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Reservoir Units Optimization in Pneumatic Spray Delivery-Based Fixed Spray System for Large-Scale Commercial Adaptation

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Abstract: A pneumatic spray delivery (PSD)-based solid set canopy delivery system (SSCDS) consists of in-line reservoirs and micro-emitter assemblies distributed throughout perennial crop canopies. The existing PSD-based SSCDS uses a large number of reservoirs, i.e., one unit per 3 m of linear spacing, which resulted in high installation and maintenance costs. These reservoirs also produces up to 25% post-spray chemical losses. Therefore, this study aimed to optimize the volumetric capacity and functionality of the existing reservoir for an efficient spray performance and the large-scale commercial adaptation of PSD-based SSCDS. Three reservoirs with volumetric capacities of 370 (1×), 740 (2×), and 1110 mL (3×) were developed to cover a spray span of 3.0, 6.1, and 9.1 m, respectively. Five system configurations with modified reservoirs and spray outlets were evaluated in the laboratory for pressure drop and spray uniformity. The three best system configurations were then field evaluated in a high-density apple orchard. These configurations had reservoirs with 1×, 2×, and 3× volumetric capacity and micro-emitters installed in a three-tier arrangement. Each replicate configuration was installed as a 77 m loop length encompassing 50 apple trees trained in a tall spindle architecture. A pair of water-sensitive paper (WSPs) samplers (25.4 × 25.4 mm) were placed on the abaxial and adaxial leaf surfaces in the bottom, middle, and top third of the canopy to evaluate the spray coverage (%). The PSD-based SSCDS showed no significant difference at the 5% level in terms of coverage among the three reservoir treatments. Coverage was more evenly distributed among the top, middle, and bottom zones for the 2× and 3× as compared to the 1× reservoir treatment. Overall, compared to the 1× reservoirs, the 2× and 3× reservoirs could potentially reduce the system costs by USD 20,000 and USD 23,410 ha^{-1}, respectively, for tall spindle apple orchards and potentially reduce maintenance needs as well.

Keywords: fixed spray delivery; SSCDS; reservoir modification; spray uniformity; pressure drop; spray coverage

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1. Introduction

Washington State is the largest producer of fresh market apples in the United States, with a 69% share in total production [1]. Air-blast sprayers are most commonly used for agrochemical spraying in commercial apple production. Such sprayers have several reported shortcomings, including a high off-target drift [2–6], adverse effects on non-targeted living organisms [7,8], worker safety [9], soil compaction [10,11], dependency on the ground condition, and high greenhouse gas emission [12]. To alleviate some of these issues associated with air-blast sprayers, variants of fixed spray delivery systems have been studied in the USA and the EU [6,13–25]. A solid set canopy delivery system (SSCDS) is one such variant consisting of an applicator and a canopy delivery system with an array of emitters installed in the canopy [6,14–16,20–23,26,27].

Recent SSCDS optimization studies have been mostly focused on the emitter configuration and their effect on spray deposition, coverage, and drift [6,14–16,22,23,26,27]. Additionally, the biological efficacy of SSCDS has been investigated, which reportedly provides comparable pest management to that of an air-blast sprayer [17,20,21,28]. Based on the spray delivery technique, SSCDS can be broadly divided into either a hydraulic spray delivery (HSD) system or a pneumatic spray delivery (PSD) system. The frictional losses in an HSD-based SSCDS result in a significant pressure drop along the spray line, leading to the non-uniformity in the spraying [29]. To overcome pertinent problems, our research group has developed a pneumatic spray delivery (PSD)-based SSCDS [22]. The PSD-based SSCDS consists of a series of reservoirs along the spray line to realize a metered volume of spray liquid delivery per unit row length. Such an approach has been reported to have a 3–20% higher spray output compared to HSD-based SSCDS [22]. However, the existing reservoir design of PSD systems results in a post-spraying chemical loss of up to 25% on the ground through the auto drain valve [26]. Such ground deposition may also cause soil contamination [30].

A modification in the reservoir design was thus sought, along with the inclusion of a self-cleaning ability in the PSD-based SSCDS. Furthermore, the existing PSD-based SSCDS uses reservoirs with a 370 mL volumetric capacity installed at a linear spacing of 3 m in modern apple orchards, which results in large numbers of reservoirs per ha. For example, an SSCDS installation in an apple orchard with a plant spacing of 1.5 m and a row spacing of 2.7 m will require about 1200 reservoir ha^{-1}. This can lead to high installation and maintenance costs. Therefore, this study was undertaken to optimize the PSD-based SSCDS in order to reduce the post-spray chemical losses and improve the system's commercial viability by increasing reservoir capacity. The specific objectives were the following:

1. Design modification of the reservoir unit in the PSD sub-system of SSCDS for larger volumetric capacity deliveries from each unit and minimize the post-spray ground losses;
2. Laboratory and field evaluation of different PSD-based SSCDS configurations for the realization of an optimal system for apple orchards trained in a tall spindle training architecture.

2. Materials and Methods

2.1. Reservoir Modification

The design of the existing reservoir unit consists of a bleed valve, floating valve, liquid column, pressure regulator, emitter supply column, and an auto drain valve (Figure 1a). Functionally, the floating valve moves down with the spray liquid during spraying operations. Once the spray cycle is over and no spray mix is left in the reservoir, the floating valve seals the reservoir to close the passage for compressed air in the emitter feedlines (Figure 1b). The surplus spray liquid in the emitter supply column of the reservoir and emitter feedlines drains onto the ground through the auto drain valve. This results in pesticide loss from each unit. For a reservoir with two emitter feedlines configured in a three-tier arrangement, Ranjan et al. (2021) [26] quantified this loss to be as high as 25%. This loss may be higher for multi-emitter feedline configurations. Therefore, the reservoir design was modified in this study. The reservoir float was eliminated, and the emitter supply column and the auto drain valve were replaced with a multiport manifold (2-, 4-, and 6-port, Figure 2b–d) to connect the emitter feedlines to the reservoir. Such modifications facilitated the uninterrupted flow of the compressed air through the emitter feedlines, with no chemical residues in the reservoir and feedlines (Figure 1d) at the end of the spraying cycle. Additionally, the orientation of the bleed valve was changed from 45° to 90° in order to improve the sealing of the filled reservoir during the charging cycle (Figure 1c).

Next, reservoirs of three different sizes, i.e., volumetric capacities (1×, 2×, and 3×), were fabricated and tested in the laboratory (Figure 2a). The size of the 1× reservoir (volumetric capacity = 370 mL) was equal to the existing reservoir and was designed to spray two trees (spray span = 3.0 m) per reservoir. The volumetric capacities of the 2× (740 mL) and 3× (1110 mL) reservoirs were two and three times that of the 1× and were designed to spray four (spray span = 6.1 m) and six trees (spray span = 9.1 m) per reservoir, respectively. The length of the liquid column was increased (Figure 2a) to augment the capacity of the reservoirs. The modified-reservoir retrofitted PSD-based SSCDS were configured in a three-tier arrangement.

