Precision airflow optimization in air-assisted orchard sprayers to reduce drift and improve coverage

Medet İtmeç*

(*Department of Agricultural Machinery and Technologies Engineering, Faculty of Agriculture, Çukurova University, Adana 01330, Türkiye*)

Abstract: The effectiveness of air-assisted orchard spraying depends on matching airflow to canopy structure, since improper airflow reduces coverage and increases spray drift. However, the optimal airflow conditions that balance coverage and drift remain unclear. A hydraulically driven axial-fan orchard sprayer capable of continuously adjusting airflow was developed, and different airflow levels were generated by regulating fan speed through a proportional valve operated at different voltage levels. Air velocities generated at different voltage levels were first quantified under laboratory conditions and subsequently validated in a pecan orchard by measuring canopy-exit air velocity under airflow-only conditions. Finally, spray applications were performed at a constant application volume while varying air velocity, and coverage and drift (ground and airborne) were evaluated using water-sensitive papers (WSP). At 4.50 V (air velocity: 21 m/s), the spray index (I_o) was close to zero and positive, indicating the optimal operating condition. Under these conditions, coverage reached 35.94% on water-sensitive papers in the middle canopy. Furthermore, ground drift was 18.15% at the closest point to the tree, whereas airborne drift was 13.58% at a height of 3 m. Appropriate adjustment of airflow directed to the canopy improved leaf surface coverage while reducing both ground and airborne spray drift. At the operating condition that resulted in the lowest overall drift and the most effective spray coverage (4.5 V, 460 r/min), fuel consumption decreased to 6.24 L/h, compared with 7.76 L/h under the conventional operating condition (5.0 V, 540 r/min). This study provides a practical methodology for determining airflow levels that balance spray coverage, drift reduction, and fuel consumption in orchard spraying applications.

Keywords: airflow configuration, orchard sprayer, drift, canopy density

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1 Introduction

With the integration of sensing technologies, decision support systems, and artificial intelligence into agricultural spraying technologies, systems capable of performing pesticide applications with high precision have become increasingly widespread[1]. Such high-precision spraying systems are essential for improving operational efficiency, reducing production costs, ensuring sustainability, and minimizing environmental impacts[2]. However, the effectiveness of precision spraying largely depends on the spray airflow and canopy structural characteristics[3]. In particular, regulating airflow using sensing technologies and decision support systems has the potential to improve spraying precision by enabling effective droplet transport and penetration within the canopy.

In orchards, the effectiveness of precision spraying is strongly influenced by canopy structural characteristics, including canopy geometry, leaf density, leaf morphology, and the vegetative and phenological stages of the trees[4]. However, once airflow enters the tree canopy, the aerodynamic resistance generated by branches and leaves reduces its kinetic energy[5], leading to a noticeable attenuation in air velocity[6-9]. Consequently, air velocity becomes a critical factor governing pesticide distribution within tree canopies, since excessive airflow may transport sprayed droplets beyond the canopy and reduce spray coverage[10-12]. Adjustments in airflow rates have been reported to improve leaf surface coverage and spray efficiency[13-16]. When airflow is not properly adjusted, agricultural pesticides applied to tree species with sparse foliage cannot be distributed effectively, resulting in inadequate coverage. Similarly, Larbi et al.[17] demonstrated that measurable spray drift in air-assisted almond orchard applications can extend up to 183 m, highlighting the critical importance of properly regulating airflow during spraying operations.

In conventional air-assisted orchard sprayers with axial fan, fan speed is typically adjusted through different blade angles and transmission ratios, generally providing operators with up to six discrete airflow settings during field operation. Duga et al.[18] investigated air jet profiles in different orchard sprayer designs using three-dimensional hot-wire anemometer measurements and flow analysis, and reported that the most uniform air jet was generated by the axial-fan system. For this reason, axial-fan systems are widely used in orchard sprayers and are frequently employed in experimental studies because of their ability to generate relatively uniform airflow patterns. There are numerous studies and various design approaches in the literature aimed at applying airflow to tree canopies. Grella et al.[19] found that leaf surface coverage in vineyards was significantly affected by the interaction between phenological stage and airflow rate, with optimal fan speeds of 1000 r/min in early growth stages and 1300 r/min in later stages. Mahmud et al.[20] developed a five-stage iris-type damper for orchard sprayers to regulate fan intake and enable variable airflow, demonstrating that higher air velocities do not necessarily improve leaf coverage and that airflow should be optimized according to canopy density and droplet penetration. Salas et al.[21] developed a

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***Corresponding author: Medet İtmeç**, Assistant Professor, research interest: precision agriculture; air-assisted orchard sprayers; variable-rate spraying technologies; spray drift reduction. Department of Agricultural Machinery and Technologies Engineering, Faculty of Agriculture, Çukurova University, 01330 Balcalı, Sarıçam, Adana, Türkiye. Tel: +90-505-2649587, Email: mitmec@cu.edu.tr.

