Comparison of Orchard Target-Oriented Spraying Systems Using Photoelectric or Ultrasonic Sensors

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Abstract: Orchard pesticide off-target deposition and drift cause substantial soil and water pollution, and other environmental pollution. Orchard target-oriented spraying technologies have been used to reduce the deposition and drift caused by off-target spraying and control environmental pollution to within an acceptable range. Two target-oriented spraying systems based on photoelectric sensors or ultrasonic sensors were developed. Three spraying treatments of young cherry trees and adult apple trees were conducted using a commercial sprayer with a photoelectric-based target-oriented spraying system, an ultrasonic-based target-oriented spraying system or no target-oriented spraying system. A rhodamine tracer was used instead of pesticide. Filter papers were fixed in the trees and on the ground. The tracer on the filter papers was washed off to calculate the deposition distribution in the trees and on the ground. The deposition data were used to evaluate the systems and pesticide off-target deposition achieved with orchard target-oriented sprayers. The results showed that the two target-oriented spraying systems greatly reduced the ground deposition compared to that caused by off-target spraying. Compared with that from off-target spraying, the ground deposition from photoelectric-based (trunk-based) and ultrasonic-based (canopy-based) target-oriented spraying decreased by 50.63% and 38.74%, respectively, for the young fruit trees and by 21.66% and 29.87%, respectively, for the adult fruit trees. The trunk-based target-oriented detection method can be considered more suitable for young trees, whereas the canopy-based target-oriented detection method can be considered more suitable for adult trees. The maximum ground deposition occurred 1.5 m from the tree trunk at the back of the tree canopy and was caused by the high airflow at the air outlet of the sprayer. A suitable air speed and air volume at the air outlet of the sprayer can reduce pesticide deposition on the ground.

Keywords: orchard spraying; target-oriented sprayer; photoelectric sensor; ultrasonic sensors; off-target deposition

1. Introduction

Pests in orchards are mainly controlled through the use of chemical pesticides, which decrease fruit loss by 66% to 90% [1–4]. Orchard air-assisted spraying technology is recommended as highly effective by the Food and Agriculture Organization (FAO) of the United Nations, and this method has been widely used for orchard pest control. Traditional orchard air-assisted spraying methods involve spraying a pesticide solution in a continuous and uniform manner. This not only requires a large amount of pesticide, but also causes environmental pollution due to the drift of excess spray into the air and onto the ground [5–8]. To address this problem, orchard air-assisted target-oriented spraying systems with various sensors have been developed, thus enabling variable-rate spraying based on information such as tree location, canopy profile and leaf density, and significantly reducing the amount of pesticides used [9–11].
Currently, orchard air-assisted target-oriented spraying systems mainly use photoelectric, ultrasonic and light detection and ranging (LiDAR) sensors. Among them, photoelectric sensors are the easiest to use in terms of applying target-oriented pesticide spraying in orchards. They allow control of the nozzle opening by detecting the position of the tree trunk or tree canopy to achieve target-oriented spraying [12–15]. Based on the photoelectric target-oriented detection technique, He et al. [16] developed a precise target-oriented spraying control system for orchards. This system has photoelectric sensors mounted at levels matching the upper, middle and lower portions of canopies to detect trees at different heights, and this system can decrease pesticide use by 50%–75%. Zhai et al. [17] located the canopy by detecting the tree trunk and used this information to design a photoelectric-based target-oriented controller for young trees. Zou et al. [18] used photoelectric sensors to detect fruit canopy positions in real time, and target-oriented spraying was realised by controlling the opening time of the nozzle according to the position of the fruit tree canopy. Because target-oriented spraying with a photoelectric sensor can only selectively spray based on the presence or absence of a tree and cannot perform variable-rate spraying based on information such as canopy profile and denseness, a target-oriented spraying system equipped with an ultrasonic sensor has been developed [11,19–21]. Maghsoudi et al. [22] acquired the volume of fruit tree canopies in real time through ultrasonic sensors and achieved variable-rate spraying according to the change in canopy volume, cutting pesticide use by 34.5% on average to achieve spraying effectiveness similar to that of conventional spraying methods. Gail et al. [23] developed an orchard sprayer equipped with ultrasonic sensors capable of variable-rate spraying according to changes in the volume of fruit tree canopies, and this sprayer reduced pesticide usage by 21.9%. Petrović et al. [24] examined the effects of a conventional spraying system and a target-oriented spraying system equipped with ultrasonic sensors on spray deposition and drift on a pear tree canopy. They found that in comparison to the conventional spraying system, the target-oriented system reduced ground drift by 48.74% and air drift by 59.16%. Compared with photoelectric and ultrasonic sensors, LiDAR sensors can obtain more information about the characteristics of fruit trees, but LiDAR point cloud data processing requires high controller performance. Osterman et al. [25] designed a target-oriented spraying system equipped with a LiDAR sensor that enables real-time sensing of the canopy shape at different tree heights and achieves form spraying by controlling the angles and positions of the upper, middle and lower spraying nozzle arms. Li et al. [26] designed a target-oriented spraying system equipped with a LiDAR sensor capable of variable-rate spraying according to the change in the volume of fruit tree canopies. Compared to traditional air-assisted sprayers and directional air-assisted sprayers, this sprayer decreased droplet drift by 23.2% and 42.7%, respectively, and ground loss by 67.4% and 58.8%, respectively. Zhu et al. [27] developed a laser-guided variable-rate sprayer for managing insects in ornamental nurseries, and field tests in the three studied nurseries with three different insect pests showed that the sprayer reduced spray volume rates by 25% to 80%.

