

Article

Study on the Cooling Effect of Double-Layer Spray Greenhouse

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Abstract: Greenhouses provide suitable environmental conditions for plant growth. Double-layer plastic greenhouses are often used in many regions to ensure normal crop growth during winter since single-layer plastic greenhouses have poor insulation. However, during summer, the high insulation of double-layer plastic greenhouses, combined with excessive external solar radiation, can cause high temperatures inside the greenhouse that are not suitable for plant growth and require cooling. In this study, we propose a double-layer spray greenhouse using a high-pressure spraying system that is placed inside the double film that allows for additional cooling capacity during the summer in order to sustain plant growth. A greenhouse platform test was set up to investigate the optimum operating conditions for the nozzles and to explore changes in greenhouse microclimate under different nozzle operating conditions. The results show that (1) the cooling rate increases with increasing water supply pressure, nozzle diameter and spraying time, and the humidification rate is consistent with the change in the rate of cooling. (2) The optimal condition for cooling in this experiment is achieved with a 120° double nozzle with a nozzle diameter of 0.30 mm, a water supply pressure of 6 MPa, and a spraying time of 15 min, which can reduce the temperature by up to 5.36 °C and serve as a reference for the summer cooling of the double-layer greenhouse.

Keywords: greenhouse cooling; fogging system; nozzle layout; microclimate



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1. Introduction

Greenhouses are facilities used in agricultural production that can extend the crop production season and increase crop yields via the adjustment of environmental factors such as indoor light, temperature and water [1]. The yield-per-unit area is 6.4 times higher in greenhouse production than in open-air production [2]. Plastic greenhouses are commonly used because of their small investment, simplicity of construction, and capacity for providing large returns. However, this type of greenhouse has relatively poor heat-insulating properties. Tang, Wu [3] designed and built a new double-layer plastic greenhouse. The double-layer film includes an additional layer of plastic film on top of the traditional single-layer film, with a controlled spacing between the top film and the bottom film. This forms an insulating layer that reduces the penetration of cold wind [4]. The use of double film increases the energy efficiency of the greenhouse and reduces energy consumption by 60% [5].

During summer, greenhouses experience an influx of excessive solar radiation and heat through their transparent cover. As a result, the interiors of greenhouses become hot, which affects crop growth and requires additional equipment for cooling to sustain production during the summer. The Yangtze River basin of China mostly belongs to a

subtropical monsoon climate, and the highest temperature in summer can reach about 40 °C. In areas where the ambient temperature exceeds 40 °C, ventilation is not a sufficient method to reduce the air temperature inside the greenhouse; evaporative cooling is the most effective means of cooling the greenhouse under these conditions [6,7]. Evaporative cooling systems include fan-pad systems, spray systems, and roof cooling systems [5]. Xu, Li [8] found that after the air has passed through the pad, the internal temperature of the greenhouse can be cooled to 27–29 °C. Arbel and Barak [9] combined fog systems with forced ventilation, and the results showed that the temperature inside the greenhouse was maintained at 28 °C at midday in the summer. Ghosal and Tiwari [10] studied the effect of adding flowing water to a shade covering on the air temperature inside the greenhouse and found the internal air temperature to be 4 °C lower than the greenhouse using only shade. Liu [11] investigated the impact of different flow rates on the thermal characteristics of the hot and humid environment of greenhouses in the summer by varying the flow rate of roof sprinklers, and the results showed that with an increasing flow rate of the roof sprinklers, the temperature reduction effect was enhanced in the greenhouse, and the temperature reduction of up to 2.3 °C. Lopez and Valera [12] found that the use of fan-pad systems led to an uneven temperature distribution in the greenhouses, with a maximum temperature difference of 11.4 °C. Continuous running of the water and poor water quality can lead to a gradual blockage of the pad, resulting in reduced cooling performance [6]. Arbel and Yekutieli [13] compared the misting system with the fan-pad system and discovered that the misting system provided more uniform temperature and humidity conditions and outperformed the fan-pad system. However, when the greenhouse fogging system does not evaporate completely, droplets of water can drip directly onto the plants, affecting plant transpiration and leading to insufficient nutrient uptake by the plants [14,15]. Considering the better cooling effect of the spray system and the unfavourable effect of direct spray on plant growth, we proposed a double-layer spray greenhouse.

If a high-pressure spray cooling system is placed inside the double layer of film, the spray forms a mist layer, and when the mist vaporizes, it absorbs heat energy, which can make the upper layer of the greenhouse cooler. It also prevents the direct spraying of water within the greenhouse, which prevents the water droplets in the spray from increasing the humidity in the environment inside the greenhouse. To solve the summer cooling problem of a double-layered plastic greenhouse, its design is modified, and a double-layer spray greenhouse is proposed; specifically, a test platform was built on which the changes in microclimate in the greenhouse were tested at different angles, spraying times and fogging indicators to determine the optimum working conditions for the nozzles and to provide a theoretical basis for the spraying and cooling of the double-layer greenhouse.

2. Materials and Methods

2.1. Building a Greenhouse Test Platform

A greenhouse test platform was built to investigate the effect of the nozzle spray on the microclimate in the greenhouse. The test greenhouse was located in Lishui, Nanjing (31°37' N, 119°10' E), constructed in a single double-decker round-arched greenhouse running north-south with an outer roof shoulder height of 1.6 m and a roof height of 2.4 m, and an inner roof shoulder height of 1.2 m and a roof height of 2.0 m. The specific dimensions are shown in Figure 1. Covered with transparent polyethylene film, the film material properties are shown in Table 1. The double spray greenhouse is fitted with an internal gutter with a one-way slope of 2.5‰ to meet the drainage requirements of the spray not evaporated to form droplets. The single-outlet, high-pressure, atomizing nozzle commonly used in greenhouses was selected as the test nozzle for the double-layer internal spray nozzle, and it is cylindrical in shape, as shown in Figure 2c. The nozzle was installed on the inner plastic film in the middle position and sprayed upwards; the water for spraying was pressurized by a booster pump.

