

Article

Design and Experiment of an Orchard Variable-Rate Spraying System Based on Canopy Volume Sensing

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Abstract

To enhance the adaptability of orchard spraying to canopy spatial variability, a LiDAR-based variable-rate spraying system was developed for trellis orchards. The system used a Livox MID-360 LiDAR to acquire canopy point clouds and generated spray control values based on canopy volume in different nozzle action regions. A canopy partitioning method combining left–right division, travel-direction grids, and sector-based spraying regions was proposed. And the voxel occupancy method was used to estimate canopy volume in each partitioned unit. Based on the calculated canopy volume, target flow rates and PWM control values were determined. Pressure stabilization and FIFO queue-based delay compensation were adopted to improve flow regulation stability and sensing–execution matching. System performance was evaluated through nozzle flow calibration, dynamic targeting tests, and spray deposition tests. Results indicated a strong correlation between the PWM duty cycle and nozzle flow rate under different supply pressures ($R^2 > 0.98$). At forward speeds of 0.3, 0.5, and 0.8 m/s, the mean targeting offsets following delay compensation were 112.5, 118.6, and 126.4 mm, respectively. Spray deposition tests showed that variable-rate spraying produced deposition responses corresponding to canopy volume or density differences. The developed system can realize real-time canopy sensing, sectional spray control, and dynamic spraying execution, providing a technical reference for precision spraying in trellis orchards.

Keywords: orchard spraying; LiDAR; fruit tree canopy volume; variable-rate spraying



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1. Introduction

Effective orchard crop protection is critical for sustaining fruit tree growth and enhancing both fruit yield and quality. Conventional orchard sprayers usually operate with a constant application rate, without considering the spatial variability of fruit tree canopies. However, canopy architecture exhibits significant three-dimensional variation along the travel, lateral, and height axes. In trellis orchards, the canopy is continuously distributed along the tree row, while local differences in canopy density, canopy volume, and spatial morphology still exist. Constant spraying under such conditions may result in off-target deposition, over-application in sparse canopy regions, uneven deposition, pesticide waste, and environmental contamination [1]. Recent literature highlights that canopy-adaptive

application is an important direction for improving pesticide utilization efficiency [2]. Comparisons of orchard pesticide dose models based on canopy characteristics provide a reference for spray amount adjustment under different canopy conditions [3]. Consequently, adjusting spray output according to canopy spatial characteristics is important for improving spraying precision and pesticide utilization efficiency.

Variable-rate spraying provides an effective approach for precision pesticide application in orchards. The core of this technology is to obtain canopy information using sensors and convert the detected canopy characteristics into executable spray control signals [4]. Recent smart tree-crop sprayers have integrated sensor fusion and artificial intelligence to support real-time spray decision-making [5]. An autonomous air-assisted sprayer based on a single hanging track has been developed and tested, indicating that air-assisted spraying structures can be integrated with automatic operation platforms [6]. In particular, LiDAR can directly acquire three-dimensional canopy information and is suitable for describing canopy geometry and spatial distribution. LiDAR-derived canopy density can provide important input for precision spray applications [7,8]. Voxel-based point cloud parameters can also support canopy volume estimation and multi-nozzle sectional control [9,10]. The CMPC LiDAR-based method further indicates that meshing-profile canopy volume can be used to support orchard target-oriented spraying [11].

Previous studies have demonstrated the feasibility of employing LiDAR and vision-based sensing methods for orchard variable-rate spraying. A laser-scanning-sensor-based orchard sprayer was designed to modulate spray output according to detected canopy information [12,13]. More recently, LiDAR-based canopy volume measurement has been further integrated with variable-rate orchard sprayers, showing the potential of point-cloud-derived canopy parameters for real-time spray decision-making [14]. These studies indicate that three-dimensional canopy perception can provide a practical basis for converting local canopy structure into spray control values. UAV-based studies have also used LiDAR-derived canopy volume to support variable-rate spraying in orchard conditions [15].

In the broader context of precision agriculture, intelligent orchard management has become an important direction for improving resource-use efficiency and reducing environmental impacts in perennial tree-crop production systems. Recent developments in Mediterranean orchard precision agriculture have demonstrated increasing research interest in sensor-based crop characterization, autonomous operation, and variable-rate input management. However, practical deployment of precision spraying systems still faces engineering challenges, particularly in establishing reliable sensor-fusion pipelines that can convert three-dimensional canopy information into real-time application decisions. Therefore, integrating accurate canopy perception with responsive spray control represents an important pathway toward next-generation precision spraying technologies for orchard production.

Although sensor-based variable-rate spraying has made considerable progress, several technical challenges persist for trellis orchard applications. First, the canopy in trellis orchards is usually continuously distributed along the row, and individual-tree boundaries are not always clear. Calculating only the total canopy volume of a tree or a canopy segment is insufficient for multi-nozzle sectional spraying. Therefore, canopy spatial information needs to be further divided into local units aligned with nozzle action regions. Second, the actual nozzle flow rate is affected by PWM duty cycle, supply pressure, and solenoid valve response characteristics. PWM spray systems have shown that duty cycle and forward speed can affect spray coverage under field conditions [16]. Thus, a stable conversion relationship among canopy volume, target flow rate, and nozzle control value needs to be established. Third, the spatial offset between the sensing and execution positions necessitates precise delay compensation to synchronize the spray output with the target

canopy architecture [17]. Beyond these primary control elements, optimizing auxiliary airflow distribution and coordinating air-liquid outputs are critical for enhancing spray penetration and deposit coverage [18–20]. Similarly, studies on air-assisted electrostatic spraying underscore that operational parameters, such as spray distance and charging mechanisms, significantly impact droplet deposition [21–23]. Prescription-map-based orchard spraying integrating GNSS positioning and canopy leaf area density also provides a reference for matching spatial canopy information with spray flow regulation [24].

In this study, a LiDAR-based variable-rate spraying system was developed for trellis orchards as an engineering approach toward precision orchard crop protection. The proposed system integrates point cloud partitioning, voxel-based canopy volume estimation, canopy-volume-driven spray decision-making, PWM flow regulation, and delay compensation, thereby establishing a sensing-to-actuation framework for canopy-adaptive spraying. The system was evaluated through nozzle flow calibration, dynamic targeting tests, and spray deposition experiments, aiming to provide a practical technical solution for improving spray precision, reducing unnecessary pesticide input, and advancing sensor-based precision spraying technologies in trellis orchard production systems.

2. Materials and Methods

2.1. LiDAR-Based Variable-Rate Spraying System

A LiDAR-based variable-rate spraying system was developed for spraying operations in trellis orchards. As illustrated in Figure 1, the system mainly consists of a crawler chassis, a Livox MID-360 LiDAR, an onboard computer, a programmable logic controller (PLC), a PWM output module, a solenoid valve group, an air-assisted variable spraying unit, a pressure sensor, a flowmeter, and a liquid supply system. During operation, the LiDAR collects 3D point cloud data of the canopy ahead of the sprayer. The onboard computer performs point cloud processing, canopy volume calculation, and spraying decision-making. The PLC drives the solenoid valves according to the control signals generated by the onboard computer, thereby enabling independent regulation of each spraying channel.

