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Research Article

Design and Testing of an Inter-row Sprayer in a Chinese Solar Greenhouse

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Abstract

Implementation of manual plant protection in a Chinese solar greenhouse (CSG) is expensive and labor-intensive. Moreover, this system cannot realize the separation of people and drugs. In a CSG, plants are cultivated at different distances, directions, and heights. Consequently, pesticide application via air-spraying is not uniform because the volume of pesticide droplets that deposit on plants is disproportionate. In this study, a CSG inter-row sprayer was designed to realize the automation of plant protection and the uniformity of pesticide application. With a double-track suspension, the sprayer could move freely along the east and west directions of the CSG and perform two spraying modes, namely, fixed boom spray and lifting spray. These modes could be applied depending on different crop growth stages and protection requirements. Electromagnetic detection and positioning technology were used to detect crop rows and satisfy inter-row spraying requirements. Automatic lifting and spraying operations based on crop height as detected by the sensor were realized by a lifting motor. The effects of inter-row lifting and fixed boom sprays on droplet deposition and penetrability were tested using mature tomatoes cultivated in the CSG. Results demonstrate that the average volumes of droplets deposited on the obverse and reverse sides of tomato leaves are 1.77 and 0.817 μL per square centimeter in the inter-row lifting spray, and the average variation coefficients of droplet volume deposition are 7.3% and 19.53%, respectively. In the fixed boom spray, the average volumes of droplets deposited on the obverse and reverse sides of tomato leaves are 1.12 and 0.086 μL per square centimeter, respectively, and the average variation coefficients of droplet volume deposition are 33.2% and 74.7%, respectively. These findings indicate that inter-row lifting spray significantly increases droplet deposition on the reverse side of tomato leaves and improves the uniformity and penetrability of droplet deposition. This study improves the automation degree of plant protection and uniformity of pesticide droplet deposition, as well as provides supplementary options for plant protection in CSGs.

Keywords: CSG, Inter-row spraying, Suspension positioning, Droplet deposition

1. Introduction

Compared with traditional agriculture, the planting mode in a CSG is affected by several factors, such as high multi-cropping index, gas environment occlusion, high temperature, and high humidity, and the cultivated plants are more prone to diseases [1]. Owing to limited space and difficulty in operating spraying equipment in CSG, plant protection largely relies on manual spraying. However, manual spraying has a low pesticide utilization rate, expensive, and poses considerable potential safety hazards. A plant protection machinery is the primary means for spraying pesticides, and its performance is crucial in ensuring the effectiveness of pesticide applications [2,3].

Manual spraying with a backpack sprayer is highly random, and the volume of sprayed pesticides is uneven. Unequal spraying negatively affects the effectiveness of pest control strategies and the quality of agricultural products. Vertical sprayers combined with an air-assisted system can effectively address the limitations of manual spraying to achieve automatic spraying and increase the volume of droplets deposited on each layer of leaves along the vertical direction of the plants. Vertical sprayers are generally large, and the spacing between two adjacent crop rows in a CSG is relatively narrow [4]. Previous studies have demonstrated that the effect of air-assisted spraying in a small space is limited [5, 6]. Thus, vertical sprayers are mostly used for plant protection operations in large multi-span greenhouses.

Because of these problems, researchers have conducted extensive research on suitable spraying machines for CSG planting modes [7-10]. Some technologies that have been invented for use in CSGs include an automatic spraying system, a self-operating mist dispenser, a spray robot, and other equipment. An automatic spray operation in CSGs has also been developed to increase the utilization rate of pesticides. However, the uneven distribution and poor permeability of pesticide droplets to plants during spraying remain unresolved. Therefore, the uniformity and penetrability of pesticide droplets and automation of spray equipment are urgent problems that should be addressed.

In this study, a CSG inter-row sprayer is designed. This sprayer has two modes of spraying: inter-row lifting and fixed boom spray. Mature tomatoes in a CSG are selected as the test subjects. The effects of spraying speed and pressure on droplet deposition and penetrability of the two spray modes are evaluated. This work aims to realize the automation of plant protection practices in CSGs and satisfy the requirements of spray uniformity and rationalization. As such, it may serve as a reference for the development and

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optimization of plant protection machinery in solar greenhouses.

