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# *Development of An Automatic Airflow Control System for Precision Sprayers Based on Tree Canopy Density*

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**ABSTRACT.** *The airflow of a sprayer is a primary component for successfully carrying spray droplets to the target trees. With the variation in orchard tree canopies, it is essential to control the airflow during spray operation. The study aimed to develop an automatic airflow control system for precision sprayers, considering the tree canopy densities for successful spray droplet depositions. The system was developed by retrofitting an iris damper at a three-point hitch airblast intelligent sprayer, which was installed at the sprayer's fans air inlet. A light detection and ranging (LiDAR) sensor was installed at the top of the sprayer. The LiDAR was used to acquire the tree canopy data, and a motor was employed to control the damper's opening with a micro-controller. To investigate the usefulness of the airflow control, a series of field tests was conducted at two different canopy density orchards with different varieties (GoldRush and Fuji). A total of eight trees (four trees from each variety) were randomly selected, and three different damper openings (full opening, intermediate opening, and full closing) were tested for each tree. Water sensitive papers (WSPs) were placed at five different locations of the tree (top, middle, bottom, back-left, and back-right). The airflows were measured at the back-side of the trees, and the spray performance was evaluated based on spray droplet depositions at the WSPs. A canopy density measurement algorithm scripted in MATLAB® was used to measure the canopy point density of individual trees. Two relationships (models) were built between 1) tree canopy points densities and airflows 2) canopy densities and damper openings. The combination of the two models was used to assess the amount of airflow required for a specific canopy density. Results of this study reported the system achieved good mean spray depositions of 37.4%, 36.09%, 51.01%, 23.0%, and 23.72% at the top, middle, bottom, back-left, and back-right positions, respectively for high-density trees using full damper opening. The intermediate opening provided some good insights for low-density trees, however, extensive investigations are needed to make the recommendation.*

**Keywords.** *Automation, Fan inlet, Precision spraying, Sensing, Tree fruit, Variable rate application.*

## 1. Introduction

In fruit orchards, the size and characteristics of tree canopies vary significantly depending on growth stages, cultivars, production practices, and growing season lengths. Variations of tree canopy characteristics are very common among different aged trees and cultivars throughout the growing season in different orchard blocks. The high variability of canopy characteristics can even be possible within trees of the same orchard block (Colaço et al., 2019). The conventional spray applications on the fruit trees using air-assisted sprayers apply chemical constantly with little or no consideration of tree canopy characteristics which is resulted in either over or under dosing with non-uniform spray deposition distribution across trees (Owen-Smith et al., 2019). Inefficient chemical applications cause spray drift and posing severe risks to human health, ecosystems and the environment (Pivato et al., 2015).

Precision sprayer using various advanced sensors is one of the best additions to the spray technologies in recent years, considers the tree canopy characteristics for making spray decisions. The sensors are attached to the sprayer unit to calculate the size, shape, density, and volume of individual trees and then apply an adjusted spray volume accordingly during spraying operations. The applications of advanced sensors have been proven effective to reduce off-target deposition and increase application efficiency (Zhang et al., 2018). Different sensors have been used to measure tree canopy characteristics, including digital cameras, ultrasonic sensors, and lidar sensors. Digital cameras offer high-resolution images to calculate canopy characteristics, but these types of sensors are highly sensitive to illumination variations and provide inferior results (Barbedo, 2019). Ultrasonic sensor system is another sensing technology not affected by illumination variations being used to recognize canopies and gap between trees and manipulate the control of nozzles (Escolà et al., 2013; Palleja & Landers, 2015; Tumbo et al., 2002). These sensors can reduce a significant amount of off-target depositions by assessing canopy characteristics through transmitting and receiving sound waves towards the target trees (Jeon & Zhu, 2012; Llorens et al., 2010). However, the low measurement resolution, limited penetration capability, and higher dependency on forward speed and weather condition are considered the main limitations of these sensors, making the ultrasonic sensing technology outdated in real-time spraying (Colaço et al., 2018). The LiDAR sensors transmitting visible laser light through a lens towards the orchard trees can penetrate to the vegetation canopies and provide fast measurement with high resolution, which is not affected by weather conditions (Berk et al., 2016). These sensors have been used to detect tree presence, canopy size, and leaf density in orchards, nurseries, and vineyards with stable and independent accuracy while taking three-dimensional measurements (Chen et al., 2012; Liu & Zhu, 2016). These types of sensors have also been successfully tested in real-time field conditions and resulted in uniform spray distribution with higher efficacy and efficiency (Boatwright et al., 2020; Cai et al., 2019; Chen et al., 2012).

Canopy density is an important canopy characteristic that can characterize tree structure and determine the appropriate spray volume for precise agrochemical applications (Hu & Whitty, 2019; Mahmud et al., 2021; Wei & Salyani, 2005). Several studies have been conducted using LiDAR sensors and showed the high precision for tree canopy density measurements aimed to help in decision making for precise/variable-rate spraying. Hu and Whitty (2019) used a mobile terrestrial system using 2D LiDAR to measure canopy density distribution of trellis-structure and standalone apple orchards. The average correlation coefficient of canopy density measurement was about 0.90. Mahmud et al. (2021) measured the tree canopy density using a 3D LiDAR in high and low-density tree orchards and achieved a high correlation of 0.95 in low-density tree orchard compared to 0.82 in high-density orchard. Berk et al. (2020) calculated leaf area density through 3D LiDAR and obtained the maximum correlation of 0.80 when establishing the relationship between tree canopy volume and leaf area density. Béland & Kobayashi (2021) used a multi-view terrestrial LiDAR sensor for mapping forest leaf area density and reported the potential of using LiDAR sensor in mapping leaf area density with even densely tree areas.