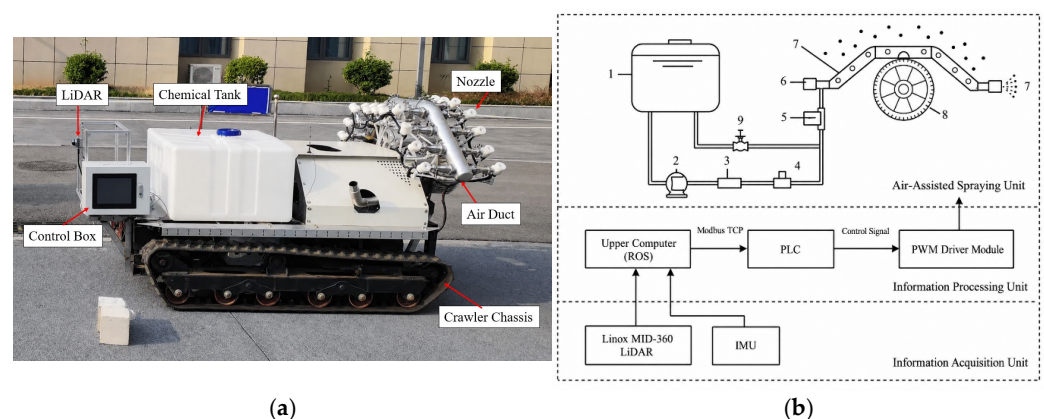


Figure 1. Overall structure of the LiDAR-based variable spraying system. (a) Prototype of the variable spraying system; (b) System components and information transmission path. 1. Tank 2. Pump 3. Flow sensor 4. Pressure sensor 5. Solenoid valve 6. Nozzle 7. Air duct 8. Fan 9. Return valve.

The system uses a crawler chassis as the mobile platform. The LiDAR is mounted at the front of the sprayer to acquire three-dimensional point cloud data of the canopy ahead. The air-assisted variable spraying unit is arranged on both sides of the rear of the machine to assist droplet transport and cover canopy regions at different heights. The

control box integrates the onboard computer, PLC, and PWM output module to perform data processing, control signal transmission, and execution control.

The system operates according to a sensing-decision-execution workflow. The sensing layer acquires three-dimensional point cloud data of the canopy. The decision layer generates PWM control values for each channel based on the partitioned canopy volume. The execution layer, consisting of the PLC, PWM output module, and solenoid valves, realizes independent nozzle regulation. Modbus TCP communication is used between the onboard computer and the PLC to transmit spraying control values in real time.

The air-assisted variable spraying unit consists of a fan, an air duct, and air-assisted atomizing nozzles. It is mainly used to provide auxiliary airflow for droplet transport and to achieve spray coverage of canopy regions at different heights. To adapt to the vertical distribution of the trellis orchard canopy, the air duct was designed as a combined structure consisting of a middle horizontal section, two inclined side sections, and a vertical inlet section. The middle horizontal section receives the airflow from the fan and distributes it to both sides, the inclined side sections are arranged along the canopy height direction, and the vertical inlet section is connected to the fan outlet. The air outlets are distributed along the duct length so that the auxiliary airflow can act on nozzles at different heights, thereby improving droplet transport into the canopy. Recent airflow graded-control sprayer research also shows that adjusting airflow according to canopy conditions can improve droplet uniformity and reduce drift risk [25].

The air-assisted atomizing nozzles developed by the research group were used in this study. The nozzles were symmetrically arranged along the air ducts on both sides, and their spray directions were oriented toward the interior of the canopy. Adjacent spray regions were designed to overlap appropriately to reduce blind areas and improve the continuity of canopy coverage. In the front view, two symmetrically arranged nozzles at the same height on the left and right sides jointly act on the corresponding canopy layer, with an included spray-region angle of approximately 30° . The inter-row working width of the trellis orchard was approximately 4 m. When the spraying unit was located in the middle of the row, the maximum spraying distance on one side was approximately 2 m. Based on an included spray-region angle of 30° , the half angle was 15° . When the spacing between adjacent nozzles was 150 mm, the minimum spraying distance at which adjacent spray regions began to intersect was approximately 0.28 m; when the spacing between the middle nozzles was 120 mm, the corresponding minimum spraying distance was approximately 0.22 m. Therefore, the minimum effective spraying distance of the system was set as 0.28 m, which is much smaller than the maximum one-sided spraying distance of 2 m. This indicates that the designed nozzle arrangement can form relatively continuous spray coverage within the working width of a trellis orchard.

The structure of the air-assisted variable spraying unit and the nozzle spraying space are shown in Figure 2. The air duct structure is used for auxiliary airflow distribution, while the nozzle arrangement determines the droplet coverage range in the left and right canopy regions.

The system workflow is shown in Figure 3. After the operation starts, the LiDAR continuously collects point clouds of the canopy ahead. The onboard computer sequentially performs point cloud preprocessing, canopy partitioning, volume calculation, and PWM control value generation. After delay compensation, the control values are sent to the PLC, which controls the solenoid valves to execute variable spraying. Meanwhile, the pressure sensor provides real-time feedback of the main pipeline pressure, and the PLC maintains stable supply pressure through closed-loop control.

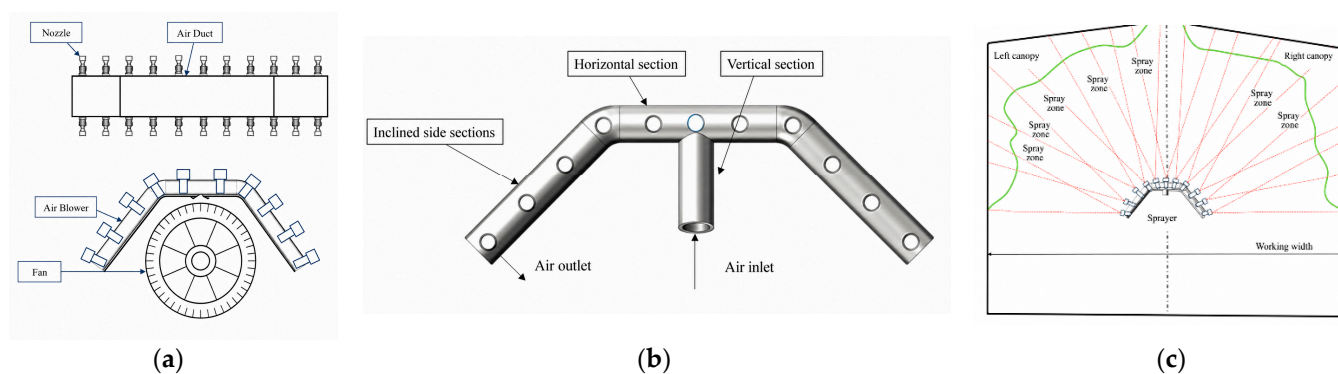


Figure 2. Schematic diagram of the air-assisted variable spraying unit and nozzle spraying space. (a) Nozzle spraying space; (b) Air duct structure; (c) Spraying unit arrangement.

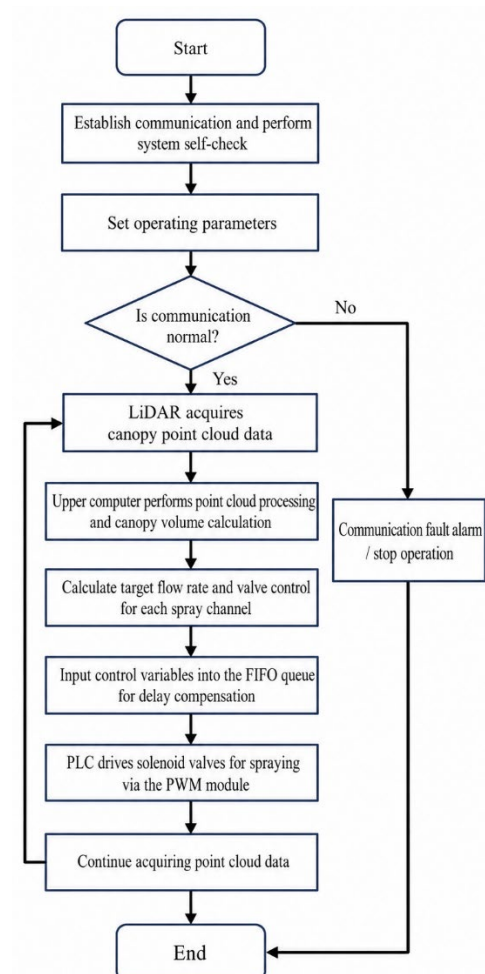


Figure 3. Workflow of the LiDAR-based variable spraying system.