Currently, compared with LiDAR sensors, photoelectric and ultrasonic sensors are low in cost and more mature in their application in orchard target-oriented spraying systems. However, different types of sensors detect the characteristics of fruit tree canopies in different ways, which affects spray deposition and drift on the canopy and ground. The objectives of the research were to evaluate a developed photoelectric-based target-oriented spraying system and a developed ultrasonic-based target-oriented spraying system and to compare pesticide off-target deposition and drift from traditional spraying with those from the two target-oriented spraying systems. Meanwhile, the target-oriented detection accuracy of the sensor-based detection methods for different target detection positions is affected by fruit tree types and canopy structure. The photoelectric-based target-oriented spraying system enables target-oriented spraying by locating the canopy position through the detection of tree trunks. Further, the ultrasonic-based target-oriented spraying system enables target-oriented spraying by directly detecting the canopy position. Young cherry trees and adult apple trees were selected to verify the influence of the target detection posi-
tion (trunk-based detection and canopy-based detection) on the target-oriented detection effect for different fruit tree types and canopy structures.

2. Materials and Methods

2.1. Orchard Target-Oriented Sprayer

The experiment was conducted in the Gaoliying orchard in Shunyi District, Beijing (116°29′54.0″N, 40°10′53.4″E), with a traction orchard air-assisted sprayer (Model SCL600, Favaro, Italy). The sprayer contains two symmetrical spraying units with six nozzles (Model ATR 80, ALBUZ, Evreuz, France) each and spraying angles that are adjustable according to canopy height. The sprayer achieves 2.0 L/min flow at a pressure of 11 bar, and the spraying angle of the nozzle is 80°. The membrane pump has a capacity of 75 L/min to a maximum working width of 8 m and a maximum working height of 12 m. The maximum air flow rate at the air outlet of the sprayer is 62,500 m³/h. In the study, the target-oriented spraying controller was equipped with photoelectric sensors or ultrasonic sensors (Figure 1).

![Figure 1. Orchard target-oriented sprayer: 1. photoelectric sensor; 2. photoelectric-based target-oriented controller; 3. tractor; 4. ultrasonic sensor; 5. ultrasonic-based target-oriented controller; 6. tank; and 7. spray unit.](image)

The operation principle of the target-oriented spraying system is shown in Figure 2. The photoelectric-based target-oriented spraying system can adjust the spray width and spray delay distance through the knob according to the fruit tree planting information. The ultrasonic-based target-oriented spraying system can independently control the work of the single-channel ultrasonic sensor. It can separately control the nozzles on the left and right sides to enable target-oriented spraying according to the spraying needs. At the same time, the operating parameters can be input through the industrial personal computer (IPC) interface for easy operation.
Figure 2. Operation principle of the target-oriented spraying system: 1. master power switch; 2. single-channel control switch of left ultrasonic sensor; 3. master control switch of left ultrasonic sensor; 4. single-channel control switch of right ultrasonic sensor; 5. master control switch of right ultrasonic sensor; 6. spray width adjustment knob; 7. spray delay distance adjustment knob; and 8. master power switch.

2.2. Photoelectric-Based Target-Oriented Spraying System

The target-oriented spraying system was equipped with photoelectric sensors (E3K100-DS100M1, Xinshe Electrical Technology Co., Ltd., Yueqing, Wenzhou, Zhejiang, China), and enabling target-oriented spraying by locating the canopy position through the detection of tree trunks. The photoelectric sensor has a detection range of 0–6 m and a 4–20 mA signal output. The spray width \(L_w\) and delay \(L_d\) of the target-oriented controller are adjustable \((L_w: 0–3 \text{ m}; L_d: 2–6 \text{ m})\). A flow chart of orchard tree target single-side detection is shown in Figure 3. The sprayer calculates the spraying speed by installing a speed-measuring disc on the walking wheel. Every time the sprayer travels a certain distance, the speed sensor generates a pulse signal. The instantaneous speed of the sprayer is calculated by calculating the length of a single pulse. When the target is detected, the controller starts the timer function to calculate the length of time \(\Delta t_1\) and the instantaneous speed \(v_1\) between detecting the target and receiving the first velocity pulse signal. The required numbers of pulses, \(n_1\) and \(n_2\), of the opening and closing of the spray solenoid valve are calculated in real time and stored in arrays \(N_1[i]\) and \(N_2[i]\), respectively. When a speed pulse is received, the sprayer has moved forward by a distance of \(\Delta l\). One is subtracted from each of the values in arrays \(N_1[i]\) and \(N_2[i]\). The data in \(N_1[i]\) and \(N_2[i]\) are then judged cyclically. A negative value indicates that no target information was recorded there and it is assigned a value of -1. A positive value indicates that the target action position recorded there has not been reached. If \(N_1[i] = 0\), the instantaneous speed \(v_1\) and the solenoid valve opening time \(\Delta t_{13}\) are calculated, and the timer \(\Delta t_{13}\) is started. When the time elapses, the solenoid valve opens. Similarly, if \(N_2[i] = 0\), the solenoid valve closing time \(\Delta t_{23}\) is calculated. When the time elapses, the solenoid valve closes. The detection accuracy of the photoelectric-based target-oriented spraying system is 100% at speeds below 1.2 m/s [17].
2.3. Ultrasonic-Based Target-Oriented Spraying System

