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Spatial Distribution of Spray from a Solid Set Canopy Delivery System in a High-Density Apple Orchard Retrofitted with Modified Emitters

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Abstract: Solid Set Canopy Delivery Systems (SSCDS) are fixed agrochemical delivery systems composed of a network of micro-sprayers/nozzles distributed in perennial crop canopies. A previous SSCDS design composed of a 3-tier configuration using hollow cone sprayer nozzles has been shown to provide excellent coverage and deposition in high-density apple orchards. However, the hollow cone nozzles substantially increases the initial system installation costs. This study evaluated the effect of irrigation micro-emitters replacement on spray deposition, coverage and off-target drift. A micro-emitter used in greenhouse irrigation systems was duly modified to enhance its applicability with SSCDS. After laboratory assessment and optimization of the micro-emitters, a replicated field study was conducted to compare 3-tier SSCDS configured with either of modified irrigation micro-emitters or traditional hollow cone nozzles. Canopy deposition and off target drift were evaluated using a 500 ppm fluorescent tracer solution sprayed by the field installed systems and captured on mylar collectors. Spray coverage was evaluated using water sensitive papers. The overall canopy deposition and coverage for treatment configured with modified irrigation micro-emitters (955.5 ± 153.9 [mean ± standard error of mean] ng cm^{-2} and 22.7 ± 2.6%, respectively) were numerically higher than the hollow cone nozzles (746.2 ± 104.7 ng cm^{-2} and 19.0 ± 2.8%, respectively). Moreover, modified irrigation micro-emitter SSCDS had improved spray uniformity in the canopy foliage and on either side of leaf surfaces compared to a hollow cone nozzle. Ground and aerial spray losses, quantified as deposition, were numerically lower for the modified irrigation micro-emitter (121.8 ± 43.4 ng cm^{-2} and 0.7 ± 0.1 ng cm^{-2}, respectively) compared to the traditional hollow cone nozzle (447.4 ± 190.9 ng cm^{-2} and 3.2 ± 0.4 ng cm^{-2}, respectively). Overall, the modified irrigation micro-emitter provided similar or superior performance to the traditional hollow cone nozzle with an estimated 12 times reduction in system installation cost.

Keywords: fixed spray delivery; SSCDS; spray drift; deposition; coverage

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1. Introduction

The United States (US) is the third largest producer of the apple (*Malus domestica*) in the world after China and European Union [1]. Total fresh market apple production in the US in the year 2018 was 3.4 million tons with a total worth 3 billion dollars—out of which 73% was produced in Washington State (WA) [2]. Commercial apple production requires numerous applications of agrochemicals including insecticides, fungicides, foliar nutrients, and plant growth regulators with the most common application equipment consisting of air-blast sprayers [3,4]. However, this technology has a high tendency to produce off-target spray drift, defined as the movement of sprayed droplets through the air away from the intended target [5]. Off target spray drift has been reported as a major contributor of environmental contamination and is among the top ten contributors causing human health risk around the world [3,6–8].

Increasing market demand, restricted labor availability, and mechanization advances have led to substantial modification to orchard systems with widespread transition to tall spindle, v-trellis, and bi-axis architectures [9–12]. Such architectural changes of moving from spherical to compact linear architectures have further intensified spray drift with traditional sprayers with large air volumes [12,13]. Growers have adopted several modified forms of air-assisted sprayers (e.g., vertical tower sprayer, tunnel sprayers, and electrostatic sprayers) which have demonstrated encouraging results in drift reduction. However, equipment size, maneuvering difficulties, high operational cost, and inconsistent performances based on canopy size are some of the reported difficulties associated with these technologies [3,14,15]. Tractor-based sprayers also contribute to soil compaction and crop loss due to physical impact between fruits and equipment [16,17]. Since heavy air-blast sprayers cannot be operated on saturated soils, critical agrochemical application timings can be missed, leading to crop loss [18]. Thus, there is a need and growing interest in the development of efficient spraying techniques designed specifically for modern orchard architectures. Recently, fixed spray application systems deemed Solid Set Canopy Delivery Systems (SSCDS) have been suggested as an alternative to tractor based sprayers for high density orchards and vineyards [12].

SSCDS have been evaluated for use in high-density apple orchards, vineyards, blueberries and other tree fruit systems with most of the work focusing on system development and measurement of deposition and coverage [12,18–23]. SSCDS pest management efficacy has been demonstrated for high-density apple orchards in Michigan and New York, USA [24–26]. A pneumatic spray delivery system was developed by Sinha et al. [21] to overcome the issue of non-uniformity in spraying associated with a hydraulic spray delivery approach. Efforts have also been made to automate the operational stages of a SSCDS for large-scale emplacements and commercial adaptation. Ranjan et al. [27] developed an electronic control system and a spray control unit for wireless and remote actuation of the SSCDS variant under study.

One of the key design constraints for SSCDS is that they rely on a large number of nozzles/micro-emitters (3000–10,400 per ha) and their placement within the canopy considerably affect the spray deposition and coverage [18,20,28]. For example, while a shower down configuration with a single nozzle atop each tree was reported as the simplest and most economical configuration, it provided reduced spray deposition in lower canopy regions and underside of leaves [22]. Another SSCDS configuration with hollow cone nozzles installed in a 3-tier (6 nozzles per tree) provided higher levels and more consistent spray deposition and coverage in a high-density apple orchard [28], but can cost prohibitive at approximately \$208,000 ha^{-1} (10,400 nozzle-assembly ha^{-1} at average \$20 nozzle-assembly^{-1}). The low-cost micro-emitters used in greenhouse irrigation may be an encouraging alternative to these nozzles. However, the spray attributes of such micro-emitters are not favorable for pesticide application in their current design. Therefore, this study evaluated the performance of a SSCDS with irrigation micro-emitters modified to mimic the spray attributes of a hollow cone nozzle. The specific objectives were to:

1. Design and evaluate a low-cost irrigation micro-emitter that mimics performance of a higher cost hollow cone nozzle.
2. Determine and compare the deposition, coverage, and off target drift performance of 3-tier SSCDS configuration that utilizes either modified irrigation micro-emitters or traditional hollow cone nozzles.