2.2. Canopy Point Cloud Processing and Volume Estimation Method

To obtain canopy volume information for variable spraying decision-making, a canopy processing and volume estimation method based on LiDAR point clouds was established. The method includes four steps: point cloud acquisition, point cloud preprocessing, canopy spatial partitioning, and voxel-based volume calculation. Recent reviews of variable-rate orchard spraying emphasize that canopy structural parameters are important inputs for orchard precision application [2]. Voxel-based volume estimation has also been applied to apple trees during the pruning period, providing a useful reference for point-cloud-based canopy volume calculation [9]. Numerical simulation of droplet deposition under

air-assisted spraying also provides a reference for understanding the interaction among airflow, droplets, and leaves [26]. The processing procedure is shown in Figure 4. LiDAR point-cloud models for thick orchard canopies have also been used to detect canopy leaf area, which provides a reference for describing local canopy structural differences [27].

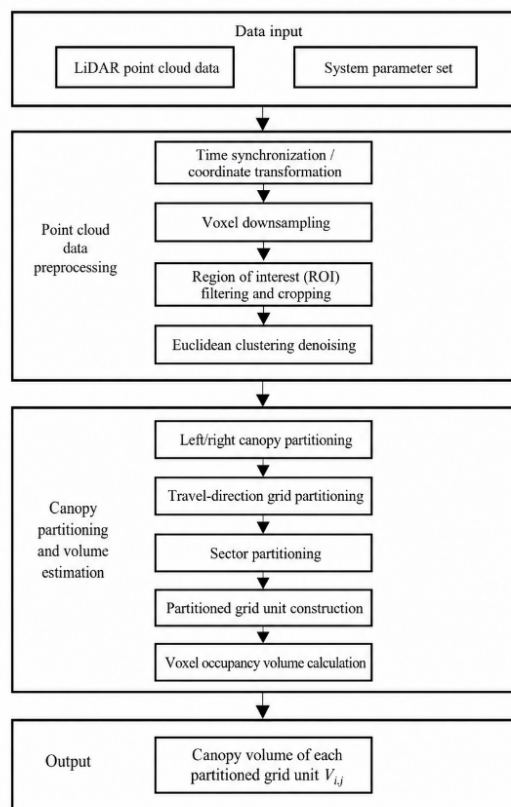


Figure 4. Flowchart of canopy point cloud processing and volume estimation.

During operation, the Livox MID-360 LiDAR collects point clouds of the canopy ahead of the sprayer in real time and publishes the point cloud data through the ROS system. After subscribing to the point cloud topic, the onboard computer transforms the raw point cloud into the sprayer operating coordinate system. A region of interest is then set according to the travel direction and nozzle action range to remove ground, background, and non-target point clouds. Voxel down sampling is subsequently used to reduce the number of points, and clustering-based denoising is applied to remove isolated noise points, thereby obtaining effective canopy point clouds.

To establish a correspondence between canopy spatial information and nozzle spraying regions, partitioned grid units were constructed. First, the point cloud was divided into left and right sides using the center plane of the sprayer as the boundary. Second, the front detection region was divided into equal-length grids along the travel direction. Finally, each side of the canopy was divided into several sector regions according to the nozzle installation positions and spray directions. The overlapping space between the travel-direction grid and the sector partition was defined as a partitioned grid unit, which served as the basic unit for canopy volume calculation and spraying control allocation.

As shown in Figure 5a, the detection region ahead of the sprayer was divided into several grid units along the travel direction. In this partitioning method, the continuous canopy was discretized into multiple spatial segments along the operating direction, which facilitated subsequent correspondence with the delayed spraying process of the nozzles.

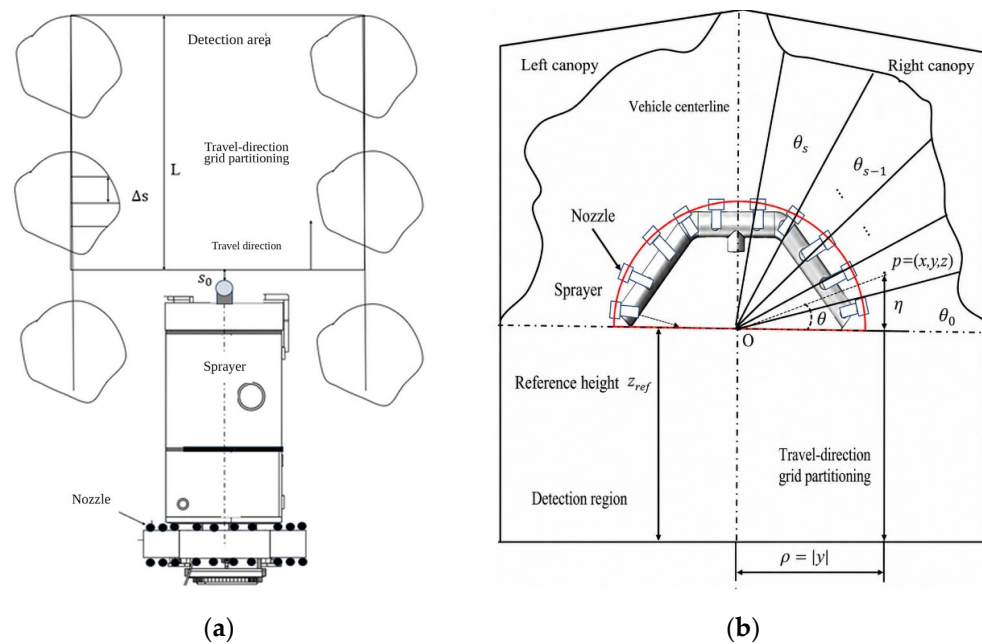


Figure 5. Canopy grid division and sector partitioning method. (a) Travel-direction grid division; (b) Sector partitioning based on nozzle action regions.

As shown in Figure 5b, based on the travel-direction grid division, the canopy point cloud within each grid was further divided into sector regions according to the nozzle action areas. To ensure a unified angular partitioning method for the left and right canopies, the lateral distance from a canopy point to the vehicle centerline and the height difference relative to a reference height were defined. For any canopy point, the corresponding angle can be calculated from its position in the lateral-height plane, and the point can then be assigned to different sector regions according to the preset angular boundaries. The sector partitions correspond to the spatial action ranges of the nozzles, thereby matching canopy spatial regions with nozzle spraying regions.

After canopy point cloud partitioning, the voxel occupancy method was used to calculate the canopy volume in each partitioned grid unit. The point cloud in each partitioned grid unit was divided into three-dimensional voxels with a specified side length, and the number of occupied voxels was counted. The canopy volume corresponding to the i -th travel-direction grid and the j -th spraying partition can be expressed as:

$$V_{i,j} = N_{i,j} l_v^3 \quad (1)$$

where $V_{i,j}$ is the canopy volume of the i -th grid and the j -th spraying partition, m^3 ; $N_{i,j}$ is the number of voxels occupied by the point cloud in the partitioned grid unit; and l_v is the voxel side length, m. For the same spraying region, the canopy volume can be obtained by summing the volumes of the corresponding partitioned grid units.

$$V_j = \sum_{i=1}^m V_{i,j} \quad (2)$$

where V_j is the canopy volume of the j spraying partition, m^3 ; and m is the number of travel-direction grids included in the spraying partition.

The voxel side length l_v directly affects the estimated canopy volume because different voxel resolutions may generate different numbers of occupied voxels for the same point cloud. A smaller l_v generally provides a more detailed description of canopy structure, while a larger l_v results in smoother volume estimation with reduced computational re-

quirements. In this study, a fixed voxel side length was used for all experiments to maintain consistency in canopy volume estimation and ensure reliable comparison of variable-rate spraying performance.

Through the above processing, the LiDAR point cloud can be converted into canopy volume information corresponding to nozzle partitions. The partitioned grid units divide the continuous canopy into multiple spatial units corresponding to the nozzle action regions, allowing canopy volumes at different positions and heights to be calculated separately and providing data inputs for subsequent multi-nozzle partitioned variable spraying control.