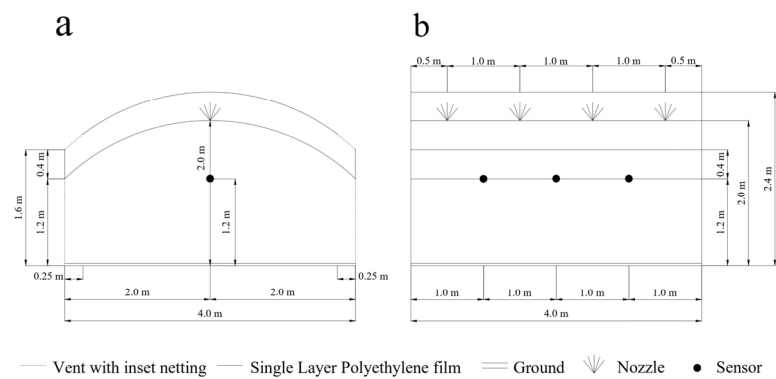


Figure 1. (a) Front view of the double-layer spray greenhouse structure and (b) Side view of the double-layer spray greenhouse structure.

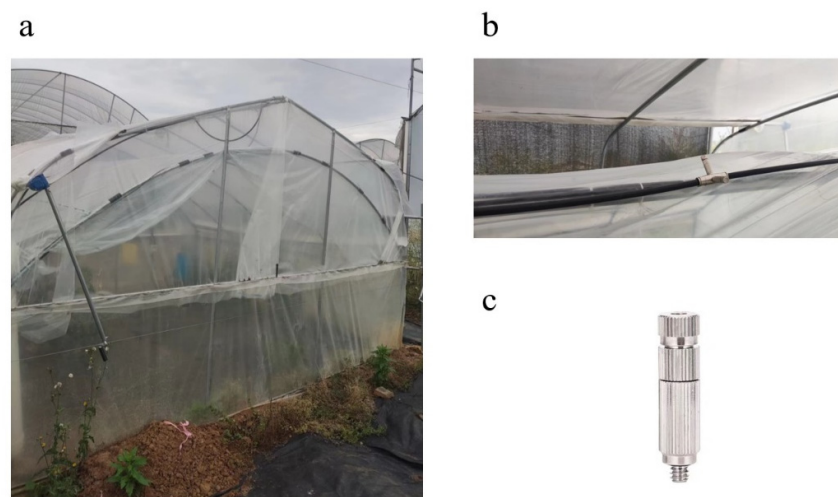


Figure 2. (a) Front view of the double-layer spray greenhouse and (b) spray pipe placement for angle test and (c) nozzle.

Table 1. Properties of the polyethylene film used to cover the greenhouse.

Properties	Polyethylene
Density	923 kg·m ⁻³
Specific heat capacity	2550 J·kg ⁻¹ K ⁻¹
Heat conductivity	0.29 W·m ⁻¹ K ⁻¹
Thickness	0.2 mm
Transmittance	78.3%
Absorptivity	0.1
Refractive Index	1.7

2.2. Measurement and Data Collection System

2.2.1. Measurement of Illuminance, Temperature and Humidity in the Greenhouse

RS-485 Illuminance, temperature and humidity sensors (Jianda Renko, RS-GZWS-N01-2-200000, Jinan, China, ± 0.3 °C $\pm 2\%$ RH $\pm 7\%$) were arranged in the east–west section of the greenhouse. The location of the test points in the greenhouse is shown in Figure 1. The sensors were spaced 1 m apart and 1.2 m above the ground. The sensors recorded data once every minute by a data logger (Jianda Renko, RS-XZJ-100, Jinan, China) and all data were mean-treated.

And the cooling effect, the humidification and the decrease in illuminance in the greenhouse after spraying are calculated as follows:

$$\Delta T = T_i - T_0 \quad (1)$$

$$\Delta U = U_i - U_0 \quad (2)$$

$$\Delta G = G_i - G_0 \quad (3)$$

where ΔT is the change in temperature, T_i is the mean temperature value at different times, T_0 is the mean temperature value at the beginning of spraying; ΔU is the change in humidity, U_i is the mean humidity value at different times, U_0 is the mean humidity value at the beginning of spraying; ΔG is the change in illuminance, G_i is the mean illuminance value at different times, G_0 is the mean illuminance value at the beginning of spraying.

2.2.2. Measurement of Nozzle Atomization Characteristics

The nozzle atomization characteristic parameters measured include atomization angle, spray flow, etc. The atomization angle is the centre of the nozzle outlet in the centre of a circular arc, and it intersects the fogging boundary at two points. The two points and the centre of the nozzle intersect, and the angle 'a' between the two connecting lines is the nozzle atomization angle, as shown in Figure 3. In this study, the spray nozzles were photographed with a camera (Nikon D5300, Tokyo, Japan) and post-processed using AutoCAD 2019 software to calculate the nozzle atomization angle. In this experiment, the spray volume was tested using the timed weighing method, whereby the spray flow from the nozzle was collected for 3 min at a stable pressure. To prevent the droplets from spreading in the air and not being measured, the spray nozzles were completely sealed in a container of known mass and measured using an electronic balance with an accuracy of 0.01 g; the data were collected and measured three times, with the measured values used as the mean volume.

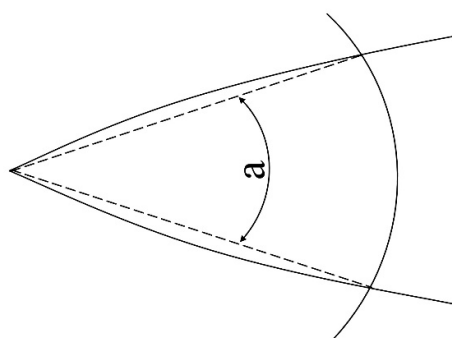


Figure 3. Measurement method of the conditional nozzle atomization angle.

2.2.3. Spray Test Method

Four factors were used in this experiment, namely: water supply pressure (5 levels), nozzle diameter (4 levels), spray duration (4 levels), and nozzle angle (3 levels), as detailed in Table 2.

Table 2. Experimental factors and levels.

Factors	Levels
Supply pressure H	3 MPa, 4 MPa, 5 MPa, 6 MPa, 7 MPa
Nozzle diameter D	D0 (0.10 mm), D1 (0.15 mm), D2 (0.20 mm), D3 (0.30 mm)
Time T	5 min, 10 min, 15 min, 20 min
Angle θ	60°, 90°, 120°

All of these factors, with the exception of the nozzle angle factor for the dual-nozzle treatment, were based on the values for a single nozzle, as shown in Figure 4.

