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Application Effect of Active Heat Storage and Release Water Bags in Solar Greenhouses in the Hetian Region

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Abstract [**Objectives**] To improve the thermal insulation performance of solar greenhouses in winter, enhance solar energy utilization efficiency, reduce additional carbon emissions, and lower winter heating costs for greenhouses. [**Methods**] An active heat storage and release water bag was added inside the solar greenhouse. Comparative experiments were conducted between the experimental greenhouse K1 equipped with the heat storage water bag and the control greenhouse K2 under different winter night weather conditions. [**Results**] On sunny days, the maximum temperature difference between K1 and K2 was 2.3 ℃, and the average temperature during the water bag's heat release period increased by 2.2 ℃; on cloudy days, the maximum temperature difference was 2.2 ℃, and the average temperature increased by 2.0 ℃; on snowy days, the maximum temperature difference was 1.8 ℃, and the average temperature increased by 1.6 ℃. Additionally, the heat storage capacities of the water bag on sunny, cloudy, and snowy days were 491.4, 453.6, and 365.4 MJ, respectively. The corresponding nighttime heat release amounts were 378, 302.4, and 226.8 MJ, respectively. The corresponding heat storage-release efficiencies were 76%, 66.2%, and 62%, respectively. The service life of the heat storage water bag can reach 10 years, with an annual operating cost of approximately 2 500 yuan. [**Conclusions**] By comprehensively analyzing the initial costs, operating expenses, and cost savings rate compared to coal burning for current main energy-saving heat storage and warming equipment in solar greenhouses, this study provides reference suggestions for the promotion, application, and selection of winter heat storage and warming equipment for solar greenhouses in different regions. Users can choose to install the equipment based on the performance characteristics of the heat storage water bag and their actual needs.

Key words Solar greenhouse, Warming, Heat storage, Water bag, Temperature

0 Introduction

In the field of vegetable production, solar greenhouses have become the most widely used horticultural facility in China. They are highly favored because they combine high economic efficiency and land utilization rates, and offer significant advantages in saving water resources, reducing pesticide and fertilizer usage, and achieving controllable greenhouse environments. In recent years, solar greenhouses have developed rapidly in the southern Xinjiang region of China, and facility agriculture has also become an important goal for promoting agricultural modernization in southern Xinjiang. As of 2023, the number of solar greenhouse facilities in the Hetian region, Xinjiang, reached 136 000[1 – 3]. Currently, research on solar greenhouse technology in the Hetian region mainly focuses on greenhouse heat storage and insulation, integrated water and fertilizer management, and desert soilless cultivation[4 – 5]. Located in the heart of the Eurasian continent, the Hetian region has a unique natural climate, abundant light and heat resources, long sunshine duration, and strong solar radiation, providing exceptional natural conditions for the development of facility agriculture.

With the continuous development of facility agriculture, some problems still exist in winter vegetable production within solar greenhouses. Many scholars have conducted research on these issues, among which the controllability of the greenhouse environment is a core advantage. The importance of temperature, as a key factor determining the success or failure of greenhouse vegetable production, is self-evident. Therefore, in recent years, fully utilizing solar energy resources and adding insulation and heat storage equipment inside greenhouses have become key research focuses for relevant scholars[6 – 11]. Currently, some scholars have conducted research on the practicality and application effects of winter heating equipment for solar greenhouses, such as installing heat storage devices like heat-collecting water bags or water tanks on the greenhouse back wall for warming[12 – 14], using phase change heat storage materials for warming[15 – 19], and applying air source heat pumps[20 – 21] and ground source heat pumps[22 – 24] for warming. However, in practical application, the requirements for greenhouse warming and insulation in winter vary across different regions. Moreover, high equipment investment costs and difficulties in promotion lead to limitations in their application from multiple aspects.

Based on previous research, this study proposes a new approach: deploying active heat storage and release water bags on the ground and north wall inside solar greenhouses in the Hetian region. This heat storage water bag absorbs heat through solar radiation during the day, and releases heat through thermal radiation at night when a temperature difference occurs in the greenhouse, thereby achieving insulation and warming. The entire process features zero pollution, low cost, and minimal investment, requiring no additional energy consumption, and the equipment has a simple structure. This research investigates the application effect of this active heat storage and release water bag through winter experi-

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ments, aiming to provide a theoretical basis and data support for the promotion, application, and production selection of winter warming equipment for solar greenhouses.