2.3. Variable Spraying Decision-Making and Execution Control Method

The core of the variable spraying decision is to convert the canopy volume of each partitioned grid unit into PWM control values executable by the nozzles. In this study, the canopy volume of each partitioned grid unit was used as the input. Combined with the required application amount per unit canopy volume, forward speed, nozzle arrangement, and nozzle flow calibration model, a variable spraying decision method from canopy volume to PWM control value was established. Sprayer-UAV stability studies showed that liquid tank shape and internal structure can affect platform stability, supporting the need for stable operating conditions during spraying execution [28]. Smart sprayer studies also support the use of sensing and decision modules to convert target information into variable spray outputs [5]. Laser scanning sensor-based orchard sprayers further support the use of detected canopy information for real-time spray regulation [12].

For the i -th travel-direction grid and the j -th spraying partition, the corresponding canopy volume is $V_{i,j}$. According to the required application amount per unit canopy volume, the target application amount of the partitioned grid unit can be calculated as:

$$A_{i,j} = \mu V_{i,j} \quad (3)$$

where μ is the required application amount per unit canopy volume, L m^{-3} ; and V is the canopy volume of the partitioned grid unit, m^3 . In this study, μ was set to 0.1 L m^{-3} based on previous canopy-volume-based variable-rate spraying studies [3,14]. These studies indicated that canopy volume can be used as an effective spatial parameter for adjusting spray output in orchard variable-rate applications. Therefore, μ was introduced as an empirical application coefficient to convert the LiDAR-derived canopy volume information into the target spray amount.

The selected value of μ was considered appropriate for the developed spraying system because the proposed method uses canopy volume as the main control input rather than directly optimizing pesticide biological efficacy. In addition, the influence of the nozzle characteristics and operating conditions was considered through nozzle flow calibration and spray deposition experiments. The developed system employed an air-assisted spraying unit with PWM-controlled solenoid valves, and the relationship between the calculated target spray amount and actual nozzle output was established through experimental calibration. The field deposition results further demonstrated that the system could generate different deposition responses according to canopy density variations.

Since μ directly determines the target application amount in Equation (3), variations in μ will proportionally influence the calculated target flow rate and corresponding PWM duty cycle. A larger μ value will increase the overall spray output, whereas a smaller μ value will reduce the application amount. However, the relative distribution pattern of variable spraying is mainly determined by the spatial variation of canopy volume obtained from LiDAR measurements. Therefore, μ primarily affects the overall application level rather than the canopy-adaptive regulation trend of the system.

During sprayer travel, the action time of the nozzle on a single grid region is related to the grid length and forward speed and can be expressed as:

$$t_i = \frac{\Delta s}{v} \quad (4)$$

where t_i is the time during which the nozzle acts on a single grid region, s; Δs is the grid length along the travel direction, m; and v is the forward speed of the sprayer, m s^{-1} . Thus, the target flow rate of the corresponding spraying partition can be obtained as:

$$q_{i,j} = \frac{60A_{i,j}}{t_i} = \frac{60\mu V_{i,j}}{t_i} \quad (5)$$

where $q_{i,j}$ is the target flow rate, L min^{-1} . Through this conversion, canopy volume information is no longer used only as a static structural parameter, but is further combined with the forward speed and nozzle action time to generate a target flow rate that can be executed by the nozzle.

Considering the spatial correspondence between the nozzles and different spraying partitions, the target flow rates of all spraying channels at the same moment can be expressed as:

$$q_i = [q_{i,1}, q_{i,2}, \dots, q_{i,n}] \quad (6)$$

where q_i is the multi-channel target flow vector corresponding to the i -th travel-direction grid, and n is the number of spraying partitions or spraying channels. This vector describes the spraying demand of each nozzle channel in the current canopy spatial segment and provides the input for subsequent PWM control value calculation.

Because the actual nozzle flow rate is affected by both supply pressure and PWM duty cycle, the mapping relationship between PWM duty cycle and nozzle flow rate must be established before variable spraying execution. In this study, nozzle flow calibration tests were carried out under different supply pressures to obtain the average nozzle flow rate at different PWM duty cycles, and a nozzle flow fitting model was established as:

$$q = f(D, P) \quad (7)$$

where q is the nozzle flow rate, L min^{-1} ; D is the PWM duty cycle, %; and P is the supply pressure, MPa. In actual control, the system calculates the corresponding PWM duty cycle from the target flow rate. After the PWM control values of all spraying partitions are obtained, the multi-channel PWM control vector corresponding to the i -th travel-direction grid can be expressed as:

$$D_i = [D_{i,1}, D_{i,2}, \dots, D_{i,n}] \quad (8)$$

where D_i is the multi-channel PWM control vector corresponding to the i -th travel-direction grid, and n is the number of spraying partitions or spraying channels. Because the spraying system operates in discrete control cycles, the multi-channel spraying control vector generated at the k -th control moment is defined as:

$$u(t_k) = D_i \quad (9)$$

where $u(t_k)$ is the multi-channel spraying control vector generated at time t_k and waiting for execution. This control vector enters the delay compensation queue together with the corresponding timestamp for subsequent nozzle position matching and delayed output.

When the target flow rate is lower than the stable spraying lower limit of the nozzle, or when no valid canopy point cloud exists in the corresponding region, the PWM output of that channel is set to 0. When the target flow rate exceeds the applicable range of

the calibration model, the maximum allowable duty cycle is used. Considering that the solenoid valve opening time is short at low duty cycles and that discontinuous atomization or flow fluctuation may occur, the effective PWM output range was limited to 20–100% in this study.

For execution control, the system adopts a control mode combining onboard-computer decision-making and PLC execution. The onboard computer performs point cloud processing, canopy volume calculation, and variable spraying control value generation, and sends the PWM control values of each channel to the PLC through Modbus TCP. After channel mapping, data conversion, and limiting, the PLC outputs the received control values to the PWM module and solenoid valve driving circuit, thereby realizing independent control of different spraying channels. Meanwhile, the PLC collects the pressure feedback signal from the main pipeline and regulates the pump output using a PID control method, so that the supply pressure remains stable under frequent solenoid valve switching and pipeline load changes. Pressure stabilization provides stable operating conditions for the PWM duty cycle-nozzle flow rate mapping relationship.

Because the LiDAR is located in front of the nozzles, there is a spatial offset between the canopy detection position and the actual spraying position. In addition, point cloud processing, communication transmission, and solenoid valve response introduce system delays. To match the spray output with the target canopy position, a FIFO queue-based delay compensation method was adopted. The control vector was bound with a timestamp and stored in the queue, and it was output to the PLC after the target delay time was reached. The control mechanism is shown in Figure 6.

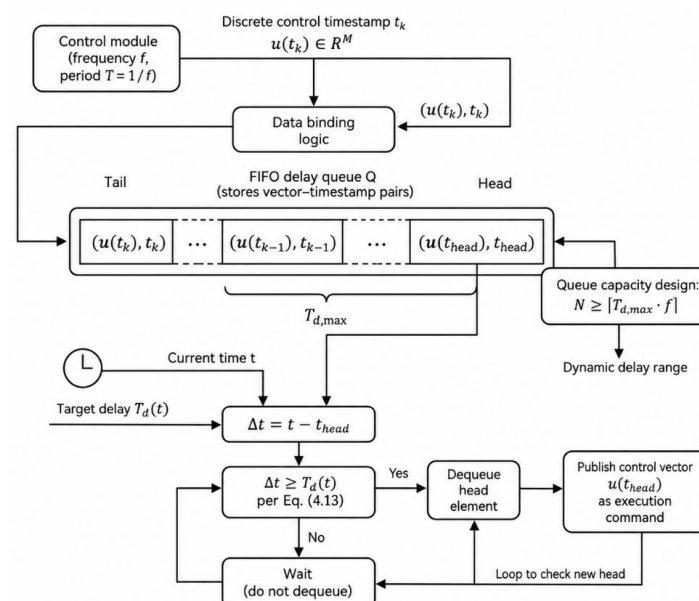


Figure 6. Schematic diagram of the spray delay compensation control mechanism.

