Design and Testing of a Crawler-Type Orchard Air-Assisted Electrostatic Sprayer

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Abstract: To address the challenges of low mobility and difficulty in depositing pesticide droplets on the backside of fruit tree leaves, this study proposes a method combining a crawler-type chassis with an electrostatic spraying system to design a crawler-type air-assisted electrostatic orchard sprayer. The developed crawler-type chassis meets the operational environmental requirements of the sprayer, with both operating speed and mobility achieving the design goals. Test results show that the designed air-assisted electrostatic nozzle can achieve a charge-to-mass ratio of 1.0 mC/kg at the outlet. The droplet coverage on the front side of leaves with electrostatic spraying is slightly lower than that of non-electrostatic spraying, but the coverage on the backside is higher. This research provides a reference for the design and application of air-assisted electrostatic sprayers.

Keywords: Orchard Sprayer; Air-Assisted Spraying; Electrostatic Spraying; Charge-to-Mass Ratio; Coverage Density

1. Introduction

Orchard pest control is a crucial aspect of ensuring healthy tree growth, improving fruit quality, and increasing yield [1-2]. Traditional spraying methods suffer from low pesticide utilization, severe environmental pollution, and safety risks for operators, making it difficult to meet the modern orchard's demand for efficient, precise, and environmentally friendly plant protection. Currently, improving pesticide utilization efficiency and reducing pesticide loss in non-target areas remain key goals for researchers. Domestic and international scholars have conducted extensive research on crawler-type air-assisted electrostatic spraying technology, focusing primarily on the following aspects: 1) Atomization Mechanism and Droplet Characteristics. Research focuses on the effects of different atomization methods, electrostatic voltage, wind speed, and other parameters on droplet size, velocity, and charge quantity to optimize atomization performance. For example, [3-4] studied the distribution patterns of droplet size under different electrostatic voltages and found that as the electrostatic voltage increases, droplet size decreases, and the distribution becomes more uniform. Additionally, the charge quantity of droplets directly affects their adhesion to target surfaces. Studies show that appropriate electrostatic voltage can significantly enhance droplet charging efficiency, thereby improving deposition performance. 2) Airflow Field Characteristics of Air-Assisted Systems. Using a combination of numerical simulation and experimental testing, researchers study the distribution patterns of airflow fields in air-assisted systems to optimize air duct structures and improve droplet transport efficiency. [5-6] employed CFD numerical simulation methods to investigate the effects of different air duct structures on airflow field distribution, providing a theoretical basis for air duct design. The design of air-assisted systems must balance airflow speed, direction, and uniformity to ensure effective coverage of target areas while reducing droplet drift and waste. 3) Deposition Characteristics of Electrostatic Spraying. Research examines the deposition patterns of electrostatic spray droplets under different targets and environmental conditions, establishing deposition models to provide a theoretical basis for precise pesticide application. [7-9] experimentally studied the deposition amounts of droplets on the front and back sides of leaves under different wind speeds and electrostatic voltages, finding that electrostatic spraying significantly increases droplet deposition on the back sides of leaves. By imparting charge to droplets, electrostatic spraying technology enables directional adsorption onto target surfaces under electric fields, making it particularly suitable for crops with complex canopy structures, such as fruit trees and shrubs. 4) Intelligent Control Technology. The application of machine vision, sensors, and automatic control technologies to crawler-type air-assisted electrostatic sprayers enables precise targeting and variable-rate spraying, improving operational efficiency and application effectiveness. [9] developed an automatic targeting system based on machine vision that can identify crop positions in real time and control spray direction, enhancing spraying accuracy. He et al. [10] combined electrostatic spraying, air-assisted spraying, and target-oriented spraying to develop an automatic target-detecting electrostatic orchard sprayer. Yang et al. [11] designed an online mixing electrostatic sprayer for orchards, with test results showing that the air-assisted electrostatic spraying system improves droplet adhesion and penetration.

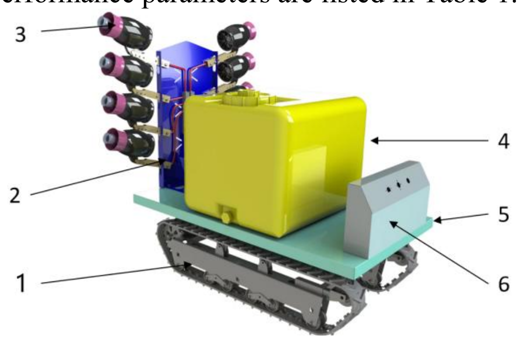
The integration of intelligent technologies allows sprayers to dynamically adjust spraying parameters based on crop growth status and pest distribution, achieving the goals of precision agriculture.

