Effects of fan speed on spray deposition and drift for targeting air-assisted sprayer in pear orchard

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Abstract: In order to reduce the application dosage of pesticides, a targeting air-assisted (TAA) sprayer was developed and tested in this study. Fruit trees were assayed by an infrared detection system to determine if the canopy needs to be sprayed. This TAA sprayer was compared with conventional air-assisted (CAA) sprayers, and the impacts of various fan speeds (0, 800 r/min, 1300 r/min, and 1800 r/min) on spray deposition, coverage, and drift amount were tested. Ponceau 2R was used as tracer to measure spray deposition under each treatment. Droplet coverage and canopy deposition were best when the CAA application fan speed was increased to 1300 r/min, but at higher fan speeds, spray deposition and coverage in canopy did not increase because extra air flow blew droplets from the ground into the air. During TAA spraying, droplet sizes increased at opening and closing moments. Optimal spray effects were achieved when the auxiliary airflow velocity was increased at a fan speed of 1800 r/min. The research provides a useful reference for the design of TAA and parameters optimization method with respect to the relationship between droplets deposition into tree canopy, ground and drift in the air.

Keywords: sprayers, infrared detectors, spray deposition, drift, fruit trees, plant protection
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1 Introduction

Pest prevention and control comprise essential management operations in orchards. Fruit trees typically need to be sprayed 8-15 times each year. Chemical control is a major way of controlling plant diseases, pests, and weeds, but it can also cause problems such as food safety issues, pollution, intensive labor, and financial costs[1-4]. Air-assisted spraying has become an efficient spraying technology that can improve work efficiency while reducing pesticide and water consumption[5,6]. Conventional air-assisted (CAA) methods apply spraying continuously and ignore spray drift in gaps between crops, thus cause a big waste of pesticide. In order to solve these problems, a new type of sprayer that combines automatic targeting and air-assisted spraying (TAA) was designed to substantially reduce pesticide volumes thereby reducing pollution and labor intensiveness[7-9].

The limitations of CAA pesticide sprayers have led to the development of TAA sprayer, which augments air-assisted spraying technologies with electronic detection equipment. Solanelles et al.[10] implemented an ultrasonic sensor to detect the characteristics of targeting fruit tree in order to compute the most appropriate pesticide spraying rates as controlled by a

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solenoid valve. Chen[11] developed a five-fingered, air-assisted, variable sprayer based on laser-sensing technology, and this sprayer finely controlled the spray rate of each nozzle in order to conserve pesticide. Lloren et al.[12] compared conventional spraying and variable spraying methods, finding that average spraying amount can be reduced by up to 58% by implementing variable spraying based on canopy width. Similarly, Hočevar et al.[13] designed a targeting sprayer that applying visual information and a multi-channel solenoid valve in order to variably spray orchards based on their canopy shapes. Zhai et al.[14] designed a detection system to identify fruit tree canopy structure, which could be fed back to users in real time from ultrasonic sensors; this system had a spraying accuracy rate exceeding 87%.

Recently, experts have acknowledged the superiority of air-assisted and targeted spraying technologies. Accordingly targeted spraying technology studies have been carried out in orchards[3,15-17]. Similarly, the technologies of ultrasonic, image capture, and laser detection have frequently been applied to assess fruit tree canopies. Although image sensors can obtain a huge amount information of tree canopy characterization, this method has a limitation in real-time performance for spraying operation[18]. Ultrasonic detection is easily affected by wind and the emitted spray itself, which causes some problems in direction orientation and accuracy[19,20]. Laser sensors are more suitable to detect the size and density of a target[13], but unsuitable for applications in economically developing regions because of its higher cost. Infrared detection technology has a lower cost and provides a remarkable economic benefit in the detection of trees for targeted spraying. As such, this technology has more values in large orchards of economically underdeveloped regions[21].

To better spray orchard canopies, it is necessary to improve the target detection system and overall performance, as well as to further explore the capabilities of air-assisted spray deposition and drift using such a target-detection technology. The fan speed was indicated the main factor to affect the deposition coverage and drift of droplets[22-24]. In order to account for wasted pesticide, both spray drift and ground deposition should be calculated.

In addition, orchard horticultural practices as well as equipment structure and performance parameters are quite different across various regions. The economic and environmental issues related pesticide application, especially in China and other developing countries, necessitates the development of an efficient orchard spraying technology adapted to each specific horticultural environment. Accordingly, this study was conducted to investigate: (1) the optimal parameters for a TAA sprayer in densely planted orchards of southern China and (2) the variation in the relationships among spray deposition in the canopy, spray drift, and ground deposition under TAA spraying and CAA spraying.