2. State of the art

Scientists have conducted extensive research on suitable spraying machines for CSG planting modes. A hand-held trolley sprayer with an air-assisted device was improved by Gallart [11] to increase the volume of droplet deposition. However, this sprayer could not distinguish people from pesticides and was accompanied by potential safety hazards. Wandkar [12] developed an automatic greenhouse sprayer for air-assisted spraying to improve the uniformity of droplet deposition and penetration in the entire plant canopy, but the difference in the volume of droplets deposited at different distances was large. Spray deposition could be improved by electrostatically charging the spray droplets to increase the attraction of droplets to plants, thus decreased the operator's exposure to pesticides and minimized environmental pollution. Air assistance could be added to the electrostatic spray to further improve spray deposition. Therefore, a semi-stationary sprayer with an electrostatic spray system and air assistance was invented by Cerqueira [13], but the author did not analyze the factors affecting the volume of droplet deposition. Rowe [14] developed an automatic greenhouse spraying system that could distinguish between people and pesticides and improve pesticide utilization. However, the author did not evaluate the volume of droplets deposited at different plant heights. Cantelli [15] designed an automatic spraying electric robot that could perform safe and accurate automatic spraying, but the robot might overspray the same plant as it turned between rows. A self-propelled sprayer developed by Sánchez-Hermosilla [16] used a vertical boom spray that effectively reduced pesticide loss on the ground and improved spray uniformity. However, the author did not consider the effect of spray speed and pressure on the volume of deposited droplets deposited. A computational fluid dynamics (CFD) model of droplet size and velocity was established by Musiu [17] and applied to evaluate the spray distribution pattern and effectiveness at various sprayer settings for a new model of greenhouse air blast sprayer. However, this design lacked a detailed analysis of spray uniformity. Wallhead [18] provided a sufficient volume of pesticide to the canopy through a variable rate sprayer and reduced the loss of pesticides on the ground and air, but the author did not verify the uniformity of the volume of droplet deposition. Based on CFD, Liu [19] installed a new type of grid-like deflector inside an air duct to ensure good consistency of wind velocity along the duct length in a gas flow field. The author improved the uniformity of droplet deposition but did not describe the spray parameters that affect this feature. Li [20] designed a new type of automatic air-assisted sprayer based on an offline optimal spraying strategy of a genetic algorithm to achieve automatic spraying and improve the uniformity of droplet deposition. However, this strategy did not address the problem of uneven spraying in different plant directions. Cui [21] improved the spray droplet drift performance by installing a cone-shaped and columnar air duct at the air outlet of a 9WZCD-25 air-feed sprayer, but the droplet deposition uniformity should be further improved. Based on a CFD simulation technology, Qi [22-24] built an air-velocity distribution model of greenhouse air-assisted sprayer and obtained the characteristic of air velocity distribution and droplet distribution area at different nozzle airflow speeds. Qiu [25] evaluated the distribution of droplet deposition in a confined space and determined the distribution curve of droplet deposition rate and variation of deposition quality along the length of the greenhouse.

These studies mainly focused on spraying machines suitable for greenhouses. However, the uneven deposition of pesticide droplets remains a problem, and only a few studies have examined the uniformity of droplet deposition, especially on ways to improve the uniformity and penetrability of droplet deposition on plants. In this study, an inter-row sprayer for CSGs is designed. With a double-track suspension, the sprayer can move freely in the east and west directions of the solar greenhouse. The electromagnetic positioning technology is employed to realize the inter-row positioning of the boom, and the inter-row spray operation is performed by lifting the boom spray. The effects of spray speed and spray pressure on droplet deposition and penetrability under two spray modes, that is, inter-row lifting and fixed boom spray, are examined using tomatoes as the test objects. The results of this work may serve as a reference for the development and optimization of plant protection machinery in CSGs.

The study is organized as follows. Section 3 describes the overall structure and working principle of the inter-row sprayer in CSGs and presents the tests designed to determine the effects of two spray modes on droplet deposition and penetrability. Section 4 discusses the relationship between spray speed and spray pressure and the volume of droplet deposition and penetrability in the two spray modes. Section 5 provides conclusions.

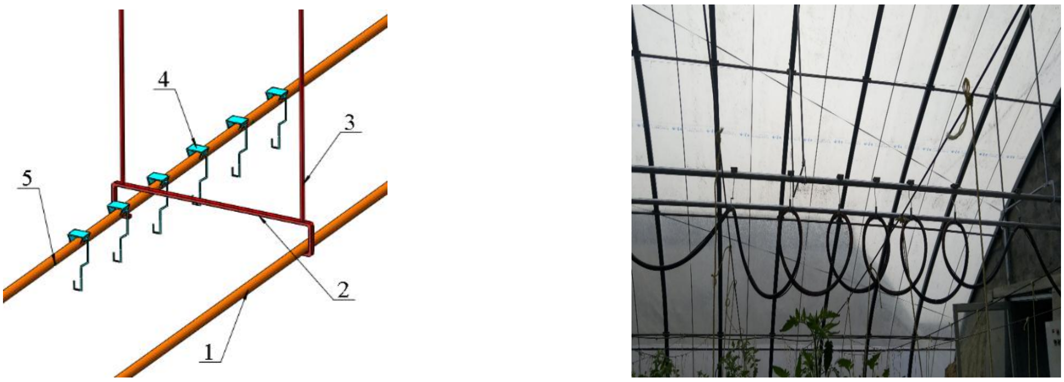
3. Methodology

3.1 Overall structure and working principle

3.1.1 Overall structure and parameters

The solar greenhouse inter-row sprayer comprises a double-track suspension positioning system and a spraying machine. The structure of the positioning system consists of two tracks arranged in parallel, vertical suspenders, a crossbar, blocks, and a magnet, as shown in Fig. 1. The tracks and the magnet serve as a traveling device and spray positioning points for the spraying machine, respectively. The block can slide along the track, and the hook-shaped lower end of the block is for fixing the water inlet pipe such that the water inlet pipe can move along with the spraying machine. The structure of the spraying machine is illustrated in Fig. 2. The spraying machine is composed of subsystems, including self-propelled, boom lifting, spray, and control systems. The proximity switches are located on both sides of the sprayer mainframe. They are used to detect the magnets on the tracks for automatic positioning of the sprayer at the spray position and automatic return after spraying is complete. The automatic detection sensor for the spray route consists of a photoelectric proximity switch and a laser ranging sensor. This sensor detects the position at which the spray starts and finishes and the real-time height of the boom spray in the inter-row lifting spray mode.