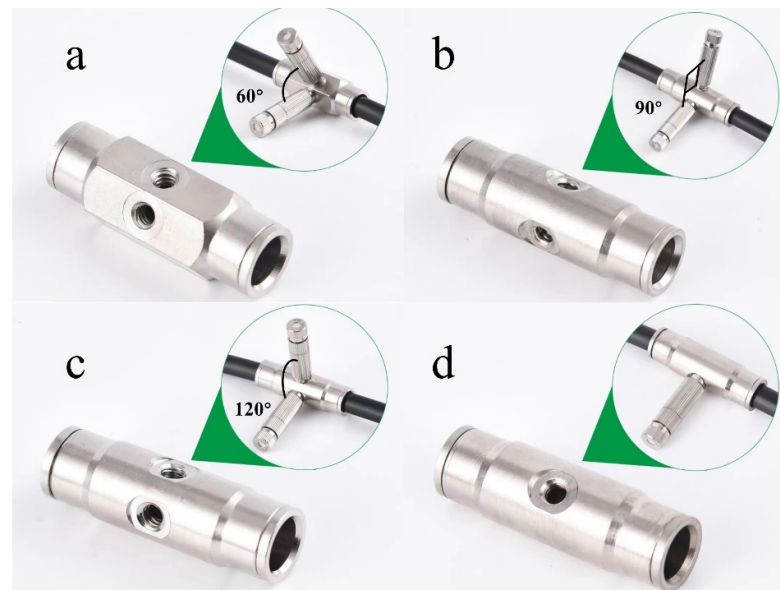


Figure 4. Nozzle connector type. (a) 60° double nozzle, (b) 90° double nozzle, (c) 120° double nozzle and (d) single nozzle.

The experiments were conducted between 16 June and 26 July 2022 under essentially the same conditions indoors and outdoors, with spraying starting at 15:00 on the day and changes in temperature, humidity and light levels in the greenhouse observed between 15:00 and 15:30; the greenhouse was under airtight conditions during spraying and only the external roof vents were opened to remove latent heat from the sprayed layer; other operational details are given in Table 3.

The formula for calculating the atomization index is as follows:

$$P_d = 1000 \times \frac{H}{D} \quad (4)$$

where P_d is the atomization index, H is the pressure, and D is the nozzle diameter.

Table 3. Specific experimental operations.

Data	Variable Factors		Other Operations
16 June		3	
17 June	Supply pressure (MPa)	4	Single nozzle, nozzle diameter 0.30 mm and 15 min spraying time.
18 June		5	
19 June		6	
20 June		7	
1 July		5	
2 July	Time (min)	10	Single nozzle, nozzle diameter 0.30 mm and supply pressure at 6 MPa.
3 July		15	
4 July		20	

Table 3. Cont.

Data	Variable Factors	Other Operations
12 July		D0-5
13 July		D0-6
14 July		D0-7
15 July		D1-5
16 July		D1-6
17 July	atomization indexes	D1-7
18 July	H(m)/D(m)	D2-5
19 July		D2-6
20 July		D2-7
21 July		D3-5
22 July		D3-6
23 July		D3-7
24 July		60°
25 July	Angle (°)	90°
26 July		120°

Single nozzle and 15 min spraying time.

Double nozzle, nozzle diameter 0.30 mm, supply pressure at 6 MPa and 15 min spraying time.

3. Results and Discussion

3.1. Nozzle Atomization Characteristics

Atomization characteristics influence the transfer of heat due to the effect of spray cooling [16–18], and an understanding of nozzle atomization characteristics is necessary to study the changes in the greenhouse environment under different treatments. The spray nozzle atomization characteristic parameters include atomization angle, spray volume, etc.

3.1.1. Spray Volume

The influence of the volume of the nozzle spray on the heat transfer performance of spray cooling is particularly important [19]. Cheng and Han [20] found that increasing the spray volume increases the heat exchange from spray cooling. The spray volumes from four different nozzle diameters were measured using different water supply pressures, and the results are shown in Table 4. Analysis of the data in the table shows that at the same pressure, the nozzle spray flow gradually increased with an increase in the nozzle diameter of 0.30 mm, the spray flow sharply increased, and the spray flow per minute was more than 100 mL. For the same type of nozzle, the spray flow gradually increased with an increase in the water supply pressure.

Table 4. Relationship between the flow rate of four nozzles and water supply pressure.

Nozzle Diameter	Spray Volume (mL·min ⁻¹)				
	3 MPa	4 MPa	5 MPa	6 MPa	7 MPa
D0 (0.10 mm)	15.47 ± 0.50	17.43 ± 0.45	20.17 ± 0.12	22.13 ± 0.15	24.63 ± 0.32
D1 (0.15 mm)	27.13 ± 0.06	32.57 ± 0.25	38.93 ± 0.23	44.17 ± 0.21	47.60 ± 0.46
D2 (0.20 mm)	48.03 ± 0.25	60.03 ± 0.21	69.03 ± 0.12	78.10 ± 0.30	80.63 ± 0.49
D3 (0.30 mm)	130.00 ± 2.33	159.23 ± 1.24	177.67 ± 2.06	203.90 ± 1.35	218.10 ± 0.82

3.1.2. Nozzle Atomization Angle

Measured data related to the atomization angle of the four nozzles in Figure 5 show that the D0 and D1 nozzles are in a straight line and the D2 and D3 nozzles are arch-shaped, both reaching a peak water supply pressure of 5 MPa. A comparison of four different high-pressure nozzles with various diameter nozzles indicated that at the same

water supply pressure (3 MPa–6 MPa), with the D2 nozzle (nozzle diameter of 0.20 mm), the atomization angle was the largest; when the water supply pressure was 7 MPa, the D1 nozzle atomization angle was the largest. At a water supply pressure of 6 MPa, the differences in atomization angle among the four types of nozzles were small.

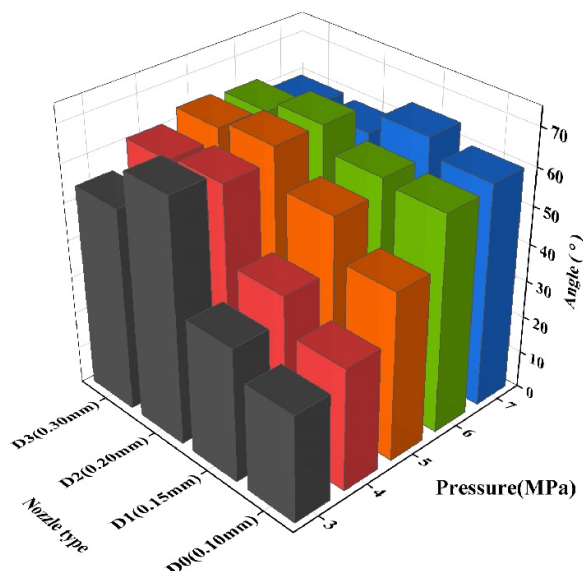


Figure 5. Atomization angle of four nozzles under different water supply pressures.