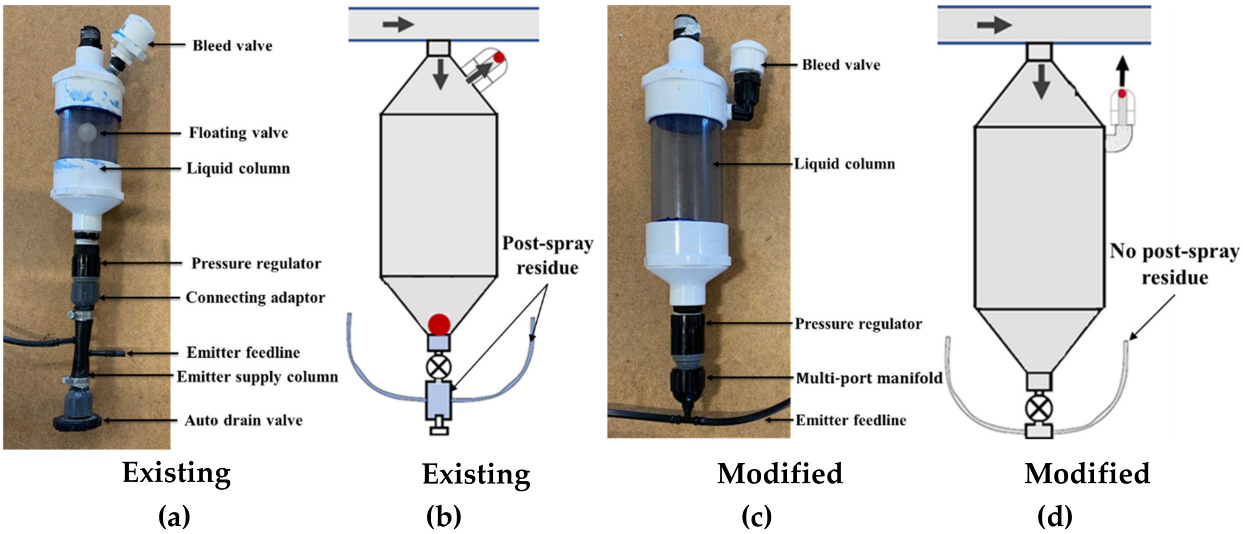

Figure 1. (**a**) The existing reservoir with (**b**) post-spray pesticide residues in the system, and the (**c**) modified reservoir with an improved self-cleaning ability and (**d**) no residues at the end of the combined spraying and cleaning cycle.

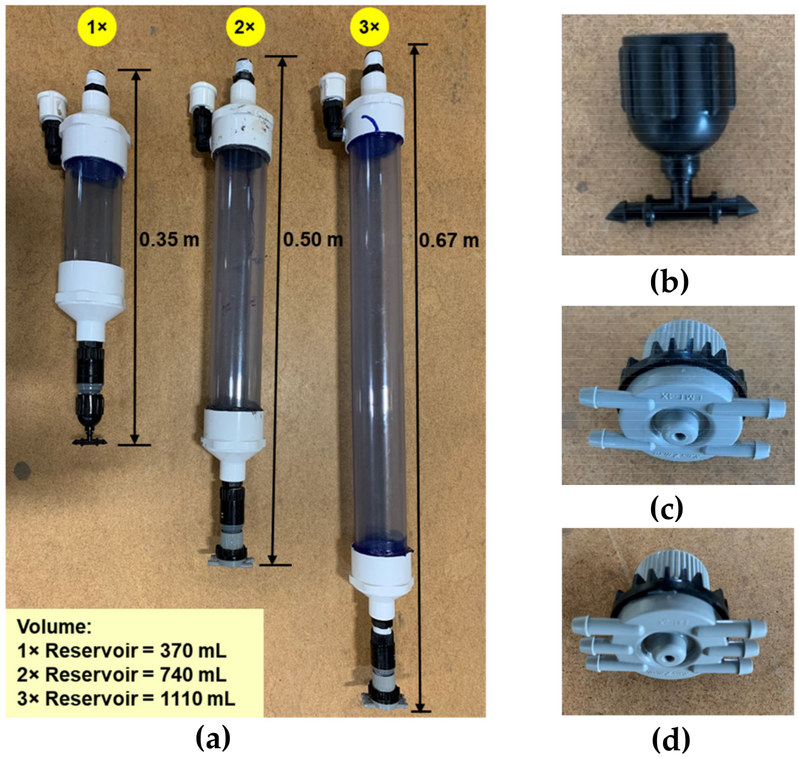

Figure 2. (**a**) Reservoirs 1×, 2×, and 3× with respective volumetric capacities of 370 mL, 740 mL, and 1110 mL fitted with (**b**) 2-port, (**c**) 4-port, and (**d**) 6-port manifolds, respectively (dimensions not drawn to scale).

2.2. Configuration Optimization

The PSD-based SSCDS retrofitted with a modified reservoir was preliminarily validated in the laboratory, and optimal configurations were further tested in the field conditions.

Laboratory Trials

The 1×, 2×, and 3× reservoirs with either a common or separate emitter feedline outlet architectures were used to realize five SSCDS configurations (C1–C5, Figure 3, Table 1). The C1 configuration had two emitter feedline offsets on the left and right sides at 0.8 m from the reservoir axis (Figure 3a), while the C2 (Figure 3b) and C3 configurations (Figure 3c) had two offsets (left and right) at 0.8 and 2.3 m. As assembled, the C4 (Figure 3d) and C5 (Figure 3e) had offsets at 0.8, 2.3, and 3.8 m on the left and right sides of the reservoir axis.

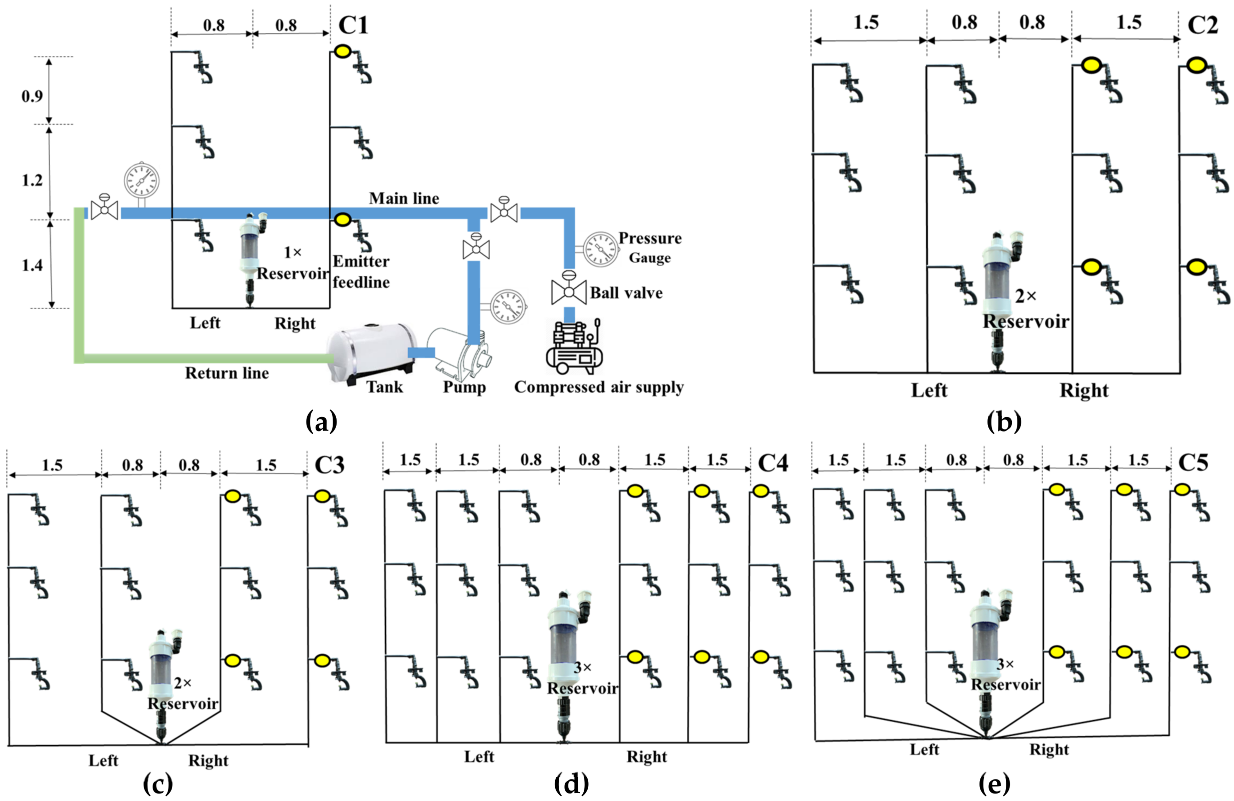

Figure 3. The (**a**) laboratory setup of the solid set canopy delivery system evaluated for configurations C1, (**c**) C3, and (**e**) C5 with separate outlets, and for (**b**) C2 and (**d**) C4 with a common outlet architecture. All the dimensions are in meters (m); represents pressure measurement point (dimension not drawn to scale).

Table 1. Details of developed configurations.

Configuration Type	Configuration	Reservoir Capacity	Number of Emitter Feedlines	Spray Span (m)
Separate	C1	1× *	2	3.0
	C3	2×	4	6.1
	C5	3×	6	9.1
Common	C2	2×	4	6.1
	C4	3×	6	9.1

* Capacity of 1× represents 370 mL volumetric capacity.