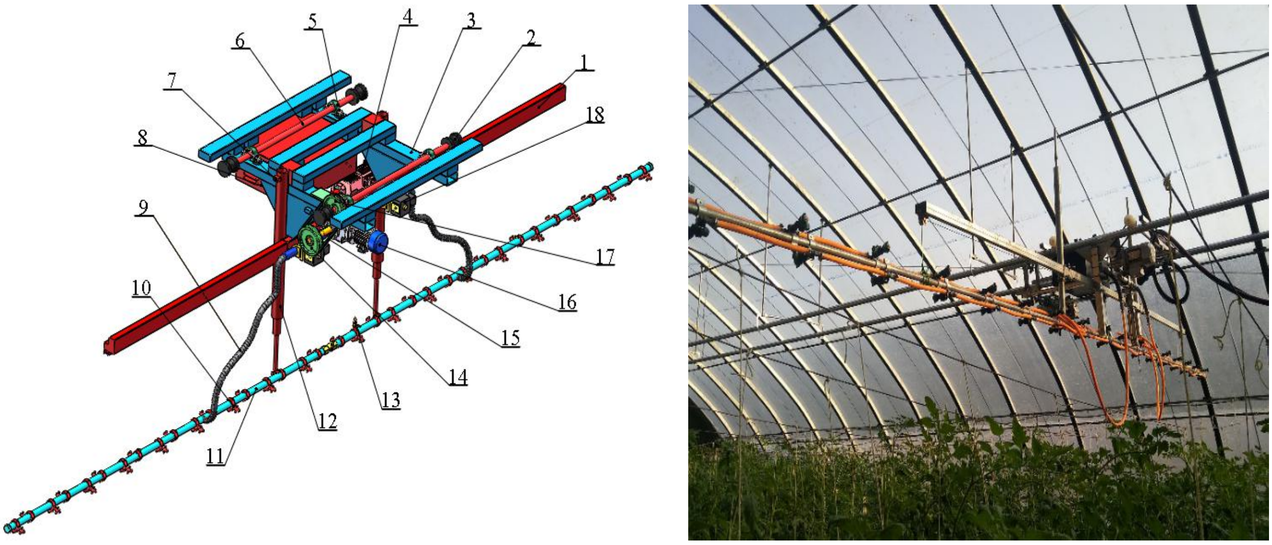
The main technical parameters of the inter-row sprayer are as follows: overall power of $2.5KW$, medicine tank capacity of $100L$, fan-shaped spray nozzle, spray boom stroke of $0 \sim 2.2m$, spray boom lifting speed of $0 \sim 0.5m/s$, and forward speed of $0 \sim 0.5m/s$, a flow rate of $\left(27.054 \sim 38.076\right) \times 10^{-5} m^3/s$.



(a) (b)

1. Track 2. Crossbar 3. Vertical suspender 4. Block 5. Magnet

Fig. 1. Structure of the double-track suspension positioning system. (a) Model of the double-track suspension positioning system. (b) Actual double-track suspension positioning system



(a) (b)

1. Cantilever 2. Roller 3. Rack 4. Lifting motor 5. Bearing 6. Driveshaft 7. Proximity switch 8. Control box 9. Outlet pipe 10. Nozzle 11. Boom spray 12. Telescopic rod 13. Spray route detection sensor 14. Driving pulley 15. Transmission belt 16. Self-propelled motor 17. Driven pulley 18. DC solenoid valve

Fig. 2. Structure of the sprayer. (a) 3D model of the sprayer. (b) Actual sprayer

3.1.2 Working principle

The inter-row sprayer has two spray modes, namely, inter-row lifting spray and fixed boom spray.

The working principle of the inter-row lifting spray is shown in Figs. 3 and 4. When the sprayer starts working, the self-propelled motor drives the sprayer along the tracks. When the proximity switch on the sprayer detects the magnet on the tracks (located between two rows of crops), the sprayer stops. The lifting motor then drives the boom down. When the boom is lowered to the position of the top leaf of the tomato plant, the photoelectric proximity switch at the bottom of the telescopic boom detects the reflected light signal from the leaf and uses this signal to start spraying. The spray system starts working after receiving a signal and sprays the crops on both sides of the boom. When the height of the boom spray during its lowering is at the set height of the control program as measured by the boom height sensor, the lifting motor reverses to drive the boom upward. Finally, the boom returns to the initial height before spraying. During the boom return process, the sprayer does not operate. In inter-row lifting spray, the nozzles on both sides of the sprayer are active at the same time, and the spray direction is parallel to the ground.

The working principle of the fixed boom spray is as follows. When the sprayer starts working, the sprayer no longer detects the magnet on the tracks. The boom does not move vertically during the whole spray process (but the initial height of the spray boom can be adjusted) and sprays the crops below the boom in the direction of movement of the sprayer. In fixed boom spray, the spray nozzles on either side of the boom spray on one side only, and the spray direction is perpendicular to the ground.

