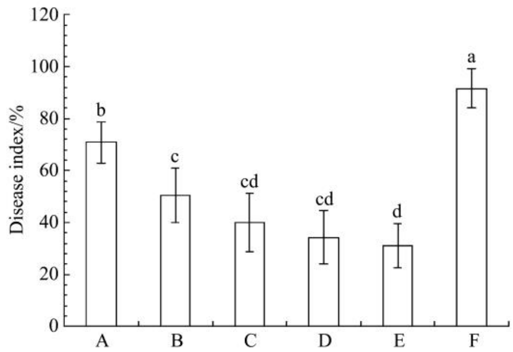


Figure 9 Effects of different heating treatments on disease index of tomato plants 150 d after transplanting

4 Conclusions

An experimental study was conducted to evaluate the effects of two different root zone heating methods of carbon crystal electrothermal film and low temperature hot water pipe on tomato plant environment, crop physiological parameters and yield in solar greenhouse. The performance of root zone heating system was tested in the coldest period of winter in Hebei Province. The results showed that the use of root zone heating system can improve the average substrate temperature by 6.8℃, and in two typical climates, the average substrate temperature of heating areas was 6.6℃ and 9.6℃ higher than that of unheated area. The root zone heating system can make the substrate temperature rise evenly, which can provide a good environment for the crop cultivation. Meanwhile, the root zone heating methods can promote plant elongation, increase the stem diameter, reduce the risk of diseases development of plants and make the output per square meter increase by 19% compared to the unheated.

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[References]

[1] Tong G H, Christopher D M, Li T L. Passive solar energy utilization: A review of cross-section building parameter selection for Chinese solar greenhouses. Renewable and Sustainable Energy Reviews, 2013; 26: 540–548.

[2] Sonneveld P J, Swinkels G L A M, Campen J, van Tuijl B A J, Janssen H J J, Bot G P A. Performance results of a solar greenhouse combining electrical and thermal energy production. Biosystems Engineering, 2010; 106(1): 48–57.

[3] Bai Y K, Wang T L, Tong G H, Liu W H. Experimental research on energy saving of solar greenhouse of type northeast of China-Type Liaoshen Solar Greenhouse. Energy Conservation Technology, 2002; 20(2): 3–5. (in Chinese)

[4] Zhang Y, Yang Q C, Fang H. Research on warming effect of water curtain system in Chinese solar greenhouse. Trans of the CSAE, 2012; 28(4): 188–193. (in Chinese)

[5] Du J, Bansal P, Huang B. Simulation model of a greenhouse with a heat-pipe heating system. Applied Energy, 2012; 93: 268–276.

[6] Bargach M N, Dahman A S, Boukallouch M. A heating system using flat plate collectors to improve the inside greenhouse microclimate in Morocco. Renewable Energy, 1999; 18: 367–381.

[7] Ntinas G K, Fragos V P, Nikita-Martzopoulou C. Thermal analysis of a hybrid solar energy saving system inside a greenhouse. Energy Conversion and Management, 2014; 81: 428–439.

[8] Gourdo L, Fatnassi H, Bouharroud R, Ezzaeri K, Bazgaou, Wifaya A, et al. Heating canarian greenhouse with a passive solar water-sleeve system: Effect on microclimate and tomato crop yield. Solar Energy, 2019; 188: 1349–1359.

[9] Kurklu A, Bilgin S, Ozkan B. A study on the solar energy storing rock-bed to heat a polyethylene tunnel type greenhouse. Renewable Energy, 2003; 28(5): 683–697.

[10] Gourdo L, Bazgaou A, Ezzaeri K, Tiskatine R, Wifaya A, Demrati H, et al. Heating of an agricultural greenhouse by a reservoir filled with rocks. Journal of Materials and Environmental Science, 2018; 9(4): 1193–1199.

[11] Gourdo L, Fatnassi H, Tiskatine R, Wifaya A, Demrati H, Aharoune A, et al. Solar energy storing rock-bed to heat an agricultural greenhouse. Energy, 2019; 169: 206–212.