2. Materials and Methods

2.1. Micro-Emitter Modification

An impaction-style micro-emitter used in both greenhouse irrigation systems (model: Modular 7000, Jain Irrigation Inc., Fresno, CA, USA) and in previous SSCDS proof of concept experiments [22] was selected for modification (Figure 1a). Such micro-emitters consist of a static impaction plate which atomizes the columnar spray jet in a radial pattern with a large cone angle (150°) and wetted diameter (2100 mm), and marginal vertical throw (320 mm) (Figure 1b). The factory impaction plate has a toothed design (Figure 1a) that tends to coarsen the spray and direct it into non-uniform radial "rays" of spray. This creates a wide statistical span in the droplet spectra and irregular deposition. While this is desirable for irrigation to mitigate evaporation, finer droplets with a narrower span are desired for canopy applications.

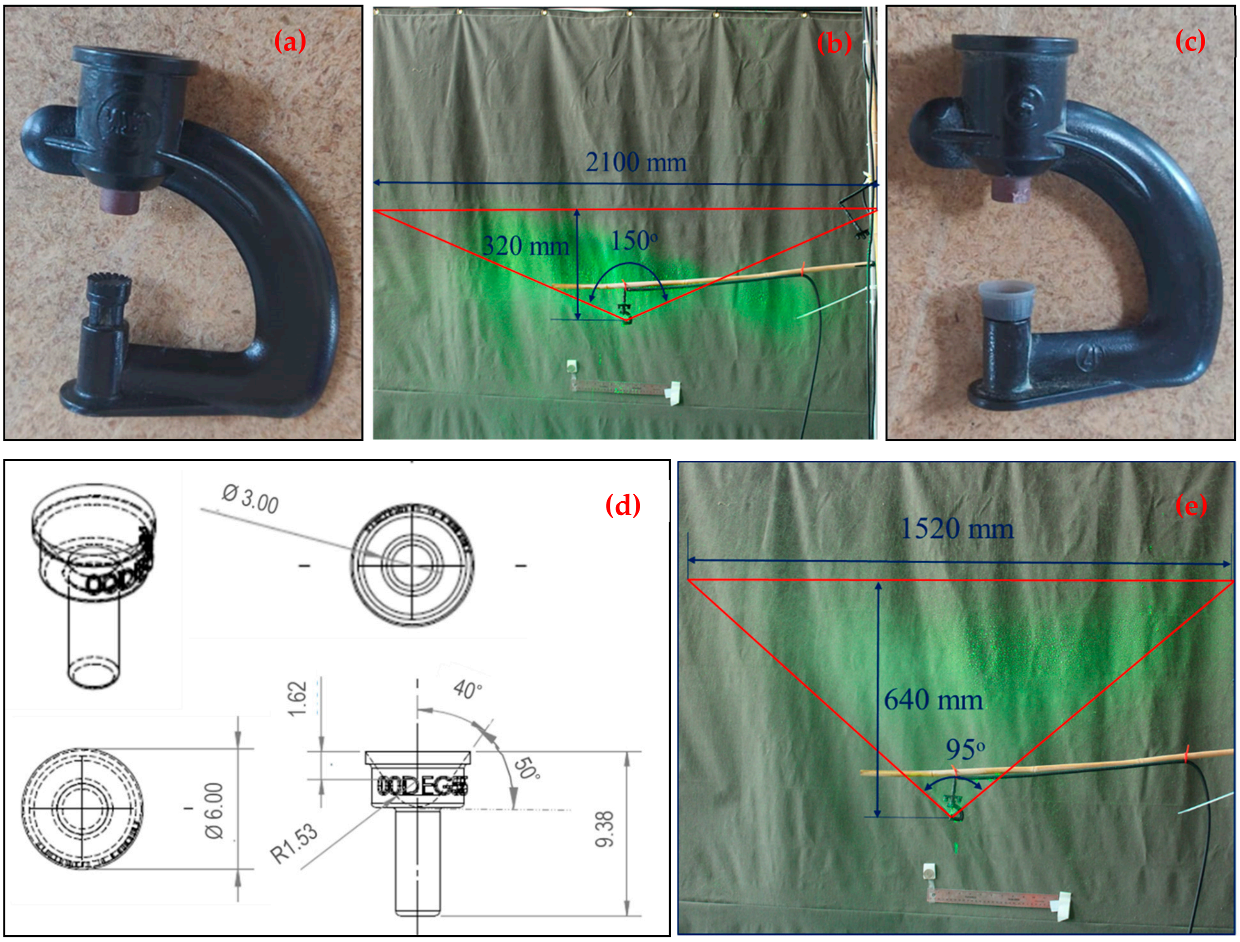


Figure 1. An off-the-shelf (**a**) micro-emitter with (**b**) a larger cone angle and wetted diameter, and a marginal vertical throw customized to (**c**) modified irrigation micro-emitter with (**d**) impactor plate concavity of 50° to acquire (**e**) a smaller cone angle and wetted diameter, and a higher vertical throw (not drawn to scale; all linear dimensions are in mm).