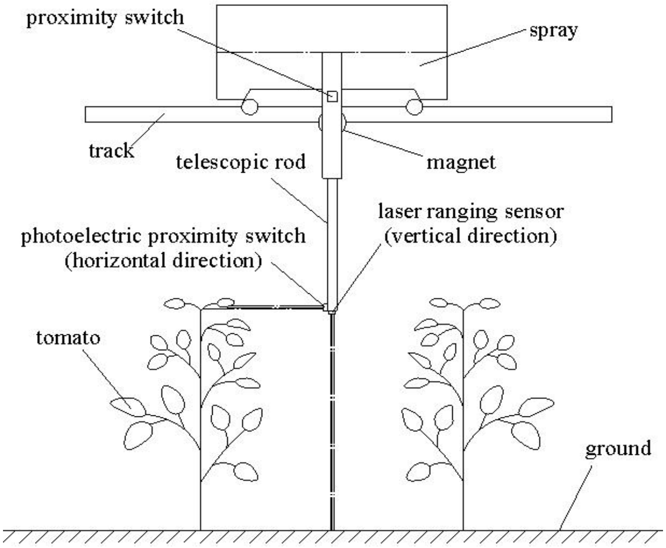


Fig. 3. Principle of spray route detection

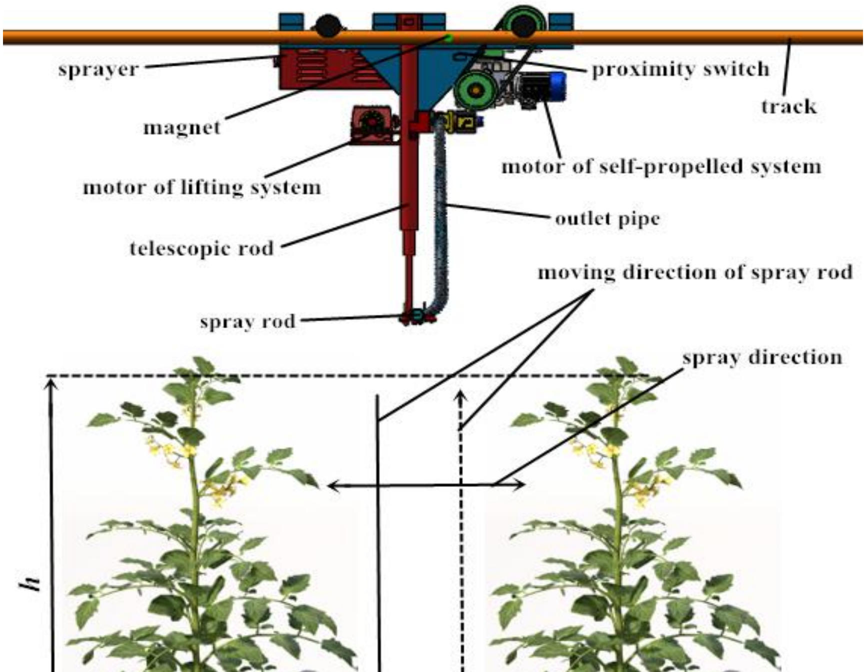


Fig. 4. Schematic of spraying

3.2 Determination of the installation distance between nozzles

As shown in Fig. 5, the planting parameters of the crops in the greenhouse should be measured to determine the installation distance between the nozzles. Table 1 shows the planting parameters of tomato plants in the solar greenhouse of Shandong Agricultural University. During parameter measurements, six rows of tomatoes were randomly selected.

The installation distance between adjacent nozzles is denoted by L, and the nozzle spray angle is denoted by α (Fig. 6). Sections 1, 2, and 3 are the positions of the outer leaves and middle leaves of the plant and the plant stem, respectively. M, N, and K are the distances of the three sections from the nozzle. If L is calculated according to N and K, part of the leaves in section 1 cannot be sprayed by the nozzle; if L is calculated according to M, some of the leaves in sections 2 and 3 are repeatedly sprayed by the adjacent nozzles. However, considering that the leaves in section 1 will obstruct the leaves of sections 2 and 3 during actual spraying, repeated spraying can enhance droplet penetrability in sections 2 and 3; thus, L is determined according to M.

Table 1. Tomato planting parameters

Row No. / Parameters	Row 1/cm	Row 2/cm	Row 3/cm	Row 4/cm	Row 5/cm	Row 6/cm	Total/cm	Average/cm
Row spacing	101	100	98	99	100	102	600	100
Ridge width	46	49	45	43	45	47	275	45.8
Plant spacing	20	23	22	23	21	22	131	21.8
Leaf distance	49	51	51	50	48	48	297	49.5

Note: Row spacing refers to the distance between the measured row and the previous row; plant spacing is the distance between two adjacent tomato plants randomly selected in the measured row.

Fig. 5. Parameter measurement

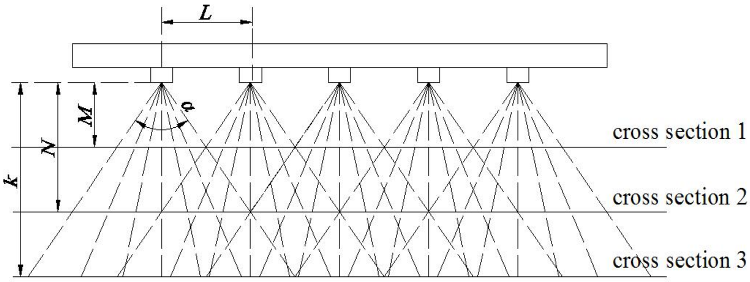


Fig. 6. Schematic of the nozzle spacing

From the geometric relationship in Fig. 6, we can obtain:

$$\tan\frac{\alpha}{2}=\frac{L}{2M} \tag{1}$$

where α is the nozzle spray angle (°); L is the nozzle installation spacing (cm); and M is the average minimum distance between the leaves and the nozzle, which is 24.75 cm. For the current system, where $\alpha = 10°$, $L = 70.69cm$, and the installation spacing of adjacent nozzles is 71 cm.

3.3 Test design and method

Spray tests were designed to evaluate the effects of spray speed and pressure changes on droplet deposition and penetrability for the two spray modes of inter-row lifting spray and fixed boom spray. Tests were separately conducted for the two spray modes.

3.3.1 Test environment

Tomatoes in the solar greenhouse of Shandong Agricultural University were selected as the spray test subject. The tests were performed in an indoor environment with an ambient temperature of $23°C$, relative humidity of 60%, and a natural wind speed of less than $0.2m/s$. The test medium was a methyl violet solution containing no solid with a suspension concentration of $0.1g/\mathrm{L}$ at normal temperature.

3.3.2 Test method

The tests were performed in six stages described below.