Sprayer airflow is a primary component for carrying the spray droplets to the target trees. A single fan operated by the tractor power take-off (PTO) located at the rear of the machine that pulls air in and redistributes it upwards into the tree canopy (Fox et al., 2008). For appropriate spray deposition and coverage, the volume of air released from the fan must be matched with the tree canopy. Currently used sprayers discharge constant airflows that are independent of the tree canopy size and density. In most cases, the airflows are either too high or too low leading to either over sprayed or under sprayed (Zhu et al., 2008). Another major problem is the fixed air velocity profiles cause off-target depositions to air and ground (Gu et al., 2014; Zhu et al., 2006). Although significant amounts of research have been conducted on nozzle flowrate control, very few studies investigated the airflow control of the orchard sprayers, particularly in real-time. Pai et al. (2009) designed and placed a deflector plate at the air outlet to control the airflow during spray operation, but their system was hindered by the limited space of at the air outlet. Gu et al. (2012) installed an iris damper at the air inlet (rear of the sprayer) to regulate air velocities. Another attempt by Gu et al. (2014) was reported to varying the airflow rates by changing the fan inlet diameter considering different sized trees and canopy densities. Both experiments were conducted at the laboratory conditions with fewer trees which must be different environment than field conditions. Among the studies surveyed, most of the researchers did not able to control the airflow in real-time, which is needed for successful spray deposition and reduce off-target deposit.

The primary aim of this study was to develop an automatic airflow control system based on tree canopy density using a LiDAR sensor and an iris damper for uniform spray deposition. The specific objectives were to (i) investigate the spray deposition on different density trees with three different damper openings, (ii) establish a relationship between tree canopy points and airflow penetration, (iii) develop a relationship between tree canopy densities and damper openings.

# 2. Materials and Methods

## 2.1. Automatic Airflow Control System Development

### *2.1.1. Hardware Integration*

A three-point hitch-mounted airblast intelligent sprayer (Smartguide Systems Inc., Indianapolis, IN, USA) was used as a base unit. This was a standard PTO-powered sprayer (Pak Blast 150, Rear's Manufacturing Co., Coburg, OR, USA) equipped with a 2D LiDAR scanner, sixteen solenoid values and hollow cone nozzles (eight per side), 567 L (150 gallons) tank, a single axial-flow fan (30 inches (0.76 m) diameter; 32° blade pitch), and operated by a tablet computer (Samsung Electronics Co. Ltd., Suwon-Si, South Korea). The 30 inches (0.76 m) PTO-driven axial-flow fan had two operating speeds (540 rpm and 1000 rpm). The 540 rpm was used in this study due to experimented with the bloom staged apple trees. The air outlet of the sprayer had an inverted U-shaped slot of 1.44 × 0.13 m on each side along its periphery. Under the standard fan setting, the total volume rate of air output was about 16 $m^3.s^{-1}$. An iris damper (Continental Fan Manufacturing Inc., Buffalo, NY, USA) was retrofitted to the sprayer air inlet for airflow control. The damper is comprised of a casing, damper blades, and a regulating nut. The internal and external diameters of the iris damper were 0.80 m (31.4 inches) and 0.81 m (32 inches). A 3D VLP-16 LiDAR scanner (Velodyne LiDAR, San Jose, CA, USA) was used to create tree canopy density point maps. The tree canopy data were scanned using the 3D LiDAR scanner, and laptop computer (Dell Technologies Inc, Round Rock, TX, USA) installed at the sprayer unit. The LiDAR scanner produced sixteen vertically separated beams (eight at the left and eight at the right) with an angular resolution of 2° were used to scan the fruit trees. The scanner was attached to an aluminum frame with a height of 1.70 m above the ground level. It has the ability to scan up to 0.3 million points per second with an accuracy of ±3 cm. The 32-inch (0.81 m) diameter iris damper was used to adjust the air inlet openings aimed to control airflows based on tree canopy densities. A high torque planetary geared stepper motor (OSM Technology Co. Ltd., Ningbo, China) was attached to the iris damper to precisely control the openings. The motor had 0.035° step angle with NEMA 17 bipolar 4-wire, a planetary gearbox ratio of 50:9:1, and a rated current of 1.68 A and resistance of 1.65 ohms. An Arduino controller was used to control the step motor as well as the airflow regulator to control the opening of the damper.

### *2.1.2. Canopy Data Collection and Airflow Measurement*

To determine ideal airflow needed for the particular sized tree, two types of data were collected, including the number of canopy points of individual tree and adequate airflow required for uniform spray coverage and deposit density. The data collections were conducted in two different sized trees from two different orchards. One orchard planted with GoldRush variety and another orchard with Fuji variety were studied. The orchards were located at the Penn State Fruit Research and Extension Center, Biglerville, Pennsylvania. The tree size was classified as low and medium density based on the number of canopy points scanned from individual trees. The 3D LiDAR scanner and the data acquisition program developed in MATLAB® (The MathWorks Inc, Natick, MA, USA) were used to scan the trees. The trees were scanned from a constant height (1.7 m above the ground level) regardless of the tree size. Targeted trees planted in the experimental rows were scanned. Four randomly selected trees from two rows (two trees per row) were scanned from each orchard.