These SSCDS configurations were evaluated for pressure drop and spray discharge uniformity. The setup simulated the existing PSD-based SSCDS (935 L ha^{-1}) [22] operating conditions. The setup was 7 m long, comprised of a 12 VDC hydraulic pump (model:

5850-101C, Delavan Fluid Power, Minneapolis, MN, USA), liquid tank (57 L), and compressed air supply feedline. For each SSCDS configuration, the spray discharge from the individual emitters was collected, vacuum-sealed in a plastic bag, and then weighed on an electronic balance (accuracy: 0.01 g, model: Adventure Pro AV2102C, Ohuas Corp., Pine Brook, NJ, USA). The spray discharge deviation was calculated for each emitter feedline installed at an offset of 0.8 m, 2.3 m, and 3.8 m on the left and right sides of the reservoir (Equation (1)). Furthermore, the coefficient of variation (CV) in emitter discharge was evaluated for each configuration (Equation (2)).

$$\text{Discharge deviation } (\%) = \frac{\mathrm{D_{ef}} - \mathrm{D_{aef}}}{\mathrm{D_{aef}}} \times 100 \quad (1)$$

$$\text{CV } (\%) = \frac{\sigma}{\overline{\mathrm{x}}} \times 100 \quad (2)$$

where $\mathrm{D_{ef}}$ is the mean discharge of a selected emitter feedline; $\mathrm{D_{aef}}$ is the mean discharge of all the emitter feedlines in an SSCDS configuration; CV is the coefficient of variation; σ is the standard deviation, and $\overline{\mathrm{x}}$ is the mean discharge from all the emitters of an SSCDS configuration.

Additionally, spray pressure was measured at the bottommost and topmost emitters installed on the right side of the reservoir (Figure 3) using pressure transducers (model: PX309-100G5V, Omegadyne Inc., Sunbury, OH, USA). The data were logged on a logger (model: CR1000, Campbell Scientific Inc., Logan, UT, USA) at a frequency of 1 Hz. The pressure drop at each emitter end was calculated as the difference between the applied pressure (310 kPa) and the pressure recorded by the transducer. The experiment was replicated five times for each of the C1–C5 configurations. The pressure drop measurement was first checked for normality. The variation between all the configurations (as treatments) was analyzed using a one-way analysis of variance (ANOVA). Next, a Tukey's Honest Significance Difference (HSD) post hoc test was performed to identify the treatment groups for each configuration. All the laboratory and field data analyses were conducted in R Studio (2021, version: 4.0.5) [31], and the results were inferred at a 5% significance level.

2.3. Field Trials

2.3.1. Study Site

The lab-optimized SSCDS configuration was further evaluated for spray performance in a commercial apple orchard (*cv.* Jazz, area: 11.91 ha; 46°18′33.7″ N, 119°50′40.1″ W, Grandview, WA, USA) (Figure 4). The apple trees were grafted onto an NIC 29-EMLA 9 rootstock in the year 2006 and trained in a tall spindle architecture supported on an eight-wire trellis system. The orchard density was about 2400 trees $\mathrm{ha^{-1}}$ with an inter-row and intra-row tree spacing of 2.74 and 1.52 m, respectively. The average tree height, width, and trunk diameter were 3.66, 0.55, and 0.10 m, respectively. The field trial was conducted on 11 May 2021.

2.3.2. Emitter Configuration Modification

An off-the-shelf micro-emitter (model: modular 7000, flow rate: 0.66 L $\mathrm{min^{-1}}$ at 310 kPa, Jain Irrigation Inc., Fresno, CA, USA) was configured in a three-tier arrangement. This emitter consists of a static impaction plate (cone angle: 150°, wetted diameter: 2.1 m, vertical throw: 0.32 m) that atomizes the columnar spray jet in a radial pattern (Figure 5) [26]. The three-tier SSCDS configurations [23,26] tested in the prior studies consisted of an emitter installed on the trellis in the bottom, mid, and top zones of the canopy. These studies were conducted in an apple (*cv.* Cosmic Crisp) research block (tree spacing: 0.9 m, row spacing: 3 m, tree height: 3 m, and plant density: 4284 trees $\mathrm{ha^{-1}}$). An inadequate spray coverage (<10%) was observed while replicating a similar configuration in a commercial orchard (*cv.* Jazz), perhaps due to the relatively higher canopy volume and dense foliar density around the trellis. Therefore, to improve the system spray performance, the emitter configuration was customized for the commercial orchard conditions. Two micro-emitters were attached

0.6 m apart onto a bamboo stick, and emitter assemblies were installed on the trellis wire at an offset of 0.3 m from the canopy center. This arrangement was chosen so as to realize emitters spraying from both sides towards the canopy (Figure 5). Three emitter assemblies were installed in between the trees in the bottom (1 m above ground level (AGL)), mid (2.1 m AGL), and top (3 m AGL) zones of the canopy (Figure 5).

Figure 4. The experimental orchard site selected for the study.

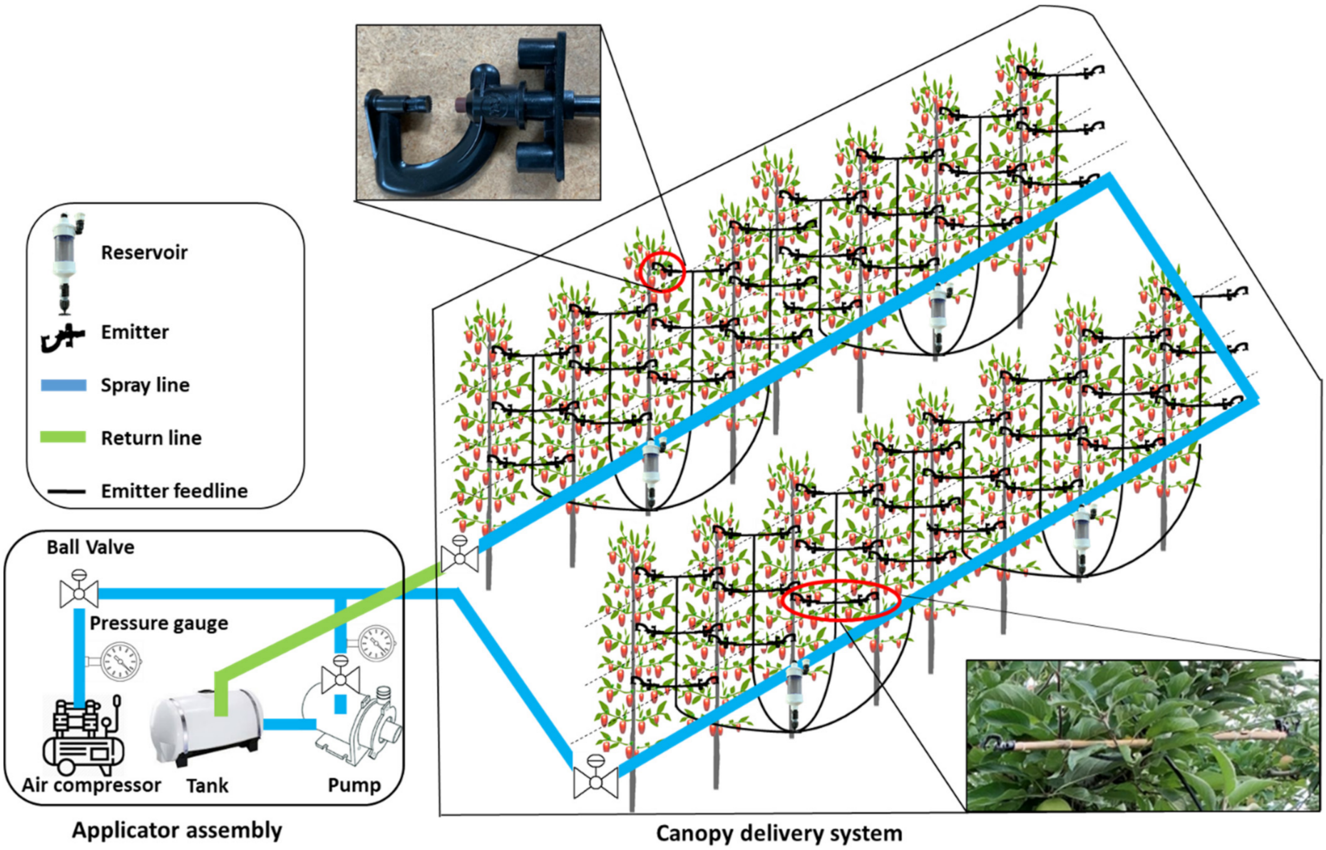

Figure 5. The layout of the pneumatic spray delivery-based solid set canopy delivery system consisting of an applicator assembly and a canopy delivery system. Three different volumetric capacity reservoirs (1×, 2×, and 3×) were evaluated for spray performance. The figure demonstrates a system configured with the 2× reservoir.