Through preliminary lab trials, it was hypothesized that increasing the static impactor plate concavity could reduce the cone angle of the spray, subsequently reducing the wetted diameter. Moreover, on vertically inverted placement of micro-emitter as depicted in Figure 1b, pertinent customization could increase the vertical throw of micro-emitters. Such modifications were critical to restrict the spray swath within the canopy, i.e., reduce off-target spray movement and increase in canopy deposition. Eliminating the teeth in the factory impaction plate and using a smooth-edged design also reduced the droplet spectrum, potentially improving in-canopy coverage. Thus, the static impactor plate of selected irrigation micro-emitter was modified with smooth edges and concavity ranging from 20–60° in an increment of 5°. The modified impactor plate was fixed to the micro-emitter assembly and evaluated in the lab. A randomly selected modified and non-modified micro-emitter was operated at 310 kPa, and a portable projector curtain was stationed in the background for imaging. A measuring scale was attached to the background for dimension referencing. The Red-Green-Blue images of the spray flux were captured using a visible-infrared sensor (model: Duo Pro R, FLIR Systems, Inc., Wilsonville, OR, USA) from a distance of 2 m and was analyzed in ImageJ (open source) software to evaluate the cone angle, vertical throw, and wetted diameter. The trial results indicated that a static spreader with 50° concavity (Figure 1d) was optimal to achieve the desired spray pattern with enhanced vertical throw and reduced wetted diameter (Figure 1c,e). Thus, the micro-emitter with modified static spreader (hereafter termed as 'modified irrigation micro-emitter') was selected for field evaluation in a SSCDS configuration. Additionally, the droplets of the micro-emitters/nozzles were characterized using a droplet size analyzer (model: VisiSize 15, Oxford Lasers Ltd., Didcot, Oxon, UK). The spray flux was passed through the optical sensing zone of the analyzer. The analyzer was set to analyze 1000 droplets, and the volume mean diameter ($D_V0.5$) corresponding to the micro-emitter/nozzle were evaluated. The droplet spectrum was classified based on the Dv0.5 values as per ASABE S572.3 standard [29].

2.2. Field Trials

2.2.1. SSCDS Spray Application System

A pneumatic spray delivery based SSCDS consisting of an applicator and a canopy delivery system (Figure 2) was selected for field trials [21]. Pertinent details regarding the applicator sub-systems with on-board pump, air-compressor, and spray tank can be found in Sinha et al. [18]. The canopy delivery sub-system consists of spray lines (main and return; ϕ = 2.54 cm), reservoir, and nozzle/micro-emitter assembly. Spray lines (main and return) were mounted on the existing orchard trellis wires at 1.4 m and 0.6 m above ground level, respectively, using poly hose trellis wire clips (ϕ = 2.54 cm, model: A32H, Jain Irrigation Inc., Fresno, CA, USA). The spray lines were connected in a loop and had manual flow control valves installed at the end of the loop. The reservoirs were mounted on the return line at an interval of 1.8 m. Each reservoir consisted of an inlet port, a bleed valve, a liquid column, an outlet port, a float, a diaphragm check valve, a nozzle supply column, pair of nozzle feed line, and an auto drain valve (Figure 2). These micro-emitters/nozzles were connected with the nozzle feed line of the reservoir using PE tubing (ϕ = 0.6 cm). The details of the micro-emitters/nozzles used in the two treatments are provided in Table 1.

The pneumatic spray delivery system has 3 operational stages, namely charging, recovery, and spraying/cleaning. In the charging stage, the reservoirs are filled with the spray mix using a hydraulic pressure of around 100 kPa through the main line. During recovery, the excess spray mix from the spray lines are recovered back to the spray tank using compressed air at 100 kPa through the return line. At this point, only the reservoirs contained spray mix and the contained volume was equivalent to one third of the application rate (234 L ha^{-1}). A diaphragm check valve (cracking pressure = 207 kPa) in the reservoir restricted any flow of spray mix through emitters during charging and recovery. After recovery, the spray mix contained in the reservoirs was sprayed under a pneumatic pressure of about 310 kPa. Once the spraying is complete, the auto drain valve in the reservoir opens to drain the residual volume onto the soil and cleaning is achieved.