The control module operates at a fixed frequency. At the k -th control moment, a control vector is generated, bound to its timestamp, and stored in the FIFO delay queue. The system reads the timestamp corresponding to the control value at the head of the queue in real time and calculates its accumulated waiting time:

$$\Delta t = t - t_{head} \quad (10)$$

When the delay condition is satisfied:

$$\Delta t \geq T_d(t) \quad (11)$$

the control value at the head of the queue is dequeued and sent to the PLC for execution; otherwise, it continues to wait. The target delay time is calculated as:

$$T_d = \frac{d}{v} + T_s \quad (12)$$

where T_d is the target delay time, s; d is the distance between the LiDAR detection position and the nozzle spraying position, m; v is the forward speed of the sprayer, m s^{-1} ; and T_s is the calibrated delay correction term considering point cloud processing, communication transmission, and solenoid valve response, s. To meet the buffering requirement under the maximum delay condition, the queue capacity should satisfy:

$$N \geq \lceil T_{d,max} \cdot f \rceil \quad (13)$$

Through the above method, temporal alignment of the spraying control values can be achieved, allowing the nozzles to output the corresponding control commands when reaching the target canopy position.

In summary, a variable spraying control method consisting of canopy volume input, target flow rate calculation, PWM control value conversion, pressure stabilization control, and delay compensation was established, providing the control basis for subsequent system performance tests.

It should be noted that μ was predefined as a constant coefficient during system operation. Therefore, the current variable spraying strategy operates in an open-loop manner with respect to actual biological efficacy. The system determines the spray output based on real-time canopy structural information and the predefined application coefficient, without feedback from pest pressure, disease severity, or crop protection effectiveness. This assumption was adopted to establish a feasible real-time canopy-adaptive spraying framework. Future studies will focus on integrating biological indicators or deposition feedback to dynamically optimize μ and achieve closed-loop application control.

2.4. System Performance Evaluation Method

To verify the control feasibility and operational adaptability of the system, nozzle flow calibration, dynamic targeting, and spray deposition performance tests were carried out. The nozzle flow calibration test was used to establish the mapping relationship between target flow rate and PWM control value. The dynamic targeting test was used to verify the effect of delay compensation. The spray deposition test was used to analyze the system response capability under different canopy spatial conditions. In this study, the water-sensitive paper method was adopted as an effective tool to evaluate spray deposition characteristics [29]. A data-driven obstacle-avoidance study for liquid-carrying plant-protection UAVs further highlights the importance of sensing and motion stability in spraying platforms [30]. Therefore, droplet coverage and distribution stability were selected as important indices for evaluating the deposition response of the proposed variable spraying system.

2.4.1. Nozzle PWM Duty Cycle-Flow Rate Calibration Test

The nozzle flow calibration test was used to establish the relationship between PWM duty cycle and actual nozzle flow rate. The nozzle type, liquid supply pipeline, and solenoid valve control mode were kept consistent. The supply pressures were set to 0.25, 0.30, and 0.35 MPa, and the PWM duty cycle was varied stepwise from 20% to 100%. Under each condition, nozzle flow data were collected after the main pipeline pressure stabilized, and the average value during the stable period was used as the nozzle flow value for that condition.

Considering that the solenoid valve opening time is short at low duty cycles and atomization may become discontinuous, the effective PWM control range was limited to 20–100%. After the test, PWM duty cycle-flow rate fitting models under different supply pressures were established for calculating variable spraying control values.

2.4.2. Dynamic Targeting Performance Test

To evaluate the effectiveness of the delay compensation method under dynamic operating conditions, a dynamic targeting performance test was conducted. This test was used to analyze the matching degree between the LiDAR detection position and the actual nozzle spraying position.

An artificial canopy was used as the target. White paper tapes were arranged before and after the target along the sprayer travel direction, as shown in Figure 7, and a moderate concentration of carmine solution was added to the spray liquid. During operation, the system generated spraying control values according to the target position detected by the LiDAR, and controlled the nozzles after delay compensation. The spray deposits formed colored traces on the paper tapes, and the targeting performance was evaluated according to the deviation between the colored region and the target reference position.



Figure 7. Schematic diagram of the dynamic targeting performance test setup.

Three forward speeds, 0.3, 0.5, and 0.8 m/s, were tested. Each speed was repeated several times. After the test, the positional deviations of the spray deposition region on the paper tape relative to the front and rear edges of the target were measured to obtain the front-edge and rear-edge delay distances, respectively. By comparing the changes in delay distance under different speeds, the sensing-execution matching capability of the system during dynamic operation was evaluated.

2.4.3. Spray Deposition Performance Test

The spray deposition performance test was used to evaluate the spraying response capability of the variable spraying system under different canopy conditions. Water-sensitive paper was used to collect droplet deposition, and droplet coverage was used as the evaluation index. The test included an artificial canopy test and a field continuous-canopy test. The former was used to analyze the correspondence between variable spray output and canopy volume differences, while the latter was used to evaluate the adaptability of the system to local density differences under real continuous-canopy conditions.

The artificial canopy test was conducted in a relatively controlled environment using an artificial canopy with spatial structural differences. Three forward speeds of 0.3, 0.5, and 0.8 m/s were set, and the supply pressure was 0.30 MPa. Constant spraying was used as the control. Under constant spraying, each nozzle maintained a fixed output. Under variable spraying, the system calculated the canopy volume of the corresponding region based

on the LiDAR point cloud and adjusted the PWM duty cycle of each spraying channel in real time.

According to the nozzle spraying range and the spatial position of the artificial canopy, the canopy was divided into three sampling regions, A, B, and C, along the travel direction. Three sampling points were arranged in each region, and water-sensitive papers were placed on the front and back surfaces of the target leaves. The arrangement is shown in Figure 8. After the test, the water-sensitive papers were collected, droplet coverage was extracted using image processing, and deposition differences under different spraying modes, sampling regions, and forward speeds were compared.



Figure 8. Arrangement of water-sensitive paper in the spray deposition performance test.

The field continuous-canopy test was conducted in a trellis orchard. Because the trees were continuously distributed along the travel direction and individual-tree boundaries were difficult to accurately define, local canopy density differences were used as the basis for region division. The test section was divided into sparse and dense canopy regions. A1, A2, and A3 denote sampling regions in the sparse canopy area, whereas B1, B2, and B3 denote sampling regions in the dense canopy area. The overall arrangement of the field sampling regions is shown in Figure 9.

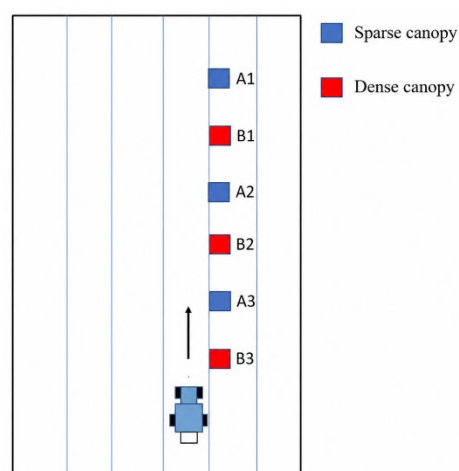


Figure 9. Overall arrangement of sampling regions in the field test. The arrow indicates the traveling direction of the sprayer.

Two forward speeds, 0.3 and 0.8 m/s, were set in the field test. During the test, the operating path, nozzle arrangement, spray pressure set value, variable spraying control algorithm, and water-sensitive paper positions were kept consistent. Three repeated tests were conducted under each speed condition. The sprayer moved uniformly along the tree row, and the system generated variable spraying control values based on real-time canopy volume results and controlled the nozzles through the PLC to complete the spraying operation. The arrangement of the water-sensitive papers is shown in Figure 10.



Figure 10. Arrangement of water-sensitive paper in different canopy density regions. (a) Sparse canopy region; (b) Dense canopy region.