1 Materials and methods

1.1 Materials The heat storage water bags used in this experiment were made of PVC high-temperature resistant coated fabric material, with water as the heat storage medium. According to the greenhouse structure, heat storage water bags of corresponding sizes were designed for the north wall and the ground respectively. The ground-based water bags were laid in a north-south direction (Fig. 1), with dimensions of length 6.5 m, width 0.5 m, and height 0.3 m. To maximize the absorption of solar radiation, the dimensions of the water bag installed on the north wall were designed as length 3 m, width 0.25 m, and height 2 m. A drainage/irrigation hole was provided at the bottom of the heat storage water bags. In winter, watering and irrigation inside the greenhouse could be performed through this hole; when not in use during other seasons, the water could be drained and the bags rolled up for storage to reduce wear and extend their service life.

1.2 Working principle An active heat storage water bag system was designed and installed inside the solar greenhouse for this experiment. Preliminary pre-tests indicated that the daytime temperature inside the solar greenhouse could reach up to 50 ℃, demonstrating abundant solar radiation and surplus heat. The active heat storage and release water bag designed based on this uses water as the heat storage medium. During the day, it absorbs heat through solar radiation and simultaneously stores a portion of the surplus heat inside the greenhouse within the bag. At night, when the temperature inside the greenhouse drops, due to the temperature difference between the heat storage water bag and the greenhouse environment, the heat within the bag is released into the greenhouse in the form of thermal radiation, thereby achieving insulation and warming effects. The working principle of the active heat storage and release water bag is shown in Fig. 2.

Fig. 1 Actual heat storage water bags inside the greenhouse

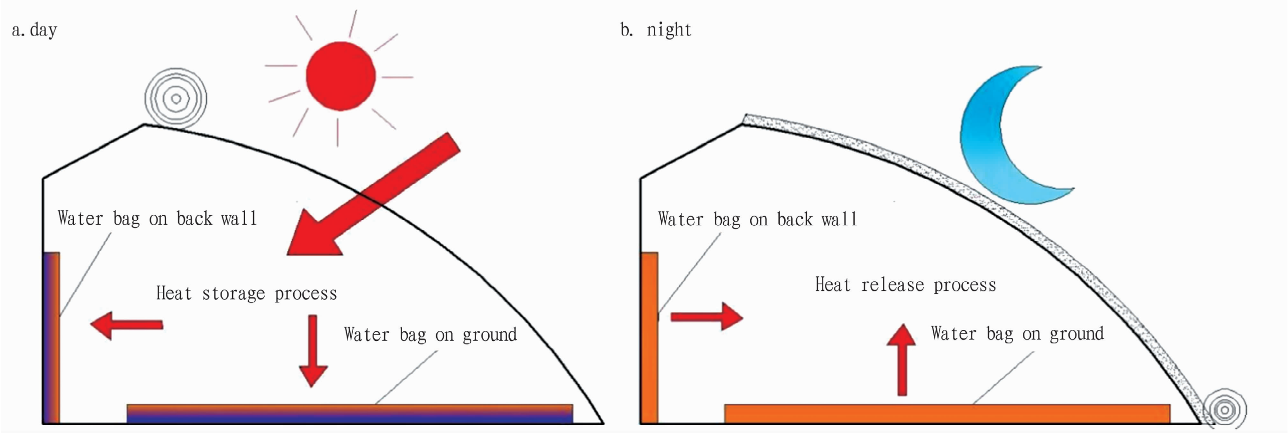

Fig. 2 Working principle of the active heat storage and release water bag

1.3 Test methods and measurement point arrangement The experiment was conducted from January 25 to February 20, 2024, in solar greenhouses at the asparagus planting base of the Damotaohuayuan Fruit and Vegetable Professional Cooperative in Baishitograk Township, Luopu County, Hetian Prefecture, Xinjiang. Comparative tests were performed between the experimental greenhouse K1 equipped with heat storage water bags and the control greenhouse K2. The greenhouse structure is shown in Fig. 3. GSP high-precision temperature and humidity recorders produced by Suzhou LECC Testing Technology Co., Ltd. were used to collect greenhouse temperature variation data. The recorder has a temperature measurement range of −30 to +60 ℃, a humidity measurement range of 0−99% RH, a temperature error of ±0.5 ℃, and a humidity error of 1% RH. The data acquisition interval was set to record every 30 min. Asparagus was planted in both the experimental and control greenhouses. During the experiment, the asparagus height was approximately 25 cm, with no leaves, resulting in minimal shading area and no shading effect on the ground-based heat storage water bags.