[12] Li B H, Xu H, Li T L, Wei X D, Wang X X. Application of solar energy soil heating system in greenhouse. Journal of Shengyang Agricultural University, 2009; 40(2): 152–155. (in Chinese)

[13] Yu W, Wang T L, Liu W H, Yu Y. Application research on the heating effect of solar geothermal heating system on soil temperature in the solar greenhouse. Journal of Shengyang Agricultural University, 2010; 41(2): 190–194. (in Chinese)

[14] Fang H, Yang Q C, Liang H, Wang S. Experiment of temperature rising effect by heat release and storage with shallow water in solar greenhouse. Transactions of the CSAE, 2011; 27(5): 258–263. (in Chinese)

[15] Ozgener L, Ozgener O. Energetic performance test of an underground air tunnel system for greenhouse heating. Energy, 2010; 35: 4079–4085.

[16] Attar I, Naili N, Khalifa N, Hazami M, Farhat A. Parametric and numerical study of a solar system for heating a greenhouse equipped with a buried exchanger. Energy Conversion and Management, 2013; 70: 163–173.

[17] Wang H L, Zou Z R, Chen H W, Zhang Y. Research advances in technologies of phase-change heat storage and its application in greenhouses. Transactions of the CSAE, 2008; 24(6): 304–307. (in Chinese)

[18] Zhou Y, Wang S X, Liu Z H, Ma J P, Wang T. Simulation study on composite phase change thermal insulation walls in solar greenhouse based on ANSYS. Acta Energiae Solaris Sinica, 2020; 41(4): 113–122. (in Chinese)

[19] Fu G H, Yang Q C, Liu W K, Yan W K. Research progress about effects of root zone temperature on physiology and ecology of protected horticulture crops. China Vegetables, 2016; (10): 20–27. (in Chinese)

[20] Chen Y. Plant root zone heating reduces greenhouse energy consumption. Greenhouse Horiticlutre, 2008; 3: 20. (in Chinese)

[21] Zhang H M, Jin H J, Ding X T, Yu J Z. Effects of different heating devices on cucumber seedling and plant growth in winter season. Chinese Cucurbits and Vegetables, 2012; 25(4): 12–15. (in Chinese)

[22] He F, Fu J L, Ding X M, Pan S J, Li Z X, Zhou C J. Design and test of seedbed hating system based on capillary network in solar greenhouse. Journal of China Agricultural University, 2017; 22(2): 123–128. (in Chinese)

[23] Zhao Y L, Yu X C, Li Y S, He C X, Yan Y. Application of electric carbon crystal soil-warming system for tomato production in greenhouse. Transactions of the CSAE, 2013; 29(4): 131–138. (in Chinese)

[24] Li Y S, Zhao Y L, He C X, Yan Y, Yu X C. Application of electric carbon crystal warming board for seedlings culture cucumber in greenhouse in winter. Journal of China Agricultural University, 2014; 19(6): 126–133. (in Chinese)

[25] Zhang B, Fan X, Liu M, Hao W. Experimental study of the burning-cave hot water soil heating system in solar greenhouse. Renewable Energy, 2016; 87: 1113–1120.

[26] He F, Hou Y, Li K, Wei X M, Liu Y Q. An investigation of a root zone heating system for greenhouse seedling and its effects on the micro-environment. Inter J of Agric & Biol Eng, 2020; 13(6): 47–52.

[27] Ding X M, He F, Duan J, Lian Q L, Zhang Q S. Design of low temperature heating system in solar greenhouse using capillary tube mat exchange. Transactions of the CSAE, 2013; 29(19): 178–184. (in Chinese)

[28] Beyza B, Halime P, Yildiz D. Root zone temperature control with thermal energy storage in phase change materials for soilless greenhouse applications. Energy Conversion and Management, 2013; 74: 446–453.

[29] Llorach-Massana P, Pena J, Rieradevall J, Ignacio Montero J. Analysis of the technical, environmental and economic potential of phase change materials (PCM) for root zone heating in Mediterranean greenhouses. Renewable Energy, 2017; 103: 570–581.

[30] Muhammad A, Wang X C, Muhammad Y, Muhammad U, Khurram Y, Yang Z J, et al. Performance evaluation of root zone heating system developed with sustainable materials for application in low temperatures. Sustainability, 2018; 10: 4130. doi: 10.3390/su10114130.

[31] Muhammad A, Zhang Z H, Wang X C, Muhammad Y, Muhammad U, Rana S N, et al. An investigation of a root zone heating system and its effects on the morphology of winter-grown green peppers. Energies, 2019; 12: 933. doi: 10.3390/en12050933.