2.3.3. Spray Application System

The PSD-based SSCDS consists of an applicator and a canopy delivery system (Figure 5). The applicator comprises a centrifugal pump (model: 1538, Hypro, New Brighton, MN, USA; flow rate: 0.17 m^3 min^{-1} at 345 kPa), a tank (capacity: 189 L), and an air compressor (model: 2475F14G, Ingersoll Rand, Davidson, NC, USA; flow rate: 0.68 m^3 min^{-1} at 1206 kPa). The canopy delivery system consists of a spray line (ϕ: 2.54 cm), reservoirs, an emitter feedline, and emitter assemblies. The spray lines were installed on an existing trellis at 1 m AGL using poly hose trellis wire clips (ϕ: 2.54 cm, model: A32H, Jain Irrigation Inc., Fresno, CA, USA) and connected in a loop with a manual ball valve at the start and end of the loop. The 1×, 2×, and 3× reservoirs were retrofitted with 2-, 4-, and 6-port manifolds, respectively, and the respective reservoir spacings of 3.0, 6.1, and 9.1 m were maintained. The reservoir ports were connected to the emitter using an emitter feed line (PE tube, ϕ: 0.6 cm). The complete spray operation was realized in four stages: (i) charging or filling, (ii) recovery, (iii) spraying, and (iv) cleaning. In the first stage, the spray mix was charged in the spray line and reservoirs at a hydraulic pressure of 103 kPa. While a fixed volume of the spray mix was stored in the in-line reservoirs, the surplus liquid in the spray line was recovered back to the applicator tank at a pneumatic pressure of 103 kPa for the second stage. After recovery, spraying was performed at a pneumatic pressure of 310 kPa in order to deliver the spray mix from the reservoirs into the canopy. Once spraying was completed, cleaning was performed at 310 kPa to purge out any liquid left in the spray delivery system. The same applicator unit was used to spray during field trials for consistency and uniformity in operations that may affect the spray performance.

2.3.4. Experimental Design

The laboratory results indicated a lower pressure drop and better spray uniformity for the configuration with separate outlets (see Section 3.1.1). Therefore, the SSCDS configurations for the 1×, 2×, and 3× reservoirs with a separate outlet architecture (i.e., C1, C3, and C5) were selected for the field trial. The trials were conducted to evaluate the spray coverage. A total of 25 1× reservoirs with separate outlets were installed (Figure 6a) in a commercial orchard at a 3.0 m spacing to conduct the SSCDS treatment (treatment 1×). Similarly, 13 2× and 9 3× reservoirs were installed at spacings of 6.1 and 9.1 m for treatments 2× and 3×, respectively. Each treatment had a loop length of 77 m (area: 0.02 ha, tree: ~50). Within the loop, three blocks comprising five trees were randomly selected, and from each block, three trees were randomly labelled for spray coverage sampling (Figure 6b). Water-sensitive paper (WSP) (dimension: 25.4 × 25.4 mm) (Syngenta Crop Protection Inc., Greensboro, NC, USA) samplers were used to quantify the spray coverage. For sampling, the trees were vertically divided into three zones, i.e., bottom (0.46–1.53 m AGL), mid (1.53–2.6 m AGL), and top (2.6–3.66 m AGL), followed by the east and west sides of the canopy (Figure 6c). In each sampling zone, a leaf was randomly selected, and the WSP samplers were placed on adaxial and abaxial surfaces using customized alligator clips.

The canopies were sprayed with water at an application rate of 935 L ha^{-1}. Due to the nature of the fixed spray system, the treatments were sprayed sequentially. The spray application was conducted with 1×, followed by 3× and 2×, and a buffer time of 90 min was maintained between two consecutive spray treatments. After a 15 min drying period for each spray trial, the WSP samplers were collected and pasted onto the labelled sheets and then stored in separate assigned envelopes. A total of 324 WSPs (3 treatments × 3 blocks/treatment × 3 trees/block × 2 sides/tree × 3 zones/side × 2 leaf surfaces/zone × 1 sampler/leaf surface) were collected for all the trials.

2.3.5. Meteorological and System Performance Data Collection

During the spray trials, the weather parameters were monitored using an all-in-one in-field weather station (model: ATMOS 41, METER Group, Pullman, WA, USA). The weather sensor was installed 1 m above the canopy [32] and programmed to log wind speed, wind direction, ambient temperature, humidity, and atmospheric pressure at a frequency of 0.07 Hz. The metrological data were recorded on a 12 VDC powered data logger (model: CR1000, Campbell Scientific Inc., Logan, UT, USA). During the spray trials, the weather parameters (wind speed: 1.0–1.2 m s^{-1}, air temperature: 13.1–18.2 °C, relative humidity: 38–49%, Table 2) were within the recommended limits for spray applications [33,34]. Additionally, a handheld weather meter (model: WFNO-02-AG, Weather Flow, Scotts Valley, CA, USA) was used to monitor instantaneous weather changes during the spray trial. The data were logged on a smart phone (model: XR, Apple Inc., Cupertino, CA, USA) with the help of an application (Wind & Weather Meter, WeatherFlow, Scotts Valley, CA, USA). The pressure drop in the SSCDS loop was monitored using wireless digital pressure gauges (model: PGW-500, Elitech Technology Inc., San Jose, CA, USA) installed at the start and end of the loop, and the data were logged at a frequency of 1 Hz on a smart phone through an application (Elitech Gauge, ver. 2.5, Elitech Technology Inc., San Jose, CA, USA).