The target-oriented spraying system equipped with photoelectric sensors only detects the presence or absence of a target and cannot calculate online the spray volume required for different fruit tree parts in real time. Thus, the spray volume is set based only on experience or set for even application of the pesticide, which leads to uncontrollable pesticide residues. The detection method of the fruit tree canopy volume is established based on the ultrasonic sensor using the integral method, and the calculation model is shown in Formula (1). The measurement accuracy of a regular shape and cherry tree canopy profile probing is 92.8% and 90.0%, respectively [28].

\[
V = \sum_{i=1}^{m} \sum_{j=1}^{n} (D - d_{ij}) \cdot h \cdot \Delta l
\]

where \(D\) is the distance from the ultrasonic wave signal-emitting surface to the centreline of the tree trunk, \(m\); \(\Delta l\) is the sampling interval, \(m\); \(m\) is the number of sampling intervals required to scan the entire tree canopy; \(d_{ij}\) is the distance from the ultrasonic wave signal-emitting surface of position \(j\) in the sampling interval \(i\) to the outer contour of the canopy, \(m\); \(h\) is the distance between the sensor installation positions, \(m\); and \(n\) is the number of sensor installation positions.

An ultrasonic-based target-oriented spraying system was developed based on the above detection method of fruit tree canopy volume. The system was equipped with two ultrasound detection arrays with a total of six ultrasonic sensors (MB7060, MaxBotix Inc., Minnesota, MN, USA), three on each side. Each ultrasonic sensor can independently control the spray and has a height detection range of 0.4–4.3 m and a width detection range of 0.2–7.65 m. The ultrasonic sensor can achieve real-time automatic calibration (voltage, humidity, ambient noise) and has a resolution of 1 cm, a read rate of 10 Hz and a transducer frequency of 42 kHz. The sprayer can detect the contour and volume of tree canopies in real time and accordingly control the spray and flow rates of the nozzles on the left and right sides to achieve precise target-oriented spraying. A flow chart of target-oriented variable spraying is shown in Figure 4. During operation, the ultrasonic sensors installed in front
of the sprayer to scan the canopy of fruit trees on both sides in real time. The controller reads the ultrasonic sensor data and calculates the canopy volume at different positions of the target in real time according to the calculation model of the fruit tree canopy volume. The pre-established spray volume demand model calculates the dose demand at different target locations and the dose demand data are stored in the form of a message queue [29]. Once the nozzle reaches the designated position, the spray volume demand data of the corresponding position are relayed. According to the spray volume demand of the current position, the pulse width modulation (PWM) value required for nozzle control in different positions is calculated. The controller controls the opening time of the solenoid valve to adjust the nozzle flow according to the PWM value to achieve target-oriented variable spraying. Furthermore, to reduce the pressure fluctuations during flow adjustment of the nozzle, proportional integral derivative (PID) control technology is used to adjust the opening of the pressure-regulating valve to achieve a constant system pressure and ensure the desired spraying effect.

![Flow chart of target-oriented variable spraying](image)

2.4. Experimental Design

Young cherry trees and adult apple trees were used as the experimental subjects, as shown in Figure 5. The characteristics of the experimental fruit trees are listed in Table 1. To examine the deposition of the spray solution on the tree canopy and the ground when different spraying systems were used, we used quartz filters (9 cm in diameter, Special Paper Co., Ltd., Hangzhou, China) to sample the spray. The filters were arranged as shown in Figure 6 and in reference to the Chinese standard GB/T 3244-2015 "Crop protection equipment—Field measurement of spray distribution in tree and bush crops" [30]. Along the x-axis, with the trunk as the centre of the x-axis, the filters were arranged at two locations with a 0.5 m interval for the cherry trees and three locations with a 1 m interval for the apple trees. Along the y-axis, three sampling points were set on the plane of the tree row and at planes parallel to the tree-row plane with an interval of L; for the cherry
trees, \( L_1 = L_2 = 0.5 \text{ m} \); and for the apple trees \( L_1 = L_2 = 1.0 \text{ m} \). Along the z-axis, three sampling points, each between two nozzles, were established (\( H_1 = 0.75 \text{ m}, H_2 = 1.15 \text{ m} \) and \( H_3 = 1.55 \text{ m} \)). The filters were placed on the ground as follows: seven points were established parallel to the tree trunk and along the x-axis. Of these points, the third point was at the tree position, where the interval between points 1, 2, 3 and 4 was 0.5 m and between points 4, 5, 6 and 7 it was 1.0 m. Along the y-axis, 10 points at 0.65 m intervals were set for the cherry trees and 11 points at 1.0 m intervals were set for the apple trees. Of these points, point 2 was at the trunk position of the first tree and point 6 was at the trunk position of the second tree. The method for placing the filter paper for canopy and ground sampling points is shown in Figure 7. For the sampling filter paper on the canopy, iron rods were fixed at both ends of the test area and cotton threads were placed (a sampling position had two cotton threads) at different height positions of the iron rods according to the test setting height. The sampling filter papers were fixed on the cotton threads by plastic clips. For the sampling filter paper on the ground, the crabsticks were fixed to the ground according to the test requirements, and the filter paper fixing method was the same as the filter paper fixing method on the canopy.