battery-powered orchard sprayer with an electrically driven fan whose rotational speed was controlled by motor current, and reported that increasing airflow significantly reduced air velocity at the canopy exit. Grella et al.[22] developed a variable-rate orchard sprayer using ultrasonic sensors to regulate airflow and spray application based on canopy density, with the control algorithm derived from experimental datasets and validated in vineyards at BBCH65 and BBCH89 stages. Feng et al.[23] modified an octopus-type orchard sprayer by introducing iris-based adjustable openings in the fan intake line, allowing the airflow rate to be regulated. Li et al.[24] applied different fan speeds to the lower, middle, and upper canopy zones using a multi-fan orchard sprayer and reported that directing greater airflow toward the upper canopy region improved leaf surface coverage in trees with large leaves. Liu et al.[25] developed a LiDAR-based autonomous sprayer capable of delivering spatially variable airflow (15-23 m/s) to different canopy zones, highlighting the importance of airflow adjustment according to canopy density for improving droplet penetration and leaf surface coverage. İtmeç and Bayat[26] developed an orchard sprayer capable of applying variable-rate airflow using a mathematical model and laser sensors. In the experiments, six conventional application settings were evaluated and their performance was compared with that of variable-rate applications. The results showed that the developed decision-support mechanism provided improved leaf surface coverage with reduced spray drift. However, accurately determining the airflow required to achieve effective spraying for a given tree species during specific vegetative and phenological stages remains crucial. In many sprayer designs, airflow is typically controlled by increasing fan speed or restricting outlet openings, which may lead to turbulence formation near the nozzle region, reduced mechanical efficiency, and increased energy consumption. Integrating such field data can contribute to the development of more reliable and generalizable smart agriculture systems through data-driven approaches.

Despite these developments, the effect of the airflow directed toward the canopy and the air velocity measured after passing through the canopy on spray coverage has not yet been quantitatively demonstrated sufficiently. The magnitude of the air velocity exiting the canopy is a critical factor affecting droplet transport and deposition on leaf surfaces. When both the air velocity directed toward the canopy and the air velocity exiting the canopy are known, airflow conditions that maximize spray performance for a given tree species can be more accurately identified. In this study, the fan of an orchard sprayer was driven by a hydraulic system instead of being operated directly by the PTO. Airflow levels determined through preliminary laboratory experiments were applied to a single tree species in orchard trials, and air velocities downstream of the canopy were measured prior to spraying. Spray applications were then conducted at different airflow levels to evaluate leaf surface coverage, ground drift, and airborne drift. Unlike previous studies that primarily focused on airflow regulation or spray deposition separately, this study quantitatively linked canopy-exit airflow with spray coverage, ground drift, airborne drift, and fuel consumption under field conditions. In this way, airflow conditions providing the best overall spraying performance were identified by simultaneously considering spray deposition efficiency, drift reduction, and operational energy requirements.

2 Material and methods

2.1 Design of the hydraulically driven orchard sprayer

The sprayer was equipped with an axial fan with a diameter of 750 mm and eight blades. During all experiments, the blade pitch angle was set to 45° and the transmission ratio between the PTO and the fan unit was fixed at 1:4.5. The power obtained from the PTO was transmitted to the liquid pump (Agrima HPP165, Türkiye) via a male-male universal shaft. The fan of the orchard sprayer was not directly driven by the pump output shaft. Instead, a gearbox (ML52, Hidroan, Türkiye) installed at the pump outlet increased the PTO speed at a ratio of 1:3 (Figure 1). The overall hydraulic scheme of the orchard sprayer and its main components are shown in Figure 2. This speed increase enabled the hydraulic oil pump (DKP30.610 CAB02SN, ASC, Türkiye) to operate more efficiently and stably. The determined input voltage was supplied to the tips of the proportional solenoid valve (DSPE7-A150/11N-II/D24K1, NG16 4/3, Duplomatic, Italy). The valve opening was controlled using voltage signals generated from the analog output of the data acquisition card. These voltage signals were adjusted through LabVIEW software (National Instruments Corporation, Austin, Texas, USA) running on a laptop computer (Intel Core i5-5200 CPU @2.20 GHz, Asus, Taiwan). Consequently, the rotational speed of the hydraulic motor (OMS 160, Danfoss, Denmark) was regulated, allowing the fan speed to be varied. In addition, the spray liquid was pressurized by the liquid pump, in accordance with conventional hydraulic system principles, and regulated to the desired pressure through a pressure regulator before being delivered to the nozzles. The sprayer was equipped with 12 full-cone spray nozzles (3/8″) with a 1.5 mm orifice diameter (PLS01, Tarizma, Bursa, Türkiye). The droplet size characteristics of the selected nozzle under the applied operating pressure were previously characterized by İtmeç[27] (Nozzle 2). Since the nozzle type and operating pressure remained constant during all experiments, droplet size distribution was assumed to be unchanged among treatments.

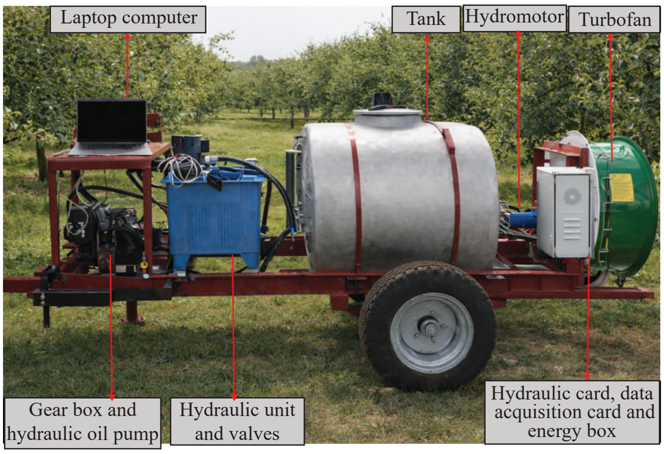
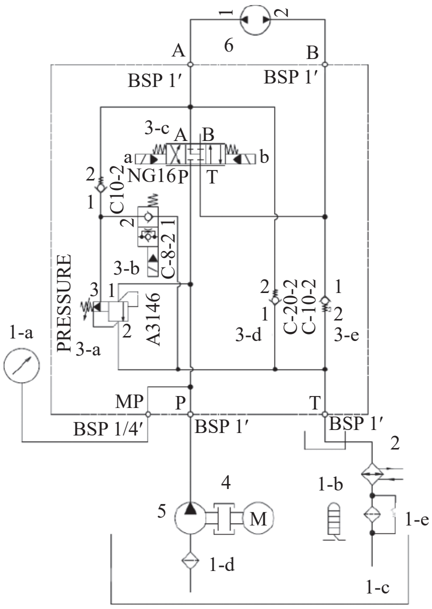