At the start of the experiment, greenhouse temperature, outdoor temperature, and water temperature data inside the water bags were synchronously collected from the experimental area K1 and the control area K2. Air temperature measurement points were arranged at a height of 1.5 m above the ground in the greenhouse. The arrangement of measurement points and the installation locations of the heat storage water bags are shown in Fig. 3 and 4.

1.4 Experimental data processing Origin2019 and GraphPad Prism 8.0 software were used for data organization, analysis, and chart creation.

2 Results and analysis

2.1 Temperature changes in typical sunny weather conditions in experimental and control areas The testing experiment began on February 4, 2024, and ended on February 22, 2024. To fully compare the impact of the heat storage water bags on the warming, insulation, and heat storage performance of the experimental greenhouse, air temperature changes in the experimental and control areas under typical sunny (February 8, 2024), cloudy (February 13, 2024), and snowy (February 18, 2024) weather conditions were selected for data analysis, in order to verify the insulation and warming effect of the active heat storage water bags on the solar greenhouse.

As shown in Fig. 5, under typical sunny weather conditions over 24 h, the temperature variation trends in the experimental and control greenhouses were consistent. At 16:30, the greenhouse temperatures in the experimental and control areas reached their highest points of 42.3 and 40.0 ℃, respectively, with a maximum temperature difference of 2.3 ℃ between the two greenhouses. After the thermal blanket was uncovered at 11:00 in the morning, the temperature in the experimental area rose faster due to heat absorption by the surface of the heat storage water bags. Therefore, between 12:00 and 14:00, the greenhouse temperature in the experimental area was higher than that in the control area. From 14:20 onwards, as solar radiation intensity increased, the surface temperature of the heat storage water bags rose and their heat storage capacity increased. The greenhouse temperature in the experimental area rose rapidly, while the temperature change trend of the water bags themselves was relatively gentle. The highest and lowest points of the water bag temperature were 23 and 19.6 ℃, respectively, with a maximum temperature difference of 3.4 ℃. After 18:00, the outdoor temperature began to drop. As the thermal blanket was covered, the indoor temperature also decreased. However, because the heat storage water bags in the experimental area had stored a certain amount of heat, the decrease in greenhouse air temperature was more gradual, and the temperature in the experimental greenhouse K1 remained higher than that in the control area K2.

2.2 Temperature changes in typical cloudy weather conditions in experimental and control areas As shown in Fig. 6, under cloudy weather conditions, due to reduced solar radiation, temperatures in both the experimental and control areas were lower than on sunny days. At 15:00, temperatures in the experimental and control areas reached their highest points of 39.6 and 37.4 ℃, respectively, with a difference of 2.2 ℃. The reduction in solar radiation on cloudy days directly affected the heat storage capacity of the water bags in the experimental greenhouse, resulting in a gentler temperature change of the water bags compared to sunny days. Additionally, the thermal blanket was covered earlier on cloudy days than on sunny days. After covering, the greenhouse temperatures in both the experimental and control areas showed a rapid downward trend. During the period from 17:00 to 19:00, because the heat storage water bags absorbed and transferred some heat, the temperature in the experimental area was briefly lower than in the control area. When the greenhouse temperature dropped close to the water temperature, the decline in temperature in the experimental area became more gradual compared to the control area, and the temperature was higher than in the control area, indicating that the heat storage water bags in the experimental greenhouse were exerting their insulation and warming effect.