2 Materials and methods

2.1 Horticultural parameters and air-assisted system

The cultivation model of fruit trees varies with soil, climate, fruit variety, and available agricultural technology. Accordingly, it is necessary to determine the appropriate parameters for sprayers among different horticultural settings. A dwarfing cultivation model with high-density trees is generally used throughout the orchards of south China. Cultivation density in the study site was 500-830 plants/hm^2 with row spacing of 4-5 m, plant spacing within rows of 3-4 m, tree heights of 2.5-3 m, and a canopy diameter of 1.5-3 m.

Typically, a sprayer fan blows droplets of pesticide from the sprayer to the fruit trees (Figure 1). The air flow produced by the fan slightly exceeds the volume of a trapezoidal prism based on the principle Equation (1) for the constant fan speed and travel speed of sprayers[25,26]:

$$\frac{Q}{2} \geq (H_1 + H_2)\frac{v}{2}LK \tag{1}$$

where, Q is theoretic fan volume (i.e., the theoretic flow rate of air), m^3/s; v is the operating speed of the sprayer, m/s (here, 1.0-1.2 m/s); H_1 is canopy height, m (here, 2.0-2.5 m); H_2 is air outlet height, m (here, 0.8 m); L is sprayer distance from trees, m (here, 1.5 m); K is air attenuation coefficient (here, 1.3).

Using parameters measured from the experimental orchards in Equation (1), the calculated necessary flow rate of air is at least 5.46 m^3/s.

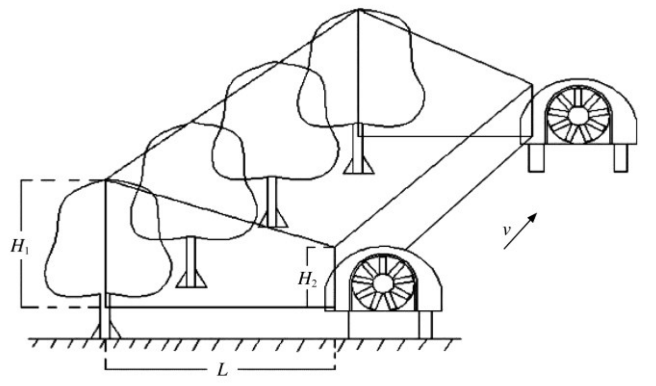


Figure 1 Air displacement system for the orchard sprayer[25]

2.2 Intelligent spray system

The intelligent spray system mainly consists of infrared target detection, spray control, and continuous regulation of fan speed. During sprayer operation, an infrared pulse signal emitted by the infrared LED transmitting tube (wavelength is 850 nm) and reflected off the target, is received by the TSOP1838 infrared receiver, and a PIN photo diode inside the module converts this infrared light into an electrical signal. After pre-amplification, carrier frequency selection, and pulse demodulation, the signal is transmitted to the AD1 of the PLC. The converted data was saved in the internal register of the PLC for processing. When the digital signal received by the PLC from the TSOP1838 infrared receiver is higher than the set threshold, the solenoid valve is opened by the PLC through controlling the relay, causing the sprayer to start spraying. When this digital signal is less than the set threshold, the solenoid valve closes and the spray then stops.

The output shaft of the gearbox is connected to the transfer case. The transfer case transmits power to the universal joint coupling and rear axle in order to supply power to the drive system. The transfer case also transmits power to the hydraulic pump, which uses hydraulic pressure to drive the hydraulic motor of the fan. The fan speed was monitored in real-time using a Yl-D15CI inductance approach switch in order to make the fan speed stable, adjustable, and independent of the output speed of the motor. Fan speed information is transmitted to the microcontroller to adjust the fan speed according to the set value. The oil pressure on the hydraulic pump is adjusted by a stepper motor to stabilize fan speed. A schematic of the intelligent control system is shown in Figure 2.