Figure 1 Design of the hydraulically driven orchard sprayer with main components

2.2 Experiments in laboratory

Laboratory experiments were conducted with the tractor stationary to characterize the airflow performance of the hydraulically driven orchard sprayer and to determine the relationship between hydraulic motor speed and fan outlet air velocity. The orchard sprayer was powered via the PTO of a TD95 New Holland tractor (four-cylinder diesel engine, 62.5 kW, Türkiye). Prior to the field experiments, the performance of the hydraulically driven orchard sprayer prototype was evaluated under laboratory conditions (Figure 3). The oil flow rate supplied to the hydraulic motor was regulated using a proportional solenoid valve powered by ±10 V (DC), enabling direct control of the motor speed through voltage-dependent valve opening. The hydraulic motor did not operate at 0 V and reached its maximum rotational speed at 10 V. To determine the relationship between hydraulic motor speed and fan outlet air velocity, air velocity measurements were conducted in accordance with ISO TS 9898. Measurements were taken at 52 locations across the fan discharge cross-section[8,28]. Experiments were performed by increasing the control voltage from 0 to 10 V in 0.25 V increments. The results indicated that the fan operated within the voltage range of 3-5 V, whereas no significant increase in fan speed was observed above 5 V, and this value was defined as the maximum voltage. Air velocity was measured using a digital vane anemometer (TA8165, Tasi, 0-45 m/s) during laboratory experiments. Fuel consumption was determined by the differential method using two flow meters (OF05ZAT, Aichi Tokei Denkei Co. Ltd., Japan) installed at the fuel supply and return lines. PTO torque and rotational speed were measured using an inline torque meter (Series 420, Datum Electronics Ltd., Isle of Wight, UK) mounted between the PTO shaft and the driveline. The hydraulic motor speed was recorded instantaneously using a laser tachometer (AR926, Smart Sensor). Fan speed (r/min), torque (Nm), and fuel consumption (L/h) were recorded with three replications. Experiments were performed at 420 r/min, 460 r/min (540E), and 540 r/min PTO speeds, a fan blade angle of 45°, and a transmission ratio of 1:4.5 under stationary condition.



1-a: manometer, 1-b: oil level indicator, 1-c: hydraulic oil, 1-d: reservoir outlet oil filter, 1-e: reservoir return oil filter, 2: oil cooler, 3-a: pressure relief valve, 3-b: poppet valve, 3-c: proportionally controlled hydraulic valve, 3-d: check valve, 3-e: check valve, 4: gearbox, 5: oil pump, 6: hydraulic motor

Figure 2 Hydraulic circuit diagram of the orchard sprayer

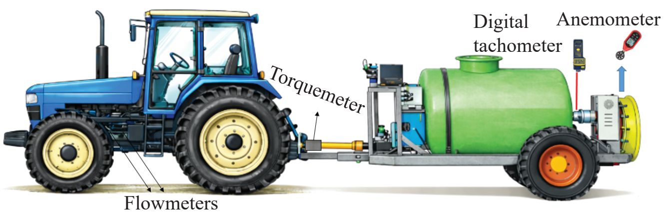


Figure 3 Schematic view of instrumentation and laboratory experiments with hydraulically driven orchard sprayer

Air velocity at the turbo fan outlet was measured at 52 locations to evaluate the spatial uniformity of the air jet distribution. The coefficient of variation (CV) of the measured air velocity data was calculated to quantify flow uniformity.

$$\mathrm{CV} = \frac{\sigma}{\mu} \tag{1}$$

The coefficient of variation (CV) was calculated and expressed as a percentage, where σ represents the standard deviation and μ denotes the arithmetic mean. For each applied solenoid voltage level, the CV (%) was used as an indicator of air-jet uniformity and flow stability. In addition to achieving high mean air velocity, maintaining a stable and uniform airflow distribution was considered essential for consistent spray performance.

2.3 Experiments in orchards

2.3.1 Airflow measurements under different voltage values

Field experiments were conducted in pecan (*Carya illinoinensis*) orchards at the BBCH 68 phenological stage, with a mean leaf area index (LAI) of 1.63. The trees had an average canopy height of 4 m and a canopy width of approximately 3.0 m, with a planting spacing of 6 m×6 m. The sprayer was operated at a PTO speed of 540E. Based on the laboratory findings, experiments were performed within a control voltage range of 3.0-5.0 V, applied in 0.25 V increments, resulting in nine treatment levels with three replications per voltage value. Air velocity measurements were obtained using four cup anemometers (measurement range: 0-20 m/s; PCE-A420, PCE Instruments, Germany) mounted vertically on a pole at 1 m intervals (Figure 4). The sensors were positioned at the outer canopy side opposite the sprayer to characterize the airflow reaching the canopy. In these experiments, airflow was directed toward the tree canopy, and the attenuation of air velocity after passing through the canopy was quantified at the outer canopy surface, considering canopy permeability and LAI. Prior to the field experiments, ambient temperature, relative humidity, and wind speed were measured as 28°C, 80%, and 0.5 m/s, respectively. All spray applications were conducted under these relatively stable environmental conditions.

Figure 4 Air velocity measurement positions using cup anemometers at the outer canopy surface during field experiments

The purpose of the airflow measurements was to quantify the mean air velocity exiting the canopy and to evaluate airflow attenuation under different operating conditions rather than to characterize instantaneous turbulent fluctuations. Therefore, cup anemometers were considered suitable because they provide reliable measurements of time-averaged airflow. The pecan trees used in the experiments had an average canopy height of approximately 4 m; consequently, four sensors were positioned vertically at 1 m intervals to represent the lower, middle, and upper canopy regions. This arrangement covered the entire canopy height and enabled the assessment of vertical airflow attenuation through the canopy. The average value obtained from the four measurement heights was used as an indicator of canopy permeability and downstream airflow penetration.