2.3 Temperature changes in snowy weather conditions in experimental and control areas As shown in Fig. 7, under snowy conditions, the temperature change trends in the experimental and control greenhouses were essentially consistent. Due to the low outdoor 24 h average temperature of −4.5 ℃ and weak solar radiation during snowy weather, the indoor temperatures in both the experimental and control areas, as well as the water temperature in the heat storage bags, were lower than during sunny and cloudy conditions. The highest greenhouse indoor temperatures in the experimental and control areas were 38.8 and 37.1 ℃, respectively, with a difference of 1.8 ℃. Benefiting from the certain amount of heat stored within the water bags in the experimental area, the overall greenhouse temperature was higher than in the control area, although the temperature change trends of both were synchronous. In terms of 24 h average temperature, the experimental and control areas were 20.7 and 19.1 ℃, respectively, with a difference of 1.6 ℃. This shows that the heat storage, insulation, and warming effects of the water bags are closely related to the actual weather environment.

2.4 Heat storage performance The calculation formulas for the heat storage and release amounts of the active heat storage and release water bag are as follows[25]:

$$Q_X = C_W \rho_W V_W \Delta_{T1} \tag{1}$$

$$Q_F = C_W \rho_W V_W \Delta_{T2} \tag{2}$$

where Q_X is the total heat storage amount of the heat storage water bag per unit time, unit kJ; Q_F is the total heat release amount of the heat storage water bag per unit time, unit kJ; C_W is the specific heat capacity of water, the heat storage medium in the water bag, value 4.2 kJ/kg·℃; ρ_W is the density of water, the heat storage medium, value 1.0×10^3 kg/m^3; V_W is the volume of water, the heat storage medium, unit m^3; Δ_{T1} is the temperature change of water during the heat storage phase of the water bag, unit ℃; Δ_{T2} is the temperature change of water during the heat release phase of the water bag, unit ℃.

In this experiment, the heat storage amount of the water bags was calculated based on the total volume of all water bags and the heat storage time (the period from removing to covering with the thermal blanket, *i.e.*, 11:00 − 18:00). Because the water bags expand when fully filled with water, the volume of the water medium was approximately 30 m^3. The heat storage amounts for sunny, cloudy, and snowy days were calculated respectively.

On sunny days, after removing the thermal blanket, the water temperature rose from 19.1 to 23.0 ℃, an increase of 3.9 ℃, resulting in a total heat storage amount of 491.4 MJ; on cloudy days, the water temperature rose from 17.3 to 20.9 ℃, an increase