In recent years, electrostatic spraying technology has emerged as a novel spraying method, offering advantages such as small droplet size, excellent charging performance, and high deposition efficiency, making it highly promising for agricultural plant protection. However, existing electrostatic spraying equipment is primarily designed for field crops, with limited availability of specialized equipment for the complex terrain and canopy structures of orchards. To address this, this study designs a crawler-type air-assisted electrostatic orchard sprayer to overcome the limitations of existing equipment in orchard applications and improve spraying efficiency and pest control effectiveness. This technology integrates crawler chassis, air-assisted delivery, and electrostatic spraying, leveraging the excellent passability and adaptability of the crawler chassis, the powerful droplet transport capability of air-assisted technology, and the efficient droplet deposition performance of electrostatic spraying to achieve precise, efficient, and environmentally friendly plant protection operations.

2. Overall Performance and Working Principle

2.1 Machine Performance Parameters

Given the characteristics of orchard environments, such as narrow row spacing, high density, overlapping canopies, low canopy height, and uneven ground, the machine's layout must be compact, with small external dimensions, appropriate height, and ground clearance. The machine uses a crawler-type chassis powered by lead-acid batteries and controlled remotely. The pesticide tank and pump are centrally located to ensure stability, while the fan and spraying equipment are placed at the rear for ease of operation. The control system and electronic components are located at the front, away from the spraying components to avoid contamination. A photo of the sprayer is shown in Figure 1. Based on plant protection machinery specifications, the sprayer's performance parameters are listed in Table 1.



1. Crawler chassis 2. Spray component bracket 3. Air-assisted electrostatic nozzle 4. Pesticide tank 5. Work platform 6. Control cabinet

Figure 1. 3D Model of the Sprayer

Table 1. Main Performance Parameters of the Sprayer

Parameter	Value
Size/mm	1700×1250×1450
Power/kW	8KW/48V
Recommended operating speed /(km/h)	0~10(adjustable)
Row spacing/m	2.5-3.5
Flow rate of diaphragm pump/($L\cdot min^{-1}$)	20
Pesticide tank volume/L	350
Number of total nozzle	8

Spray pressure/ MPa	0.5
Spray rate/($L\cdot min^{-1}$)	8
Axial fan speed/($r\cdot min^{-1}$)	1000
Induction voltage/V	7000

2.2 Working Principle

The sprayer is powered by a pure electric drive, with the battery's output power distributed to the walking motor, liquid pump motor, atomizer motor, and other components. The pesticide liquid is distributed to each nozzle via the liquid pump, distribution valve, and solenoid valve. Part of the liquid flows back to the pesticide tank through the pressure regulator for recirculation and mixing. The controller allows for the switching of the electrostatic system, fan, and movement control.

3. Key Components and Parameters

3.1 Theoretical Calculation of Crawler Chassis Power

The walking power of the crawler chassis is determined by factors such as gravity (G), center of gravity, track contact length (L), track width (b), track center distance, and working conditions.

Track contact pressure, (P);

$$P=\frac{G}{2Lb} \quad (1)$$

Walking resistance;

$$R = Gf \quad (2)$$

- G: gravity
- f: coefficient of friction

Walking resistance (Ra) at a maximum slope of 15°;

$$R_a = Gf\cos\theta + G\sin\theta \quad (3)$$

Turningresistance, F_r;

$$F_r = \frac{M_R}{B} = \frac{GL\mu}{4B}[1-(2n/L)^2]^2 \quad (4)$$

Turning resistance F_r when climbing a 15° slope;

$$F_{r''}=F_r\cos15^0 \quad (5)$$

Where:

- M: Turning resistance moment
- n: Longitudinal eccentricity of the track
- μ: Turning resistance coefficient
- B: Track center distance

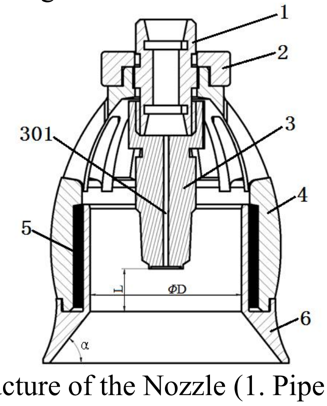
Walking power (N):

$$N = \frac{Fv}{100\eta} \quad (6)$$

Where, F is Comprehensive resistance, horizontal turning: $F=R+2F_r$; slope turning: $F=R\cos\theta+2F_{r''}$. η is the track transmission efficiency; V is walking speed.