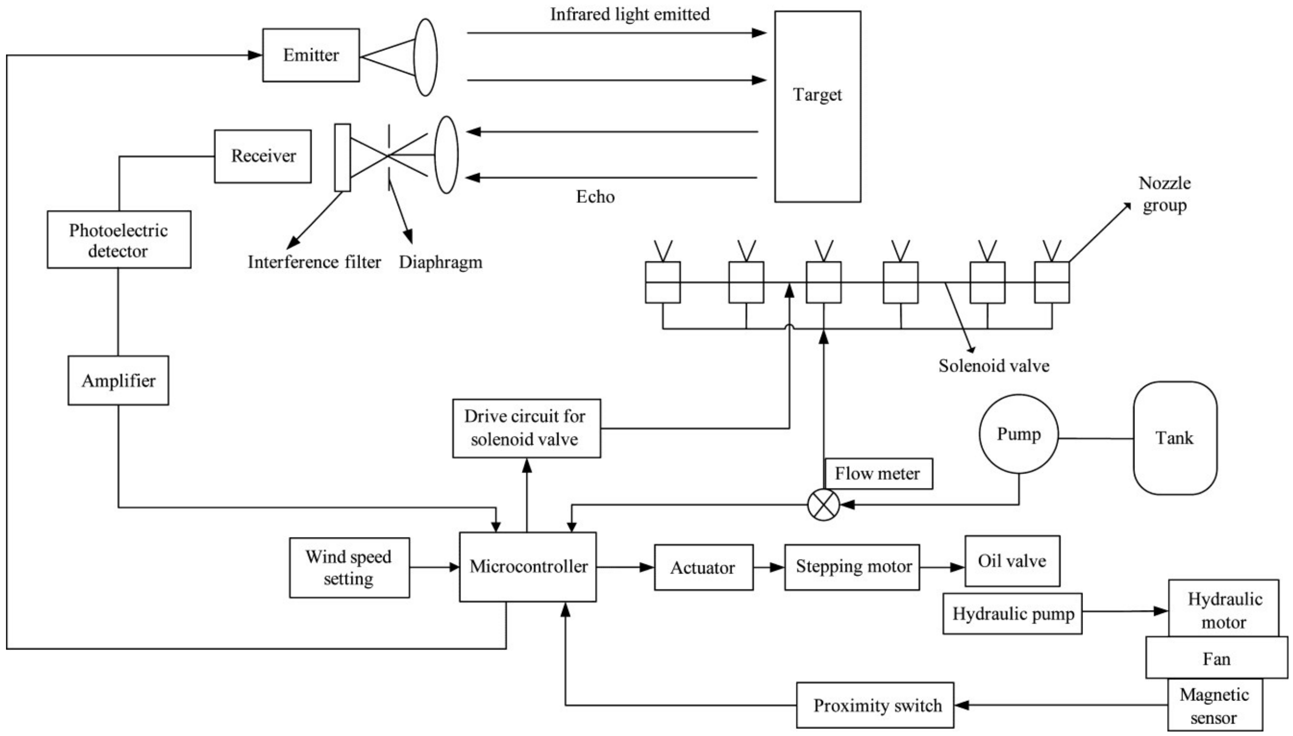
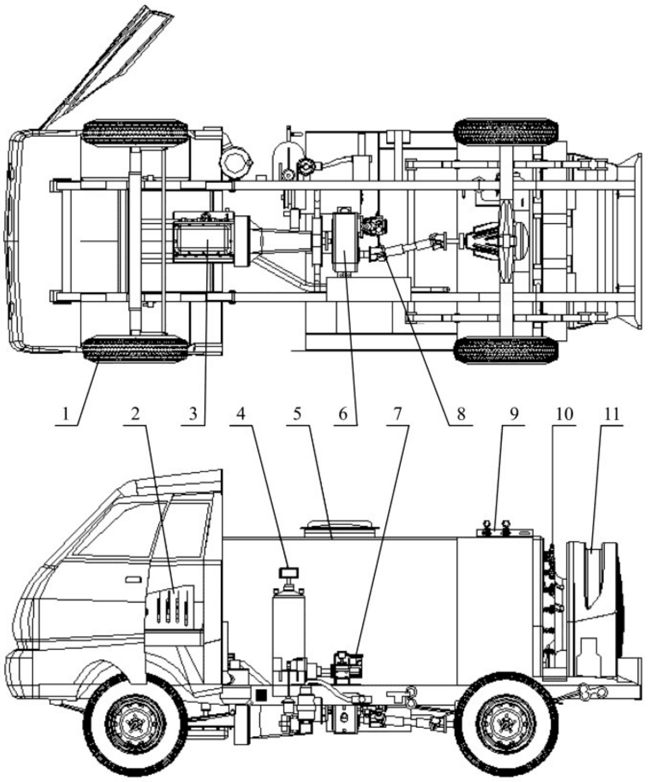


Figure 2 Schematic diagram of the intelligent control system

2.3 Field tests

2.3.1 General experiment information

There are several processes of self-propelled orchard TAA Sprayer's operation, including water injecting, pesticide mixing, and air-assisted spraying (Figure 3). The sprayer is powered by a 28 kW motor with a spray width of 4-5 m, and a spray height of 3-4 m. Six NH-101 nozzles (Taizhou Sunny Agricultural Machinery Co., Ltd., Taizhou, China) are located on each side of the front of the fan. Nozzle diameters are adjustable between 1.2 mm and 1.5 mm. When the fan rotates, the airflow is drawn from behind the fan and blown outward radially in a cone extending outward beyond the front of the fan. Fan speed can be set to any speed between 0-2000 r/min, and the impeller diameter is 700 mm. Infrared transmitters and receivers were installed in front of each nozzle, at 30 cm to each side, in order to detect trees. The operational detection distance is 0.22-2.30 m.