To determine the effective airflow required for particular density trees, the spray operations were performed with different openings of the air inlet by changing the opening of the iris damper. Three different openings were used, including full opening, intermediate opening, and full closing with opening diameters of 31.4 (0.80 m), 22.34 (0.57 m), and 13.3 (0.34 m) inches, respectively (Fig. 1). The 0.80 and 0.34 meters were the maximum and minimum opening diameter of the damper.

(a) (b) (c)

**Fig. 1. Three different damper openings used for this study (a) full opening, (b) intermediate opening, (c) full closing**

The spray operation was accomplished using an intelligent sprayer with one damper opening at a time in each targeted tree, and the airflow was recorded at the back-side of the tree (0.64 m from the tree trunk) (Fig. 2b). The airflow was recorded using a handheld Kestrel 3550AG weather meter (Kestrel Instruments, Boothwyn, PA, USA) at a constant height (1.55 m) due to maintaining the uniformity of the data collection. One airflow reading was recorded from one tree because it would not be possible to control the opening of the damper more than once at a time for a tree. The spray operation was conducted three times on the same trees with three different damper openings. Water sensitive papers (WSP) (Syngenta Crop Protection AG, Basel, Switzerland) with size 26 mm × 76 mm were placed at five different locations of the tree before each spray operation. Five locations were top (L1), middle (L2), bottom (L3), and the other two (L4 & L5) were at the back-sides (back-left and back right when facing toward the tree) of the L2 at the same height parallel to the driving direction (Fig. 2a). The WSPs were used to assess the uniformity of the coverage because of their simplicity of visualization (Salyani & Fox, 1999; Cerruto et al., 2019) (Fig. 3). The papers were collected after WSPs, and leaves of trees were dry and stored in the sealed bags until they were brought for laboratory analysis. After collecting WSPs for one spray operation, the new WSPs were placed for the next spray operation with different damper opening. The collected WSPs were scanned in the laboratory using a portable business card scanner (CSSN Inc., Los Angeles, CA, USA) with imaging resolution at 600 dpi and a scan capability width up to 10.5 cm. The spray coverage and deposit density on each scanned WSP were accessed using the DepositScan program (Zhu et al., 2011).

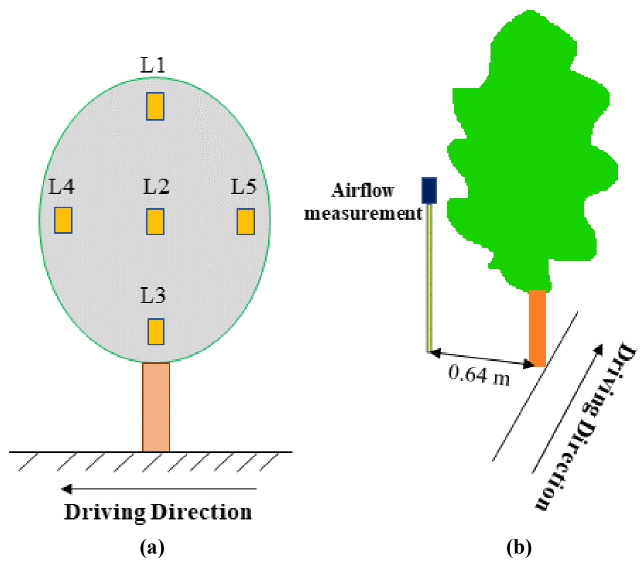


**Fig. 2. Experimental setup for (a) spray deposition (L1 to L5 are the position of water-sensitive paper) and (b) airflow measurements**

(a) (b)

**Fig. 3. Water sensitive papers placed at the tree (a) before and (b) after spray operation**

### *2.1.3. Canopy Data Processing for Density Measurement*

Tree canopy density measurement procedure described by Mahmud et al. (2021) was applied to calculate canopy density for eight scanned trees from two orchard blocks. The scanned tree included point cloud data represent the geometric coordinates of tree canopies. Transformation of the point cloud data was performed to render the tree straight as like original orientation of the tree. The scanned point cloud data also included points from grounds and tree from the same and other rows, were removed during the pre-processing. Only the canopy points from the targeted tree were segmented by setting region of interest (ROI). The ROI was different among the two variety trees due to different tree heights and widths. The ROI of -1 to 0.5 m in the x-axis, 2 to 4 m in the y-axis, and -2 to 1.5 m in the z-axis were chosen for GoldRush trees. The ROI of -0.5 to 0.4 m in the x-axis, 1.75 to 2.75 m in the y-axis, and  -1.5 to 1 m in the z-axis were selected for Fuji trees. The number of canopy points was counted from individual ROI using a custom *findPointsInROI* and *select* functions. The first function was applied to find the canopy indices, and the second function was applied to count the number of canopy point within the ROI. The total number of counted points was used to assess the density of targeted trees (Fig. 4).