(1) Selection of sampling targets. The solar greenhouse was 40 m long and 7 m wide. Ten rows of tomatoes were randomly selected. A tomato plant in the middle of each row was selected, together with one tomato plant from either side of the central tomato plant at the same distance. The adjacent tomato plants were 2.5 m apart. Three tomato plants were selected as the sampling targets in each tested row, as shown in Fig. 7.

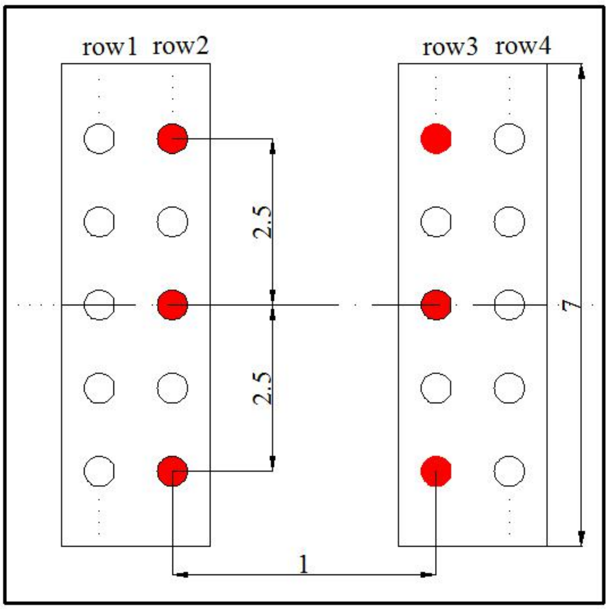


Fig. 7. Selected sampling targets

(2) Selection of sampling points. According to plant height, tomato leaves were divided into three layers: upper, middle, and lower layers. At each layer of the sampling target, a filter paper was placed on one leaf. Thus, a filter paper was placed at three positions on each tomato plant. The three positions were numbered 1 to 3 from top to bottom, and the six layout positions of the two other plants were numbered in the same way: from 4 to 6 and from 7 to 9. The obverse and reverse sides of the sampled leaves were selected as sampling points, with a total of 18 sampling points per row, as shown in Fig. 8. The heights of leaves at different levels are shown in Table 2.

Table 2. Heights of leaves at different layers

Position	**Leaf No.**	**Height from the ground/cm**
Upper	1,4,7	160-180
Middle	2,5,8	100-120
Lower	3,6,9	40-60

(3) Placement of filter papers. A filter paper with a diameter of 9 cm was used to measure droplet deposition. A piece of filter paper was fixed on either side of the leaf with a clip, and the number of the filter paper was recorded by the position of the sampling point, as shown in Fig. 9a.

(4) Spraying. A methyl violet solution with a concentration of $0.1\,g/L$ was used instead of a pesticide for spraying. Two separate spray tests were conducted to compare the distributions of droplet deposition for the two modes, as shown in Fig. 9b. The influence of boom lifting speed on deposition distribution was evaluated by applying constant pressure (0.3 MPa) with variable speed (0.1, 0.2, and 0.3 m/s); the influence of spray pressure was examined by using a constant speed ($0.2m/s$) with variable pressure (0.2, 0.3, and 0.4 MPa). The condition of 0.3 MPa and $0.2m/s$ was common to both experiments; thus, five unique spraying conditions were required. Each measurement was repeated three times with a total of 15 tests. For the fixed boom spray mode, the spray speed was the advancing speed of the spraying machine because the spray direction was perpendicular to the ground. In the fixed boom spray mode, two spray speeds (0.15 and 0.3 m/s) and three spray pressures (0.2, 0.3, and 0.4 MPa) were applied. Each test required six sprays and repeated three times with a total of 18 tests.

(5) Collection of filter papers. After the spray tests were completed, the filter papers were collected and placed in a ventilating environment to dry. Thereafter, the filter papers were placed in a valve bag on which information about the spray position and parameters was marked for subsequent processing.

(6) Filter paper treatment. The solubility of methyl violet on the recycled filter papers was determined via spectrophotometry. The deposition volume on the leaves was calculated and recorded, and the results were analyzed.

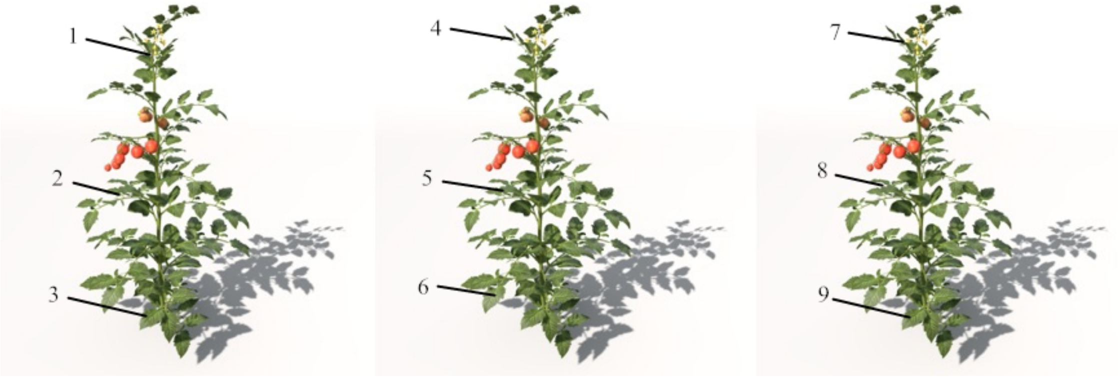


Fig. 8. Selected sampling points


(a)
(b)

Fig. 9. Determination of droplet deposition properties. (a) Placement of filter paper. (b) Spraying