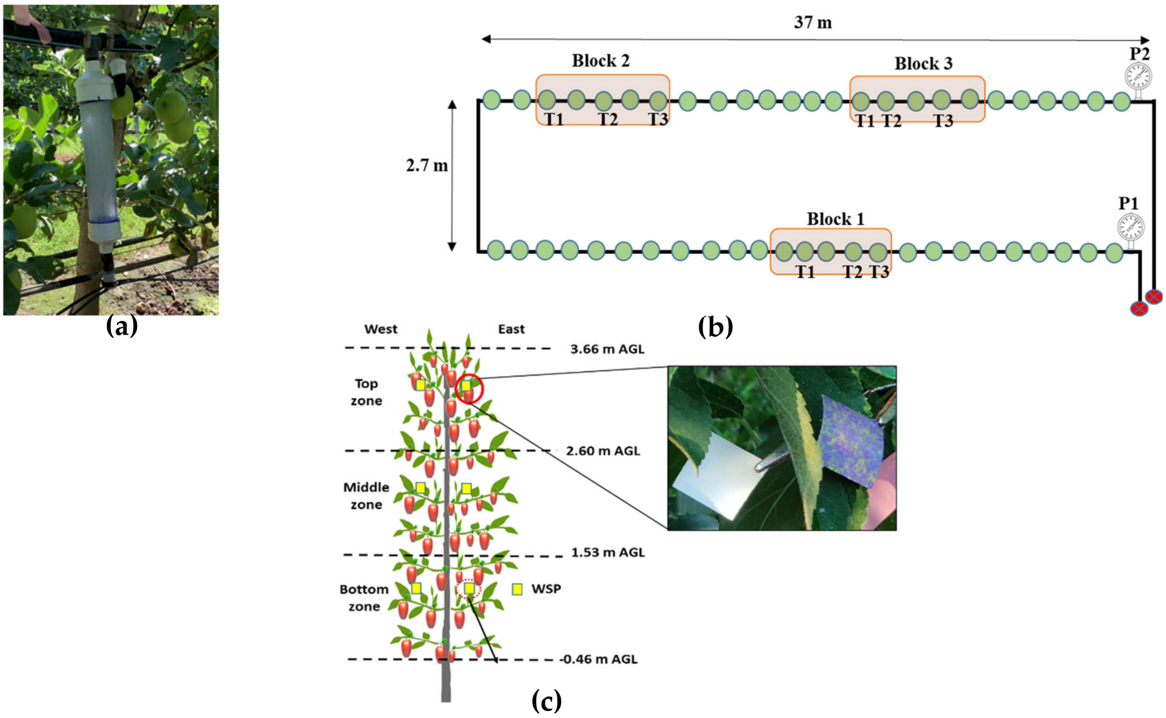

Figure 6. In-line (**a**) reservoir installed in a 77 m long pneumatic spray delivery-based SSCDS. (**b**) Three blocks (block-1, -2, and -3) were randomly selected, with samplers installed on three trees per block (T1, T2, and T3). Each tree was divided into (**c**) six canopy zones, with water-sensitive paper (WSP) samplers on adaxial and abaxial leaf surfaces (not drawn to scale). Due to the nature of the fixed spray system, the treatments (1×, 2×, 3×) were tested in a sequential manner within each block, allowing for a 90 min drying time between treatments and new samplers per trial.

Table 2. Summary of the weather parameters during the field trials.

Treatment (Reservoir)	Wind Speed (mean ± SD, m s^{-1})	Wind Direction (a) (mean ± SD, °)	Air Temperature (mean ± SD, °C)	Relative Humidity (mean ± SD, %)
1×	1.0 ± 0.4	15.5 ± 23.5	13.1 ± 0.3	49.1 ± 1.0
2×	1.2 ± 0.4	21.0 ± 32.2	18.2 ± 0.6	38.0 ± 1.2
3×	1.0 ± 0.4	23.2 ± 21.0	15.8 ± 0.3	42.9 ± 0.8

(a) Wind direction is given in azimuth degrees, where 0° or 360° represents wind from the north and tree rows have a north–south orientation.

2.4. Data Analysis

The collected WSP samplers were scanned at 1200 dpi resolution using a digital scanner (model: Epson Perfection V37, Seiko Epson Corporation, Suwa, Nagano, Japan) and labeled using a photo editor (Microsoft Photos, Microsoft Corporation, Redmond, WA, USA). The digitalized and labelled WSP samplers were analyzed with the help of the GOTAS software [35] to evaluate the percentage of the stained area on the water-sensitive surface of the sampler, i.e., spray coverage (%). The coverage dataset was normalized using cube root transformation, and ANOVA was conducted on the transformed data with treatments (1×, 2×, and 3×), sampling zones (top, mid, and bottom), and leaf surfaces (adaxial and abaxial) as independent categorical variables. Additionally, a post hoc Tukey's HSD test was performed for the multiple mean comparisons.

3. Results

3.1. Laboratory Results

3.1.1. Discharge Deviation

The spray discharge deviation for the emitter feedline in C1 was the least (~0.3%) amongst all the tested configurations. The deviations increased in the following order: C3 (0.1–2.8%), C5 (0.1–4.6%), C4 (0.9–6.6%), and C2 (6.3–6.9%, Figure 7a). The minimum deviation (0.1%) was observed at a 0.8 m offset on the right side for C3, while the maximum deviation (6.9%) was observed at a 2.3 m offset on the right side for C2 (Figure 7a). Moreover, the CV of the emitter discharge was the lowest for the C3 configuration (7.1%), followed by C5 (8.0%), C1 (8.6%), C2 (8.9%), and C4 (9.3%, Figure 7b). Between the two configuration types, the one with a separate outlet configuration (C1, C3, and C5) had lower discharge deviation and CV.

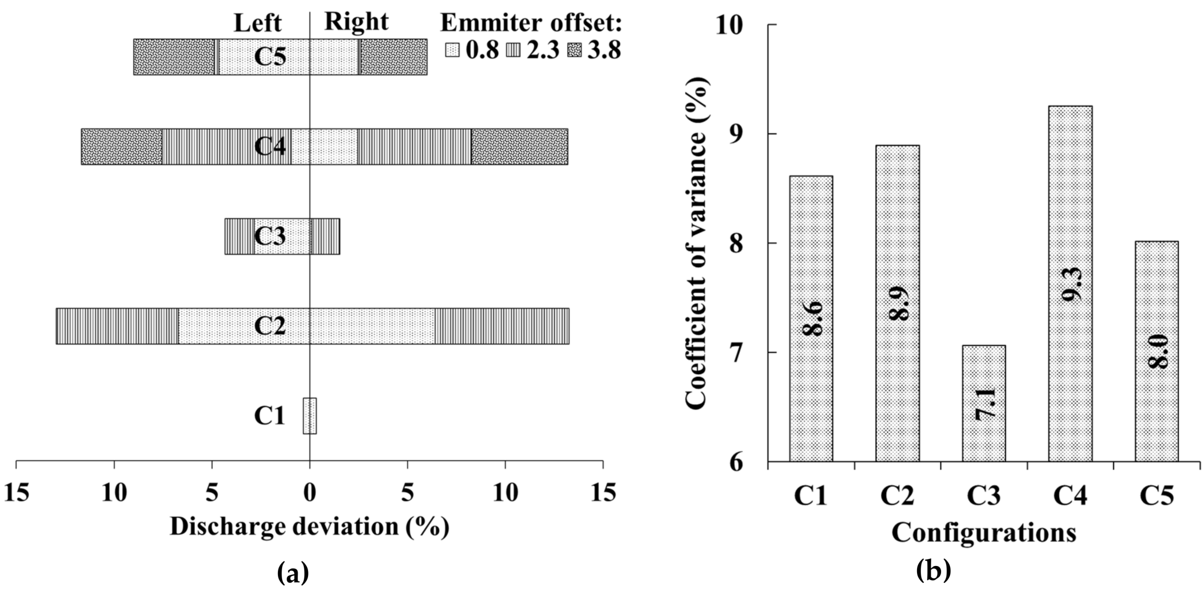

Figure 7. (**a**) Discharge deviation (%) and (**b**) coefficient of variance (%) for tested solid set canopy delivery system configurations (C1–C5).

3.1.2. Pressure Drop

Significant differences were observed between the pressure drops for developed SSCDS configurations (one-way ANOVA, $F_{4,105} = 49.86$, $p < 0.001$). The lowest mean pressure drops were recorded for configurations C5 (141.2 ± 2.2 kPa, mean ± standard error), C3 (148.6 ± 3.4 kPa), and C1 (161.4 ± 3.5 kPa) as compared to C4 (185.0 ± 3.3 kPa) and C2 (188.4 ± 3.4 kPa) (Figure 8). Moreover, the pressure drops increased with the height of the emitters above the reservoir outlet as well as the offset emitter feedline distance from the reservoir (Figure 9a–e). The minimum pressure drop was observed in the bottom emitter, mounted at a 0.8 m offset in configuration C5 (125.5 ± 4.5 kPa) (Figure 9e) and C3

(131.2 ± 5.1 kPa) (Figure 9c). The pressure drop was higher at the top emitter, mounted at a 3.8 m offset in configuration C4 (209.5 ± 1.7 kPa) (Figure 9d) and at a 2.3 m offset in configuration C2 (205.1 ± 4.6 kPa) (Figure 9b). Overall, the three best configurations with a common outlet (C1, C3, and C5), which resulted in the lowest pressure drop, spray discharge deviation, and CV, were selected for further field evaluations.

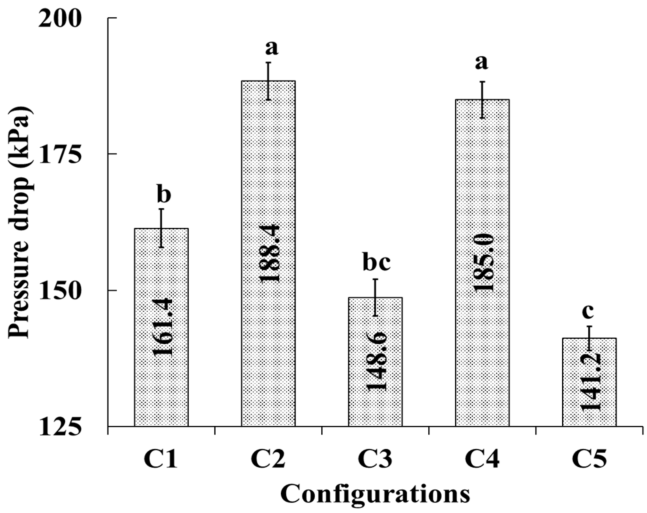

Figure 8. Mean pressure drop recorded for the developed configurations (C1–C5). Error bars indicate the standard error, and different lowercase letters above the bars indicate significantly different groups.