1. Wheel 2. Valves 3. Power system 4. Water tank (for hand washing) 5. Pesticide tank 6. Transfer case 7. Spray pump 8. Hydrostatic power unit for the fan 9. Infrared target detector 10. Nozzle 11. Fan

Figure 3 Orchard sprayer

Experiments were conducted at the Jiangpu Farm Pear Garden, Nanjing Agricultural University in June 2013. The ambient temperature of the experimental site was 22°C-28°C with ambient humidity of 68%-72.3% and average air velocities of 0.8-1.2 m/s. The pear trees cultivar was the ‘Hosui’, and the trees canopy was about 2 m in width and 2.25-3 m in height. The row space was 4 m and tree space was 3 m. Bare soil of 10 m away from the orchard boundary was used as the drift sampling zone. Three individual pear trees were subjected to the test spraying; canopy data for each tree are provided in Table 1.

Table 1 Characteristics of test sprayed fruit trees

Tree No.	Height/m	Max. Width/m	Leaf-area index
1	2.5	1.95	2.24
2	2.38	2.10	2.17
3	3	2.26	1.96
Mean	2.62 ± 0.33	2.1 ± 0.16	2.12 ± 0.15

Note: All values are presented as averages ± standard deviations.

2.3.2 Arrangement of sampling points

2.3.2.1 Sampling within canopies

The number and locations of sampling points were determined based on the shape and density of the canopy. In the vertical direction (i.e., the *z*-axis), the canopy was divided into upper and lower planar sections at 1.5 m and 1.0 m above the ground. Each section was then divided with 0.5 m grids so that the *x*-axis was parallel to the direction of the air-assisted spraying and the *y*-axis was parallel to the motion of the sprayer vehicle. The vertices of each grid were established as the individual sampling points (Figure 4). At each sampling point, two paper cards were clamped by a paper clip onto the tops and the bottoms of leaves in order to determine spray deposition and coverage.

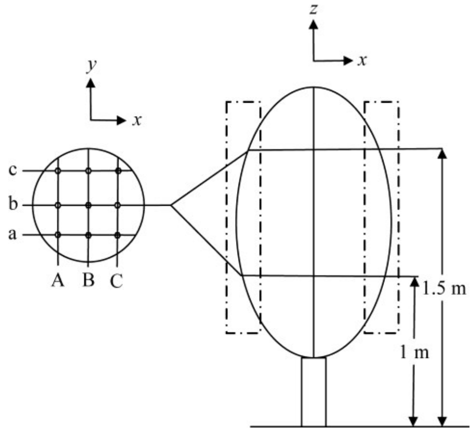


Figure 4 Sampling points in the canopy

2.3.2.2 Sampling to assess drift

In accordance with the international standard ISO 22866[27], five poles of 5 m in length were inserted into the ground at intervals of 2 m, starting at 2 m from the fruit trees on the side of the fruit tree row opposite to the sprayer. Eleven paper cards facing the sprayer and target tree were affixed to the poles at vertical intervals of 0.5 m in order to receive spray drift droplets. Similarly, the ground was sampled for spray drift droplets onto the ground (i.e., ground deposition) using cards arranged on the ground as shown in Figure 5.