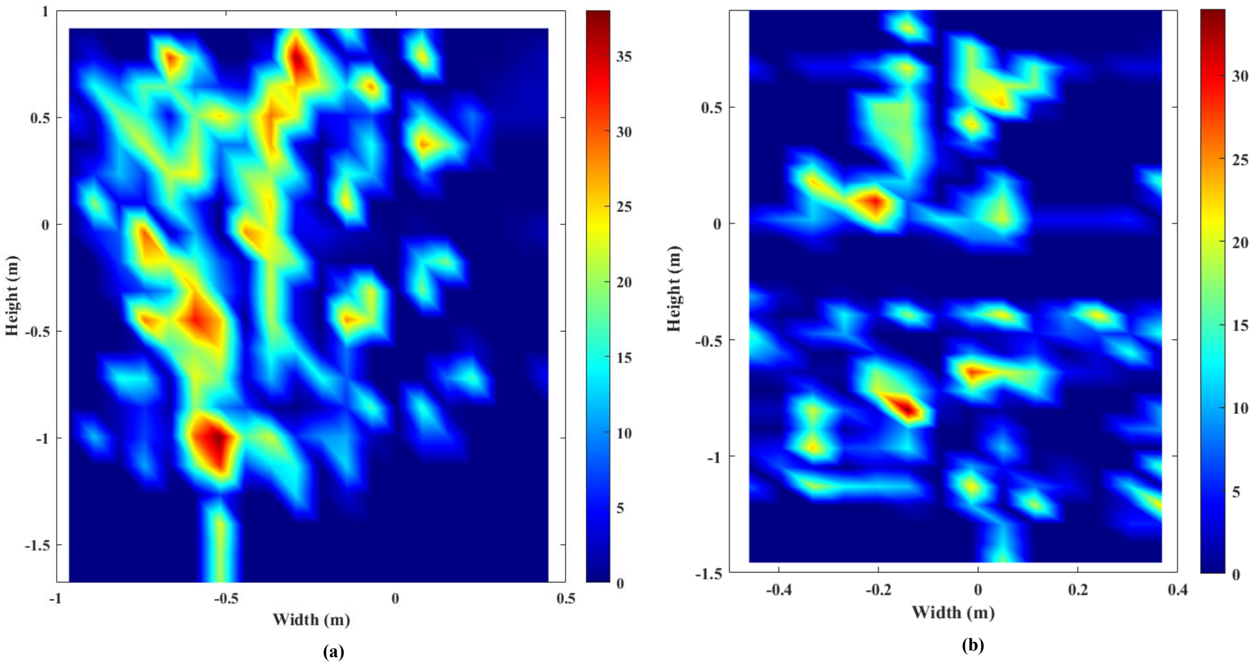


**Fig. 4. Canopy density map (a) tree from GoldRush orchard (b) tree from Fuji orchard**

### *2.1.4. Model Development and Automatic Airflow Control*

The damper opening and corresponding airflow for the targeted trees were selected based on counting the highest number of WSPs with uniform spray coverage and deposit density among three different openings and their airflows. Suppose the sprayer with damper opening 31.4 inches (diameter) and airflow of 4.5 ms-$^{1}$ had five WSPs with uniform spray coverage and deposit density on the targeted tree no. 4 (canopy point density of 1200) to other openings and airflows. This study selected an opening of 31.4 inches and airflow of 4.5 ms$^{-1}$ for this particular density tree. The similar procedure was followed for all the targeted trees used for these experiments. The recorded targeted tree's canopy points, damper openings, and airflows were used for developing three mathematical models to predict the required airflow for particular density trees. The recorded tree canopy densities and corresponding selected airflows were used to develop a regression model to predict the required airflow according to the tree canopies. Another mathematical model was developed to assess the damper opening required after calculating the tree canopy density. To control the damper opening using a stepper motor, a model was built between motor steps and damper opening to control the opening precisely and varying the airflow with respect to openings during spraying operation (Fig. 5).

An algorithm was developed to locate the current position of the damper blades. Subtraction was performed from the required damper opening to the current damper blades position. Based on the subtraction, the algorithm was found out either the rotation is needed in the clockwise or anti-clockwise directions. The resulting damper opening diameter was converted to the required steps. The rotation direction was sent to the Arduino Uno micro-controller to adjust the damper opening in the required direction. The microcontroller was communicated to the MATLAB® software through serial communication. A stepper motor control program was uploaded to the Arduino to receive steps and rotations information to control the damper openings for automatic airflow control during the spraying operation. The overall procedure for the automatic airflow control system is summarized in Figure 6.