3.2. Effect of Different Spray Conditions on Greenhouse Microclimate

3.2.1. Effect of Different Pressures on Greenhouse Microclimate

The working pressure is an important feature of the atomization system, which largely determines the performance and associated costs of the atomizing system [21].

Figure 6a shows a clear pattern of increasing and then decreasing cooling for all treatment methods. This is because as the spraying time increases, the volume content of the water mist inside the double-layer membrane gradually rises, and the heat absorbed by the evaporation of the water mist is greater than the external heat absorbed by the greenhouse, resulting in a significant cooling effect. When the spraying ends, the remaining water mist evaporates to absorb less heat than the greenhouse does, and the cooling effect begins to slow down. As the pressure of the water supply increases, the cooling effect of the spray increases. The reason for this is that the higher the pressure is, the higher the spray flow and the more heat is absorbed by the evaporation of the water mist. When the water supply pressure reached 7 MPa, the spray cooling effect increased insignificantly, with a maximum cooling of 5.73 °C, a difference of 0.37 °C compared to the maximum cooling at a water supply pressure of 6 MPa. Since the cooling effect of spraying is also influenced by the humidity of the air, the higher the relative humidity is, the less effective the cooling effect becomes [22]. In the confined double space, the spray flow rate is higher at 7 MPa than at 6 MPa, resulting in a higher air humidity than at 6 MPa, limiting the cooling effect.

Figure 6b shows an increasing trend in the humidity in the greenhouse, as it gradually increases and then stabilizes before subsequently decreasing. The largest increase in humidity among the treatments was 18.90% at 7 MPa pressure, and the smallest increase was 15.60% at 3 MPa pressure. There was little difference in the measured humidity among the treatments, likely because the spray located on the inner membrane did not interact directly with the humid air inside the greenhouse but rather had an indirect influence on humidity by affecting the air temperature. Crops are more susceptible to pests and diseases in high humidity, and the incidence and severity of disease increases with increasing humidity [23–25]. Therefore, a spray pattern with a water supply pressure of 3 MPa is less likely to cause plant pests and diseases based on the humidity level alone. However,

considering the beneficial impact of high temperatures on increased crop growth and production, a spray pattern with a pressure of 6 MPa is more appropriate.

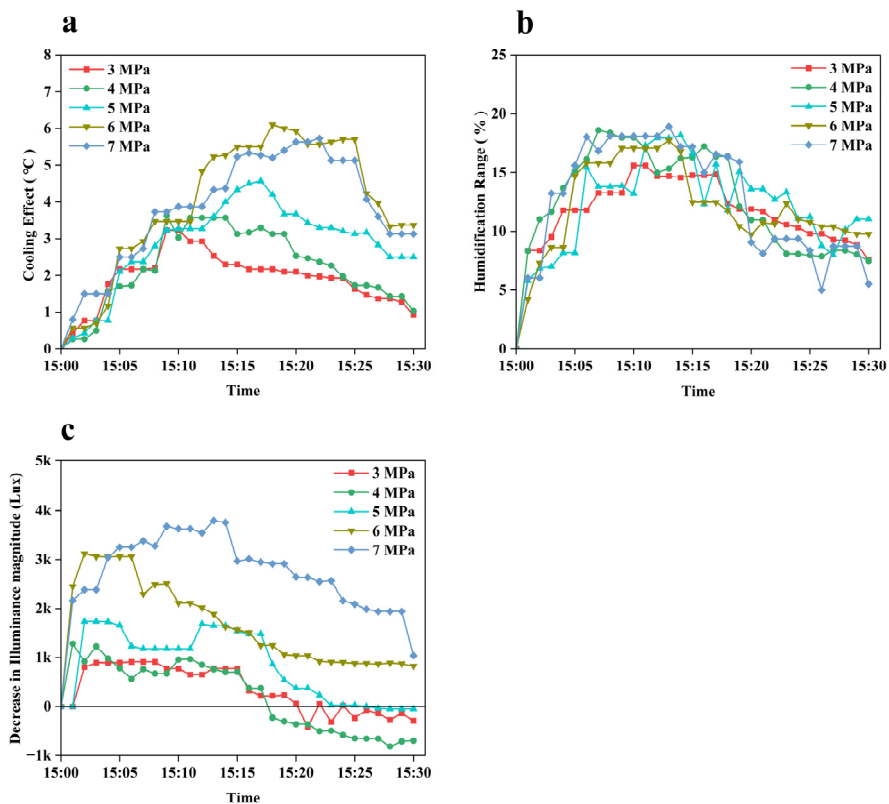


Figure 6. (a) Variation in greenhouse cooling amplitude under different pressures and (b) variation in humidification amplitude in the greenhouse under different pressures and (c) variation in the magnitude of the decrease in illuminance in the greenhouse under different stresses.

As shown in Figure 6c, the trend of illuminance drop in the greenhouse was to reach a constant value about one minute after the start of spraying and then vary above and below this value; and the drop in illuminance in the greenhouse varied considerably with increasing spray pressure, with a maximum drop of 3792 Lux at the 7 MPa treatment. Higher pressure, higher spray flow and greater water mist shading meant a greater drop in illuminance [26]. When the spraying ended, the drop in illuminance became weaker and even increased as the water mist evaporated and dissipated.

3.2.2. Effect of Different Spray Durations on Greenhouse Microclimate

Figure 7a shows the temperature changes in the test greenhouse for different spray durations. The results show that within 4 min after the start of spraying, the cooling rate of different treatments was stable at approximately 1 °C. By 6 min, the cooling rate showed a trend of first increasing and then gradually decreasing. All treatments reached their maximum cooling effect at 4 min after the end of spraying, except for the 20 min spraying time. As the spray duration increases, the water mist content in the interior of the double layer is higher and better able to absorb the high external temperatures, and the spray cooling effect continues to strengthen, but when the spray duration reaches 20 min, the maximum temperature reduction is only 0.28 °C higher than that for a 15 min duration. Therefore, from the viewpoint of the cooling effect and energy consumption, a spray duration of 15 min is reasonable.