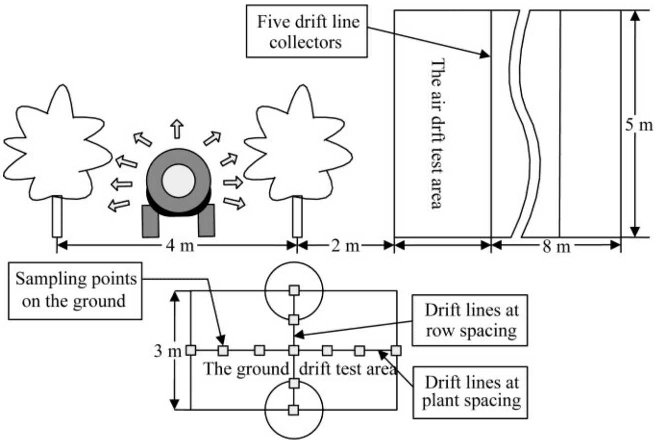


Figure 5 Sampling diagram for one replication

2.3.3 Operational conditions of the orchard sprayer

The orchard air-assisted sprayer moved in the space between rows of pear trees at a speed of 1 m/s, and spray pressure was 1 MP, which produced a single nozzle flow rate of 1.2 L/min. The spray tank was filled with 5‰ (w/v) Ponceau 2R (Shanghai SSS Reagent Co., Ltd., Shanghai, China) in place of pesticide (Figure 6). Based on the structural parameters of the fruit canopy tested, four fan speeds of 0 r/min, 800 r/min, 1300 r/min, and 1800 r/min were used to measure the spray deposition under both CAA and TAA applications across a range of settings. At fan speeds of 0 r/min, 800 r/min, 1300 r/min, and 1800 r/min, the air flow velocities of 0 m/s, 10.6 m/s, 15.8 m/s, and 21.9 m/s, respectively, were produced.

Figure 6 Field operation of the orchard sprayer

2.3.4 Analysis and expression of results

2.3.4.1 Measurement of droplet coverage density and deposition distribution

Paper cards (7.6 cm × 7.6 cm; Shanghai M&G Stationery Inc., Shanghai, China) were labeled and placed on the fronts and backs of leaves at each of the sampling point to receive spray drift. After spraying, dried paper cards were collected and stored in plastic packaging bags. Paper card were scanned with a MRS-3200PU2 scanner (Shanghai Microtek Technology Co., Ltd., Shanghai, China) in the laboratory, and these images were processed by image analysis system to obtain droplet coverage estimates (Figure 7).

Figure 7 Paper card after spraying

Then each paper card was shredded and placed into an individual beaker filled with 25 mL of distilled water, and the paper card was allowed to soak under agitation for 30 min allowing the Ponceau 2R to dissolve into the water. The absorbance of the Ponceau 2R solution was measured with a 722 N visible spectrophotometer (Shanghai Tianpu Instrument Co., Ltd., Shanghai, China). The spray deposition a (in μg) onto the paper card was calculated using Equation (2):

$$a=\frac{\delta V}{K} \tag{2}$$

where, V is the volume of added water expressed in mL (here, 25 mL); δ is the absorbance of the Ponceau 2R solution, and K is the absorbance ratio coefficient (here, 0.038).

2.3.4.2 Measurement and calculation of drift

The deposition onto each paper card (i.e., a_1, a_2, …, a_{11}) on each pole was measured. Because there are a certain distance between the nozzles and the ground, droplets received by the cards on poles were concentrated regionally within 1.5-2.5 m above the ground. The card representing the maximum drift of each pole was identified, and the distance between this card and ground was marked as t. The equations $y=f(x)$ and $y=g(x)$ were fitted to spray depositions on the intervals $[a_1, a_t]$ and $[a_t, a_{11}]$, respectively, to infer deposition more accurately by the least squares method. The total spray deposition q on each pole was calculated by Equation (3):

$$q=\int_0^t f(x_1)\mathrm{d}x+\int_t^{h_p} g(x_2)\mathrm{d}x \tag{3}$$

where, t is the height of the maximum drift card to the ground, m; h_p is the length of the pole, 5 m; $y_1 = f(x_1)$ describing the relationship between drift and card position along the interval [0, t]); x_1 is the height variable between [0, t]; $y_2 = g(x_2)$ describing the relationship between drift and card position along the interval [t, 5], and x_2 is the height variable between [t, 5].

The spray deposition q for each pole (i.e., q_1, q_2, q_3, q_4, and q_5) was obtained. The equations $y_3 = p(x_3)$ were fit to estimate drift. The drift calculated by Equation (3) only considers the space between two adjacent trees. Accordingly, the drift for only one tree can be calculated using Equation (4):

$$Q_1 = S\frac{\int_{d_1}^{d_2} p(x_3)\mathrm{d}x}{b\times 10^6} \tag{4}$$

where, Q_1 is the total spray drift, g; S is plant spacing, 3 m; d_1 and d_2 are drift region boundary locations (d_1= 2 m and d_2=20 m); $y_3 = p(x_3)$ describing the relationship between drift amount and downwind pole position; x_3 is pole position in the downwind direction, m; b is the width of paper cards, 0.076 m.