![Figure 5. Experimental fruit trees: (a) Young cherry trees, (b) Adult apple trees.](image)

**Table 1.** Characteristics of the experimental fruit trees.

| Attributes          | Young Cherry Trees                  | Adult Apple Trees                   |
|---------------------|-------------------------------------|-------------------------------------|
| Variety             | Golden red                          | Red Fuji                            |
| Rootstock           | Big green leaf                      | Flowering crabapple                 |
| Planting system     | Artificial planting                 | Artificial planting                 |
| Size of the trees   | Row spacing of 4.5 m                | Row spacing of 4.5 m                |
|                     | Plant spacing of 2.7 m              | Plant spacing of 5.0 m              |
|                     | Height of 2.7 m (average)           | Height of 3.4 m (average)           |
|                     | Canopy width of 1.2 m (average)     | Canopy width of 2.8 m (average)     |

The field site after setting the sampling points is shown in Figure 8, the key experiment parameters are listed in Table 2, the \( L_w \) values of the photoelectric-based target-oriented spraying controller were set to 1.2 m and 3.2 m for the cherry trees and apple trees, respectively. The sprayer was driven along a white centre line (Figure 8) to conduct conventional off-target spraying and target-oriented spraying with photoelectric sensors or ultrasonic sensors. At the end of each spraying operation, the filters at the sampling points were collected and placed in labelled plastic bags. Each test was repeated three times.
Figure 6. Sampling point layout: X: spraying direction, Y: running direction of sprayer, Z: canopy height direction.

Figure 7. Sampling filter paper fixed: (a) canopy sampling points, (b) ground sampling points.

Figure 8. Spray experiment scheme.
Based on the layout shown in Figure 5, three different sizes of rectangles were outlined on the ground, with the filter paper in the centre of each rectangle. For the apple trees, the areas of rectangles A, B and C were 0.50 m$^2$, 0.75 m$^2$ and 1.0 m$^2$, respectively, and for the cherry trees, the areas were 0.325 m$^2$, 0.4875 m$^2$ and 0.65 m$^2$, respectively.

The ground deposition amount from the commercial sprayer without any target-oriented spraying system was low for the cherry trees, while that of the sprayer with the photoelectric-based target-oriented spraying system was low for the apple trees, and by 21.66% or 29.87%, respectively, for the adult trees. The existing relevant research has shown that the spray volume savings of photoelectric-based target-oriented spraying system or that with the ultrasonic-based target-oriented spraying system were 15% to 75%, and the approximate spray volume savings of the photoelectric-based target-oriented spraying system was decreased by 50.63% or 38.74%, respectively, for the young trees and by 21.66% or 29.87%, respectively, for the adult trees.

### 2.5. Data Processing

During the experiment, the pesticide stock solution was prepared as follows: 100 L of water was added to the tank of the sprayer and then 490 mL of rhodamine solution was added. They were thoroughly mixed and 5 mL of stock solution was moved and diluted 200 times. The tracer concentration of the stock solutions was measured according to the absorbance value of the tracer analyser (Evolution 350, Thermo Scientific, Waltham, MA, USA). The average concentration of the stock solutions was 218.48 mg/L. After the experiment was completed, the rhodamine contents of the filter papers collected from the sampling points in the canopy and on the ground were analysed. The deposition amount from the spray at each sampling point was calculated based on the tracer content on the filter paper using Formula (2). The average of three test results was used as the final deposition amount at each sampling point.

\[
Deposition = \frac{1000 \times C_{\text{paper}} \times V}{C_{\text{tank}} \times S_{\text{paper}}} \tag{2}
\]

where \(Deposition\) is the deposition amount of pesticide, mL/m$^2$; \(C_{\text{paper}}\) is the tracer concentration of the solution prepared from the filter paper, mg/L; \(V\) is the volume of the solution prepared from the filter paper after adding 20 mL of water, L; \(C_{\text{tank}}\) is the concentration of the stock solution, mg/L; and \(S_{\text{paper}}\) is the area of a single filter paper, m$^2$.

Each filter paper at every sampling point covered a circular area with a diameter of 9 cm. To calculate the spray deposition amount on the ground, a rectangular area surrounding each filter paper was outlined on the ground, as shown in Figure 9. The amount of spray deposition in the rectangular area was the product of the amount of pesticide deposition on each filter paper and the area of the rectangle. The total amount of spray deposition in all the rectangles was considered the ground spray deposition amount. Based on the layout shown in Figure 5, three different sizes of rectangles were outlined on the ground, with the filter paper in the centre of each rectangle. For the apple trees, the areas of rectangles A, B and C were 0.50 m$^2$, 0.75 m$^2$ and 1.0 m$^2$, respectively, and for the cherry trees, the areas were 0.325 m$^2$, 0.4875 m$^2$ and 0.65 m$^2$, respectively.