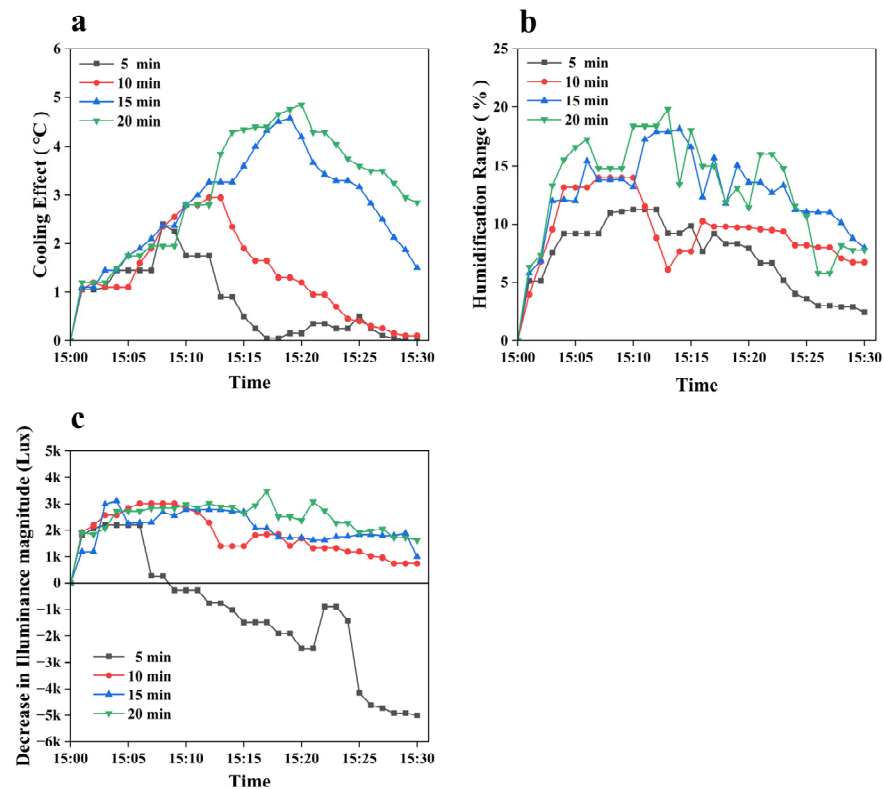


Figure 7. (a) Change in temperature drop amplitude at different times and (b) the range of humidification changes at different times and (c) variation in illuminance reduction at different spray times.

Figure 7b shows the changes in humidity in the test greenhouse at different spray durations. The strongest humidification was 19.80%, followed by 18.17%, 14.00% and 11.27% for different spray lengths, and the maximum humidification occurred at 20 min, 15 min, 10 min, and 5 min of spraying, respectively. The overall change in the magnitude of humidification tends to increase, and then decrease, in line with the change in the magnitude of cooling. Locally, the treatments with spray durations of 15 min and 20 min exhibited up and down fluctuations in humidification between the 15th and 20th min after spraying, probably due to gusts of wind at that time of the day.

Figure 7c shows the change in illuminance in the greenhouse at different spraying durations. At the beginning of spraying, the illuminance in the greenhouse decreased at approximately the same rate in all treatments and remained between 2000 and 3000 Lux. Compared with the other spray duration treatments, the treatment with a spray duration of 5 min showed a rapid increase in illuminance in the greenhouse at the end of spraying, which corresponds to the extent of cooling, the higher the light intensity in the greenhouse, the stronger the absorbed solar radiation and the higher the greenhouse temperature, namely the worse the cooling.

3.2.3. Effect of Different Atomization Indexes on Greenhouse Microclimate

The effects of different spray pressures on greenhouse temperature and humidity were compared above. A pressure of 5–7 Mpa was selected to further compare the effects of different atomization indexes $H(m)/D(m)$ on the greenhouse microclimate.

Figure 8a–c shows the variation in cooling for different nozzle diameters at operating pressures of 5 to 7 Mpa, respectively. The results show that each treatment has an increasing and then decreasing temperature variation, with the nozzle diameter of 0.10 mm showing a gradual increase in temperature at all working pressures, with the highest temperature drop being only 1.63 °C. The temperature reduction is directly related to the nozzle diameter. The cooling effect is influenced by the spray flow rate; within a certain range, the higher

the flow rate is, the stronger its effect on cooling [19,20]. The spray flow rate for the nozzle diameter of 0.30 mm is much higher than for the other diameters at the same pressure, so the cooling effect with the nozzle diameter of 0.30 mm is significantly higher than for the other nozzles. The largest reduction in temperature among the treatments was D3-6, which showed an atomization index of 2.00×10^7 . The atomization index $H(m)/D(m)$ and the droplet size are exponentially related; as the atomization index increases, the droplet size decreases. Considering the variation between the different atomization indexes and the magnitude of cooling in Figure 8 together, there is no correlation between the two. Indirectly, the cooling effect was shown to be independent of the droplet size, in line with Hideki, Gyuyoug [27] and Wang, Tu [28].