It should be noted that the field experiment was designed as a preliminary validation of the proposed variable spraying system. Due to the complexity of orchard field conditions and experimental constraints, only two forward speeds (0.3 and 0.8 m/s) were selected, and each condition was repeated three times. The number of sampling positions within each canopy density zone (A1–A3 and B1–B3) was also limited. Therefore, the current field results should be interpreted as an indication of the canopy-adaptive response capability of the proposed system rather than a comprehensive statistical evaluation of spraying performance. Further experiments with more operating conditions, larger sampling populations, and longer-term field validation are required to statistically verify the robustness and general applicability of the proposed method.

2.5. Data Processing and Evaluation Indices

The test data included nozzle flow data, dynamic targeting delay distances, and droplet deposition data from water-sensitive paper. The nozzle flow data were used to establish the fitting relationship between PWM duty cycle and flow rate. The dynamic targeting data were used to evaluate the spray position deviation after delay compensation. The water-sensitive paper image data were used to analyze deposition responses in different canopy regions. Data processing included raw data organization, outlier checking, average calculation, and evaluation index calculation.

In the nozzle flow calibration test, nozzle flow data were collected under different supply pressures and PWM duty cycles. For each condition, the average flow rate during the stable period was selected as the effective flow value, and a fitting model between PWM duty cycle and nozzle flow rate was established. The fitting performance was evaluated using the coefficient of determination, which characterized the explanatory ability of the fitting model for the measured flow data.

In the dynamic targeting performance test, the delay distance was calculated according to the positional relationship between the colored deposition region on the paper tape and the target reference line. Let the distance from the leading edge of the spray deposition region to the target front edge be D_f , and the distance from the trailing edge of the

deposition region to the target rear edge be D_b . The average delay distance under a given speed can be expressed as:

$$D_m = \frac{D_f + D_b}{2} \quad (14)$$

where D_m is the average delay distance, mm; D_f is the delay distance relative to the target front edge, mm; and D_b is the delay distance relative to the target rear edge, mm. By comparing the changes under different forward speeds, the sensing-execution matching capability of the system during dynamic operation can be evaluated.

Water-sensitive paper images were processed using a unified procedure. After the spraying test, the papers were collected promptly and scanned at 600 dpi. The software of “DepositScan 1.0” was then used to identify droplet deposition areas and calculate droplet coverage. To reduce the effects of cropping, shadows, and local contamination, the relatively complete central region of each water-sensitive paper was selected as the effective analysis area.

To evaluate the dispersion of droplet deposition within the same sampling region, the coefficient of variation (CV) of coverage was calculated as:

$$CV = \frac{\sigma}{\bar{C}} \times 100\% \quad (15)$$

where σ is the standard deviation of the water-sensitive paper coverage within the same sampling region; and $\bar{C}$ is the average coverage of that sampling region. A smaller CV indicates smaller fluctuation in droplet coverage within the same sampling region and relatively more stable deposition distribution.

In the result analysis, the nozzle flow calibration results were used to characterize the regulation capability of PWM control values on flow rate. The dynamic targeting delay distance was used to evaluate the spray position deviation after delay compensation. Droplet coverage and the CV obtained from water-sensitive paper were used to analyze deposition responses in different canopy regions.

3. Results

3.1. Nozzle Flow Calibration Results

The calibration results of PWM duty cycle and average nozzle flow rate under different supply pressures are shown in Table 1 and Figure 11. Under the three pressure conditions of 0.25, 0.30, and 0.35 MPa, the average nozzle flow rate increased with increasing PWM duty cycle, indicating that PWM modulation can regulate nozzle flow. At the same duty cycle, a higher supply pressure resulted in a higher average nozzle flow rate.

Table 1. Relationship between PWM duty cycle and average nozzle flow rate under different.

Solenoid Valve PWM Duty Cycle (%)	Flow Rate (L min ^{−1})		
	0.25 MPa	0.3 MPa	0.35 MPa
20	0.16	0.19	0.31
30	0.44	0.50	0.64
40	0.75	0.80	0.87
50	1.09	1.26	1.35
60	1.32	1.45	1.47
70	1.42	1.70	1.81
80	1.46	1.67	1.89
90	1.46	1.71	1.86
100	1.47	1.72	1.89

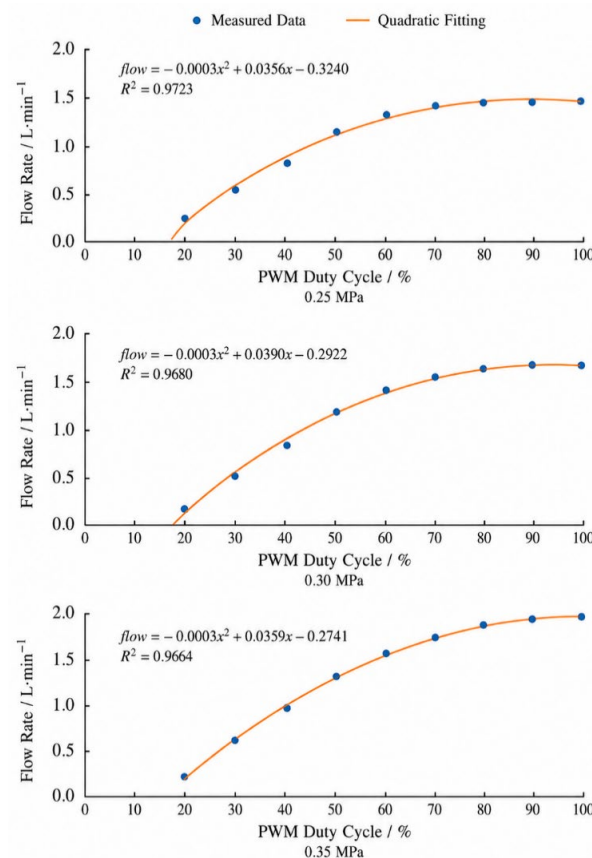


Figure 11. Relationship between flow rate and solenoid valve PWM duty cycle under different pipeline pressures.

As shown in Figure 11, the nozzle flow rate increased rapidly in the low-to-medium duty cycle range and gradually leveled off in the high duty cycle range, indicating a certain saturation characteristic. This may be related to the opening and closing response of the solenoid valve, the flow capacity of the nozzle, and the fluid inertia in the pipeline. When the duty cycle is high, the effective valve opening time is close to the fully open state, and further increasing the duty cycle results in a smaller gain in average flow rate.

The fitting results showed that the coefficients of determination of the models under the three pressure conditions were all greater than 0.98, indicating that the quadratic model could effectively describe the variation of average nozzle flow rate with duty cycle. Under stabilized pressure conditions, a stable functional mapping relationship existed between PWM duty cycle and average nozzle flow rate, which can be used for subsequent calculation of variable spraying control values.

3.2. Dynamic Targeting Performance Results

The results of the dynamic targeting performance test are shown in Table 2. At the three forward speeds of 0.3, 0.5, and 0.8 m/s, the measured targeting delay distances were all positive, indicating that the actual nozzle spraying position generally lagged behind the detected target canopy position. The average delay distances at the three speeds were 112.5, 118.6, and 126.4 mm, respectively, and were generally concentrated within the range of 0.11–0.13 m.

Table 2. Targeting accuracy measurements at different forward speeds.

Speed (m/s)	Test No.	Delay Distance (mm)		Mean Delay Distance (mm)
		Target Front Edge	Target Rear Edge	D_m
0.3	1	98	125	112.5
	2	108	114	
	3	115	110	
	4	103	127	
0.5	1	118	115	118.6
	2	112	120	
	3	135	124	
	4	109	116	
0.8	1	135	110	126.4
	2	126	115	
	3	128	124	
	4	130	143	

As shown in Table 2, as the forward speed increased from 0.3 to 0.8 m/s, the average targeting offset after delay compensation showed a slight increasing trend but remained within a relatively small range. This phenomenon can be attributed to the fact that time delays caused by point cloud acquisition, data processing, communication transmission, and solenoid valve response are more easily converted into spatial deviations at higher forward speeds. Therefore, even small temporal errors may result in slight spatial mismatches between canopy detection and nozzle actuation.