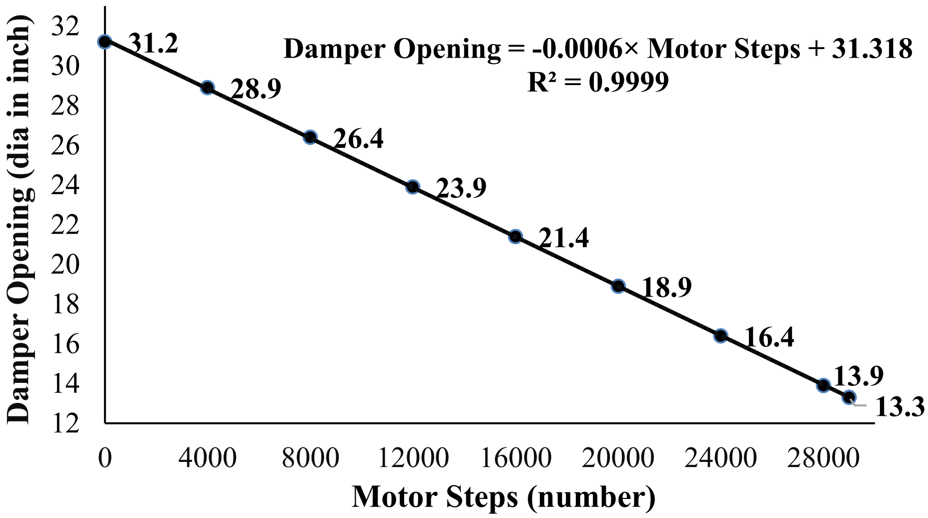


**Fig. 5. Relationship between motor steps and damper openings**

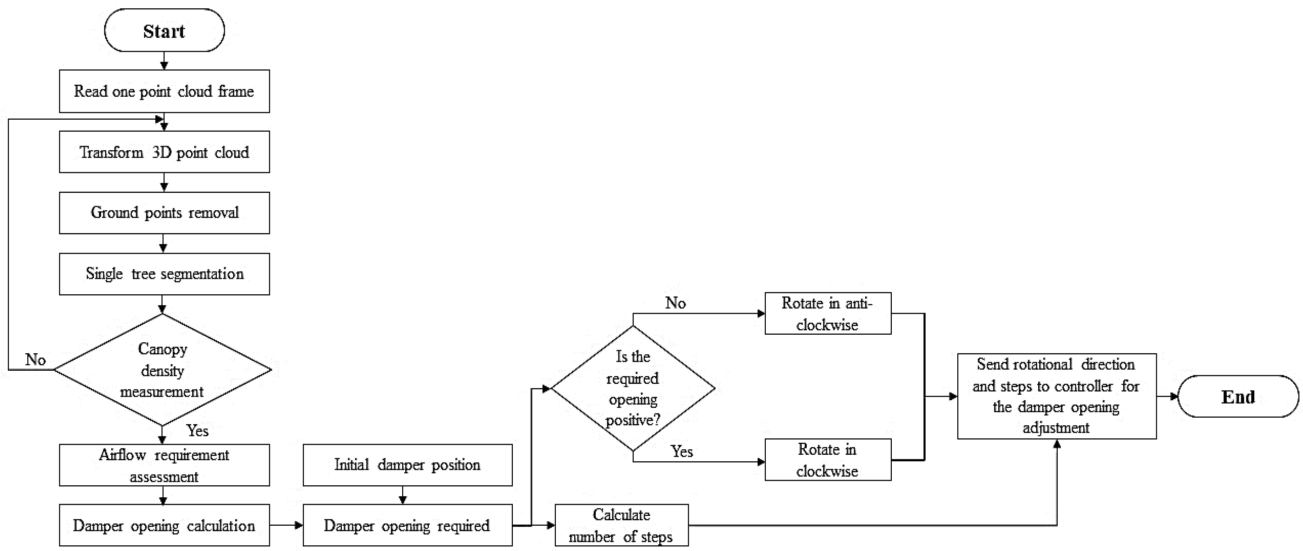


**Fig. 6. Flowchart for automatic airflow control based on tree canopy density**

### 2.2. Statistical Analysis

One-way Analysis of Variance (ANOVA) along with Tukey's test was performed to examine the difference of spray depositions among three different opening using Minitab® 18 statistical software (Minitab® Inc., State College, PA, USA). The coefficient of determination ($R^2$) was calculated between tree canopy points and airflows and between tree canopy points and damper openings for performance evaluation.

## 3. Results and Discussion

### 3.1. Spray Deposits for GoldRush Orchard

As shown in Figure 7, the spray deposits were significantly affected by the damper openings at the confidence level of 95.0%. It is worth noting that the sprayer nozzles were discharged the same amount of spray volume in case of all three openings because the decisions of spray volume were made after calculating tree canopy density. The variations of the spray deposits were observed due to the change of the airflows. The mean depositions of 37.4%, 36.09%, 51.01%, 23.0%, and 23.72% at top, middle, bottom, back-left, and back-right positions, respectively, were comparatively higher when sprayed with full opening than intermediate opening and closing stage. The statistical results reported a significant difference between damper openings (full opening, intermediate opening, and closing). The sprayer with full damper opening offered significantly good depositions at the middle and back-side sections compared to the other two openings, where the non-significant depositions resulted at top and bottom sections. Even though there were mean differences of 10.72% and 8.6% at the top and bottom sections between full and intermediate openings, the sprayer was also given fairly good spray depositions at the top and bottom sections using intermediate opening. The spray deposition of the intermediate opening was poor for the middle and back-side sections due to the lack of airflows generated in that particular sections by the sprayer unit. A significant amount of spray droplets was deposited to the ground due to the greater distance between the sprayer and trees while spraying and environmental airflow blown from the opposite side of the spraying direction. There might be a chance that the sampler position had also significantly influenced the spray deposits and coverages. However, trees themselves did not significantly affect the spray coverage, only when spraying with different damper openings. The lowest depositions of 0.0%, 3.91%, 0.8%, 0.08%, and 0% for the top, middle, bottom, back-left, and back-right positions, respectively were accomplished with closing full damper. These were due to the airflow generated by the sprayer was too low because of the closed air inlet, where the good airflow is needed to send the spray droplets to the targeted positions was in lack. At closed damper, most spray droplets appeared to fall on the ground before reaching the targets.