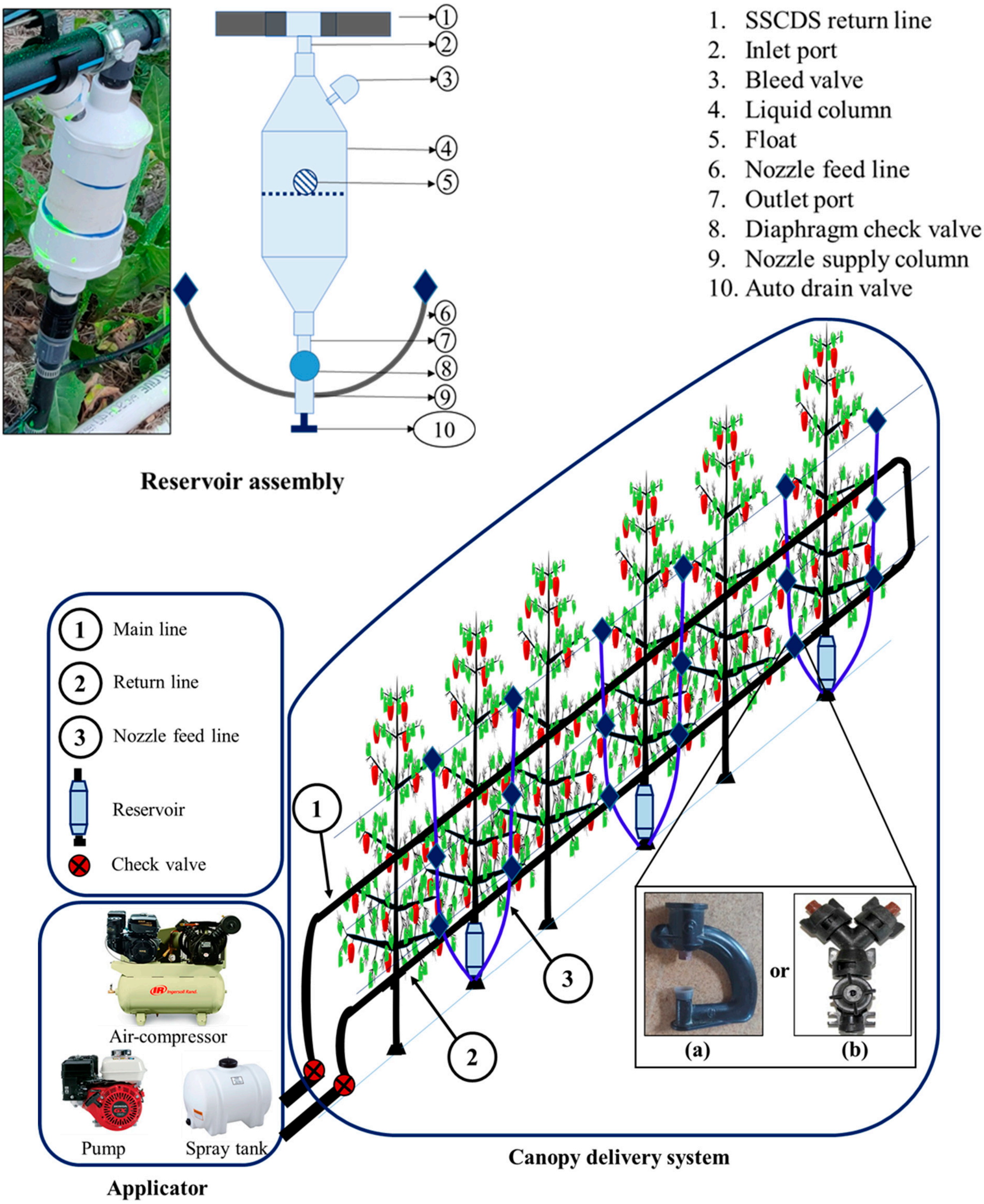


Figure 2. The schematics of tested pneumatic spray delivery based SSCDS with an applicator and canopy delivery system configured with (**a**) modified irrigation micro-emitter or (**b**) hollow cone nozzle in 3-tier arrangement (diamond shape with solid blue fill represents micro-emitter/nozzle).

Table 1. Specification of emitters tested in this study.

Emitter	Model	Manufacture	Spray Pattern	Flow Rate (L min^{-1})	Cost (USD $/Unit)
Modified micro-emitter	Modified	Jain Irrigation Inc.	Hollow cone	0.9	1.5
Hollow cone nozzle	TXVS12	TeeJet Technologies	Hollow cone	0.8	20.0

2.2.2. Treatment Details

Treatment T1, or 'irrigation micro-emitter treatment', was SSCDS configured with modified micro-emitters (Figure 2a) installed in a 3-tier arrangement (i.e., 3 micro-emitters per tree) (Table 1). The micro-emitters were installed between two trees on the existing orchard trellis wires at 1.0 m, 1.8 m and 2.6 m above ground level using the self-locking zip tie wire. Installation insured that the spray was directed upward into the canopy and provided spray coverage to one-third of the tree canopy. Sinha et al. [18] observed that directing spray upward into the canopy was critical to achieve spray coverage and deposition on abaxial leaf surfaces. The treatment T2 or 'hollow cone nozzle treatment' was also a pneumatic spray delivery based SSCDS, with emitter arrangement similar to T1. However, the micro-emitters were substituted with a pair of off-the-shelf hollow cone nozzles (TXVS12, TeeJet Technologies, Wheaton, IL, USA) connected to the spray line using a Y shaped quick-connect adapter (adapter: QJ90–2–NYR, nozzle body: QJ98590, TeeJet Technologies, Wheaton, IL, USA), with two mirrored spray outlets at 45° (Figure 2b). The quick-connect adapters were secured at each location (i.e., 1.0 m, 1.8 m and 2.6 m above ground level) to a PVC support pipe (ϕ = 1.3 cm) which was installed midway between two trees.

2.2.3. Study Site and Experimental Plot Layout

The spray trials were conducted in an apple orchard (cv. Cosmic Crisp) planted on M9-NIC29 rootstock in year 2013 and was trained in a tall spindle architecture. The research orchard was located in Roza Farm (46.29° N, 119.73° W) of Washington State University. The planting density of the experimental plot was 4284 tree ha^{-1} with an inter-row spacing of 3 m, plant to plant distance of 0.9 m, and mean tree height of 3 m.

A set of 11 apple trees planted between two wooden posts, positioned 10 m apart (hereafter termed as blocks), were designated for the system installation. Out of the 35 blocks in the experimental orchard, 6 were randomly selected for the spray trials and, in each of the blocks, a 10 m long pneumatic spray delivery based SSCDS was installed with modified micro-emitters or hollow cone nozzles in a 3-tier arrangement. Three blocks were treated with a modified irrigation micro-emitter (T1), while the other three blocks were treated with a hollow cone nozzle SSCDS (T2) (Figure 3). To ensure that the two treatments did not interact, the treatment specific spray trials were conducted on two different dates (i.e., T1: 22 July 2019 and T2: 24 July 2019). On a given day, three replicate trials were conducted within 45 min of time window.