2.3.2 Evaluation of orchard sprayer spray applications in terms of coverage and drift

During the orchard spraying experiments, the sprayer was operated at a PTO speed of 540E. Sampling locations for water-sensitive papers (WSP) were defined following [29, 30], whereas ground losses and airborne drift were quantified according to the procedures described by [31, 32] (Figure 5). Rather than evaluating each region individually, the data were compared to assess spray distribution along the spray direction, travel direction, and canopy height[26]. Tracer deposition and coverage were horizontally averaged and analyzed across regions Y1 (mean of A1-A3), Y2 (mean of A4-A6), and Y3 (mean of A7-A9). Tracer deposition and coverage at different canopy depths were compared using S1 (mean of B1-B3) and S2 (mean of A2-A8) values. Ground losses (endodrift) were quantified by placing water-sensitive papers (WSPs) at regions C1-C3 at 30 cm intervals from the tree trunk toward the sprayer. Airborne drift, defined as spray droplets transported 1 m beyond the outer canopy without reaching the target, was also measured. Additional WSPs were placed on a vertical pole at four heights with 1 m spacing and designated as D1-D4. Tap water was used as the spray solution during the experimental trials. In the experiments, the distance between the orchard sprayer and the tree was set to 1.0 m. The tractor forward speed was maintained at 5 km/h, and the application volume was determined as 384 L/hm^2.

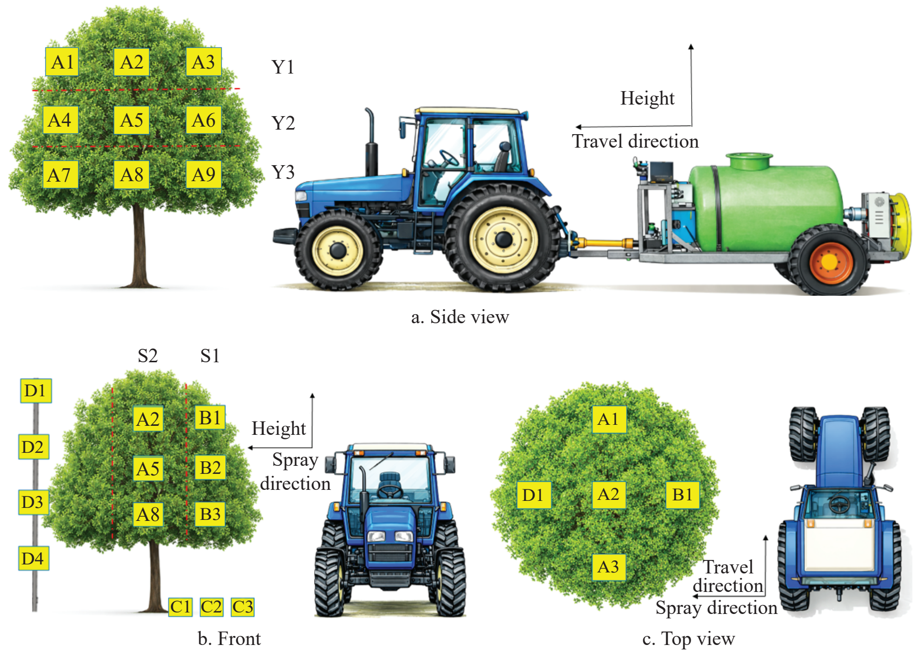


Figure 5 Sampling layout for coverage, tracer deposition, and drift measurements in orchard experiments

2.4 Data evaluation and statistics

After drying, WSPs were stored in envelopes to prevent stain spreading prior to analysis. Spray coverage was quantified using ImageJ software. The WSPs were scanned in grayscale at a resolution of 600 dpi and digitally processed to determine percentage coverage. Coverage values exceeding 30% were considered excessive, and the spray index (I_o) was calculated according to [30] using Equation (2) for comparative evaluation.

$$I_o = \frac{\text{CO} - 30}{100 - 30} \tag{2}$$

where, I_o represents the spray index and CO denotes the percentage spray coverage measured on the WSPs.

Statistical analyses were performed using IBM SPSS Statistics 20 (IBM Corp., Armonk, NY, USA). Coverage data were analyzed using two-way analysis of variance (ANOVA) to evaluate main and interaction effects. When significant differences were detected, sequential Bonferroni-adjusted pairwise comparisons were applied. Group differences were further assessed using Tukey's HSD test, with statistical significance set at p<0.05. Separate two-way ANOVA models were performed for each dataset. The factors included in the analyses were Voltage×Measurement Height for airflow measurements, Voltage×Canopy Position for canopy coverage, Voltage×Spray Depth for penetration analysis, Voltage×Ground Drift Position for ground drift assessment, and Voltage×Airborne Drift Height for airborne drift assessment.

3 Results

3.1 Performance evaluation of the sprayer under laboratory conditions

Based on the laboratory experiments, both PTO speed and the voltage applied to the proportional valve exhibited statistically significant main effects on airflow (Table 1). In addition, the interaction between these factors was also found to be significant.

Table 1 Statistical analysis of the dependents PTO speed and voltage with interactions on air velocities

Source	*df*	*F*	*Sig.*
PTO speed	2	29.740	0.000*
Voltage	8	429.180	0.000*
PTO speed × Voltage	16	0.168	0.005*

*p < 0.05 was statistically significant.