In the ground deposition assay, the deposition per unit area was calculated from the total deposition on cards in row spacing and plant spacing. Similarly, the ground deposition estimated using Equation (5) considered only the space between two adjacent trees. Accordingly, ground deposition was calculated for each tree as well. The area in which ground deposition occurred was calculated as the result of row spacing multiplied by plant spacing. Ground deposition per tree was calculated using Equation (5):

$$Q_2 = lS\frac{\sum_{i=1}^{n}\sum_{j=1}^{m}(l_i + S_j)}{(n+m)S_c\times 10^6} \tag{5}$$

where, Q_2 is the total ground deposition, g; l is row spacing, 4 m; l_i is ground deposition at sampling point i along the axis of the row, μg; S_j is ground deposition at sampling point j along the axis perpendicular to the row, μg; n is the total number of sampling points along the axis of the row; m is the total number of sampling point along the axis perpendicular to the rows; S_c is the area of each paper card, here, 0.0058 m^2.

2.3.4.3 Spray flow calculation

Spraying flow amounts differ under CAA spraying and TAA spraying because of the different working distances. The working distance for CAA spraying was consider as the spacing between plants while the working distance for TAA spraying was consider as the canopy width. The spray flow amount can be calculated using Equation (6):

$$Q_s = \frac{q_n\times n_s}{v}\times B_s \tag{6}$$

where, Q_s is the spray flow amount, L; q_n is the flow rate from a single nozzle, L/s (here, 0.02 L/s); n_s is the number of nozzles on a single side (here, 6 nozzles); v is the speed of sprayers, m/s; B_s is working distance in the direction of the sprayer's movement, m.

3 Results and discussion

3.1 Spray distribution under CAA spraying at different fan speeds

Four different fan speeds were examined for their effects on spray coverage, deposition, and drift when spraying pear trees. Under CAA spraying, the coverage and deposition were obviously reduced in the air-assisted spraying direction within the canopy, and the deposition was positively correlated with coverage. This indicates that air-assisted spraying can improve the dispersion of droplets and mitigate overloading leaves with insecticide (Table 2).

Table 2 Spray deposition distribution measured in the canopy

Fan speed /r·min^{-1}	Section	CAA		TAA	
		Coverage/ %	Deposition/ μg·cm^{-2}	Coverage/ %	Deposition/ μg·cm^{-2}
0	A	10.11±1.75	2.72±0.41	8.55±3.16	2.49±0.92
	B	0.31±0.07	0.30±0.01	0.36±0.23	0.25±0.08
	C	0.02±0.02	0.15±0.004	0.03±0.01	0.20±0.06
800	A	16.33±0.61	3.10±0.32	9.59±6.01	2.20±0.95
	B	5.54±1.62	1.50±0.28	4.67±4.37	1.34±0.64
	C	0.93±0.92	0.63±0.22	0.22±0.13	0.36±0.08
1300	A	23.54±2.02	4.62±0.72	17.62±0.13	2.35±0.30
	B	17.47±4.74	3.19±0.72	11.00±4.66	1.76±0.56
	C	3.44±3.51	1.23±0.37	2.55±2.54	0.67±0.23
1800	A	25.21 ± 7.94	4.43 ± 1.59	24.51 ± 5.62	4.35 ± 0.62
	B	16.84 ± 3.10	3.31 ± 0.21	16.13 ± 4.78	2.94 ± 0.76
	C	2.73 ± 2.37	1.03 ± 0.46	2.32 ± 2.00	0.93 ± 0.07

Note: All values are presented as averages ± standard deviations.

The variability in coverage and deposition along the travel direction of sprayers was far less than variability along the direction of air-assisted spraying (Tables 2, 3). Spray deposition variability along the axis of air assistance is important, so fan speeds should be optimized to improve the penetration of droplets into the canopy.

Table 3 Spray deposition distribution in the canopy

Fan speed /r·min^{-1}	Section	CAA		TAA	
		Coverage/ %	Deposition/ μg·cm^{-2}	Coverage/ %	Deposition/ μg·cm^{-2}
0	A	3.59±1.55	1.16±0.33	3.44±2.31	1.02±0.72
	b	2.30±1.66	0.80±0.47	2.74±2.09	1.05±0.70
	c	4.56±1.43	1.21±0.38	2.97±1.91	0.94±0.41
800	a	5.86±2.19	1.56±0.56	4.56±3.93	1.29±0.81
	b	6.73±2.00	1.59±0.24	4.39±3.86	1.18±0.52
	c	10.22±1.78	2.07±0.35	5.54±3.22	1.43±0.26
1300	a	20.42±0.56	3.48±0.21	14.56±3.37	2.04±0.40
	b	10.60±3.70	2.74±0.53	5.04±3.09	1.06±0.55
	c	13.42±3.76	2.81±0.90	10.69±2.12	1.58±0.16
1800	a	16.66±4.89	3.30±0.36	20.95±1.95	3.33±0.16
	b	11.30±1.39	2.59±0.71	13.30±3.36	2.77±0.38
	c	16.82±2.44	2.88±0.31	8.71±2.57	2.11±0.43