To further evaluate the effectiveness of the FIFO queue-based delay compensation method, the theoretical spatial offset without compensation was analyzed. Without FIFO compensation, the detected canopy position cannot be synchronized with the actual spraying position because the sprayer continues moving during the system response period. The uncompensated spatial offset is determined by the interaction between forward speed and total system delay, and can be expressed as:

$$\Delta x = v \times t_d \quad (16)$$

where Δx represents the spatial mismatch between canopy detection and nozzle actuation without compensation, v represents the forward speed, and t_d represents the total system response delay.

This theoretical analysis indicates that the spatial mismatch would continuously accumulate during the sensing-to-actuation process if no compensation strategy were applied. In contrast, the proposed FIFO queue-based compensation method compensates for the time delay by shifting the spraying command according to the calculated response time. The measured residual targeting offsets after FIFO compensation were maintained within 112.5–126.4 mm under different forward speeds, demonstrating that the FIFO mechanism effectively reduced the delay-induced spatial mismatch and improved the temporal synchronization between canopy sensing and spraying execution. Overall, the FIFO queue-based delay compensation method achieved reliable temporal alignment between the sensing position and spraying position under different forward speeds.

3.3. Spray Deposition Performance Results

3.3.1. Spray Deposition Results for the Artificial Canopy

The spray deposition results for the artificial canopy are shown in Table 3. At the three forward speeds, the droplet coverage on the front leaf surface was generally higher

than that on the back surface, indicating that droplets were more likely to deposit on the windward side of the canopy and the leaf surface. Deposition on the back surface was more affected by canopy shielding, airflow disturbance, and droplet penetration ability. As the forward speed increased, the front- and back-side coverage generally decreased, indicating that higher speed shortened the nozzle action time and reduced the deposition level.

Table 3. Mean droplet coverage on front and back leaf surfaces in each sampling region under different spraying modes and forward speeds.

Spraying Mode	Sampling Region	Droplet Coverage (%)					
		0.3 m/s		0.5 m/s		0.8 m/s	
		Front Leaf	Back Leaf	Front Leaf	Back Leaf	Front Leaf	Back Leaf
Constant spraying	A	70.73	46.50	55.13	39.51	51.50	32.02
	B	78.64	43.98	60.33	37.69	48.84	29.45
	C	64.12	42.11	53.99	36.06	47.86	26.25
Variable spraying	A	17.30	10.15	14.64	5.12	12.67	2.93
	B	24.44	9.09	22.77	4.71	20.64	1.19
	C	17.19	10.81	14.86	6.58	11.90	2.05

Because constant spraying and variable spraying have different spray output mechanisms, the absolute coverage values should not be used directly as a criterion for judging their relative superiority. To analyze the correspondence between variable spraying and canopy spatial structure, the relative distributions of coverage in regions A, B, and C within the total coverage were further compared, and dimensionless processing was applied to canopy volume and front-side leaf coverage.

The canopy volume statistics of each region are shown in Table 4.

Table 4. Canopy volume statistics in regions A, B, and C under different operating conditions.

Canopy Region	Canopy Volume (m ³)		
	Speed (m/s)		
	0.3	0.5	0.8
A	0.101	0.088	0.074
B	0.175	0.153	0.129
C	0.097	0.099	0.105
Total volume	0.373	0.340	0.308

In this study, the ratio of the index value of each region to the total value of the three regions was used as a dimensionless parameter to reflect the relative contribution of that region to the whole. The dimensionless expressions for canopy volume and front-side leaf coverage are as follows:

$$R_{V,i} = \frac{V_i}{\sum_{i=1}^3 V_i} \quad (17)$$

$$R_{C,i} = \frac{C_i}{\sum_{i=1}^3 C_i} \quad (18)$$

where $R_{V,i}$ and $R_{C,i}$ denote the dimensionless values of canopy volume and coverage of the i -th region, respectively; V_i and C_i denote the corresponding canopy volume and coverage of the i -th region. After dimensionless processing, the sum of the dimensionless values of the three regions is 1, which can be used to compare the matching relationship between deposition distribution and canopy volume distribution among different regions.

As shown in Table 5, under constant spraying, the front-side leaf coverage proportions in regions A, B, and C were relatively close, indicating that the coverage distribution tended toward overall uniform deposition. Under variable spraying, the front-side leaf coverage proportion in region B was consistently higher than those in regions A and C, with values of 0.4148, 0.4357, and 0.4565, respectively. Region B also had a relatively high proportion of canopy volume. It can be observed that the distribution trend of spray coverage was generally consistent with the canopy volume distribution. To further quantify the agreement between canopy structure and spray deposition, Pearson correlation coefficients were calculated between $R_{v,i}$ and $R_{c,i}$ under different spraying conditions. The Pearson correlation coefficient was used to evaluate the similarity between the spatial distributions of canopy volume and spray coverage, where a higher coefficient indicates a stronger agreement between the two distributions.

Table 5. Dimensionless distributions of canopy volume and front-side leaf coverage under different.

Spraying Mode	Dimensionless Type	Canopy Region	Speed (m/s)		
			0.3	0.5	0.8
Constant spraying	Coverage	A	0.3313	0.3253	0.3475
		B	0.3683	0.3560	0.3296
		C	0.3004	0.3186	0.3229
Variable spraying	Coverage	A	0.2936	0.2800	0.2802
		B	0.4148	0.4357	0.4565
		C	0.2916	0.2843	0.2633
Variable spraying	Volume	A	0.2708	0.2588	0.2403
		B	0.4692	0.4500	0.4188
		C	0.2601	0.2912	0.3409

It should be noted that droplet deposition is not determined solely by canopy volume; it is also affected by nozzle atomization characteristics, air-assisted airflow, leaf posture, local shielding, and sprayer travel status. Therefore, the dimensionless distribution of coverage and the canopy volume distribution should not be interpreted as a strict one-to-one relationship, but rather as an evaluation basis for the response trend of variable spraying. Recent air-assisted spraying experiments based on canopy volume and leaf area further show that canopy structure and inlet airflow jointly affect droplet deposition characteristics [31]. To further quantify the consistency between canopy volume distribution and spray coverage distribution, the Pearson correlation coefficient between $R_{v,i}$ and $R_{c,i}$ was calculated under different spraying conditions.

$$r = \frac{\sum_{i=1}^n (R_{v,i} - \overline{R_v})(R_{c,i} - \overline{R_c})}{\sqrt{\sum_{i=1}^n (R_{v,i} - \overline{R_v})^2 \sum_{i=1}^n (R_{c,i} - \overline{R_c})^2}} \quad (19)$$

In summary, the coverage allocation under constant spraying was closer to uniform deposition, whereas the coverage distribution under variable spraying exhibited a stronger correlation with the canopy volume distribution, especially in region B. Based on Table 5, the proportions of canopy volume, constant-spraying coverage, and variable-spraying coverage in regions A, B, and C were plotted for comparison, as shown in Figure 12.