In laboratory experiments, air velocity exhibited a regular and approximately linear increase with increasing voltage applied to the proportional valve at all PTO speed levels (Figure 6). The lowest air velocities were obtained at 3 V, whereas the maximum values were observed at 5 V. Furthermore, increasing the PTO speed from 420 to 540 r/min significantly enhanced air velocity across all voltage levels, and higher PTO speeds consistently produced greater air velocities at each voltage step. Consistent with the experimental results, Endalew et al.[33] reported that a fan with an 800 mm inlet diameter generated an average outlet air velocity of 30 m/s.

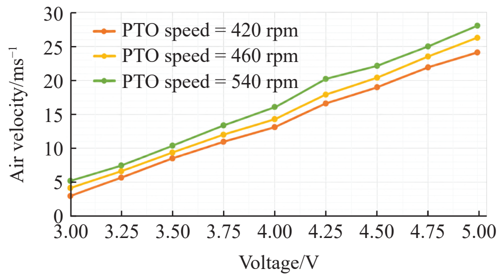


Figure 6 Airflow performance of the sprayer at different PTO speeds and voltage levels

During laboratory experiments, PTO was operated at different speed levels while the voltage applied to the poppet of proportional valve in the hydraulic system was gradually increased. The results indicated that, regardless of the PTO speed, increasing the applied voltage led to a consistent and simultaneous rise in fan speed, torque requirement, and fuel consumption. The increased power demand directly elevated the torque load and was accompanied by a noticeable increase in fuel consumption (Table 2).

Furthermore, increasing the PTO speed from 420 to 540 r/min resulted in higher fan speeds, PTO torque, and fuel consumption even at identical voltage levels, indicating that system outputs were governed by the combined influence of PTO speed and applied voltage. A higher coefficient of variation (CV, %) indicated increased instability and fluctuations in the air jet generated by the turbo fan, reflecting reduced flow uniformity[34]. In contrast, lower CV values represent a more uniform and stable jet structure. Similarly, Salcedo et al.[35] reported that, for a stable air jet, the coefficient of variation should remain below the threshold value of 30%. Since the CV values at 420 r/min were higher than those at 460 and 540 r/min, indicating less stable airflow conditions, this operating condition was excluded. Although fuel consumption was higher at 540 r/min, this operating condition provided a wider fan speed range. This allowed the air velocity experiments to be conducted within a more precise range. Therefore, orchard experiments were carried out at a 540E PTO speed in order to control the air velocity within a narrower range and obtain more reliable results.

3.2 Assessment of spray and airflow characteristics under orchard conditions

3.2.1 Determination of airflow characteristics under orchard conditions

In orchard experiments, the voltage applied to the proportional valve had a statistically significant effect (p<0.05) on air velocity (Table 3). Increasing voltage levels led to significant and progressive changes in air velocity, resulting in higher airflow rates. Measurement height also significantly affected air velocity (p<0.05), with air velocity decreasing significantly as the measurement height increased. Furthermore, an interaction of significant voltage with height was detected (p<0.05), indicating that the effect of increasing voltage on air velocity varied depending on the measurement height.

The air velocity values measured at different canopy heights (1-4 m) clearly demonstrated that the airflow generated by the orchard sprayer underwent a pronounced attenuation as it propagated upward through the canopy (Figure 7). The highest mean air velocity values were recorded at a height of 1 m for each experiment, followed by a systematic decrease with increasing canopy height, indicating that the airflow experienced substantial aerodynamic losses within the canopy environment. This behavior could be attributed to the reduction in kinetic energy resulting from continuous interactions between the air jet and canopy elements, such as leaves and branches, after entering the canopy. At the upper canopy levels (particularly 3-4 m), the increased distance traveled by the airflow within the tree structure led to a marked reduction in air velocity, limiting the magnitude of airflow reaching these layers. Similarly, Larbi and Salyani[5] reported a progressive decline in airflow momentum and velocity as the airflow propagated through the canopy due to the combined effects of canopy permeability, leaf area index, and tree canopy width, which impose aerodynamic resistance on the airflow. The dense vegetative structure within the canopy dissipated airflow energy through resistance and redistribution, resulting in lower air velocities at the upper canopy regions. Consequently, the narrower range and lower magnitude of air velocity values observed at the upper canopy indicated that the airflow in these regions became more uniform but substantially weaker. This attenuation of airflow directly influences droplet transport within the canopy. As airflow loses momentum while passing through the canopy, the ability of droplets to penetrate into inner and upper canopy regions decreases. Consequently, insufficient airflow may result in poor spray deposition and increased ground losses. Conversely, increasing airflow improves droplet transport and canopy penetration; however, excessive airflow may carry droplets beyond the target canopy, thereby increasing airborne drift.

Table 2 Comparison of fan speed, torque, fuel consumption, and calculated CV values under laboratory conditions

PTO/ r·min⁻¹	Voltage/V	Fan speed/ r·min⁻¹	CV%	Torque/ N·m	Fuel consumption/ L·h⁻¹
420	3.00	234	18.38	40	3.08
	3.25	464	20.47	62	3.47
	3.50	594	20.60	78	3.95
	3.75	707	19.57	100	4.36
	4.00	837	19.83	161	4.71
	4.25	972	18.38	219	5.26
	4.50	1143	20.92	286	5.95
	4.75	1269	19.96	356	6.52
	5.00	1413	16.98	390	7.14
460	3.00	311	18.02	55	3.41
	3.25	513	16.57	71	3.94
	3.50	716	16.18	85	4.32
	3.75	864	14.62	122	4.76
	4.00	1053	17.65	173	5.08
	4.25	1152	16.47	234	5.61
	4.50	1368	16.14	316	6.24
	4.75	1449	17.47	370	6.88
	5.00	1706	15.85	410	7.38
540	3.00	378	18.17	69	3.75
	3.25	639	16.27	114	4.28
	3.50	815	16.06	159	4.78
	3.75	1031	17.13	202	5.06
	4.00	1247	14.13	252	5.52
	4.25	1413	14.96	296	6.06
	4.50	1634	17.03	354	6.72
	4.75	1805	18.97	422	7.22
	5.00	1998	18.91	468	7.76