As fan speeds increased from 0 to 800 r/min and 1300 r/min, the coverage and deposition of the droplet in the canopy significantly increased. At 1800 r/min, deposition was 2.92 μg/cm^2, which was slightly lower than 3.01 μg/cm^2 at a fan speed of 1300 r/min. As fan speeds increased, the total spray drift per tree increased, but the total ground deposition per tree gradually decreased. At 0 and 800 r/min fan speeds, no spray drift was detected on any pole; at 1300 r/min and 1800 r/min fan speeds, the total spray drift was 0.4 g/tree and 1.11 g/tree, respectively. As fan speeds increased up to 1300 r/min, spray coverage and deposition in the canopy significantly increased. However, the deposition and coverage of droplets at 1800 r/min were not higher than those at 1300 r/min, though spray drift was greatly increased and ground deposition was somewhat reduced (Table 4).

Table 4 Spray deposition distribution and drift measured under CAA

Fan speed /r·min^{-1}	In the canopy		Drift	
	Coverage/ %	Deposition/ μg·cm^{-2}	Total spray drift/g	Total ground-based deposition/g
0	3.48±0.61^{c}	1.06±0.14^{c}	0^{c}	1.39±0.11^{a}
800	7.60±0.61^{b}	1.74±0.27^{b}	0^{c}	0.73±0.15^{b}
1300	14.81±1.07^{a}	3.01±0.28^{a}	0.40±0.01^{b}	0.56±0.06^{bc}
1800	14.93±2.38^{a}	2.92±0.38^{a}	1.11±0.25^{a}	0.42±0.18^{c}

Note: Rows with same letters are not significantly different ($p \leq 0.05$). Same below.

3.2 Spray distribution under TAA spraying at different fan speeds

Under TAA spraying, the coverage and deposition at all sections in the canopy gradually decreased in the direction of air flow. As fan speeds increased within the 0-1800 r/min range, spray coverage and deposition in the canopy significantly improved (Table 5), and coverage and deposition on the back of leaves also remarkably increased. At 0 and 800 r/min fan speeds, no spray drift was detected on any pole, but ground deposition remained high. As fan speed increased, ground deposition gradually decreased, while spray drift remarkably increased. The spray deposition in the canopy was 2.74 μg/cm^2 at 1800 r/min, which exceeded spray deposition in the canopy of 1.58 μg/cm^2 at 1300 r/min. Total spray drift was 0.24 g/tree at 1800 r/min, exceeding the total spray drift of 0.004 g/tree at 1300 r/min. However, ground deposition decreased from 0.36 g/tree at 1300 r/min to 0.22 g/tree at 1800 r/min (Table 5).

Table 5 Spray deposition distribution and drift measured under TAA

Fan speed /r·min^{-1}	In the canopy		Drift	
	Coverage/ %	Deposition/ μg·cm^{-2}	Total spray drift per tree/g	Total ground deposition per tree/g
0	3.02±1.00^{c}	0.99±0.33^{b}	0^{b}	0.62±0.17^{a}
800	4.83±3.41^{c}	1.30±0.51^{b}	0^{b}	0.52±0.22^{a}
1300	10.22±1.54^{b}	1.58±0.26^{b}	0.004±0.002^{b}	0.36±0.06^{ab}
1800	14.32±0.87^{a}	2.74±0.20^{a}	0.24±0.01^{a}	0.22±0.05^{b}

3.3 Comparison of spray distribution between the two spraying methods

The sprayer operated continuously under CAA spraying, and the CAA spray volume was 0.36 L/tree as calculated by Equation (6). Under intermittent spraying, TAA spraying was focused on canopies one by one. As shown in Table 1, the mean canopy width of tested fruit trees was 2.1 m, so the TAA spraying volume was 0.252 L/tree according to Equation (6). TAA spraying effectively reduced application volume by 30%.