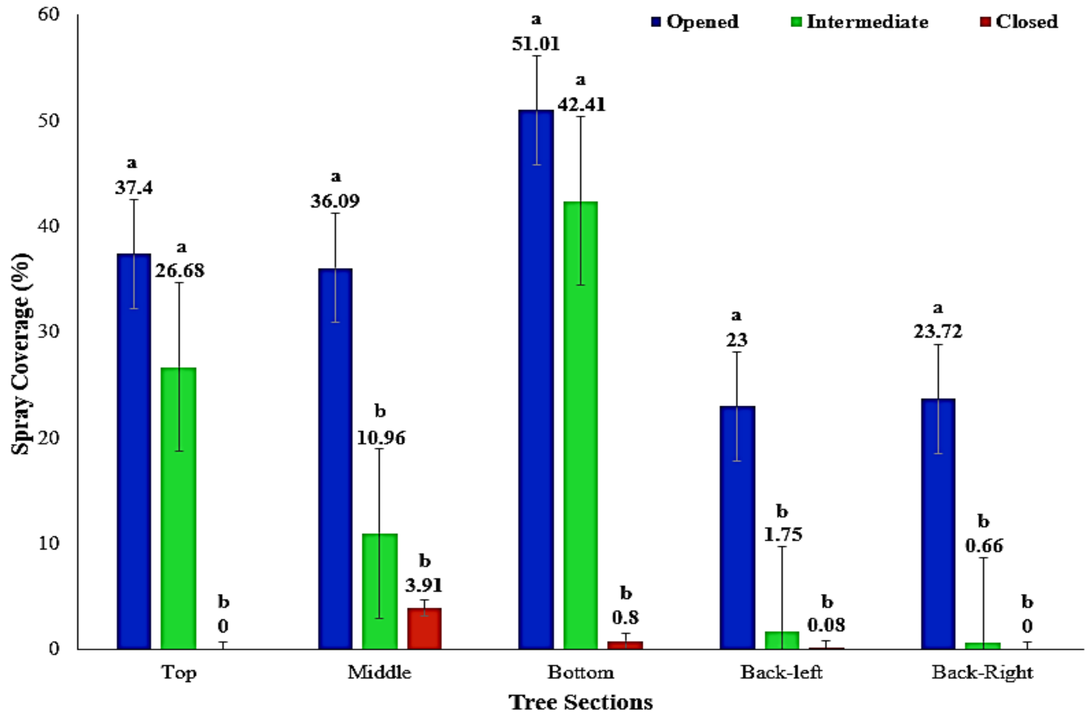


**Fig. 7. Spray coverage for GoldRush orchard**

### 3.2. Spray Deposits for Fuji Orchard

The spray deposition results for the Fuji orchard using three different openings were presented in Figure 8. The highest mean depositions were from full damper opening with spray coverages of 63.37%, 65.3%, 80.06%, 53.63%, and 64.88% for top, middle, bottom, back-left, and back-right positions, respectively, where the lowest mean depositions were 33.5%, 50.92%, 41.12%, 40.98%, and 40.35% from the closed damper. The experimental results were reported non-significant spray depositions among full opening, intermediate opening, and closing stages. The major reason for these non-significant results was the smallest sized tree with very low canopy density. The generated airflows with three different damper openings were able to contribute to the depositions. Also, the distance between the sprayer and trees were very close, which yielded the depositions for all three openings. The variation of the experimental spray depositions was large among the three openings due to the movement of the samplers during spray operations. Some of the samplers were turned around, some were faced inclined, and some were twisted while spraying. The sampler attached to the tree branches was thin that could not sustain the sprayer airflows that caused these kinds of sampler movements. Although the results reported non-significant differences among openings, the spray operation with full opening caused mostly overdosing. The depositions using intermediate opening was comparatively good, especially in the top, bottom, and back-side of the trees, however, the middle section was over-sprayed. The generated airflow from the sprayer was not distributed to the different sections of the tree due to lower air speed. There were also good spray depositions within different sections using the closed damper because of testing with the small tree with spraying from a very close distance. However, the deposition using a closed damper could be greatly affected by tree size, and the distance of spray operation may not be suitable for uniform spray deposition within different sections of the fruit trees.