**Table 2. The key parameters of the experiment.**

| Parameters                  | Values | Parameters                  | Values         |
|-----------------------------|--------|-----------------------------|----------------|
| Nozzle angle                | 80°    | Spray unit angle            | 0°             |
| Spraying pressure           | 1.1 MPa| Wind speed                  | 0.76 m/s (average) |
| Fan speed                   | 960 r/min | Air temperature           | 32.42 °C (average) |
| Travel speed                | 1.0 m/s| Relative humidity           | 34.36% (average) |
|                             | 2.25   |                             |                |
|                             | 2.09   |                             |                |
| Left nozzle flow rate       | 2.01   | Right nozzle flow rate      | 1.96           |
| (From bottom to top)        |        | (From bottom to top)        | 2.01           |
|                             | 1.99   |                             | 2.00           |

Figure 9. Schematic diagram of the ground deposition calculation.
3. Results
3.1. Ground Deposition

We calculated the amount of spray deposition at each sampling point based on the tracer content on the filter paper at the point. Based on this information, a spray deposition distribution histogram of the sampling points was generated using MATLAB software. As shown in Figure 10, for the adult apple trees and young cherry trees, the spray deposition distribution pattern on the ground differed significantly among the three spraying methods. The ground deposition amount from the commercial sprayer without any target-oriented spraying system was significantly higher than that from the sprayer with the photoelectric-based target-oriented spraying system and the sprayer with the ultrasonic-based target-oriented spraying system. In addition, the ground deposition amount of the commercial sprayer with the ultrasonic-based target-oriented spraying system was low for the apple trees, while that of the sprayer with the photoelectric-based target-oriented spraying system was low for the cherry trees. The ground deposition of the commercial sprayer without any target-oriented spraying system for the adult apple trees at the 6th and 7th sampling points in the spray direction 1.5 m from the trunk of the fruit tree was larger than that at other locations (red circled area in Figure 10). Meanwhile, when using the sprayer with the ultrasonic-based target-oriented spraying system on the young trees, the deposition on the ground close to the nozzle was abnormal, with greater ground deposition at this position than at other positions (red circled area in Figure 10).

![Figure 10. Ground deposition distributions for adult trees and young trees: X: location of sampling point in spray direction, Y: location of sampling point in running direction of sprayer.](image-url)

The ground deposition amounts from the different spraying methods applied to the apple trees and cherry trees were calculated based on the data from the ground sampling points. The spray volume savings under different spraying systems, are shown in Table 3. Compared with that of the commercial sprayer without any target-oriented spraying system, the ground deposition amount from the commercial sprayer with the photoelectric-based target-oriented spraying system or that with the ultrasonic-based target-oriented
spraying system was decreased by 50.63% or 38.74%, respectively, for the young trees and by 21.66% or 29.87%, respectively, for the adult trees. The existing relevant research has shown that the spray volume savings of photoelectric-based target-oriented spraying system are 15% to 75%, and the approximate spray volume savings of the ultrasonic-based target-oriented spraying system are 15% to 60% [16,22–24,31]. Compared with existing systems, the two developed target-oriented spraying systems in this paper could well realize spray volume savings.

Table 3. Spray volume savings under different spraying systems.

| Fruit Tree Types   | Spraying System                  | Total Ground Deposition in the Sampling Area (mL) | Spray Volume Savings (%) |
|--------------------|----------------------------------|--------------------------------------------------|--------------------------|
| Young cherry trees | Photoelectric-based target-oriented | 160.33                                           | 50.63                    |
|                    | No target-oriented                | 324.73                                           | Compare object           |
|                    | Ultrasonic-based target-oriented | 198.92                                           | 38.74                    |
|                    | Photoelectric-based target-oriented | 319.06                                           | 21.66                    |
|                    | No target-oriented                | 407.25                                           | Compare object           |
|                    | Ultrasonic-based target-oriented | 285.59                                           | 29.87                    |

To further compare the ground deposition amounts on the tree canopy and in the gap positions among the three spraying systems, we obtained the ground deposition distribution patterns for the fruit trees at different positions by calculating the ground deposition amounts at different sampling points. As shown in Figures 11 and 12, the conventional off-target spraying system had a higher ground deposition amount than the other two spraying methods at the tree gap position and tree position. For the adult apple trees, the ground deposition was higher at the tree gap position than at the tree position, and among the systems, the commercial sprayer with the ultrasonic-based target-oriented spraying system had the lowest ground deposition at the tree position. For the young cherry trees, the commercial sprayer with the photoelectric-based target-oriented spraying system had the lowest ground deposition at both the tree gap position and the tree position.

Figure 11. Distributions of ground deposition at the gap and tree positions of the adult apple trees.
cherry trees, the commercial sprayer with the photoelectric-based target-oriented spraying system had the lowest ground deposition at both the tree gap position and the tree position.

Figure 11. Distributions of ground deposition at the gap and tree positions of the adult apple trees.

Figure 12. Distributions of ground deposition at the gap and tree positions of the young cherry trees.

The spray deposition amounts at different locations on the ground along the spray pathway were calculated (Figure 13). The results showed that along the spray pathway, with increasing distance from the position of the sprayer nozzle, ground deposition showed a trend of first increasing and then decreasing, peaking at 1.5 m from the tree trunk. The ground deposition resulting from the traditional off-target spraying system was higher than that of the target-oriented spraying systems equipped with a photoelectric sensor controller or ultrasonic sensor controller at 1.5 m from the tree trunk.

Figure 13. Deposition variation at different positions on the ground: the negative values of the abscissa represent the sampling point locations in front of the trunk in the spray direction, and the positive values represent the sampling point locations at back of the trunk in the spray direction.