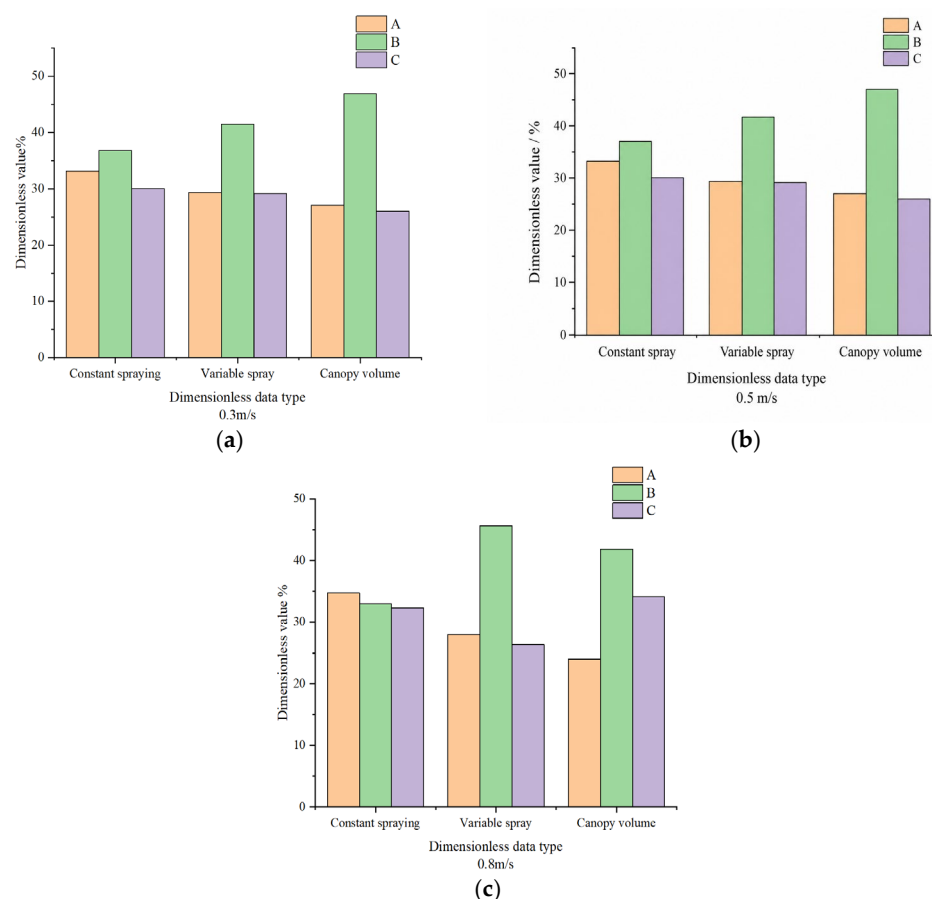


Figure 12. Comparison of the dimensionless distributions of canopy volume and front-side leaf coverage under the same operating conditions. (a) is in regions A; (b) is in region B; (c) is in region C.

3.3.2. Field Variable Spraying Deposition Results

In the field continuous-canopy test, each sampling region was used as the basic analysis unit. The mean coverage, standard deviation, and CV of the water-sensitive papers in each region were calculated at different speeds, as shown in Table 6. Mean coverage was used to characterize the spray deposition level, and the CV was used to reflect the dispersion of repeated sampling results within the same region.

Table 6. Statistical results of droplet coverage in each sampling region at different forward speeds.

Speed (m/s)	Sampling Region	Mean Droplet Coverage (%)	Standard Deviation (%)	CV (%)
0.3	A1	37.1	1.43	3.9
	A2	30.9	3.54	11.5
	A3	42.8	1.97	4.6
	B1	50.2	3.97	7.9
	B2	55.5	4.91	8.9
	B3	61.8	2.02	3.3
0.8	A1	25.9	1.66	6.4
	A2	22.4	1.99	8.9
	A3	29.0	2.92	10.1
	B1	34.6	1.77	5.1
	B2	41.0	3.54	8.6
	B3	46.5	4.82	10.4

Based on Table 6, the mean coverage and standard deviation of each sampling region at different forward speeds were plotted, as shown in Figure 13. The A1, A2, and A3 represent sampling regions in the sparse canopy area, while B1, B2, and B3 represent sampling regions in the dense canopy area.

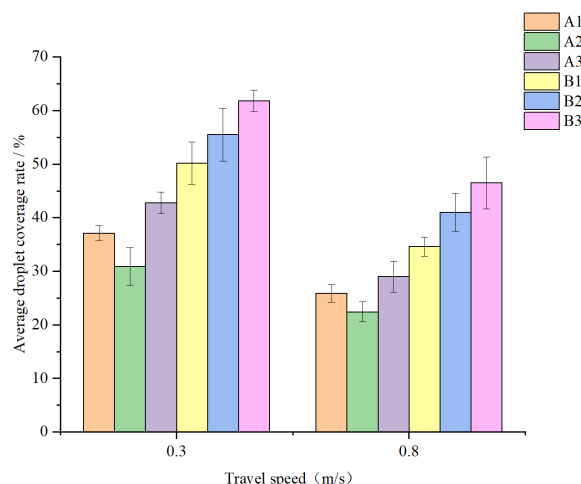


Figure 13. Mean coverage and standard deviation of each sampling region at different forward speeds.

Combined with field observations of canopy morphology, the branch and leaf distribution in the A-type regions was relatively sparse, whereas that in the B-type regions was denser. As shown in Table 6 and Figure 13, at both 0.3 and 0.8 m/s, the coverage in the B-type regions was generally higher than that in the A-type regions, indicating that the system could produce deposition responses corresponding to canopy density differences under field continuous-canopy conditions. As the speed increased from 0.3 to 0.8 m/s, the coverage in all regions generally decreased, indicating that higher forward speed weakened droplet deposition. However, the B-type regions still maintained relatively high coverage, suggesting that the variable spraying regulation trend persisted at the higher speed.

In terms of the coefficient of variation, the CV values of each sampling region were generally low, indicating that the deposition results within the same region had relatively stable deposition. Under field conditions, droplet deposition is also affected by canopy shielding, natural wind disturbance, and driving stability. Therefore, these results mainly indicate that the system can generate deposition responses corresponding to canopy density differences, rather than a strict linear relationship between coverage and canopy volume.

4. Conclusions

A LiDAR-based variable spraying system for fruit tree canopies was developed for variable spraying operations in trellis orchards. Nozzle flow calibration, dynamic targeting, and spray deposition performance tests were conducted. The main conclusions are as follows:

- (1) A variable spraying system based on a Livox MID-360 LiDAR, ROS onboard computer, PLC, PWM output module, solenoid valve group, and air-assisted spraying unit was constructed. The system integrated canopy information acquisition, spraying control value calculation, and multi-nozzle partitioned execution. Partitioned grid units were constructed through left-right division, travel-direction grids, and sector partitioning. The voxel occupancy method was used to calculate the canopy volume in each spraying region, providing spatially corresponding volume inputs for variable spraying decision-making.

- (2) A variable spraying decision-making and execution control method based on canopy volume was established. According to partitioned canopy volume, required application amount per unit canopy volume, forward speed, and the nozzle flow calibration model, canopy volume was converted into target flow rate and PWM control value. The nozzle flow calibration results showed a good fitting relationship between PWM duty cycle and nozzle flow rate under different supply pressures, with coefficients of determination greater than 0.98, indicating that PWM control can be used for spray flow regulation.
- (3) The dynamic targeting test results showed that the FIFO queue-based delay compensation method improved the temporal matching between the LiDAR detection position and the nozzle spraying position. At forward speeds of 0.3, 0.5, and 0.8 m/s, the average targeting delay distances were 112.5, 118.6, and 126.4 mm, respectively, and the overall delay offset remained within 0.11–0.13 m.
- (4) The spray deposition test results showed that the system could generate corresponding spray deposition responses according to canopy volume or density differences. In the artificial canopy test, the dimensionless distribution of variable spraying coverage showed a certain consistency with the canopy volume distribution. In the field continuous-canopy test, the coverage in dense regions was generally higher than that in sparse regions, indicating that the developed system has a certain canopy-adaptive spraying capability and engineering application potential.

From the perspective of precision agriculture development, the proposed system represents an engineering approach toward intelligent orchard spraying by integrating three-dimensional canopy sensing and real-time application control. Compared with conventional uniform spraying strategies, the system utilizes LiDAR-derived canopy information to achieve spatially adaptive spray regulation. Although the current framework mainly focuses on structural adaptation based on canopy characteristics, it provides a foundation for future integration of additional biological indicators, such as pest pressure, disease severity, or deposition feedback, to further develop closed-loop precision spraying systems.

Overall, the LiDAR-based variable spraying system for fruit tree canopies developed in this study can realize real-time canopy information sensing, variable spraying control value calculation, and dynamic spraying execution. It can provide a technical reference for the development of precision application equipment for trellis orchards. Future work should further optimize the canopy volume estimation model, delay compensation parameters, and spraying control strategy, and conduct long-term field validation under more operating conditions.

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