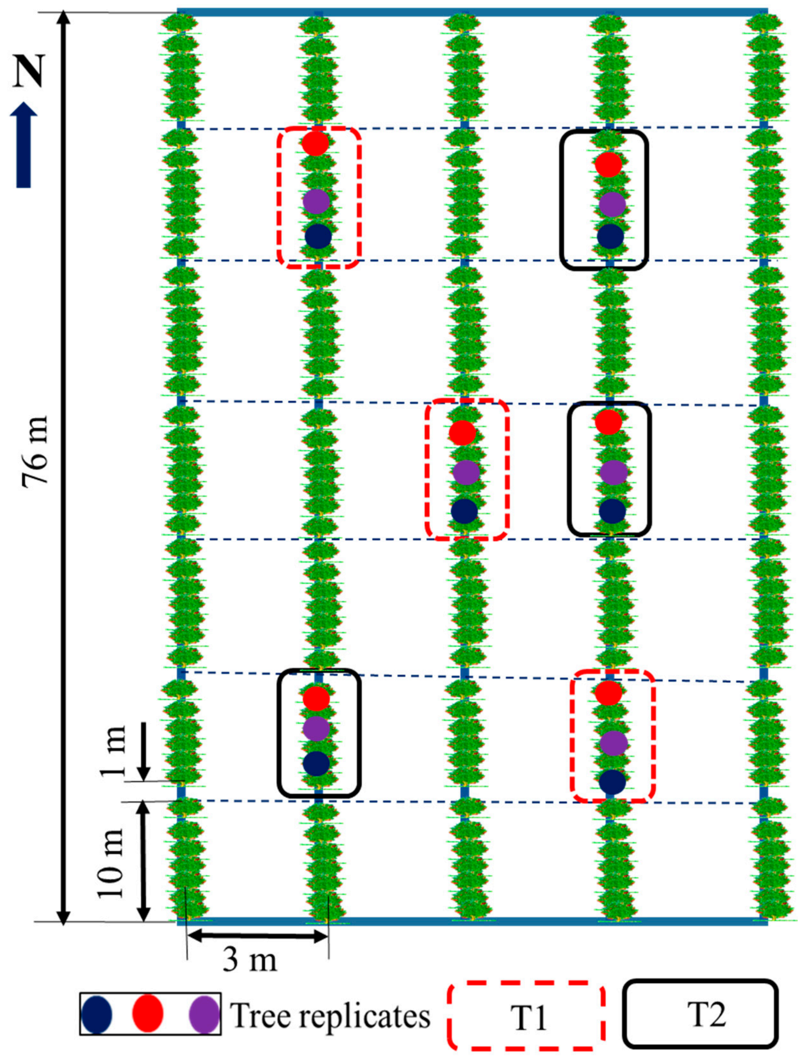


Figure 3. The schematics of experimental plot (not drawn to the scale). The dotted red boxes indicate the blocks treated with irrigation micro-emitter (T1), the solid blue boxes indicate the blocks with hollow cone nozzle treatment (T2), and the circular dots represents the sampled trees within a block.

2.2.4. Experimental Design

Spray Deposition and Coverage Evaluation

The spray trials quantified spray deposition and coverage following a randomized split-split plot design. Mylar cards (size: 5.1 × 5.1 cm, Stark Boards, CA, USA) and water sensitive papers (WSP) (size: 2.5 × 2.5 cm, Syngenta Crop Protection Inc., Greensboro, NC, USA) were used to quantify spray deposition and coverage, respectively (Figure 4). The spray deposition was enumerated by evaluating the amount of active ingredient deposited on the unit area of the mylar card (ng cm^{-2}). The spray coverage was defined as the percentage area of the WSPs stained by the spray mix. Three trees were randomly selected from the treatment blocks (Figure 3), and the sampling trees were divided into east and west canopy sides. The canopy was further divided in three zones (bottom: 0.6 to <1.4 m, mid: 1.4 to <2.2 m and top: 2.2 to 3.0 m) that resulted in six sampling zones per tree (top-east, top-west, mid-east, mid-west, bottom-east, and bottom-west) (Figure 4e). In each of the sampling zones, two leaves were randomly selected to install mylar card and WSP samplers. The samplers were installed in each of the canopy zones by clamping them onto the adaxial and abaxial leaf surfaces using customized alligator clips. The active surface of WSPs were oriented upward and downward at adaxial and abaxial leaf surfaces, respectively (Figure 4d). A total of 108 mylar cards and WSP samplers (3 blocks × 3 trees/block × 2 sides/tree × 3 zones/side × 2 leaf surface/zone × 1 sampler/leaf surface) were collected for each treatment under study.

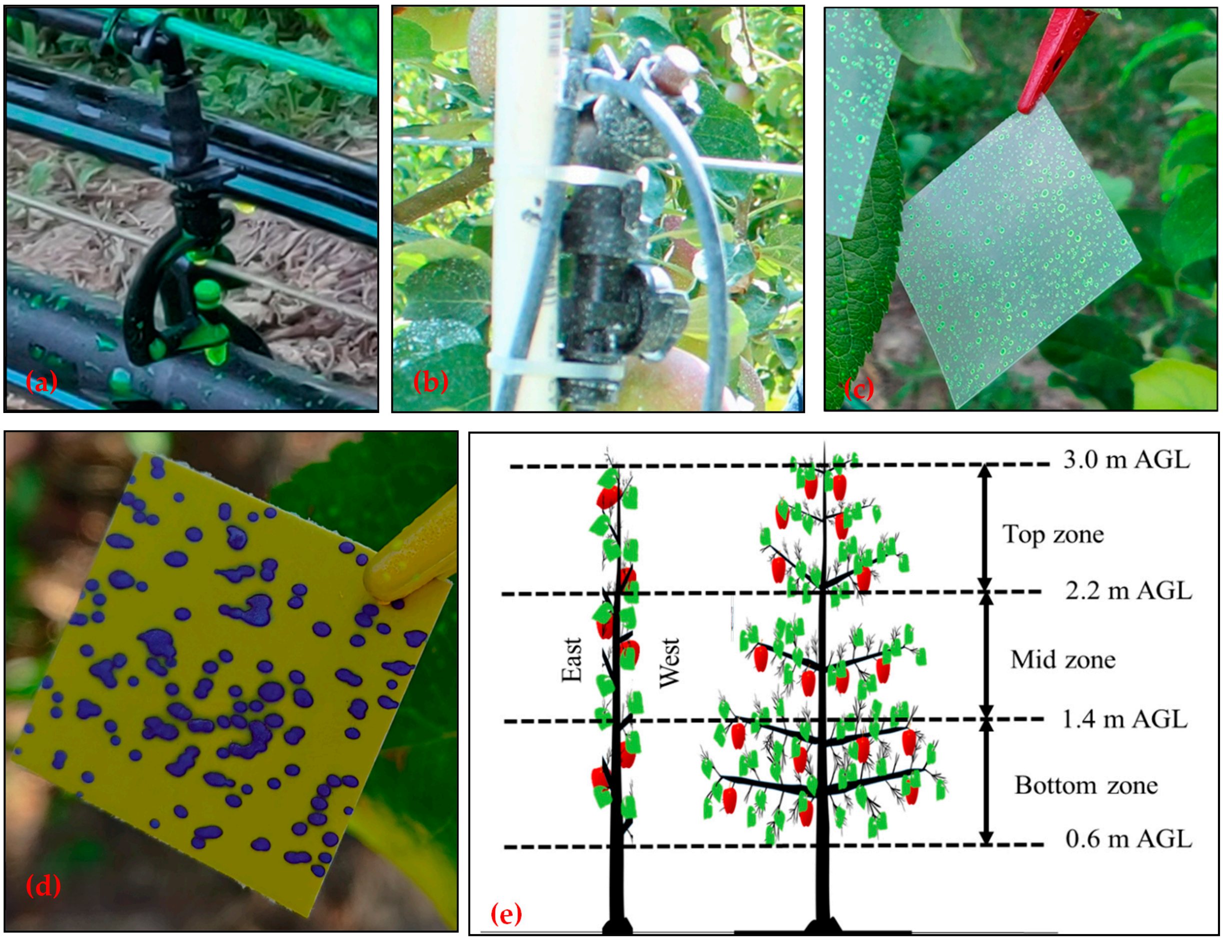


Figure 4. The field installation of (**a**) modified irrigation micro-emitter and (**b**) off-the-shelf nozzle utilized for respective SSCDS treatments, and the deposition and coverage analysis of the tested treatments with help of the (**c**) mylar card and the (**d**) water sensitive paper samplers installed in (**e**) three canopy zones on east and west side (top-east, top-west, mid-east, mid-west, bottom-east, and bottom-west).