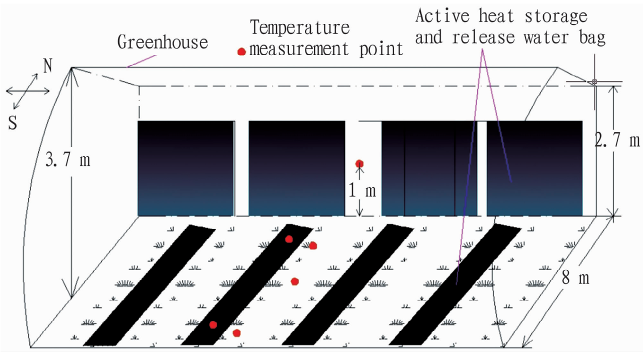

Fig. 3 Greenhouse structure and arrangement of measurement points

Fig. 4 Exterior view of the greenhouse

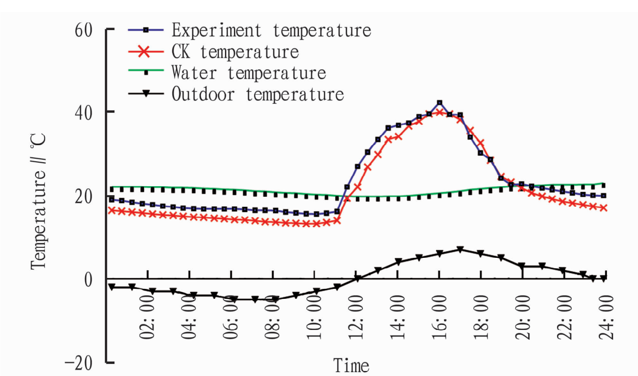

Fig. 5 Temperature changes on a typical sunny day

of 3.6 ℃, resulting in a total heat storage amount of 453.6 MJ; on snowy days, the water temperature rose from 15.9 to 18.8 ℃, an increase of 2.9 ℃, resulting in a total heat storage amount of 365.4 MJ. The heat release period of the water bags was defined as the time interval when the water temperature decreased from its peak until just before removing the thermal blanket the next day. Based on calculations, during heat release on sunny days, the water temperature change was 3.0 ℃, the heat release amount was 378 MJ, and the heat storage-release efficiency was 76.0%; during heat release on cloudy days, the water temperature change was 2.4 ℃, the heat release amount was 302.4 MJ, and the efficiency was 66.2%; during heat release on snowy days, the water temperature change was 1.8 ℃, the heat release amount was 226.8 MJ, and the efficiency was 62.0% (Table 1). The data indicate that the utilization efficiency of solar radiation by the heat storage water bags is significant. However, various parameters still need further optimization. Moreover, external factors such as greenhouse insulation performance, the light transmittance of the plastic film, and the service life will also affect its effectiveness.

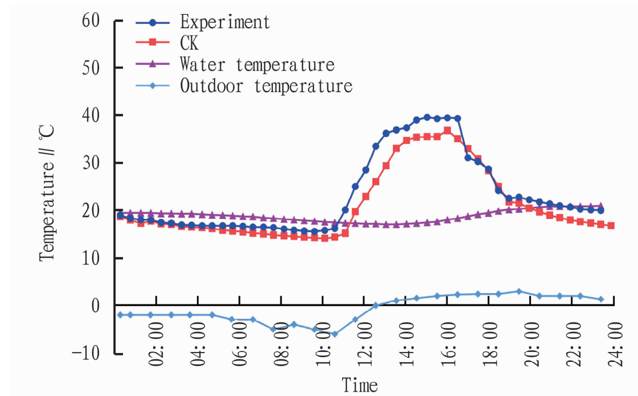

Fig. 6 Temperature changes on a typical cloudy day

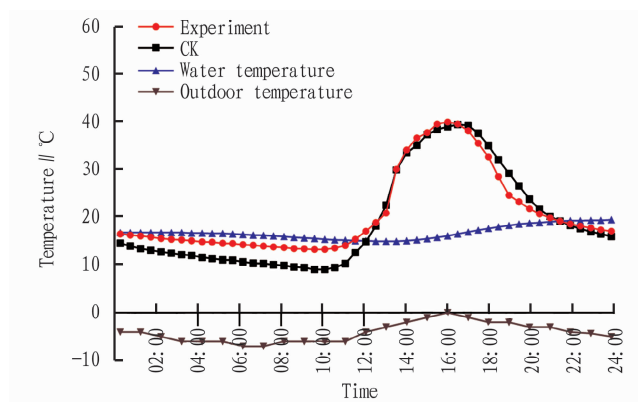

Fig. 7 Temperature changes on a snowy day

Table 1 Analysis of heat storage and release performance of the water bags

Weather	Heat storage // MJ	Heat release // MJ	Heat storage and release efficiency // %
Sunny	491.4	378	76.0
Cloudy	453.6	302.4	66.2
Snowy	365.4	226.8	62.0

2.5 Economic feasibility of the heat storage water bag In designing and installing the heat storage water bags, this experiment fully considered the production costs and durability for vegetable production. Everything from the selection of raw materials (durable PVC material) to the usage and maintenance after fabrication was optimized. Based on calculations, the expected service life of the heat storage water bags used in this experiment can exceed 10 years. The total cost for fabrication, transportation, installation, commissioning, and labor for the water bags in one solar greenhouse is 25 000 yuan. Calculated over a 10-year usage period, the average annual operating cost is 2 500 yuan. Additionally, the heat storage water bags can serve as a substitute for weed barrier fabric, suppressing weed growth on the greenhouse floor and saving labor costs for weeding; in low-temperature winter environments, if the irrigation water temperature cannot be guaranteed, the medium water inside the heat storage water bags can be directly used for watering and irrigation, avoiding additional production costs.