Table 3 Two-way ANOVA results for the effects of voltage and measurement height on air velocity in orchard experiments

Source	*df*	*F*	*Sig.*
Voltage	8	1520.4	0.000*
Height	3	2310.7	0.000*
Voltage×Height	24	42.6	0.000*

**p* < 0.05 was statistically significant.

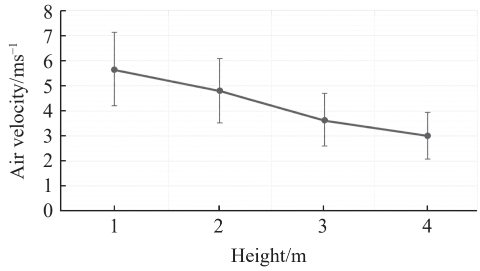


Figure 7 Vertical distribution of air velocity measured downstream of the pecan tree canopy

As the control voltage increased, the mean air velocity measured behind the tree also increased, based on the average of four vertical positions between 1 and 4 m (Figure 8). Despite the reducing effect of the canopy, this trend indicated that voltage-based airflow control effectively regulated downstream air velocity, suggesting that adjusting the control voltage could be an effective approach for maintaining adequate airflow penetration through the canopy. Similarly, Salcedo et al.[8] demonstrated that, assuming a uniform distribution of leaves and a known drag coefficient associated with vegetative growth, the airflow entering and exiting the tree canopy could be described using a logarithmic function. Vigo-Morancho et al.[36] reported that airflow attenuation within olive tree canopies could be modeled using canopy structural parameters and that an air velocity of ≥2 m/s within the canopy represented a practical threshold for adequate spraying performance.

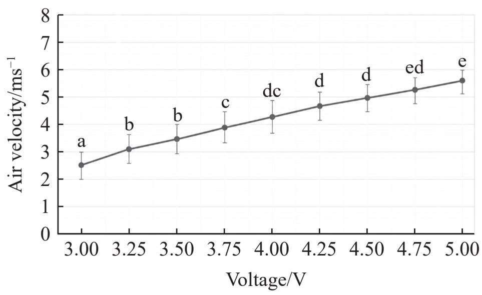


Figure 8 Relationship between voltage and mean air velocity measured downstream of the tree (Different letters in the same columns indicate significant differences at the p<0.05 level)

The relationship between the inlet air velocity directed toward the pecan tree from a distance of 1.0 m and the mean air velocity measured downstream at the same distance, averaged over four vertical positions (1-4 m), was well described by a mathematical model (Figure 9). The high R^2 value (0.9989) indicates that the system behavior can be modeled with high accuracy. These results show that, despite the attenuating effect of the pecan tree canopy, the inlet air velocity associated with fan speed is an effective parameter for quantitatively characterizing airflow downstream of the canopy. Consistent with these findings, Sidahmed and Brown[37] showed that an air velocity of 30 m/s at the fan outlet can decrease to below 10 m/s at a distance of 5 m. Similarly, Zhang et al.[38] developed a practical model combining jet theory with a porous medium approach, demonstrating that the canopy significantly attenuates airflow in air-assisted orchard spraying, with an average error of approximately 15%.

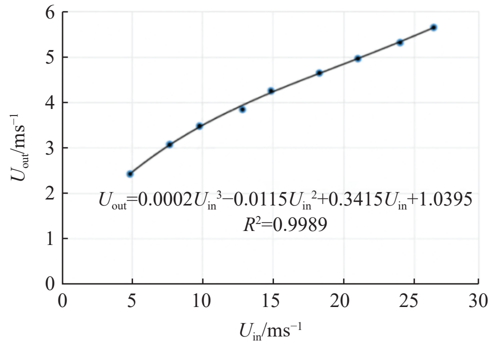


Figure 9 Empirical relationship between average inlet air velocity and average downstream air velocity behind the pecan tree

3.3 Evaluation of spray coverage in orchard trials

3.3.1 Spray coverage variation across canopy height

When all experimental data were considered together, two-way ANOVA indicated that applied voltage to the tips of the proportional valve had a significant main effect on the coverage values (p<0.05). The Y1, Y2, and Y3 values presented in Table 4 represented the mean spray coverage value measured from the upper to the lower canopy positions, respectively. When all data were evaluated together, spray coverage was found to increase consistently from the upper to the lower positions, regardless of the applied voltage level. As the voltage increased, the magnitude of the airflow also increased, which in turn enhanced the amount of droplets transported into the canopy. The Y2 position exhibited spray coverage values that were statistically closer to both the upper (Y1) and lower (Y3) canopy positions within the voltage range of 4.0-4.75 V. This suggests that the airflow conditions generated at these voltage levels may have contributed to a more homogeneous spray distribution in the pecan tree canopy. Zhang et al.[39] determined the optimal terminal air velocity range within a pear canopy by analyzing airflow attenuation toward inner layers. Most velocity reduction occurred in the outer 0-0.3 m of the canopy. While increasing air velocity improved droplet deposition in the middle and inner layers, excessively high velocities reduced deposition uniformity. The optimal airflow range was identified as 2.70-3.18 m/s; within this range, coverage increased, the CV was reduced to 42.25%, and drift decreased by 12.59 μg/cm². When the mean coverage values were evaluated in terms of the spray index, it could be stated that the coverage was insufficient at voltage levels up to 4.5 V. Indeed, as reported by Fessler et al.[40], negative spray index values indicate inadequate spray coverage.