Off-Target Spray Losses

Off-target spray losses were assessed in line with the randomized plots of canopy evaluations. Run-off and drift deposited on the ground and losses in the air were evaluated based on the schematic depicted in Figure 5. Sub-tree run-off includes the spray deposited underneath the trees because of the spray droplets settled to the tree bottom under gravity, rebounded droplets from the canopy and run-off due to canopy saturation. The run-off was evaluated with mylar card samplers (size: 5.1 × 5.1 cm) installed on a wooded block (size: 10 × 10 cm) placed below the replicate trees. Similarly, the downwind mid-row ground drift losses were evaluated using mylar card samplers located at a distance of 1.5, 4.5 and 7.5 m from the block being sprayed (Figure 5). The aerial drift losses were assessed by evaluating the tracer deposition above the tree canopy downwind to the block being sprayed. A customized PVC mast was utilized to hold mylar card samplers at a height of 3.3, 3.6 and 3.9 m above ground level. Two masts, carrying three samplers, were positioned 3 and 6 m downwind to evaluate the aerial drift losses (Figure 5). In addition to mylar card samplers, WSP samplers (size: 2.5 × 2.5 cm) were also installed at each of the drift quantification location to cross verify any contamination of mylar card samplers while handling and analysis [21].

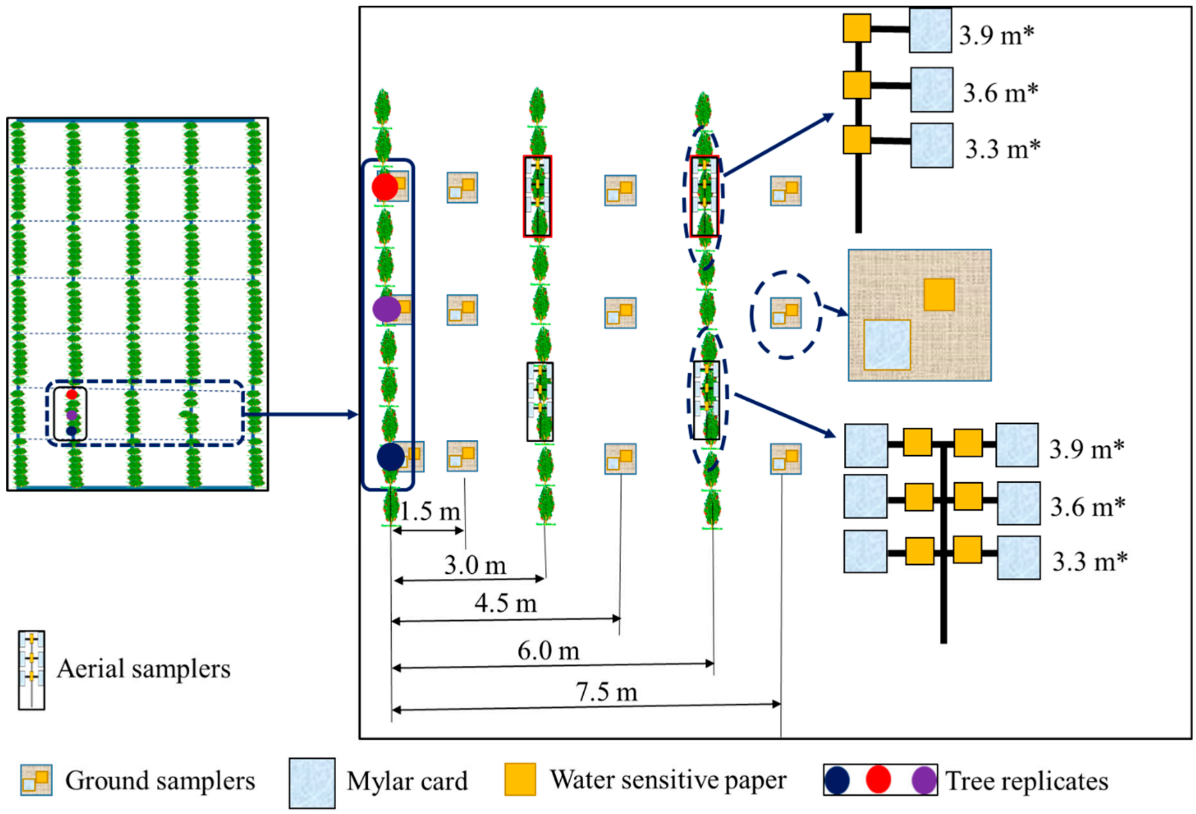


Figure 5. The off-target drift sampler layout (schematic not drawn on the scale) with ground samplers consists of a mylar card and water sensitive paper (WSP) kept on a wooden block beneath the tree and in the mid-row alley at a distance of 1.5 m, 4.5 m and 7.5 m away from the treated canopy. Three replicates of aerial drift samplers fixed on PVC mast at 3 m and 6 m downwind with mylar cards and WSPs fixed at a height of 3.3 m, 3.6 m and 3.9 m above the ground level (* distance measured above ground level).

2.3. Data Collection Protocol

A 500 ppm solution of Pyranine, a biodegradable fluorescent tracer (10G®, Keystone Inc., Chicago, IL, USA) was prepared with tap water. The spray mix was agitated thoroughly to create a homogeneous solution. Tank samples were collected pre- and post-spraying to monitor any change in tracer concentration during spraying and subsequent normalization of field samples [20].