3.2. Fruit Tree Canopy Deposition

Similarly, the deposition distributions on the tree canopy were obtained (Figures 14 and 15). The results showed that the pesticide deposition distribution patterns at various canopy positions were similar among the three spraying methods for both the young cherry trees
and adult apple trees. Pesticide deposition on the front side of the trees was greater than that on the back of the trees. The three spraying methods did not significantly differ in pesticide deposition at various canopy positions for the adult apple trees. However, compared with that from the commercial sprayer without any target-oriented spraying system, the fruit tree canopy deposition from the sprayers with the photoelectric-based and ultrasonic-based target-oriented spraying system was reduced, with the largest reduction observed for the sprayer with the ultrasonic-based target-oriented spraying system.

Figure 14. Canopy deposition distribution among the young cherry trees.

Figure 15. Canopy deposition distribution among the adult apple trees.

4. Discussion

4.1. Ground Deposition

There was an abnormality in the ground deposition from the commercial sprayer with the ultrasonic-based target-oriented spraying system for the young cherry trees, as indicated by the red area in Figure 10. The area of abnormal ground deposition was close
to the nozzle position. This abnormal deposition occurred because the nozzle at the bottom of the sprayer dripped during spraying and the droplets landed on the filter papers close to the dripping nozzle. The ground deposition of the red circled area in Figure 10 was abnormal because two sampling points were located in the gap between the two fruit trees (fruit tree gap in Figure 16). The amount of pesticide deposition on the fruit tree canopy was reduced and the ground deposition was increased. Meanwhile, the ground deposition in fruit tree gap 1 was smaller than that in fruit tree gap 2 because the gap distance in fruit tree gap 1 was greater than that in fruit tree gap 2, and there were branches and leaves between the fruit tree canopies on both sides in the fruit tree gap 2. The air speed at the air outlet of the sprayer was affected by the branches and leaves. The drift distance of pesticides in the air would decrease, which in turn would increase the amount of pesticide deposition on the ground behind the canopy of fruit trees.

Figure 16. Sampling point location of abnormal data.

For the two target-oriented spraying methods, the ground deposition amount was significantly lower than that from the commercial sprayer without any target-oriented spraying system. The photoelectric-based target-oriented spraying system performed the best on the young cherry trees, while the ultrasonic-based target-oriented spraying system performed best on the adult apple trees with large and dense canopies. In addition, the ground deposition at the tree gap position was lower than that at the tree position, indicating that the two target-oriented spraying systems successfully targeted their spraying according to the presence or absence of trees. At the tree gap position, compared with that of the young cherry trees, the ground deposition of the adult apple trees was increased under target-oriented spraying. This increased deposition was observed because the large canopy size of the adult apple trees leads to small tree gaps such that the spray at the edge of the canopy can easily drift into the gap between the trees. Target-oriented spraying is suitable for orchards with obvious fruit tree gaps; the larger the fruit tree gaps are, the more obvious the reduction in ground deposition.

The largest amount of ground deposition was located 1.5 m behind the trunk. The canopy widths of the young cherry trees and adult apple trees were 1.2 m and 2.8 m, respectively, and 1.5 m from the tree trunk corresponded to the back of the canopy. The results suggest that during spraying, the airflow at the air outlet of the sprayer is strong, resulting in the drift of a large amount of pesticide to the rear of the canopy. This pesticide is thus wasted. The high airflow at the air outlet of the sprayer affects the deposition of pesticide on the ground. Therefore, it is necessary to control the sprayer to provide a suitable air speed and air volume to reduce pesticide deposition on the ground.

4.2. Fruit Tree Canopy Deposition

The canopy deposition distribution for the young cherry trees and adult apple trees indicated that fruit tree type affected the outcome of target-oriented spraying. The three spraying methods yielded different deposition distributions on the young cherry tree canopy. This result was likely due to the large gaps between the young trees and the continuous spraying of the traditional off-target spraying system, whereby at the tree gap
position, some of the spray drifted into the canopy, thus increasing canopy deposition. However, the target-oriented spraying system equipped with photoelectric sensors enabled target-oriented spraying by locating the canopy position through the detection of tree trunks. The canopy symmetry between the two sides of the trunk was lower for the young cherry trees than for the adult apple trees, which affected the deposition distribution on the tree canopy. The target-oriented spraying system equipped with ultrasonic sensors detected the profile of the young cherry tree canopy through the ultrasonic sensor array and implemented target-oriented, variable-rate spraying according to the volume of the tree canopy. The sparse canopy of the young cherry trees affected the signal reflection intensity and detection accuracy of the ultrasonic sensor. In comparison to the target-oriented spraying system equipped with photoelectric sensors (trunk-based target-oriented detection), that of the system equipped with ultrasonic sensors (canopy-based target-oriented detection) led to spray skips in sparse canopies, causing increased deposition on the canopy. However, because of the dense canopies and small inter-tree gaps of the adult trees, this scenario did not occur in the adult trees.

For the young cherry trees, there were small differences in canopy deposition between the target-oriented spraying system equipped with photoelectric sensors and the commercial sprayer without any target-oriented spraying system; however, ground deposition was significantly reduced with the former. Meanwhile, the ground deposition amount of the commercial sprayer with the photoelectric-based target-oriented spraying system was lower than that with the ultrasonic-based target-oriented spraying system. This showed that the young trees were suitable for detecting the trunk to achieve target-oriented spraying for the maximum spray volume savings. For the adult apple trees, the three spraying methods did not significantly differ in canopy deposition, but for ground deposition, the amount yielded by the commercial sprayer with the ultrasonic-based target-oriented spraying system was minimal. This showed that the adult trees were suitable for detecting the canopy to achieve target-oriented spraying for the maximum spray volume savings. Therefore, the trunk-based target-oriented detection method can be considered more suitable for young trees, whereas the canopy-based target-oriented detection method can be considered more suitable for adult trees.