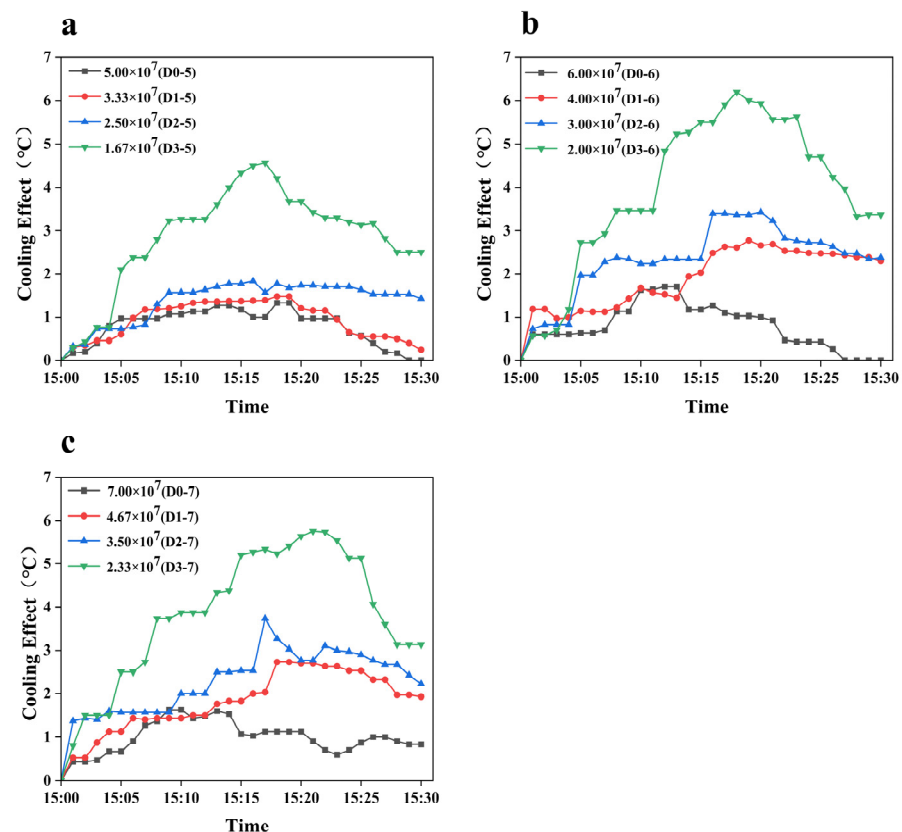


Figure 8. (a) amplitude of temperature drop with different nozzle apertures under 5 Mpa pressure, (b) amplitude of temperature drop with different nozzle apertures under 6 Mpa pressure and (c) amplitude of temperature drop with different nozzle apertures under 7 Mpa pressure.

Figure 9 shows changes in the magnitude of humidification for each treatment. The difference in humidification between different pressure treatments for the same nozzle diameter is minor, and the humidification increases overall with increasing nozzle diameter. The increase in humidity was the same as the decrease in temperature, with the largest increase of 27.53% in the D3-5 treatment. The treatments that maintained 20.00% and above for 10 min were D3-5, D3-7, and D2-7, with D2-7 staying below 20.00% until 12 min after the end of spraying. Although the spray nozzles with 0.10 mm and 0.15 mm nozzle diameters have a low rate of humidification, the model with a pressure of 6 MPa and a nozzle diameter of 0.30 mm (D3-6) has a better overall effect on cooling.

Figure 10 shows the variation of illuminance reduction for each treatment. The results show that the reduction in illuminance for each treatment showed an increase followed by a decrease, with the nozzle diameter of 0.10 mm showing a gentle reduction in illuminance at each operating pressure, none of which exceeded 2000 Lux. The D1-5 treatment had a larger atomization index and smaller droplet size than the D2-6 treatment, but it had

a lower reduction in illuminance inside the greenhouse. The reason for this is that the smaller the droplet size, the more effectively it scatters light, thus making it more slowly reflected. Conversely, larger droplets absorb and scatter light more, resulting in weakened light transmission.

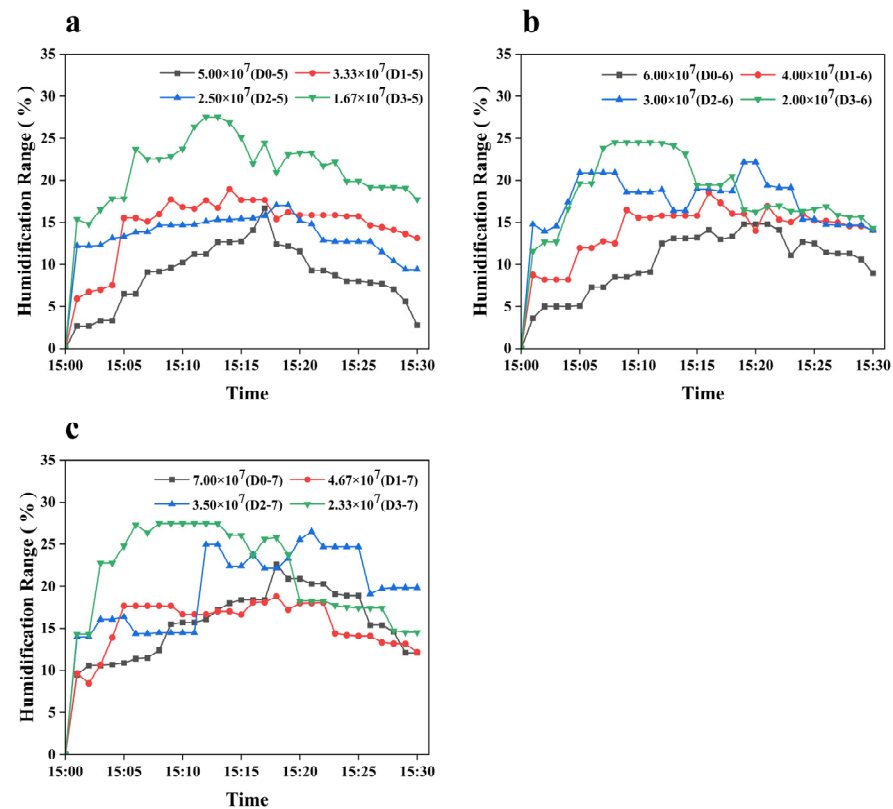


Figure 9. (a) Humidification amplitude of different nozzle apertures under 5 MPa pressure, (b) humidification amplitude of different nozzle apertures under 6 MPa pressure, and (c) humidification amplitude of different nozzle apertures under 7 MPa pressure.

3.2.4. Effect of Nozzle Angles on Greenhouse Microclimate

Figure 11a shows that the cooling effect of the dual spray nozzles at different angles differs from the cooling effect of the single nozzle, which cools down to 4 °C in a short amount of time. Since the spray flow from a double nozzle is much greater than that from a single nozzle for the same amount of time, the heat absorbed by the evaporation of the water mist is much greater than the external heat absorbed by the greenhouse, which has a significant cooling effect. However, the difference in spray cooling effect between treatments is not clear, with the maximum cooling effect of the double nozzle at an angle of 120° reaching 6.80 °C, only 0.20 °C and 0.50 °C higher than the highest cooling effect at angles of 60° and 90°. Variations in nozzle angle directly relate to the droplet coverage. The range that can be reached by a 120° twin nozzle is greater than with angles of 60° and 90°, and the spray overlap is smaller. Figure 11b shows the variation in the magnitude of humidification of the spray from the dual spray nozzles at different angles. The results show that the humidity increase of the dual spray nozzles at an angle of 60° was higher than the rest of the angles, and the humidity increase was maintained above 15.00% for more than 25 min for all treatments. Figure 11c shows that the change of illuminance in the greenhouse at angles of 60° and 90° was greater than that at an angle of 120°, because the spray nozzles at angles of 60° and 90° had a greater overlap of spray ranges, and the droplets became larger in particle size after aggregation and absorbed more sunlight. The double-nozzle spray on the greenhouse inside the illuminance reduction does not show as a single-nozzle spray to maintain a relatively stable state, but shows a gradual reduction

trend, inferred as the outer roof vents on the double film inside the space of the heat transfer efficiency, is higher, the fog evaporates faster, more efficient cooling.