4 Results and discussion

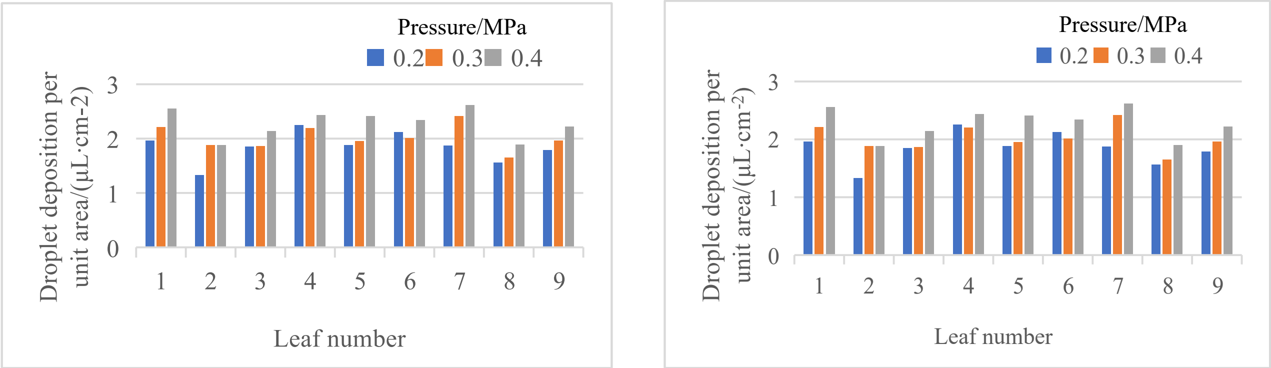
4.1 Droplet deposition in the inter-row lifting spray mode

(1) Effects of different spray pressures on droplet deposition distribution

Fig. 10 shows the volume of droplets deposited on the obverse and reverse sides of the tomato leaves under different spray pressures in the inter-row lifting spray mode. With increasing pressure, the volume of droplets deposited on the obverse side of leaves at all layers increased. Moreover, droplet penetrability and the flow rate of each nozzle increased with increasing spray pressure. On the reverse side of the leaves, deposition also increased with increasing spray pressure, albeit to a lesser extent than on the obverse side. This result was due to the mutual occlusion of the leaves with a considerable effect on droplet deposition on the reverse side. Among the three different levels, deposition volume and penetrability were the highest on the upper and lower leaves because the upper leaves were small, sparse, and not fully developed. The lower leaves were also relatively sparse under the combined effects of natural senescence and defoliation and artificial defoliation. By contrast, the middle leaves were large, dense, and fully developed. Therefore, the droplet penetrability on the upper and lower leaves and their deposited volume were greater than those on the middle leaves.

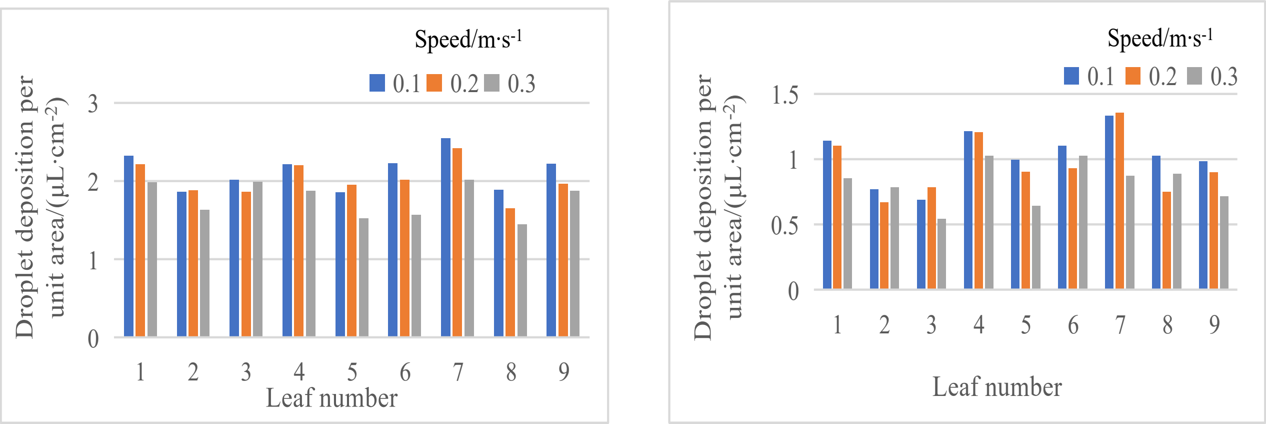
(2) Effects of different boom lifting speeds on sedimentary distribution

Fig. 11 shows the volume of droplets deposited on the obverse and reverse sides of the leaves at different lifting spray speeds in the inter-row lifting spray mode. With increasing spray speed, the droplet deposition decreased on both sides of the leaves at all layers. The spray speed decreased the contact time between leaves and droplets, thereby reducing the volume of droplet deposition.