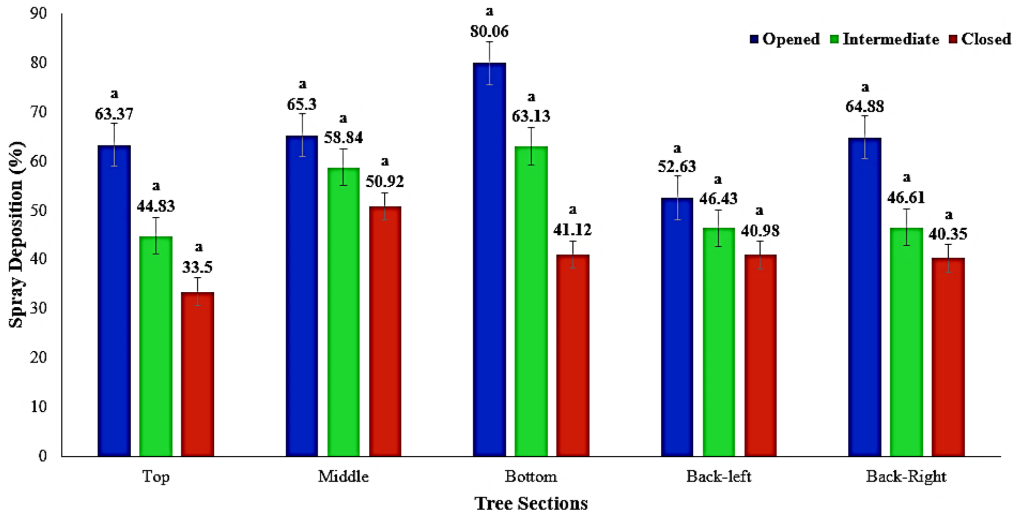


**Fig. 8. Spray coverage for Fuji orchard**

### 3.3. Quality of Spray Deposits

According to Garcerá et al. (2011), the high coverage does not necessarily indicate the effective spray application. The effective coverage depends on the uniformity of the spray droplets. Fig. 9 shows images of the spray coverage on WSPs located at the five positions of a tree from the GoldRush orchard. Higher coverages with uniform deposition were observed when the target tree sprayed with the full damper opening. The intermediate opening also presented good deposition in the top, middle, and bottom sections but provided poor depositions at the back-side of the tree. The fully closed damper seemed to have very little or no coverage, especially in the top and back-side of the tree, which was not suitable for high-density trees.

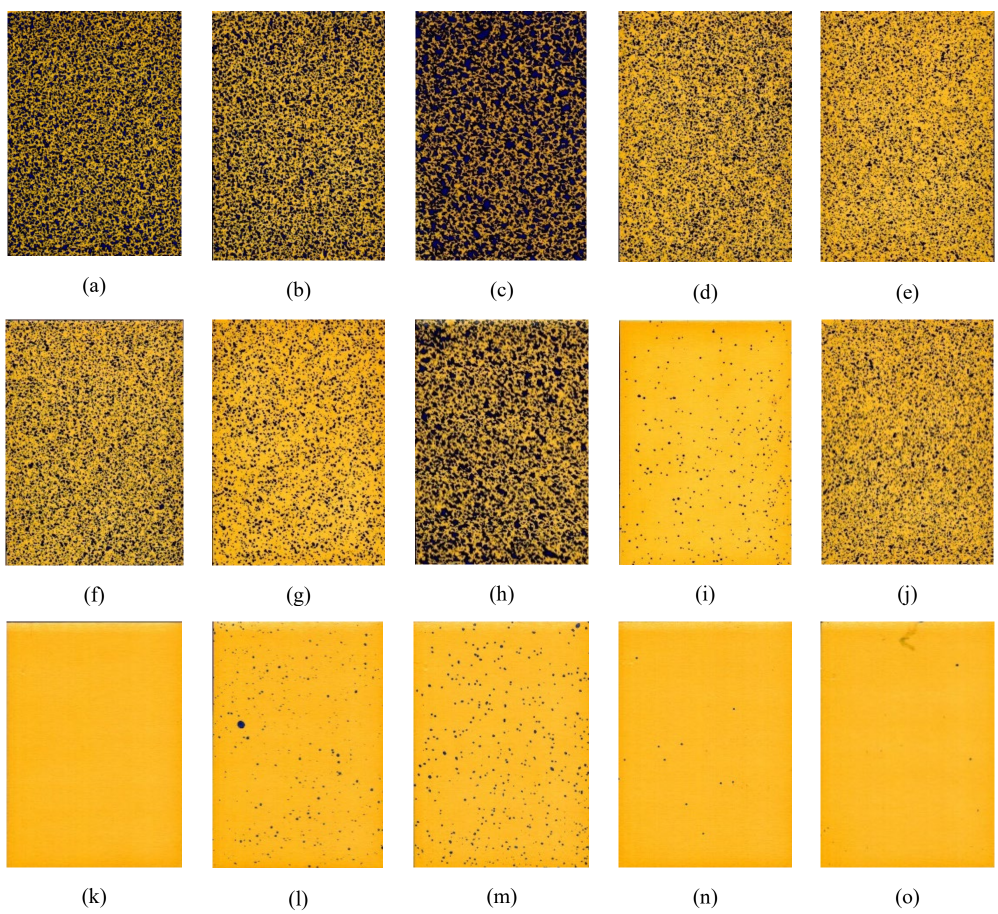


**Fig. 9. Spray coverage for a GoldRush tree at the top, middle, bottom, back-left, and back-right positions (a → e: using full opening damper, f → j using intermediate opening damper, and k → o using closed damper)**

### 3.4. Airflow Measurements and Damper Openings

An airflow measurement model was built between tree canopy points and sprayer airflows to calculate the required air speed for different density trees (Fig. 10). The relationship was built using the airflow measured at a certain distance from the back of the tree. The airflow was higher at the low-density trees compared to the high-density trees. The air could easily pass through low-density trees where it was interrupted by the canopies for the high-density trees. In these experiments, the high-density trees provided good deposition than the low-density trees. It is worth mentioning that it may be useful for the low-density tree to spray at a low air speed. Despite the results from the Fuji orchard with low canopy density showed some good insights, more investigations are expected to develop a strong airflow prediction model for effective spray operations. The preliminary findings of this study highlight that the airflow between 4-5 mph might be good for the uniform spray deposition.