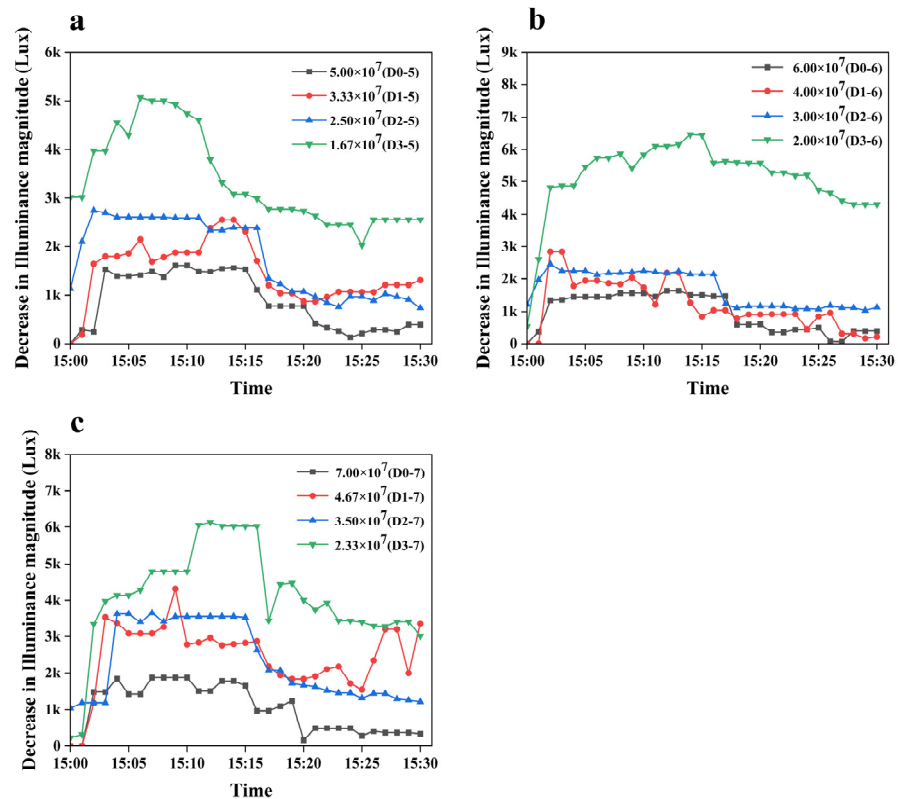


Figure 10. (a) Decrease in illuminance for different nozzle orifices at 5 MPa pressure and (b) decrease in illuminance for different nozzle orifices at 6 MPa pressure and (c) decrease in illuminance for different nozzle orifices at 7 MPa pressure.

3.3. Effect of Spray Cooling

The experiment, which examined the cooling effect of spraying in a double greenhouse, was run on 8 and 9 June 2023, from 09:30 to 17:00. Without applying any cooling techniques, the greenhouse was shut down on 8 June. Spraying was done on 9 June at 120° double nozzles, water pressure of 6 MPa, nozzle diameter of 0.30 mm, and spraying every 15 min for 15 min. Start spraying at 9:30 a.m., spray each 15 min and rest for 15 min.

Figure 12 shows unequivocally that the greenhouse's interior temperature was much higher than its exterior temperature in the absence of any cooling methods. Without any cooling measures, the maximum temperature inside the greenhouse was 51°C , whereas the maximum temperature with the spray cooling effect was 43°C . Without any cooling measures, the greenhouse's daily average temperature was 45.67°C , whereas it was 40.09°C after the spray cooling action. The relationship between temperature and relative humidity was also negative. Without any cooling measures, the greenhouse's daily average relative humidity was lower than the spray treatment's, which was 35.68%. Additionally, the spray-treated greenhouse's daily average relative humidity was 47.44%.

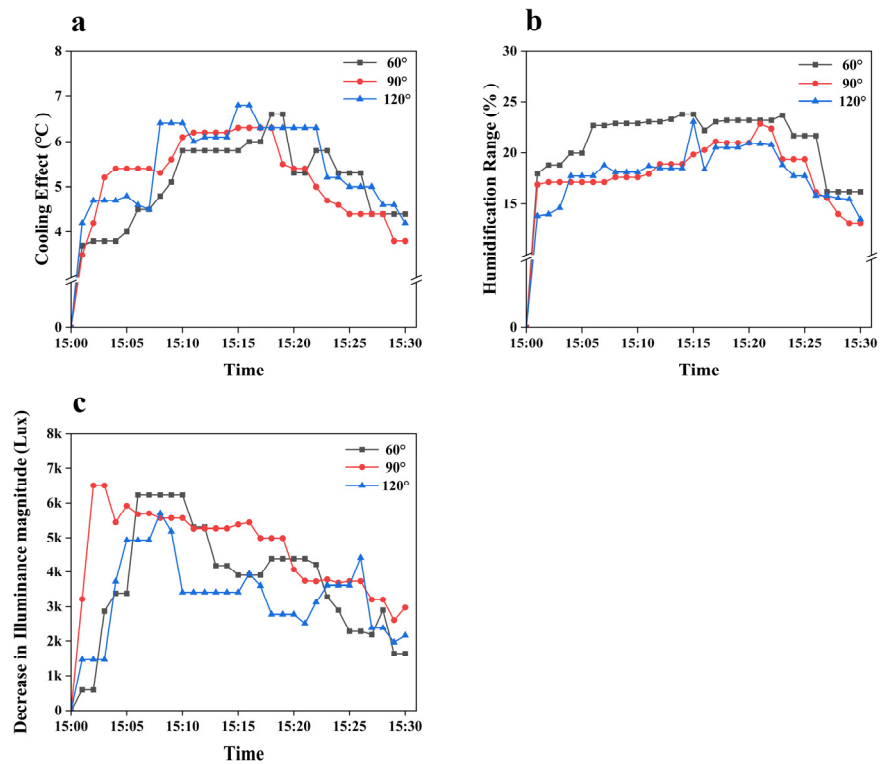


Figure 11. (a) Different angles of the double nozzle spray cooling effect and (b) variation in spray humidification amplitude of the double nozzle at different angles and (c) variation in the magnitude of illuminance reduction in greenhouses at different angles of dual nozzle spraying.