3.2 Air-Assisted Electrostatic Nozzle

The electrostatic spraying unit primarily comprises a pipe connector, an atomizing nozzle, and a nozzle housing. The housing features a mounting platform at its upper end, through which the pipe connector extends, connecting to the top of the housing, as depicted in Figure 2. Positioned within the housing, the atomizing nozzle is affixed to the lower end of the pipe connector. A circular electrode is situated at the base of the housing, with an electrode ring positioned between the circular electrode and the housing's inner wall. During the design phase, the parameters of the electrostatic nozzle were meticulously optimized. The electrode ring's thickness is ideally between 2-3mm, with a 3mm thickness adopted in the actual production. The electrode ring's induction voltage is optimally set at 6-8KV, with 7KV being the operational standard. The inner ring's base inclination angle (α) is optimally set at 52°. The spatial relationship between the atomizing nozzle and the electrode ring is defined by D=2~2.4L, where D represents the electrode ring's inner diameter, and L denotes the vertical distance from the atomizing nozzle's base to the electrode ring's base.



a. Structure of the Nozzle (1. Pipe joint 2. Mounting base 3. Nozzle 4. Airflow channel 5. Ring electrode 6. Inner front deflector)

b. Photos of the Nozzle

Figure 2. Electrostatic Nozzle Diagram

4. Characteristics Test

4.1 Nozzle Pressure-Flow Characteristics

The stability of flow rate across individual nozzles in a sprayer is one of the critical performance parameters of the equipment and a primary factor influencing the uniformity of droplet deposition distribution on crops. The spray volume under varying pressures was measured using a graduated cylinder over a 1-minute interval, with test results averaged from three repeated trials. As illustrated in Figure 3, the data indicate that within specific spray pressure ranges, the spray volume increases proportionally with elevated spray pressure

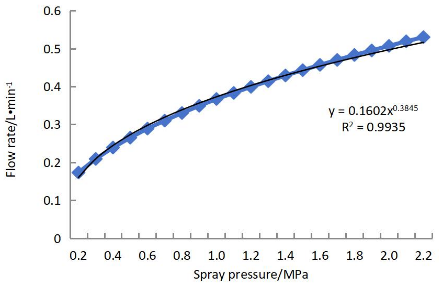


Figure 3. The Flow Characteristics of the Nozzle

4.2 Initial Airflow Characteristics of Spray

Turbulence intensity, which quantifies the temporal and spatial variations in wind speed, is a critical parameter influencing the effectiveness of airflow in flipping fruit tree leaves during air-assisted spraying. It serves as a key indicator for characterizing airflow field properties. In this study, turbulence intensity was measured using a Kestrel 4500 portable meteorological anemometer (NK5925), which integrates a digital compass and high-precision sensors to capture multidimensional environmental parameters, including instantaneous wind speed (0.4–40.0 m/s), turbulence fluctuations, and directional data (0–360°). Airflow Stability result is shown in the figure 4.

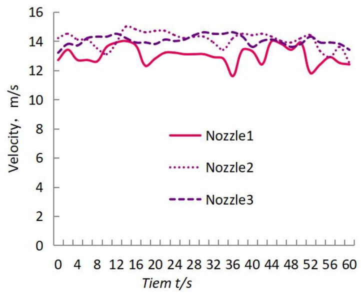


Figure 4. Airflow Stability

4.3 Charge-to-Mass Ratio of Single Nozzle

The Faraday cup method was employed to measure the charge quantity. The nozzle was mounted along the central axis at a distance of 200 mm from the inlet of the Faraday cup (inner diameter: 550 mm) to collect all droplets. A Keysight 34410A digital multimeter (100 µA range, 6½-digit resolution) was used to measure the discharge current I of the charged droplets. The mass of the droplet flow collected by the Faraday cup within 1 minute was recorded. Charge-to-mass ratio (CMR) was tested at spray heights of 1 m and 0.5 m, with measurement points at 0.2 m, 0.6 m, 1.0 m, 1.4 m, and 1.8 m along the spray trajectory. Experimental results are shown in Figure 5. The charge-to-mass ratio was calculated using Equation (7):

$$A_i = \frac{Q}{m} = \frac{It}{m} \quad (7)$$

Where I is the discharge current of charged droplets, m is the total mass of droplets, and t is the measurement time.