(a) (b)

Fig. 10. Droplet deposition per unit area at each sampling point under different pressures in the inter-row lifting spray mode. (a) Obverse side. (b) Reverse side



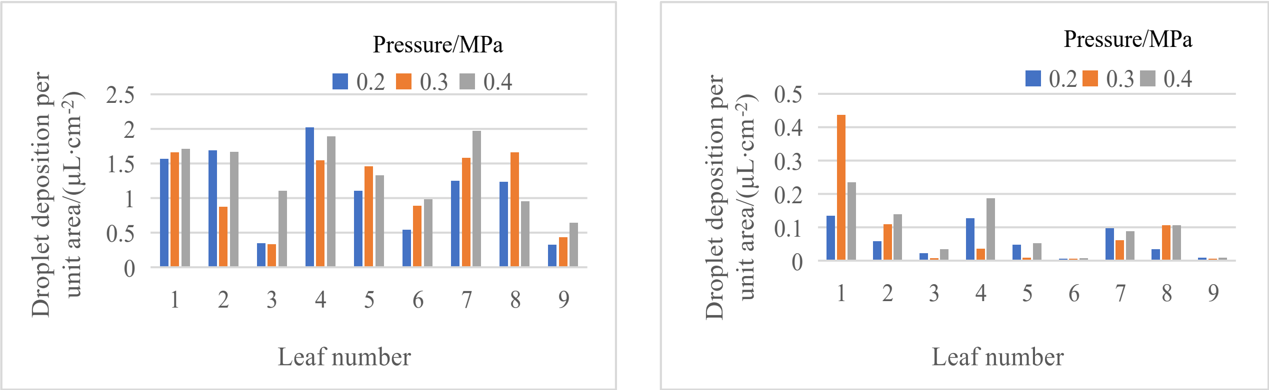
(a) (b)

Fig. 11. Volume of droplets deposited per unit area at each sampling point at different speeds in the inter-row lifting spray mode. (a) Obverse side. (b) Reverse side

4.2 Droplet deposition in the fixed boom spray mode

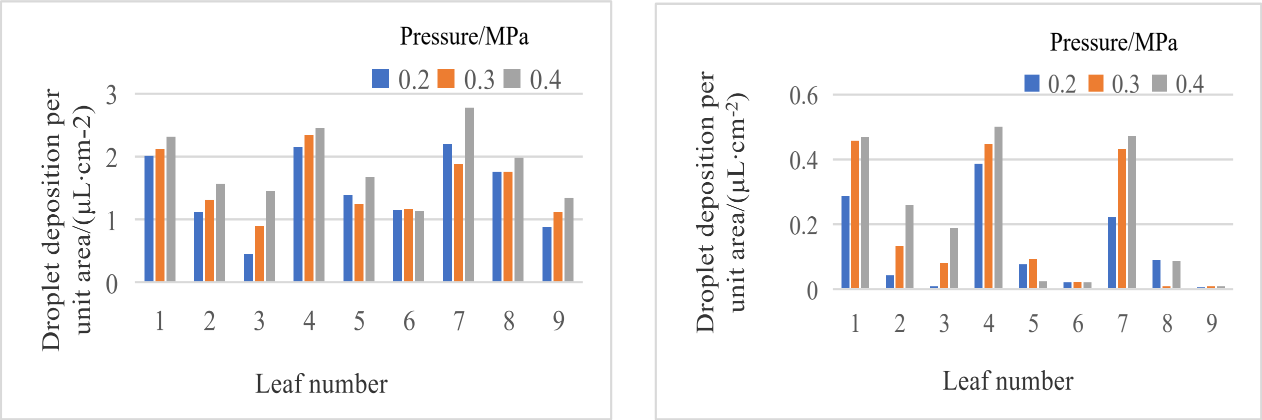
Fig. 12 shows the volume of droplets deposited on the obverse and reverse sides of the leaves after spraying in the boom fixed spray mode with a spraying speed of $0.3m/s$. The volume of droplets deposited on the obverse side of the leaves at all layers generally increased with increasing spray pressure. The volume of droplets deposited on the obverse sides of the upper and middle leaves was substantially greater than that of the lower leaves because of the occlusion effect of the upper and middle leaves on the lower leaves. The volume of droplets deposited on the reverse side of leaves at all layers decreased more drastically than on the obverse side. Given that the upper leaves were not fully developed and located below the nozzle, the droplets that were not obstructed by other leaves were able to penetrate them strongly. The volume of droplets deposited on the reverse side of the upper leaves was the greatest of all leaves at all three layers.

Fig. 13 shows the volume of droplets deposited on the obverse and reverse sides of the leaves in the fixed boom spray mode with a spraying speed of $0.15m/s$. The difference in deposition between layers was similar to that at spraying speed of $0.3m/s$ but with several clear differences. At a speed of $0.15m/s$, droplet deposition at all layers was greater than that at $0.3m/s$. Droplet deposition on the obverse sides of the lower leaves considerably increased at a low spray speed because of the prolonged residence time of the nozzles above the plants and the high volume of droplets that passed through the middle and upper leaves to the obverse sides of the lower leaves. Droplet deposition on the obverse side of the lower leaves was more sensitive to the spray speed than the leaves at the other layers. The volume of droplets deposited on the reverse side of the upper leaves decreased with increasing spray speed because the upper leaves were almost unobstructed. Moreover, a lower spray speed allowed a higher volume of droplets to pass through the obverse sides of leaves that then moved to the reverse side.



(a) (b)

Fig. 12. Volume of droplets deposited per unit area at each sampling point at a speed of $0.3m/s$ in the fixed boom fixed spray mode. (a) Obverse side. (b) Reverse side



(a) (b)

Fig. 13. Volume of droplets deposited per unit area at each sampling point at a speed of $0.15m/s$ in the fixed boom spray mode. (a) Obverse side. (b) Reverse side

4.3 Comparison of droplet deposition between the two spray modes

The effects of inter-row lifting spray and fixed boom spray modes on droplet distribution in the direction of plant height were tested. For the inter-row lifting spray mode, the spray pressure was 0.3 MPa and the lifting speed was $0.3m/s$. For the fixed boom spray mode, the spray pressure was 0.3 MPa and the advancing speed of the spraying machine was $0.3m/s$. The test results are shown in Table 3.