5. Future Directions

The fruit tree type influences the performance of target-oriented spraying systems using photoelectric sensors and ultrasonic sensors. However, feature information, such as canopy volume, profile and leaf area density, differs among growth stages. Future research on target-oriented spraying will focus on the development of a system suitable for the full growth cycle of fruit trees.

Warneke et al. (2021) summarised the advantages, disadvantages and approximate costs of precision sprayers with a photoelectric-based target-oriented spraying system, an ultrasonic-based target-oriented spraying system or a LiDAR-based target-oriented spraying system (Table 4). Compared with photoelectric and ultrasonic sensors, LiDAR sensors can provide abundant information on the characteristics of fruit trees, and such sensors have become a topic of major interest in current research on target-oriented spraying methods. However, due to price constraints, the system has not yet been widely applied. Commercial sprayer with LiDAR-based sensor controls are currently applicable to orchards with large planting areas. In the future, the control algorithm of target-oriented spraying for photoelectric and ultrasonic sensors will be further optimised. Simultaneously, our research team is developing a LiDAR-based target-oriented spraying system. Three different target-oriented spraying treatments for different types of fruit trees will be conducted.
Table 4. Advantages and disadvantages and approximate costs of precision sprayers.

| Sprayer Types                             | New Unit Cost (USD) | Approximate Spray Volume Savings (%) | Advantages                                                                 | Disadvantages                                                                                     |
|-------------------------------------------|--------------------|-------------------------------------|-----------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------|
| Photoelectric-based target-oriented spraying system | 2500–5000          | ≤40                                 | Low cost                                                                     | Red light intensity and driving speed can affect sensing ability<br>Narrow field of view<br>Unable to resolve plant structure characteristics or modulate spray output |
|                                            |                    |                                     | Little impact of temperature and humidity on sensing accuracy<br>Decreased chemical, water usage and drift |                                                                                                  |
|                                          |                    |                                     | Easy to implement, flexible crop types<br>Can resolve plant structure<br>Decreased chemical, water usage and drift |                                                                                                  |
|                                          |                    |                                     | Automatic modulation of spray to match crop characteristics<br>Fine resolution of crop structure<br>Rapid measurement, rich data acquisition capability<br>Decreased chemical, water usage and drift |                                                                                                  |
| Ultrasonic-based target-oriented spraying system | 15,000             | 15–40                              |                                                                                           | Limited resolution of plant structure<br>Need multiple sensors to detect plant structure<br>High initial purchase cost<br>Limited availability for purchasing and of specialised personnel for repairs<br>Electronics not easily serviceable by the owner |

6. Conclusions

Two target-oriented spraying systems, one based on photoelectric sensors and one based on ultrasonic sensors were developed in this study. Three spraying treatments were applied to young cherry trees and adult apple trees and revealed that the two target-oriented spraying systems can greatly reduce the ground deposition caused by off-target spraying. Compared with that from the commercial sprayer without any target-oriented spraying system, the ground deposition from the sprayers with the photoelectric-based target-oriented spraying system (trunk-based target-oriented detection) and the ultrasonic-based target-oriented spraying system (canopy-based target-oriented detection) was decreased by 50.63% and 38.74%, respectively, for the young fruit trees and by 21.66% and 29.87%, respectively, for the adult fruit trees. The trunk-based target-oriented detection method can be considered more suitable for young trees, whereas the canopy-based target-oriented detection method can be considered more suitable for adult trees.

Along the spray pathway, as the distance from the sprayer nozzle increased, the ground deposition first increased and then decreased, peaking 1.5 m from the tree trunk. The highest deposition occurred at the back of the canopy and was caused by the high airflow at the air outlet of the sprayer. To reduce ground deposition and improve pesticide deposition in fruit tree canopies, it is necessary to control the sprayer to provide a suitable air speed and air volume.

Author Contributions: Conceptualization, H.D., L.C. and C.Z.; methodology, H.D., L.C. and C.Z.; software, H.D. and W.Z.; validation, H.D., C.Z. and X.W.; formal analysis, X.W.; investigation, H.D.; resources, H.D., C.Z. and W.Z.; data curation, H.D.; writing—original draft preparation, H.D. and L.C. and C.Z.; writing—review and editing, H.D. and L.C.; funding acquisition, C.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Special Project of Chongqing Technology Innovation and Application Development, grant number cstc2019jscx-gksbX0089, and Natural Science Foundation of China, grant number NSFC-31971775.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.
Conflicts of Interest: The authors declare no conflict of interest.