3.3.2 Spray coverage variation with spray depth

Two-way analysis of variance indicated that both spray depth and voltage had significant main effects on spray coverage (p<0.05). When spray depth was evaluated, spray coverage values obtained in the inner canopy blocks (A2, A5, and A8) were found to be lower than those measured in the outer canopy blocks (B1, B2, and B3) (Table 5). This behavior was attributed to the aerodynamic resistance created by the branches and leaves of the tree, together with the progressive reduction in the kinetic energy of the airflow as it penetrated deeper into the canopy. In addition, a portion of the droplets entering the canopy was retained in the outer regions and contributed to spray deposition there, thereby limiting the amount of droplets reaching the inner canopy zones. As the voltage applied to the proportional valve increased, the airflow intensity increased accordingly, which resulted in a clear enhancement of spray coverage within the inner canopy section. Moreover, increasing the voltage level led to simultaneous increases in both spray depth and overall spray coverage. When the spray index values of the S1 and S2 zones were examined, the applied airflow was found to be insufficient at voltage levels up to 4.25 V. This finding indicates that, within this voltage range, the corresponding airflow levels were inadequate in terms of spray coverage and that the spray application was not able to effectively penetrate to the mid-canopy region of the tree.

Table 4 Mean spray coverage values and spray index values at different canopy height positions under varying voltage levels

Voltage	Coverage/%			I_o		
	Y1	Y2	Y3	Y1	Y2	Y3
3.00	23.33±0.12 c	24.93±0.58 b	26.34±0.36 a	–0.072	–0.072	–0.052
3.25	23.79± 0.28 c	25.13±0.17 b	26.39±0.29 a	–0.089	–0.070	–0.052
3.5	24.20±0.38 c	25.49±0.14 b	27.04±0.25 a	–0.083	–0.064	–0.042
3.75	24.82±0.19 c	26.37±0.16 b	28.07±0.22 a	–0.074	–0.052	–0.028
4.00	26.16±0.18 b	28.09±0.17 ba	30.32±0.18 a	–0.055	–0.027	0.005
4.25	28.19±0.47 b	30.52±0.42 ba	33.24±0.20 a	–0.026	0.007	0.046
4.5	31.17±0.66 b	35.94±0.33 ba	38.35±0.57 a	0.017	0.085	0.119
4.75	35.29±0.41 b	38.34±0.26 ba	41.47±0.32 a	0.076	0.119	0.164
5.00	38.49±0.57 c	42.15±0.32 b	46.33±0.29 a	0.121	0.174	0.233

Note: Values sharing the same letter are not significantly different based on Tukey's multiple comparison test (p<0.05).

Table 5 Mean spray coverage values and spray index values at different spray depth positions under varying voltage levels

Voltage	Coverage/%		I_o	
	S1	S2	S1	S2
3.00	46.20±0.64	24.77±1.44	0.23	–0.076
3.25	47.80±0.46	25.09±1.18	0.25	–0.070
3.50	48.26±0.48	25.65±1.08	0.26	–0.062
3.75	49.70±0.56	26.38±1.33	0.28	–0.052
4.00	50.95±0.53	28.16±1.82	0.30	–0.026
4.25	53.49±0.71	30.59±2.32	0.34	0.008
4.50	56.11±0.47	34.68±2.86	0.37	0.067
4.75	61.72±0.70	38.26±2.90	0.45	0.118
5.00	66.62±1.40	42.32±3.41	0.52	0.176

3.4 Comparative analysis of airborne and ground drift

3.4.1 Ground drift

Two-way ANOVA revealed significant overall effects of voltage and ground drift on spray coverage (p<0.05) (Table 6). Ground losses were higher under conditions of low air velocity. At lower voltage levels, no statistically significant differences were observed in ground loss values among the three sampling zones. This finding indicated that a substantial portion of the sprayed droplets failed to reach the tree canopy and was instead lost to the ground. The effect of the air stream became evident at a voltage level of 4.25 V, at which statistically significant differences among sampling zones were detected. As the voltage level increased, ground losses exhibited a decreasing trend. Nevertheless, in samples collected from areas close to the tree trunk, spray drift could not be completely eliminated even under maximum air power.

3.4.2 Airborne drift

The two-way ANOVA showed that airborne drift was significantly influenced by voltage level and trial (p<0.05), with trial-related differences observed within individual voltage levels (Table 7). Up to a voltage level of 3.75 V, no airborne drift was detected, as the mass flux entering the tree canopy was insufficient to generate drift. Therefore, data corresponding to these voltage levels were excluded from the statistical analysis. With increasing air velocity, a greater amount of airborne droplets was observed, particularly in the lower sampling zones. When the voltage level ranged between 4.00 and 4.50 V, no airborne drift was detected at the highest sampling position (D1). However, with the continued increase in air velocity, airborne drift was observed even at the highest sampling positions.

Table 6 Coverage-based ground losses under different voltage levels

Voltage	Coverage/%		
	C1	C2	C3
3.00	62.25±3.05 a	66.31±2.48 a	65.51±5.83 a
3.25	58.21±0.90 a	62.59±0.40 a	68.44±0.11 a
3.50	58.42±0.65 a	60.95±1.62 a	66.84±1.54 a
3.75	42.91±1.37 a	47.34±0.94 a	50.10±0.10 a
4.00	35.06±1.06 a	34.27±2.03 a	35.22±2.88 a
4.25	28.11±0.16 a	22.60±0.37 ba	15.80±1.59 b
4.50	18.15±0.98 a	15.04±1.00 a	8.44±0.62 b
4.75	13.11±1.06 a	4.25±1.51 b	0.00±0.00 b
5.00	5.27±1.01 a	0.93±1.62 b	0.00±0.00 b

Note: Within each voltage level, mean values followed by the same letter are not significantly different.