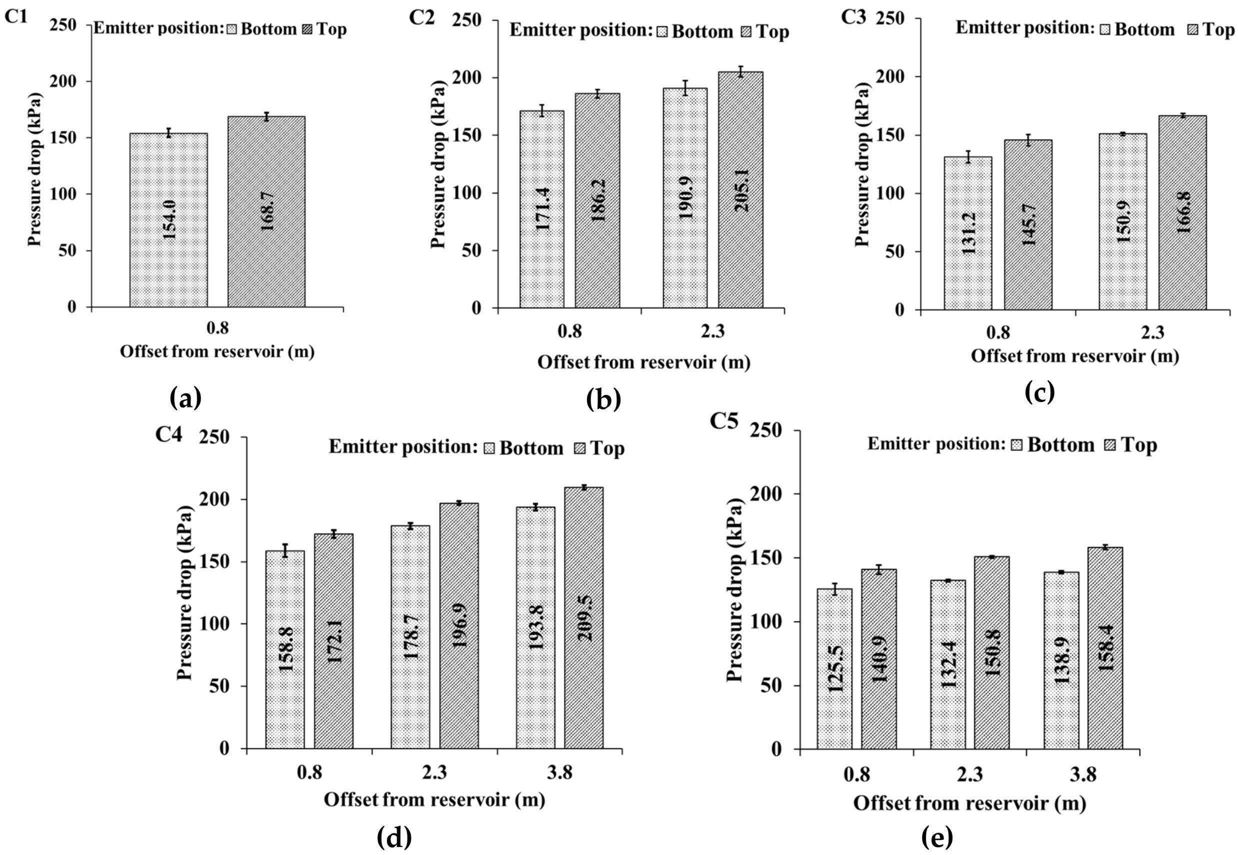

Figure 9. Pressure drop recorded at the top and bottom emitters, and offset feedline distances from the reservoir for all the developed configurations (C1–C5, (**a**–**e**), respectively). Error bars indicate the standard error.

3.2. Field Trial Results

The analysis of the spray coverage indicates that as a main effect, there was no significant difference in coverage for the reservoir treatments (i.e., 1×, 2×, and 3×) ($F_{2,108}$ = 0.13, p = 0.88) (Table 3, Figure 10a). However, a significant difference in the spray coverage was observed between the canopy zones ($F_{2,108}$ = 4.28, p = 0.01) and leaf surfaces ($F_{1,162}$ = 82.03, $p = 2 \times 10^{-16}$). Furthermore, there was no significant interaction between reservoir treatments, canopy zones, and leaf surfaces.

Table 3. ANOVA results of the cube root-transformed canopy coverage data. 'Treatment' is the reservoir size (1×, 2×, 3×).

Variables	df	MS	F	*p*
Main Plot				
Block	2	1.26		
Treatment	2	0.09	0.13	0.88
Error (a)	2	0.39		
Canopy Zone	2	3.11	4.28	0.01
Leaf surface	1	59.61	82.03	2×10^{-16}
Treatment × Canopy Zone	4	0.07	0.09	0.98
Treatment × Leaf Surface	2	0.49	0.67	0.51
Canopy Zone × Leaf Surface	2	1.43	1.97	0.14
Treatment × Canopy Zone × Leaf Surface	4	0.1	0.14	0.97
Errors (b)	284	0.73		

(a) Variability within the treatments, and (b) variability within interactions (treatments, canopy zones and leaf surfaces).

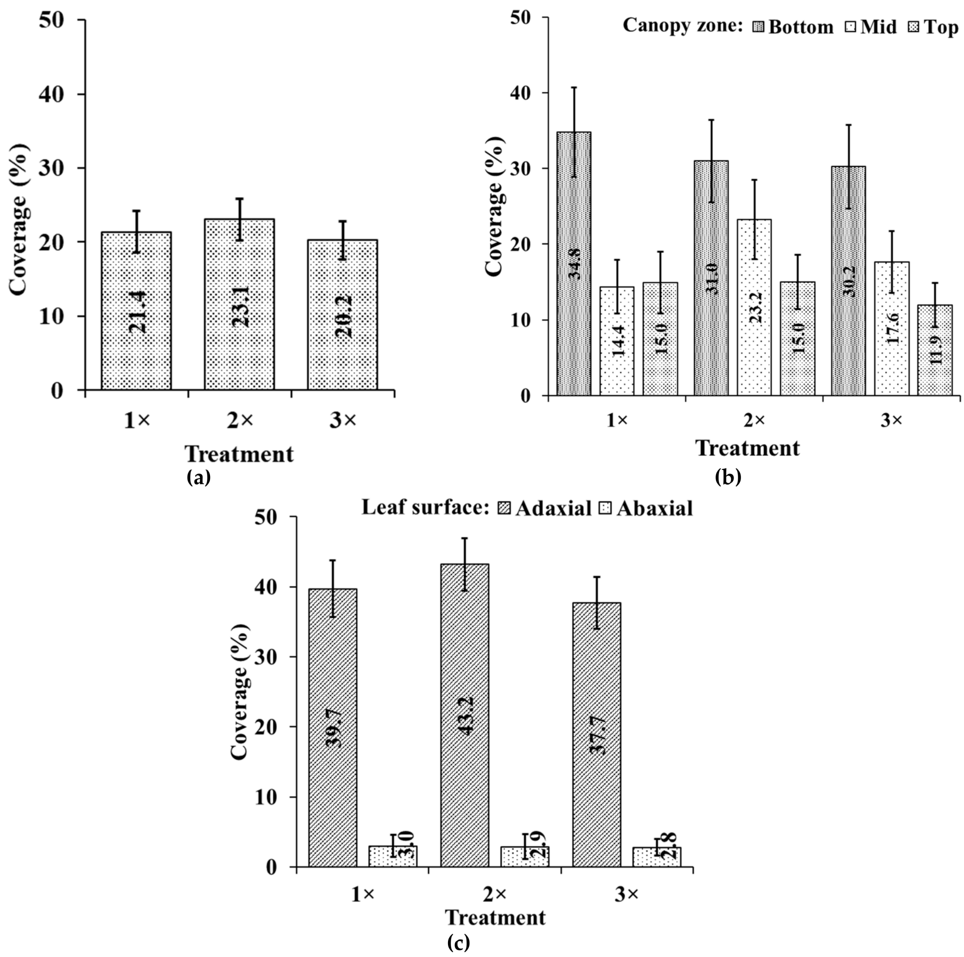

Figure 10. Mean spray coverage evaluated for different (**a**) treatments, (**b**) canopy zones, and (**c**) leaf surfaces. Different lowercase letters above individual bars indicate significantly different treatment groups based on transformed data. Error bars indicate the standard error.