As shown in Figure 5, the initial charge-to-mass ratio of the electrostatic nozzle reached 1.0 mC/kg. However, the CMR decayed rapidly along the spray trajectory. When the spray distance exceeded 1 m, the CMR dropped below 0.3 mC/kg.

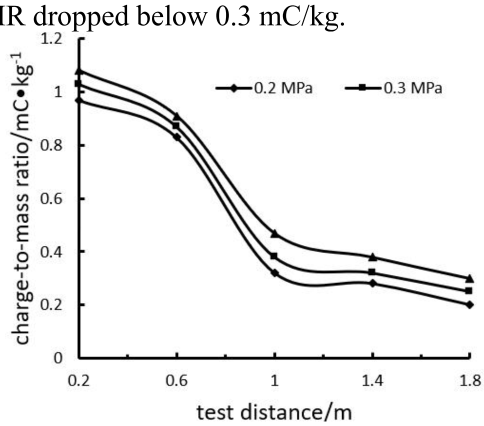


Figure 5. The Law of CMR Attenuation

4.4 Spray Deposition Performance Test

The test was conducted from November 14–16, 2024, at the premises of Suzhou Yuanliang Intelligent Equipment Co., Ltd. During the test, the ambient temperature ranged from 8–12°C with a relative humidity of 55%. The test subject was an 8-year-old cycad planted with a row spacing of 3.5 m and plant spacing of 2 m. Sampling Methodology Water-sensitive paper (26×76 mm, Syngenta Crop Protection AG, Switzerland) was used as the sampling medium, with deionized water as the spray solution. A zonal sampling strategy was adopted (see Figure 6 for the layout). The experimental site is shown in Figure 7. The tree was divided into 9 sampling zones at heights of 0.3 m, 0.7 m, and 1.2 m. Outer zones: 3 sampling points per zone. Central zone: 6 sampling points. Each sampling point used 2 sheets of water-sensitive paper to measure droplet coverage density on both the adaxial (front) and abaxial (back) surfaces. Results represent the average of three trials. The sprayer operated at rated parameters, applying electrostatic and non-electrostatic sprays separately across the sampling zones. After drying, the water-sensitive papers were labeled, stored in sealed bags, and imaged the same day using a microscopic camera. A droplet image analysis system quantified droplet coverage density (number of droplets per cm²).

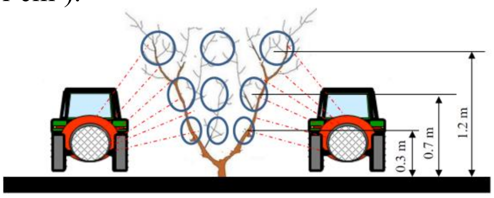


Figure 6. The Zonal Sampling Strategy

Figure 7. The Test Site

Figure 8 compares the average droplet coverage between electrostatic and non-electrostatic spraying. 1) Front surface: Electrostatic spray coverage was slightly lower than non-electrostatic spray. 2)Back surface: Electrostatic spray coverage was significantly higher than non-electrostatic spray.

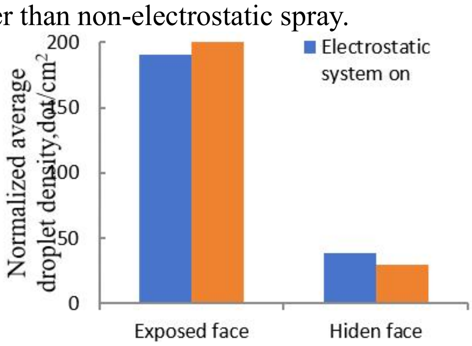


Figure 8. The Effects of the Electrostatic Spray on Coverage

5. Conclusions

The crawler type pneumatic electrostatic spray developed in this paper meets the design requirements, and its main performance parameters meet the effect of pest control. The following conclusions are drawn, providing technical support for the subsequent application of spray:

(1) The crawler chassis demonstrated excellent adaptability to operational environments, achieving target travel speed and maneuverability.

(2) The electrostatic nozzle achieved a charge-to-mass ratio (CMR) of 1.0 mC/kg at the outlet.

(3) Electrostatic spraying improved back-surface deposition while maintaining comparable front-surface coverage.

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