The mylar cards and WSP samplers were installed in respective sampling zones prior to spray application as discussed in the Section 2.2.4. Since the pneumatic spray delivery based SSCDS used in this study was designed for 234 L ha^{-1}, the system was operated three times to obtain an application rate of 702 L ha^{-1}. The operating pressure during spraying stage was set at 310 kPa [21,22]. A pair of thin film pressure transducer (model: 1502B81EZ100psiG, PCB Piezotronics Inc., Depew, NY, USA) coupled with a data logger (model: CR1000, Campbell Scientific, Logan, UT, USA) was installed at 1.5 and 22 m away from the inlet port to log pressure data at 1 Hz. Additionally, an all-in-one weather station (model: ATMOS 41, METER Group, Inc., Pullman, WA, USA) coupled with a data logger (model: CR1000, Campbell Scientific, Logan, UT, USA) was installed at a height of 1 m above the canopy (ISO 22522, 2007) (Table 2) to monitor the in-field weather parameters. The weather parameters were logged at 0.2 Hz.

After spraying, the mylar card and WSPs samplers were allowed to dry for 15 min and collected and stored according to protocol described in Sinha et al. [20,22].

Table 2. Weather parameters recorded during the field data collection.

Treatment	Date	Trial	Weather Parameters (Mean ± Std. Dev.)			
			Wind Speed (m s^{-1})	Wind Direction (°) *	Air Temperature (°C)	Relative Humidity (%)
Irrigation micro-emitter	22 July 2019	1	1.0 ± 0.2	297.3 ± 13.6	18.7 ± 0.4	44.8 ± 1.5
		2	0.7 ± 0.2	219.0 ± 27.9	19.4 ± 0.1	48.4 ± 0.4
		3	0.6 ± 0.3	216.7 ± 37.0	21.0 ± 0.2	49.2 ± 1.0
Hollow cone nozzle	24 July 2019	1	1.2 ± 0.6	271.1 ± 20.8	14.1 ± 0.1	57.1 ± 0.6
		2	0.9 ± 0.4	254.4 ± 32.8	15.8 ± 0.1	57.3 ± 1.1
		3	1.4 ± 0.4	218.9 ± 18.9	17.2 ± 0.2	50.8 ± 0.4

* Reported with reference to true north and the tree rows were oriented north–south.

2.4. Data Analysis

The mylar cards and WSP samplers were analyzed using fluorometry analysis and image processing, respectively. The analysis was conducted in accordance with Sinha et al. [23] to estimate the tracer deposition per unit area (ng cm^{-2}) (hereafter termed as 'deposition') on the mylar card and spray coverage (%) (hereafter termed as 'coverage') on the WSP samplers.

The deposition and coverage data were analyzed in R studio (2017, version: 3.4.1) [30]. The datasets were cube root transformed for normalization. The transformed data were analyzed using a 2 × 3 × 2 factorial analysis of variance (ANOVA) with treatment (modified irrigation micro-emitter and hollow cone nozzle SSCDS), canopy zone (top, mid, and bottom), and leaf surface (adaxial and abaxial) as fixed factors. A Tukey Honest Significance Difference (HSD) post-hoc test was performed for multiple comparisons. The coefficient of variation (CV) in spray deposition along the leaf surface was evaluated to assess the spray uniformity for the tested treatments. Separate ANOVA models were run for the sub-tree run-off, mid-row ground, and aerial drift with deposition and coverage as the response variables. Pertaining to this, the treatments (modified irrigation micro-emitter and hollow cone nozzle SSCDS), downwind ground sampler distance (1.5 m, 4.5 m and 7.5 m), and aerial sampler height above the ground (3.3, 3.6 and 3.9 m) were used as a fixed factor. A confidence level of 95% was considered in all analyses.

3. Results

3.1. Spray Droplet Characterization

The customization of the micro-emitter resulted in reduced cone angle and wetted parameter and enhanced vertical throw for modified irrigation micro-emitter (concavity = 50°, cone angle = 95°, vertical throw = 640 mm and wetted diameter = 1520 mm) (Figure 1c,e) compared to the original micro-emitter (cone angle = 150°, vertical throw = 320 mm and wetted diameter = 2100 mm). Furthermore, modified micro-emitters produced a medium droplet size spectrum ($D_V0.5$ = 256.2 µm), while a hollow cone nozzle resulted in a fine droplet size spectrum ($D_V0.5$ = 130.9 µm) (Table 3). The pressure data indicate a marginal drop of 2 kPa between the main inlet and return outlet for both treatments. Such a small pressure drop eliminates the chances of variation in droplet characteristics due to reduction in pressure along the spray line.

Table 3. The volumetric droplet size distribution of the modified irrigation micro-emitter and hollow cone nozzle.

Emitter	Volume Percentile Diameter (µm) #			Category *
	$D_V0.1$	$D_V0.5$	$D_V0.9$	
Modified micro-emitter	134.6	256.2	416.8	Medium
Hollow cone nozzle	72.5	130.9	360.9	Fine

Reported volume percentile diameter at a pressure of 310 kPa, * Droplets have been categorized based on $D_V0.5$ as per ASABE S-572.3 standard [29].

3.2. Canopy Deposition

There were no significant differences in deposition for the main effects of SSCDS treatments ($F_{1,108} = 0.49, p = 0.48$), canopy zones ($F_{2,72} = 0.23, p = 0.79$) nor leaf surface ($F_{1,108} = 1.14, p = 0.29$) (Table 4) from ANOVA. Likewise, no significant interaction effects were detected. Although not significant, the modified irrigation micro-emitter treatment provided numerically higher overall spray deposition (955.5 ± 153.9 ng cm^{-2}) (mean ± standard error of mean [SEM]) compared to the hollow cone nozzle SSCDS (746.2 ± 104.7 ng cm^{-2}) (Figure 6).

Table 4. ANOVA of cube root transformed canopy deposition data.