References
1. He, X. Research progress and developmental recommendations on precision spraying technology and equipment in China. *Smart Agric*. 2020, 2, 133–146.
2. Wandkar, S.V.; Bhatt, Y.C.; Jain, H.K.; Nalawade, S.M.; Pawar, S.G. Real-time variable rate spraying in orchards and vineyards: A review. *J. Inst. Eng. Ser. A* 2018, 99, 385–390. [CrossRef]
3. Zhai, C.; Zhao, C.; Wang, N.; Long, J.; Zhang, H. Research progress on precision control methods of air-assisted spraying in orchards. *Trans. Chin. Soc. Agric. Eng.* 2018, 34, 1–15.
4. Zhang, Z.; Wang, X.; Lai, Q.; Zhang, Z. Review of variable-rate sprayer applications based on real-time sensor technologies. *Autom. Agric. Secur. Food Supplies Future Gener.* 2018, 4, 53–79.
5. Hassen, N.S.; Sidik, N.A.C.; Sheriff, J.M. Advanced techniques for reducing spray losses in agrochemical application system. *Life Sci. J.* 2014, 11, 56–66.
6. Eugen, M.; Mihai, M.; Mihaela, N.; Gabriel, G. Experimental researches regarding assessment of coverage degree obtained by orchard spraying machine. In Proceedings of the 16th International Scientific Conference: Engineering for Rural Development, Jelgava, Latvia, 24–26 May 2017.
7. Michael, C.; Gil, E.; Gallart, M.; Stavrinides, M.C. Influence of Spray Technology and Application Rate on Leaf Deposit and Ground Losses in Mountain Viticulture. *Agriculture* 2020, 10, 615. [CrossRef]
8. Osterman, A.; Godeša, T.; Hočevar, M.; Širok, B.; Stopar, M. Real-time positioning algorithm for variable-geometry air-assisted orchard spraying. *Trans. Chin. Soc. Agric. Eng.* 2017, 33, 56–63.
9. Giles, D.K.; Delwiche, M.J.; Dodd, R.B. Sprayer control by sensing orchard crop characteristics: Orchard architecture and spray drift reducing application strategies in orchards. *J. Fruit Ornam. Plant Res.* 2011, 19, 175–182.
10. Holownicki, R.; Doruchowski, G.; Świechowski, W.; Godyń, A.; Holownicki, R. Automatically controlled sprayer to implement spray drift reduction. In *Proceedings of the IEEE International Conference on Cyber Technology in Automation, Shenyang, China, 8–12 June 2015*; pp. 697–702.
11. Zhou, L.; Xu, X.; Zhou, L.; Zhang, L.; Ding, S.; Chang, C.; Zhang, X.; Chen, C. Research situation and progress analysis on orchard variable-rate spraying technology. *Trans. Chin. Soc. Agric. Eng.* 2017, 33, 80–92.
12. Zhai, C.; Zhao, C.; Wang, X.; Lai, Q.; Zhang, Z.; Zhang, Z. Review of variable-rate sprayer applications based on real-time sensor technologies. *Autom. Agric. Secur. Food Supplies Future Gener.* 2018, 4, 53–79.
13. Giles, D.K.; Delwiche, M.J.; Dodd, R.B. Sprayer control by sensing orchard crop characteristics: Orchard architecture and spray drift reducing application strategies in orchards. *J. Fruit Ornam. Plant Res.* 2011, 19, 175–182.
14. He, X.; Zeng, A.; Liu, Y.; Song, J. Precision orchard sprayer based on automatically infrared target detecting and electrostatic spraying techniques. *Int. J. Agric. Biol. Eng.* 2011, 4, 35–40.
15. Zhou, L.; Xu, X.; Zhou, L.; Zhang, L.; Ding, S.; Chang, C.; Zhang, X.; Chen, C. Research situation and progress analysis on orchard variable-rate spraying technology. *Trans. Chin. Soc. Agric. Eng.* 2017, 33, 80–92.
16. Zhai, C.; Zhao, C.; Wang, X.; Liu, Y.; Xue, W. Design and experiment of young tree target detector. *Trans. Chin. Soc. Agric. Eng.* 2012, 28, 18–22.
17. Zou, W.; Wang, X.; Deng, W.; Su, S.; Wang, S.; Fan, P. Design and test of automatic toward-target sprayer used in orchard. In *Proceedings of the IEEE International Conference on Cyber Technology in Automation, Shenyang, China, 8–12 June 2015*; pp. 697–702.
27. Zhu, H.; Rosetta, R.; Reding, M.E.; Zondag, R.H.; Ranger, C.M.; Canas, L.; Fulcher, A.; Derksen, R.C.; Erdal Ozkan, H.; Krause, C.R. Validation of a laser-guided variable-rate sprayer for managing insects in ornamental nurseries. *Trans. ASABE* 2017, 60, 337–345.

28. Zhai, C.; Zhao, C.; Wang, X.; Zou, W.; Zhang, R. Probing method of tree spray target profile. *Trans. Chin. Soc. Agric. Eng.* 2010, 26, 173–177.

29. Zou, W.; Wang, X.; Feng, Q.; Fan, P.; Jiang, K. Design of variable spraying control system based on ultrasonic target detection. *J. Chin. Agric. Mech.* 2020, 43, 58–63.

30. Yan, H.R.; Chen, J.B.; Lin, Y.H.; Xue, X.Y.; Qiu, B.J. Crop protection equipment–Field measurement of spray distribution in tree and bush crops. In *National Agricultural Machinery Standard Technical Committee*; GB/T 3244–2015; Standardization Administration of China: Beijing, China, 2015.

31. Warneke, B.W.; Zhu, H.; Pscheidt, J.W.; Nackley, L.L. Canopy spray application technology in specialty crops: A slowly evolving landscape. *Pest Manag. Sci.* 2021, 77, 2157–2164. [CrossRef]