Table 7 Mean spray coverage values and spray index values at different spray depth positions under varying voltage levels

Voltage	Coverage/%			
	D1	D2	D3	D4
3.00	0.00±0.00	0.00±0.00	0.00±0.00	0.00±0.00
3.25	0.00±0.00	0.00±0.00	0.00±0.00	0.00±0.00
3.50	0.00±0.00	0.00±0.00	0.00±0.00	0.00±0.00
3.75	0.00±0.00 a	0.00±0.00 a	0.00±0.00 a	12.54±1.46 b
4.00	0.00±0.00 a	0.00±0.00 a	16.47±2.05 b	24.63±2.00 c
4.25	0.00±0.00 a	4.75±8.22 b	23.51±1.03 c	33.00±1.13 d
4.50	0.00±0.00 a	13.58±1.14 b	26.42±1.99 c	32.20±1.76 d
4.75	16.91±1.15 a	27.60±2.89 b	35.55±2.51 c	42.55±0.37 d
5.00	17.56±1.24 a	29.10±6.74 b	36.39±6.99 c	47.96±3.54 d

When the ground drift and airborne drift results are evaluated together, it becomes evident that airflow intensity plays a critical role in droplet transport. At low airflow levels, a considerable proportion of the sprayed droplets cannot effectively reach the tree canopy and are deposited beneath the tree, resulting in high ground drift values. As airflow intensity increases, droplet transport and canopy penetration improve, leading to a progressive reduction in ground drift. However, further increases in airflow also result in higher airborne drift. This indicates that excessive airflow not only facilitates droplet penetration into the canopy but also promotes the transport of droplets beyond the target zone. Therefore, the simultaneous decrease in ground drift and increase in airborne drift can be considered an expected outcome in air-assisted spraying systems. Although drift-related losses cannot be completely eliminated, appropriate airflow selection can minimize these losses and improve spraying efficiency.

When evaluated in terms of canopy height, all applications below 4.5 V produced spray index values lower than zero across all canopy levels. Negative spray index values indicate insufficient spray coverage. Similarly, when spray depth results were examined, all applications at 4.25 V and below resulted in negative spray index values in the S2 zone, which represents the inner canopy region. These findings indicate that, under low airflow conditions, droplets were unable to adequately penetrate into the canopy. Consistent with the coverage results, ground drift values were considerably higher at 4.25 V and lower voltage levels. This suggests that a substantial proportion of the sprayed droplets fell beneath the tree before reaching the canopy. In contrast, the airborne drift results showed that no deposition was detected at the highest sampling position (D1), even at 4.5 V. This finding indicates that the airflow generated at 4.5 V was sufficient to transport droplets into the canopy while not causing significant transport beyond the target area. When the coverage and drift results are considered together, it can be concluded that applications at 4.5 V and above provided adequate spray coverage. Although some additional improvements in coverage were observed at 4.75 V and 5.0 V, these gains were achieved at the expense of higher fuel consumption. Furthermore, increasing airflow intensity also increased the risk of airborne drift. Therefore, considering canopy coverage, ground drift, airborne drift, and fuel consumption simultaneously, the 4.5 V operating level was identified as the optimum operating condition under the canopy conditions evaluated in this study. When this value was applied without spraying, the developed mathematical model (Figure 9) predicted an average air velocity of approximately $U_{out} \approx$ 5 m/s behind the tree. In addition, Balsari et al.[41] reported that canopy-exit air velocities around 5 m/s are desirable for improved spray coverage. If the system had been operated at full voltage power and 540 PTO r/min prior to determining the optimal airflow, the fuel consumption would have been 7.76 L/h (excluding draft power); however, once the optimal airflow was established, this value decreased to 5.61 L/h, corresponding to a reduction of approximately 27.7%. Similarly, Doruchowski et al.[42] employed hydraulically driven fans and reported fuel savings ranging from 20% to 40% through airflow adjustment according to canopy requirements.

4 Conclusions

In this study, the axial fan performance of a hydraulically driven orchard sprayer was first evaluated under laboratory conditions, and the airflow values generated at different voltage levels applied to the proportional valve along with the key system performance parameters were determined. The obtained airflow values were then applied to the tree canopy, and the air velocities at the canopy exit were measured. Finally, spray applications were carried out at each airflow level, and the effect of airflow on spray coverage was determined. Accordingly, (ⅰ) the magnitude of the airflow at the outer canopy required to ensure adequate leaf surface coverage was determined; (ⅱ) a more balanced and homogeneous spray distribution across different regions of the canopy was achieved; (ⅲ) although it could not be completely eliminated, operating conditions under which both airborne and ground drift remained at low levels were identified; and (ⅳ) appropriate airflow levels resulted in reduced fuel consumption.

The development of such systems may contribute to increasing agricultural profitability by reducing unnecessary pesticide use and fuel consumption. In addition, this approach may provide a basis for creating an experimental data infrastructure that can be used in the development of data-driven and artificial intelligence-based airflow control systems for future orchard applications. The optimal airflow conditions identified in this study are specific to pecan trees at the BBCH 68 phenological stage under the evaluated canopy conditions (LAI=1.63). Since canopy density influences airflow attenuation and droplet penetration within the canopy, different canopy densities may require different airflow levels to achieve optimal spray performance. Therefore, the results should not be directly generalized to other tree species, canopy architectures, canopy densities, or phenological stages without further validation. Future studies should investigate the interaction between airflow requirements, canopy density, droplet size characteristics, tree architecture, and different phenological stages in order to develop more generalizable airflow recommendations for orchard spraying applications.

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