2.6 Comprehensive performance comparison of different energy-saving heat storage and warming equipment for solar greenhouses In this experiment, compared to other energy-saving warming and heat storage equipment in practical application, the heat storage water bags exhibited problems of insufficient insulation and limited heat storage capacity. However, in greenhouse production, the cost of warming and heat storage equipment is a crucial factor that must be considered. If cost is disregarded, the application of such equipment in actual production would lose its significance. Therefore, in practical applications, it is necessary to comprehensively analyze the equipment's fabrication/construction cost, operating cost, operational effectiveness, *etc.*, to evaluate its heat storage and warming performance along with cost-effectiveness. In recent years, responding to the national call for energy conservation and emission reduction, many regions have prohibited coal burning for heating in solar greenhouses during winter. Currently, winter greenhouse warming and heating mainly rely on electricity-based equipment such as electric hot air furnaces, electric heaters, electric boilers, as well as alcohol-based fuels, air source heat pumps, and other devices. This study primarily conducts a comparative analysis of the comprehensive performance of different heating and heat storage equipment under the same conditions.

As shown in Table 2, calculating costs per square meter of greenhouse area, the construction cost of air source heat pumps is the highest, but their operating cost efficiency for winter warming is also the highest compared to traditional coal-fired hot air furnaces; the construction cost of the heat storage and release water bag is the lowest, and its winter warming cost saving ratio is relatively high. However, because its winter warming and heat storage performance is constrained by the demand for solar radiation heat and requires abundant solar thermal resources, it has geographical applicability limitations, generally being more suitable for regions with abundant solar resources such as Northwest and North China. In practical applications, suitable warming and heat storage equipment should be selected based on factors such as weather conditions, the greenhouse's own insulation performance, the type of vegetable crops grown, and winter temperature requirements.

Table 2 Comprehensive performance analysis of different warming and heat storage equipment

Warming and heat storage equipment	Equipment cost yuan/m^2	Operating cost yuan/day	Winter cost saving ratio vs coal furnace//%	Primary application regions
Heat storage and release water bag	15 – 18	0	80	Northwest China, North China
Gas heating	20 – 24	40 – 45	40	Northeast China, Qinghai – Tibet alpine regions
Electric hot air furnace	20 – 24	30 – 40	35	Northeast China, Qinghai – Tibet alpine regions
Electric heater	20 – 25	35 – 40	30	Northeast China, Qinghai – Tibet alpine regions
Water source heat pump	30 – 40	75 – 90	25	North China
Air source heat pump	80 – 95	130 – 150	85	North China

3 Conclusions

In this study, by installing an active heat storage and release water bag system in the greenhouse, utilizing daytime solar radiation and surplus heat within the greenhouse to raise the temperature of the water medium, and releasing heat during low nighttime temperatures, warming and insulation of the solar greenhouse were achieved. The study analyzed the application effect, heat storage-release performance, and comprehensive benefits of the heat storage water bags, leading to the following conclusions.

3.1 Significant warming and insulation effects Under different weather conditions such as sunny, cloudy, and snowy days, the active heat storage water bags demonstrated significant warming and insulation effects. Specifically, on sunny days, the maximum temperature difference between the experimental area K1 and the control area K2 reached 2.3 ℃, with an average difference of 2.2 ℃; on cloudy days, the maximum difference was 2.2 ℃, with an average difference of 2 ℃; on snowy days, the maximum difference was 1.8 ℃, with an average difference of 1.6 ℃.

3.2 Good heat storage and release performance Based on calculations, under sunny, cloudy, and snowy conditions, the heat storage amounts of the water bags were 491.4, 456.3, and 365.4 MJ, respectively, the heat release amounts were 378, 302.4, and 226.8 MJ, respectively, corresponding to heat storage-release efficiencies of 76%, 66.2%, and 62%, indicating significant heat storage and release effectiveness.

3.3 Outstanding economic advantages The heat storage water bags are made of wear-resistant PVC material, with a durability of up to 10 years, and an average annual operating cost of only 2 500 yuan. Furthermore, during use, they can substitute for weed barrier fabric to suppress weed growth, saving labor costs.

3.4 A reference for equipment selection and promotion By comparing the construction costs, operating costs, and winter coal substitution benefits of different energy-saving solar greenhouse equipment, a reference is provided for equipment selection and promotion in different regions.

This experimental research exhibits clear advantages and disadvantages: The heat storage water bags rely on solar radiation for heat storage, requiring no additional energy consumption, but their warming and heat storage capacity is limited. They are primarily suitable for regions with abundant solar resources, such as North China and Northwest China. In practical applications, installation should be reasonably chosen based on greenhouse production requirements.

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