3.2.1. Coverage within Canopy Zone

There was a significant difference in the spray coverage among the canopy zones (Table 3). However, no significant interaction was observed between canopy zones and reservoir treatments. Among the canopy zones, the highest coverage was observed in the bottom zone (30–35%) as compared to the mid (14–23%) and top zones (12–15%). The latter two zones (mid and top) had comparable or not significantly different coverage. For the different treatments in the bottom zone, the highest coverage was observed for 1× (34.8 ± 5.9%), while there was no significant difference between 2× (31.0 ± 5.5%) and 3× (30.2 ± 5.5%) (Figure 10b). In the mid zones, there was no significant difference between the 3× (17.6 ± 4.1%) and 1× (14.4 ± 3.6%) treatments, while 2× (23.2 ± 5.2%) showed more coverage. In the top canopy zone, there were no significant differences among the treatments. However, 3× yielded a numerically lower coverage (11.9 ± 2.9%) than the 2× (15.0 ± 3.6%) and 1× (15.0 ± 4.1%) treatments (Figure 10b).

3.2.2. Coverage on Leaf Surfaces

There was a significant difference in the adaxial and abaxial leaf surface coverage of all the treatments (Figure 10c). However, the effect of the interaction between the treatment and the leaf surface was not significant (Table 3). The spray coverage for the adaxial surface (37.7–43.2%) was higher than the abaxial surface (~3%). For the different treatments, although non-significantly different, coverage on the adaxial surface was numerically higher for 2× (43.2 ± 3.7%), followed by 1× (39.7 ± 4.0%) and 3× (37.7 ± 3.7%) (Figure 10c).

4. Discussion

The goal of this study was to optimize the reservoir of PSD-based SSCDS for the reduction of post-spray chemical losses and the enhancement of commercial viability through a larger volumetric capacity. The laboratory study revealed that the separate outlet reservoir configurations (C1, C3, C5) had less discharge deviation as compared to the common outlet configuration. This can be attributed to the uniform distribution of the spray mix at the reservoir outlet for the entire emitter assembly. For the common outlet configurations, the spray liquid was divided at multiple junctions on the emitter feedline (Figure 3b,d), which might have led to the non-uniform distribution of the spray liquid. Such disparity in liquid volume distribution can result in a higher deviation in the mean spray discharge. Additionally, the higher pressure drops caused by the elevated frictional losses at multiple junctions on the feedline in the common outlet configuration may also be attributed to the higher discharge deviation. Therefore, a separate outlet configuration is recommended for the commercial adaptation.

Field trial results indicate that all three reservoir volumes provided comparable spray performance. This is promising for future reservoir designs that are customized for specific rates and varying canopies. It indicates that other factors such as nozzles and canopy structure are more influential on coverage than reservoir capacity.

Overall, the bottom zone coverage for all the treatments were higher as compared to the mid and top canopy zones, ranging from 7.0 to 22.9% more coverage. The 2× and 3× treatments were not significantly different from each other in the zones, yet they showed higher coverage in the mid zones than 1×, making coverage in the 2× and 3× treatments more even among the zones than 1×. This disparity can be explained by the shower-down phenomenon of the spray droplets. The spray droplets that miss the target in the top and mid zones drip down and settle on the bottom canopy. Similarly, the spray run-off from the top and mid canopy zones settles at the bottom, which perhaps resulted in a higher spray coverage in the bottom zone. Similar results were also observed by Ranjan et al. (2021) [26] while evaluating a modified SSCDS emitter configuration in an apple orchard.

The adaxial leaf surface coverage was similar among all the treatments. The adaxial leaf coverage (37.7–43.2%) for all the treatments was higher than the marginal abaxial coverage (~3%). Similar abaxial coverage was observed by several researchers [15,20–23] while evaluating different emitter configurations for SSCDS in apple orchards and vineyards. Spray droplets from the emitter are usually dispersed onto the canopy by compressed air pressure and gravity. While the emitter sprays toward the canopy, the inward inclination of the leaves results in the lower exposure area of the abaxial surface. Therefore, the WSPs installed on the underside of leaves are more likely to receive fewer spray droplets as compared to the upper side. Furthermore, once a droplet loses its kinetic energy, it is subjected to air drift and gravity. The recommended marginal wind speed during spray operation and the relatively coarser droplet size [26] can minimize the chances of lateral droplet movement, and the spray droplets can settle down onto the adaxial leaf surface under gravity. These effects combinedly result in higher adaxial coverage as compared to abaxial coverage. Despite marginal abaxial coverage, Panneton et al. (2015) [28] observed an equivalent apple scab control in a fixed spray system as compared to an air-blast sprayer under severe pest infection conditions, as did Owen Smith et al. (2019) [20,21]. Additional investigations on biological efficacy are thus recommended to further validate this finding.

There was a 33% reduction in cost per unit with the modified reservoir as several parts were eliminated, including the emitter supply column and the auto drain valve (USD 22.1, original; USD 14.8, modified). Furthermore, the SSCDS treatment retrofitted with the 2× and 3× reservoirs reduced the required number of reservoirs to 50% (600 reservoirs ha^{-1}) and 33% (400 reservoirs ha^{-1}), respectively, as compared to the current system configured with the 1× reservoirs (1200 reservoirs ha^{-1}). The reduction in the number of parts and reservoirs could reduce the installation cost by USD 20,000–23,410 ha^{-1}. Fewer reservoirs shall also reduce the maintenance cost of the system. Note that the above cost is associated with a solid set installation per hectare and does not include the applicator unit cost, which can be up to USD 24,000. The reduction in installation and maintenance costs can enhance the commercial viability of fixed spray systems. The PSD-based SSCDS can be generalized to all tall spindle architecture-trained orchards. Customization to other modern orchard systems (i.e., modified vertical shoot position-trained grapevine, upright fruiting offshoots-trained sweet cherries) will require case-by-case solid set modifications. Our future study will compare the spray performance of the optimized SSCDS configuration in terms of spray efficacy (coverage, deposition, and ground and aerial drift) and biological efficacy to the conventional air-blast sprayer.

5. Conclusions

The following are the conclusions from the study:

1. The reservoir modification retrofitted PSD-based SSCDS successfully eliminated the post-spray chemical losses associated with the prior design. The reservoir with the separate outlet configurations performed better in terms of spray uniformity as compared to the common outlet configurations.
2. The three-tier PSD-based SSCDS configured with a large volumetric capacity reservoir (740 mL or 1110 mL) provided more even zonal coverage as compared to the systems configured with the 370 mL reservoirs. Using such a configuration will thus aid in the substantial reduction of the system installation and maintenance costs.