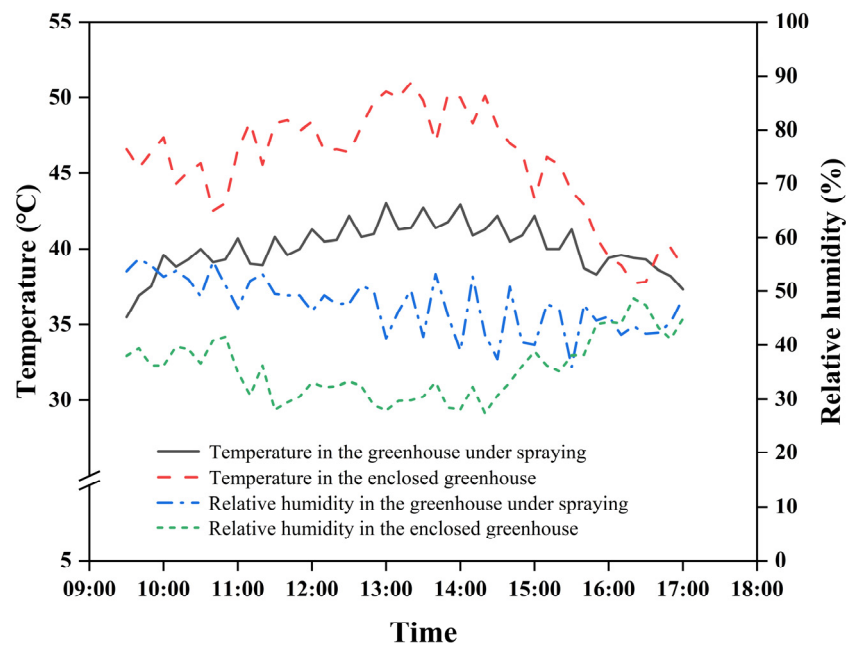


Figure 12. Temperature and humidity in the greenhouse without cooling measures and spray cooling.

In this study, a single double-layer greenhouse with an outer rooftop height of 2.4 m and an inner rooftop height of 2.0 m was employed to make it simpler to change the spray system within the double layer. The results were a good indicator of the cooling impact of the double-layered spray greenhouse, despite the fact that the test greenhouse was considerably smaller than the one used in actual crop cultivation. Additionally, we

discovered that the NVAC (Natural Ventilation Augmented Cooling) greenhouse presented by McCartney [29], which used a 1:4 greenhouse model for the cooling test, has a distinctive roof structure that served as inspiration for the renovation of double spray greenhouses in the future. The NVAC greenhouse integrates natural ventilation and spray cooling, resulting in temperature reductions of 1.9–12.6 °C and relative humidity increases of 1.4–31.2%. In comparison to the double-layer spray greenhouse mentioned in this study, the maximum cooling effect of the double-layer spray greenhouse was lower than that of the NVAC greenhouse, but it exhibited a more stable cooling performance.

3.4. Cost

The cooling system for this test double-layer greenhouse primarily utilizes a high-pressure spray system to evaluate the cooling efficiency under optimal spray system conditions. The cost estimates for this system are outlined in Table 5, amounting to a total of \$498.63. In larger double greenhouses, additional nozzles, nozzle piping, and connectors can be easily added without imposing a significant financial burden, as indicated in Table 5 where these costs contribute a small proportion.

Table 5. Cost of high-pressure spray cooling system.

Item	Numbers	Cost
9.52 mm polyethylene pipe	10 m	\$2.38
0.3 mm diameter nozzle	8	\$3.36
120° double nozzle connector	4	\$2.80
Spray machine (including 10 MPa booster pump, 100 mm filter stage filter, 16 L water tank, automatic switch)	1	\$490.09
Total		\$498.63

4. Conclusions

An experimental study was conducted on the impact of internal spraying on the microclimate in the greenhouse under various atomization indexes, spraying times, and nozzle angles in this study in order to explore the rational layout of the spray nozzles and the optimal use conditions. The results revealed the following conclusions:

- (1) The principle of spray cooling is vaporization and heat absorption. The pressure of the water supply and the diameter of the nozzle has a significant impact on the effectiveness of spray cooling. The greater the water supply pressure and nozzle diameter are, the greater the spray flow, and the more significant the cooling effect. Additionally, the spray creates a fog layer, and when light travels through the fog layer after passing through the outer film, the light is scattered with the fog droplets, creating a new propagation path in a different direction for light that would otherwise travel in a straight line. In Addition, the fog droplets absorb part of the spectral range, which reduces the amount of radiant energy entering the interior of the greenhouse, lowering the internal evaporative cooling. The atomization index is pressure dependent; the higher the pressure and the smaller the nozzle diameter are, the greater the atomization index, and the smaller the droplet particle size. The results of this paper show that the cooling effect is not significantly related to the atomization index but is more closely related to the volume of the spray flow rate. Within certain limits, the higher the spray flow rate, the greater the fog layer shading. When the nozzle diameter is 0.30 mm, the water supply pressure is 6 MPa, the spacing is 1 m and the spray duration is 15 min, the temperature can be reduced by a maximum of 5.36 °C.
- (2) The effect of different spray durations on greenhouse temperature and humidity is significant, with the cooling effect increasing with the duration of the spray and not increasing significantly when the spray duration reaches 20 min. Prolonged spraying leads to less efficient water mist evaporation, and the formation of water droplets collect and then migrate down the inner membrane. This water eventually absorbs into the surrounding land and contributes to increased evaporation from the

saturated soil, which increases the relative air humidity inside small greenhouses. High humidity in greenhouses can cause plant pests and diseases, so a spraying time of 15 min is the most appropriate to minimize that risk. And a water recovery device can be subsequently designed to collect water from the spray that has not evaporated to form droplets and provide a portion of the water for the spray, reducing the consumption of water energy.

- (3) The optimum conditions for cooling in this test are: 120° double nozzles, 6 MPa water supply pressure, 0.30 mm nozzle diameter, and 15 min spraying duration, which provide a reference for the summer cooling of the double-layer greenhouse. Additionally, spraying does have a cooling impact, but it needs to be combined with other cooling techniques to create a climate better suited for crop growth.

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