The spray coverage and deposition in canopies under TAA spraying were slightly lower than those under CAA spraying, and spray drift and ground deposition were also obviously less than those under the latter treatment. No spray drift was detected on any pole in these two applications at 0 and 800 r/min fan speeds. At

1300 r/min, spray drift and ground deposition were 0.004 g/tree and 0.36 g/tree under TAA spraying, respectively, while they were 0.4 g/tree and 0.56 g/tree, respectively, under CAA spraying. At 1800 r/min, spray drift and ground deposition were 0.24 g/tree and 0.22 g/tree, respectively under TAA spraying, while they were 1.11 g/tree and 0.42 g/tree, respectively, under CAA spraying (Tables 4 and 5). Spray drift and ground deposition under TAA spraying were substantially less than those under CAA spraying.

4 Discussion

Airflow parameters are among the most important factors affecting pesticide deposition and coverage[28-30], while TAA spraying technology is an effective means for reducing spray drift[31,32]. The influence of applying pesticides at different fan speeds under TAA and CAA were studied to identify optimal fan speed settings. Across all fan speeds, coverage and deposition in the canopy under TAA spraying were slightly lower than those under CAA spraying (Tables 2 and 3). This might have occurred for the following reasons. First, the fruit trees gaps exhibited improved spray deposition and coverage in the canopy under CAA spraying because of air and droplet diffusivity, but this also resulted in more pesticide waste and pollution. Second, reaction speed, the number of sensors, and canopy shape may also increase arrant spraying.

However, coverage and deposition distribution within canopy are not the only considerations[33]; spray drift is also very important[22,34]. Ground deposition and spray drift under TAA spraying were obviously lower than those under CAA spraying (Tables 4 and 5); thus, TAA spraying effectively minimized pesticide waste thereby reducing environment pollution.

Spraying parameters should be determined for specific working conditions[35,36]. The optimal fan speed for TAA spraying was also different than that for CAA spraying. Accordingly, the most suitable fan speed parameters for TAA spraying should be explored in more depth. Fan speed adjustments can have a strong influence on spray drift[37]. Ground deposition should also be considered. The effects of CAA spraying were improved when the fan speed was increased from 0 to 1300 r/min, and the spray deposition in the canopy was maximized at 1300 r/min. However, at 1800 r/min, the spray deposition and coverage in the canopy did not obviously increase and even appeared to decrease. Because droplets were blown further through the air, ground deposition decreased but spray drift obviously increased (Table 4).

Under TAA spraying, ground deposition at a fan speed 1800 r/min was reduced considerably relative to lower fan speeds, but the deposition and coverage of the canopy as well as spray drift were obviously increased; thus, these may be the best spraying effects obtained (Table 5). Because the spray volume under TAA spraying was substantially less than that under CAA spraying, it requires more force (i.e., kinetic energy) to make the droplets penetrate the canopy and thus distribute pesticide more effectively. Droplet size can be decreased by high-speed fans that droplets can be better transported into the inner canopy[38-40]; thus, higher fan speeds are necessary to increase coverage distribution within the canopy under TAA spraying.

5 Conclusions

The optimal air-assisted system parameters for the horticultural characteristics of modern orchards was determined; the TAA sprayer and fan speed regulation systems worked effectively in combination with infrared detection technology. TAA spraying could dramatically reduce spray volumes, ground deposition, and spray drift, though spray deposition and coverage in the canopy under TAA spraying were also slightly lower than those under CAA spraying. At a fan speed of 1300 r/min, CAA spraying produced the best overall spray results: 3.01 μg/cm^2 spray deposition in the canopy, 0.4 g/tree spray drift, and 0.56 g/tree ground deposition. When fan speed increased within a certain range, spray deposition and coverage in the canopy obviously improved under CAA spraying. However, when fan speed exceeded 1300 r/min, the deposition and coverage of droplets did not substantially improve and was even reduced in the canopy as spray drift increased. Accordingly, air flow parameters have a critical effect on spraying. Under

CAA spraying, optimal spraying effects were achieved at a fan speed of 1300 r/min. One of the key difference between CAA and TAA spraying is that the former sprays continuously, while the latter sprays intermittently to reduce waste. Because of this, droplet sizes differ such that sprayed droplets are larger at the moment a nozzle intermittently opens under TAA spraying. Thus, stronger air flow may be necessary to adequately blow droplets onto the leaf surfaces. This may explain the optimal TAA spray results at a relatively high fan speed of 1800 r/min.

Therefore, for air-assisted sprayer, if the tree canopy and other spray parameters are remained to be constant, there must be an optimum air velocity with respect to the relationship of droplet deposition in the tree canopy, ground and drift in the air. Compared with conventional air-assisted sprayer, targeting air-assisted sprayer needs a larger air velocity.

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