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References

1. USDA NASS. Press Release, National Agricultural Statistics Service Dated 08.10.20. 2020. Available online: https://www.nass.usda.gov/Statistics_by_State/Washington/Publications/Current_News_Release/2020/VOP_WA.pdf (accessed on 20 September 2021).
2. Herrington, P.J.; Mapother, H.R.; Stringer, A. Spray retention and distribution on apple trees. *Pestic. Sci.* **1981**, *12*, 515–520. [CrossRef]
3. Cross, J.V. Deposits on apple leaves from medium volume, low volume and very low volume spray applications with an axial fan sprayer. *BCPC Monogr.* **1991**, *46*, 263–268.
4. Cross, J.V.; Walklate, P.J.; Murray, R.A.; Richardson, G.M. Spray deposits and losses in different sized apple trees from an axial fan orchard sprayer: 1. Effects of spray liquid flow rate. *Crop Prot.* **2001**, *20*, 13–30. [CrossRef]
5. Cross, J.V.; Walklate, P.J.; Murray, R.A.; Richardson, G.M. Spray deposits and losses in different sized apple trees from axial fan orchard sprayers: 2. Effects of spray quality. *Crop Prot.* **2001**, *20*, 333–343. [CrossRef]
6. Grieshop, M.J.; Emling, J.; Ledebuhr, M. Re-envisioning agrichemical input delivery: Solid set delivery systems for high density fruit production, Impacts on off-target deposition. In Proceedings of the 2018 ASABE Annual International Meeting, Detroit, MI, USA, 29 July–1 August 2018; pp. 2–9.
7. Gil, Y.; Sinfort, C. Emission of pesticides to the air during sprayer application: A bibliographic review. *Atmos. Environ.* **2005**, *39*, 5183–5193. [CrossRef]
8. Tsai, M.Y.; Elgethun, K.; Ramaprasad, J.; Yost, M.G.; Felsot, A.S.; Hebert, V.R.; Fenske, R.A. The Washington aerial spray drift study: Modeling pesticide spray drift deposition from an aerial application. *Atmos. Environ.* **2005**, *39*, 6194–6203. [CrossRef]
9. Ford, D.; Dunn, M.; Morrison, J.; Willis, C. Human Exposure to Pesticide Drift: Washington State Report 2017. Available online: https://columbialegal.org/wp-content/uploads/2018/11/PesticideReportFINALWeb.pdf (accessed on 20 September 2021).
10. Håkansson, I.; Voorhees, W.B.; Riley, H. Vehicle and wheel factors influencing soil compaction and crop response in different traffic regimes. *Soil Tillage Res.* **1988**, *11*, 239–282. [CrossRef]
11. Vogeler, I.; Cichota, R.; Sivakumaran, S.; Deurer, M.; McIvor, I. Soil assessment of apple orchards under conventional and organic management. *Aust. J. Soil Res.* **2006**, *44*, 745–752. [CrossRef]
12. Maraseni, T.N.; Cockfield, G.; Apan, A. A comparison of greenhouse gas emissions from inputs into farm enterprises in Southeast Queensland, Australia. *J. Environ. Sci. Health A* **2007**, *42*, 11–18. [CrossRef]
13. Agnello, A.; Landers, A.J. Current progress in development of a fixed spray pesticide application system for high-density apple plantings. *N. Y. Fruit Q.* **2006**, *14*, 22–26.
14. Grieshop, M.; Gut, L.; Wise, J.; Smith, P.O.; Sundin, G.; Miller, S.; Flore, J.; Lang, G.; Perry, R. Development of solid set delivery systems for high density apples. *N. Y. Fruit Q.* **2015**, *23*, 16–20.
15. Sharda, A.; Karkee, M.; Zhang, Q.; Ewlanow, I.; Adameit, U.; Brunner, J. Effect of emitter type and mounting configuration on spray coverage for solid set canopy delivery system. *Comput. Electron. Agric.* **2015**, *112*, 184–192. [CrossRef]
16. Sharda, A.; Karkee, M.; Hoheisel, G.; Zhang, Q.; Mangus, D. Design and Evaluation of Solid Set Canopy Delivery System for Spray Application in High-density Apple Orchards. *Appl. Eng. Agric.* **2019**, *35*, 751–757. [CrossRef]
17. Verpont, F.; Favareille, J.; Zavagli, F. Fixed spraying system: A future potential way to apply pesticides in an apple orchard? *Julius-Kühn-Archiv* **2015**, *448*, 53–54.
18. Niemann, S.M.; Whiting, M.D.; Hanrahan, I. Efficacy of a solid set canopy delivery system (SSCDS) in sweet cherry and apple. In Proceedings of the XXIX International Horticultural Congress on Horticulture: Sustaining Lives, Livelihoods and Landscapes, Brisbane, Australia, 17 August 2016; Volume 1130, pp. 145–150.
19. Otto, S.; Loddo, D.; Schmid, A.; Roschatt, C.; Venturelli, M.; Innerebner, G. Droplets deposition pattern from a prototype of a fixed spraying system in a sloping vineyard. *Sci. Total Environ.* **2018**, *639*, 92–99. [CrossRef]
20. Owen-Smith, P.; Perry, R.; Wise, J.; Jamil, R.Z.R.; Gut, L.; Sundin, G.; Grieshop, M.J. Spray coverage and pest management efficacy of a solid set canopy delivery system in high density apples. *Pest Manag. Sci.* **2019**, *75*, 3050–3059. [CrossRef]
21. Owen-Smith, P.; Wise, J.; Grieshop, M.J. Season long pest management efficacy and spray characteristics of a solid set canopy delivery system in high density apples. *Insects* **2019**, *10*, 193. [CrossRef]
22. Sinha, R.; Ranjan, R.; Bahlol, H.Y.; Khot, L.R.; Hoheisel, G.A.; Grieshop, M.J. Development and performance evaluation of a pneumatic spray delivery based solid set canopy delivery system for spray application in a high–density apple orchard. *Trans. ASABE* **2020**, *63*, 37–48. [CrossRef]
23. Sinha, R.; Khot, L.R.; Hoheisel, G.A.; Grieshop, M.J. Field performance of a solid set canopy delivery system configured for high-density tall spindle architecture trained apple canopies. *Trans. ASABE* **2021**, *64*, 1735–1745. [CrossRef]
24. Innerebner, G.; Roschatt, C.; Schmid, A. Efficacy of fungicide treatments on grapevines using a fixed spraying system. *Crop Prot.* **2020**, *138*, 105324. [CrossRef]

25. Imperatore, G.; Ghirardelli, A.; Strinna, L.; Baldoin, C.; Pozzebon, A.; Zanin, G.; Otto, S. Evaluation of a fixed spraying system for phytosanitary treatments in heroic viticulture in north-eastern Italy. *Agriculture* **2021**, *11*, 833. [CrossRef]
26. Ranjan, R.; Sinha, R.; Khot, L.R.; Hoheisel, G.A.; Grieshop, M.; Ledebuhr, M. Spatial distribution of spray from a solid set canopy delivery system in a high-density apple orchard retrofitted with modified emitters. *Appl. Sci.* **2021**, *11*, 709. [CrossRef]
27. Ranjan, R.; Sinha, R.; Khot, L.R.; Hoheisel, G.A.; Grieshop, M.; Ledebuhr, M. Effect of emitter modifications on spray performance of a solid set canopy delivery system in a high-density apple orchard. *Sustainability* **2021**, *13*, 13248. [CrossRef]
28. Panneton, B.; Philion, V.; Chouinard, G. Spray deposition with conventional nozzles, low-drift nozzles, or permanent sprinklers for controlling apple orchard pests. *Trans. ASABE* **2015**, *58*, 607–619.
29. Sharda, A.; Karkee, M.; Zhang, Q. Fluid dynamics of a solid set canopy spray delivery system for orchard applications. In *2013 ASABE Annual Meeting*; Paper No. 131620688; ASABE: St. Joseph, MI, USA, 2013.
30. EPA. Safe Disposal of Pesticides 2021. Available online: https://www.epa.gov/safepestcontrol/safe-disposal-pesticides (accessed on 28 April 2022).
31. R Studio, R Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2021; Available online: http://www.R-project.org/ (accessed on 25 January 2022).
32. *ISO 22522:2007 (E)*; Crop Protection Equipment—Field Measurement of Spray Distribution in Tree and Bush Crops. ISO: Geneva, Switzerland, 2007.
33. *ASABE*, *S561.1*; Procedure for Measuring Drift Deposits from Ground, Orchard, and Aerial Sprayers. ASABE: St. Joseph, MI, USA, 2004.
34. Tepper, G. *Weather Essentials for Pesticide Application*; Grains Research & Development Corporation: Barton, Australia, 2017.
35. Chaim, A.; Pessoa, M.C.P.Y.; Camargo Neto, J.; Hermes, L.C. Comparison of microscopic method and computational program for pesticide deposition evaluation of spraying. *Pesqui. Agropecu. Bras.* **2002**, *37*, 493–496. [CrossRef]