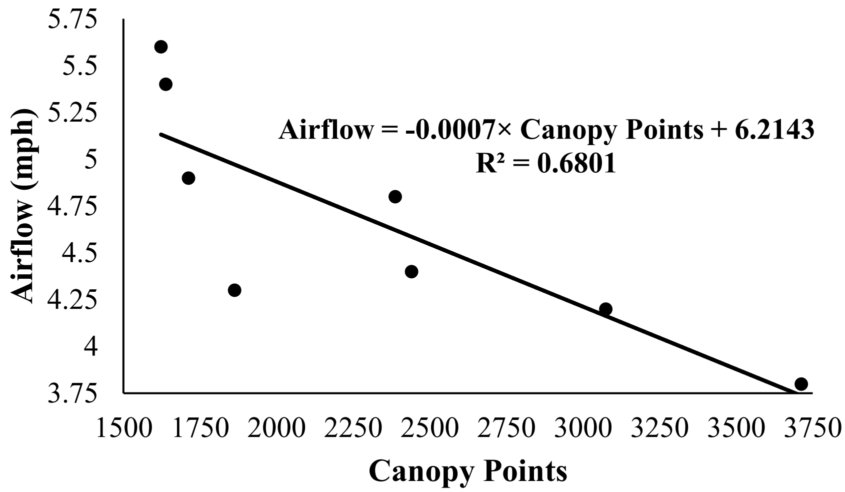


**Fig. 10. Relationship between tree canopy points and airflows**

Another relationship was developed between canopy points and damper opening diameters to predict the opening needed for the particular density trees aimed to generate efficient airflow for uniform spray deposition (Fig. 11). The opening diameter increased with increased canopy points. The model is developed in this study using three opening diameters with two types of density trees, however, a good model has to be built with different density trees with varying diameters of opening.

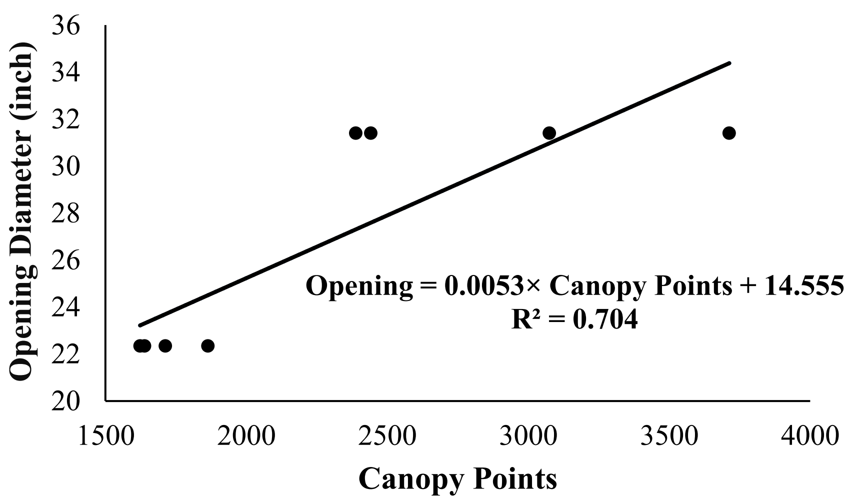


**Fig. 11. Relationship between tree canopy points and damper openings**

The primary attribute of the airflow in airblast sprayers is its capability to agitate canopies and to transmit the spray droplet to the target tree positions. The measurement of effective airflow is important considering various tree canopy densities. Although this study was conducted with two tree canopy densities, the findings of this research will be a basis for the future precision sprayer design with capabilities of variable-rate airflow control. In addition, the experimental test results reaffirmed that the adjustment of fan air inlet could improve airflow penetration into tree canopies and be capable of reducing off-target spray depositions and drift. Even though the developed automatic airflow control system is not validated in the orchard conditions, the preliminary observations have highlighted the challenges of real-time airflow adjustment due to mechanical motions of the airflow regulator. The motions may not be fast enough to make the real-time constant adjustment based on individual tree canopy density. However, it might be possible to adjust the air inlet (damper opening) within few trees using this approach. Moreover, modern fruit trees planted in a row are not having tremendous variation in canopy density unless the trees are affected by severe diseases. Thus, instead of adjusting airflow for individual trees, it may be more realistic to control the airflow after certain trees for variable-rate spraying operation. The fast controller and mechanical systems may make this developed system suitable for controlling airflow based on the individual tree will be studied in the future. Continuation of this study with different tree canopy densities with various air inlet openings in the future will guide the development of the automatic airflow control system for real-time airflow adjustment and spray operation for individual trees.

# 4. Conclusions

Airflow in airblast sprayers is a critical parameter for spray applications, responsible for spray drift and poor deposition. This study developed an automatic airflow control system that distributes adequate air aimed to carry the droplets from the sprayer nozzles to the target trees and reduce off-target deposition and drift. An electro-mechanical control system was developed with the capability of changing air inlet diameter. Two density trees (low and high) were studied, and results reported that air penetration decreased as canopy density increased. The airflow to the targeted tree decreased as the iris damper opening diameter (air inlet diameter) decreased. The full damper opening offered higher deposition compared to the other two openings; however, it is not suitable for spraying low-density trees. The intermediate damper opening could be suitable for low-density fruit trees, but more experiments are needed to weigh up its potential. The evaluation of spray coverage is necessary to assess the quality of spraying because always the high coverage does not certainly mean good deposition. The developed mathematical models could be able to calculate the airflow amount and required damper opening for uniform sprayer depositions. However, validation of these models is necessary before using them for actual spray operations. The developed automatic control system is functional in real-time changing of airflow from an intelligent airblast sprayer; however, mechanical motions of the airflow regulator is not fast enough, as it is constrained by the limitations of the iris damper installed at the sprayer air inlet. Therefore, the improvement of the mechanical motion for the iris damper should be performed in order to make the idea practical for controlling the airflow of individual trees.

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