Table 3 shows that the volume of the droplets deposited on the obverse side of the upper leaves for the inter-row lifting spray and fixed boom spray modes was 1.958 and 1.483 $\mu L/\text{cm}^2$, respectively. The volume of droplets deposited on the obverse sides of the middle leaves was 1.532 and 1.331 $\mu L/\text{cm}^2$ for the two modes, respectively; the volume on the obverse sides of the lower leaves was 1.809 and 0.548 $\mu L/\text{cm}^2$, respectively. The variation in droplet deposition was negligible on the obverse sides of the upper, middle, and lower leaves in the inter-row lifting spray mode. By contrast, the variation was substantial in the upper, middle, and lower leaves in the fixed boom spray mode. This result arose because the nozzles were located above the plants in the fixed boom spray, and the obverse sides of the upper and middle leaves were well positioned to receive droplets from the top nozzles. The droplets deposited easily on the obverse side of leaves, and only a few droplets reached the lower leaves because they were covered by the upper and middle ones.

In the two spray modes, the volume of droplets deposited on the reverse side of leaves at all layers was lesser than that on the obverse side. However, a higher volume of droplets was deposited on the reverse side of the leaves in the inter-row lifting spray mode than that on the reverse side in the fixed boom spray mode. The variation in droplet deposition was great, especially in the middle and lower layers, where the leaves grew densely. With the middle leaves as an example, the volume of droplets deposited in the inter-row lifting spray mode and the fixed boom spray mode was 0.772 and 0.074 $\mu L/\text{cm}^2$, respectively. These results indicated that inter-row lifting spray considerably improved droplet deposition on the reverse side of the middle and lower leaves of mature tomato plants.

In the inter-row lifting spray mode, the variations in the volume of droplets deposited on the obverse and reverse sides of the leaves were $3.7\% \sim 12\%$ and $10\% \sim 32.2\%$, respectively; in the fixed boom spray mode, the variations were $14.4\% \sim 54.4\%$ and $20.4\% \sim 126.8\%$, respectively. Thus, the distribution of droplets deposited on both sides of the leaves at all layers of the tomato plants was more uniform in the inter-row lifting spray mode than in the fixed boom spray mode.

Table 3 Comparison of the volume of droplets deposited on the leaves at different heights in the inter-row lifting spray and fixed boom spray modes

Leaf layer	**Leaf number**	**Leaf surface type**	**Total deposition Volume / ($\mu L/\mathrm{cm}^2$)**	**Average deposition volume /($\mu L/\mathrm{cm}^2$)**		**Mean variation coefficient (%)**	
				Obverse side	**Reverse side**	**Obverse side**	**Reverse side**
Upper layer	1	Obverse	5.952/4.983	1.958/1.483	0.917/0.177	3.7/14.4	10.5/126.8
		Reverse	2.556/1.308				
	4	Obverse	5.628/4.572				
		Reverse	3.084/0.105				
	7	Obverse	6.042/4.749				
		Reverse	2.613/0.183				
Middle layer	2	Obverse	4.899/2.616	1.532/1.331	0.772/0.074	6.2/30.8	15.9/76.9
		Reverse	2.358/0.324				
	5	Obverse	4.563/4.374				
		Reverse	1.929/0.024				
	8	Obverse	4.329/4.986				
		Reverse	2.661/0.315				
Lower layer	3	Obverse	5.961/0.984	1.809/0.548	0.762/0.006	12.0/54.4	32.2/20.4
		Reverse	1.629/0.021				
	6	Obverse	4.701/2.661				
		Reverse	3.081/0.015				
	9	Obverse	5.616/1.287				
		Reverse	2.148/0.015				

Note: Data on the left side of '/' is for the inter-row lifting spray mode and on the right side are for the fixed boom spray mode.

5. Conclusions

An inter-row sprayer that can realize inter-row lifting spray and fixed boom spray modes was designed to improve the uniformity and penetrability of droplet deposition during spraying in a CSG. With mature tomatoes grown in a greenhouse as the test subject, the effects of two spray modes on the uniformity and penetrability of droplet deposition were tested, and the results were analyzed. The following conclusions were drawn:

(1) When the spray pressure was constant, the contact time between leaves and droplets increased with decreasing spray speed, and the volume of droplets deposited increased. When the spray speed was constant, the penetrability of the droplets increased with increasing spray pressure, and the volume of droplets deposited on the reverse side of the leaves increased.

(2) Under the same speed and pressure, the volume of droplets deposited on the upper, middle, and lower leaves of tomato plants in the inter-row lifting spray mode showed a trend of troughs, but the overall difference was not significant. However, the volume of droplets deposited showed a significant decreasing trend when the fixed boom spray mode was used. In the inter-row lifting spray, the volume of droplets deposited on the reverse side of the upper layer was relatively high, which can meet the requirements of plant protection. The highest volume of droplets deposited on the reverse side in the fixed boom spray was only approximately 30% of the inter-row lifting spray, and the plant protection requirements could not be met at all times. Therefore, the inter-row lifting spray can more effectively increase the uniformity and penetrability of droplet deposition than the fixed boom spray.

Thus, an inter-row sprayer can improve the degree of automation of plant protection operations and the uniformity and penetrability of plant droplet deposition in CSGs. It serves as an option for plant protection operations in solar greenhouses. However, only the effects of inter-row spraying on the droplet deposition and penetrability of mature tomato plants were verified in this study. Therefore, tomato seedling and flowering stages should be tested in future studies, and the specific relationship between spray effect and parameters, such as spray speed and pressure, should be clarified.

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