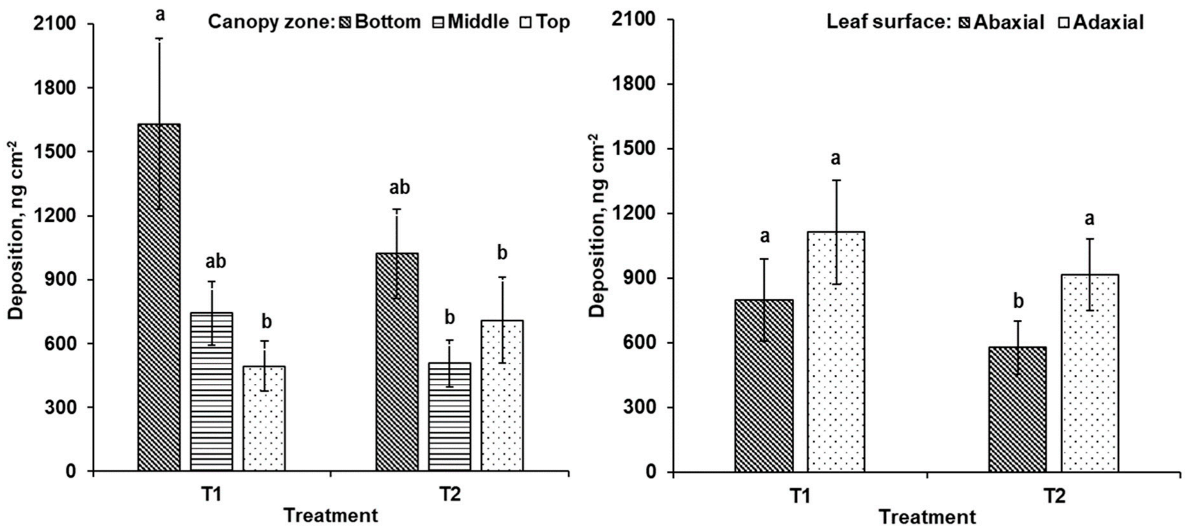
Variables	df	MS	*F*	*p*
Main plot				
Block	2	34.53		
Treatment	1	7.46	0.49	0.48
Error (a)	1	97.21		
Canopy zone	2	3.56	0.23	0.79
Leaf surface	1	17.34	1.14	0.29
Treatment × Canopy zone	2	23.07	1.52	0.22
Treatment × Leaf surface	1	1.51	0.1	0.75
Canopy zone × Leaf surface	2	20.12	1.32	0.268
Treatment × Canopy zone × Leaf surface	2	4.12	0.27	0.76
Error (b)	192	15.2		

3.2.1. Canopy Zone Level Deposition

ANOVA indicates non-significant differences in spray deposition among the canopy zones for both SSCDS treatments (Table 4). Moreover, there was no significant interaction effect between treatments and canopy zones. The bottom zone deposition for modified irrigation micro-emitter treatment i.e., T1 (1630.5 ± 401.1 ng cm^{-2}) was the highest followed by the bottom zone deposition for hollow cone nozzle treatment i.e., T2 (1022.3 ± 209.2 ng cm^{-2}) (Figure 6a). The least spray deposition was reported for the top canopy zone in treatment T1 (493.1 ± 117.6 ng cm^{-2}) and was significantly different than bottom zone deposition of corresponding treatment. These results indicate that similar deposition in different canopy zones may be achieved with modified irrigation micro-emitter SSCDS.

3.2.2. Leaf Surface Level Deposition

Spray deposition data collected at samplers installed on abaxial and adaxial surface of the leaves revealed that there was no significant difference in spray deposition on either surface of leaves regardless of the SSCDS treatments. Moreover, there was no significant interaction between treatment and leaf surface (Table 4). The highest spray deposition was reported for adaxial leaf surface treated with modified irrigation micro-emitter i.e., T1 (1112.3 ± 242.2 ng cm^{-2}) followed by hollow cone nozzle SSCDS i.e., T2 (914.5 ± 167.1 ng cm^{-2}) (Figure 6b). The abaxial deposition in T1 (798.7 ± 190.1 ng cm^{-2}) was also numerically higher than T2 (577.9 ± 123.4 ng cm^{-2}). Nevertheless, the differences were not significant with an HSD test. Furthermore, the CV in spray deposition on the leaf surfaces for T1 and T2 were 23.2% and 31.9%, respectively.



(a) (b)

Figure 6. Mean spray deposition evaluated at (**a**) different canopy zones and (**b**) leaf surfaces for modified irrigation micro-emitter (T1) and hollow cone nozzle (T2) treatment. Different lowercase letters above individual bar plots indicate significance of mean differences in transformed data at 5% level and associated error bars indicate standard error; non-transformed deposition (ng cm^{-2}) values are presented.

3.3. Canopy Coverage

There was no significant difference in coverage corresponding to the SSCDS treatment ($F_{1,108} = 1.2$, $p = 0.27$) and canopy zones ($F_{2,72} = 0.36$, $p = 0.70$) (Table 5) as main effects. On the contrary, a significant coverage difference was reported between the leaf surfaces ($F_{1,108} = 8.91$, $p = 0.02$). Furthermore, there was no significant interaction between SSCDS treatments, canopy zones, and leaf surfaces. Overall, modified irrigation micro-emitter had numerically higher canopy coverage (22.7 ± 2.6%) compared to hollow cone nozzle SSCDS (19.0 ± 2.8%).

Table 5. ANOVA result of cube root transformed canopy coverage data.

Variables	df	MS	*F*	*p*
Main plot				
Block	2	0.04		
Treatment	1	2.00	1.20	0.27
Error(a)	1	9.85		
Canopy zone	2	0.60	0.36	0.70
Leaf surface	1	1.00	8.91	0.02
Treatment × Canopy zone	2	3.30	1.99	0.14
Treatment × Leaf surface	1	2.24	1.35	0.24
Canopy zone × Leaf surface	2	0.42	0.25	0.78
Treatment × Canopy zone × Leaf surface	2	0.68	0.41	0.66
Error(b)	192	1.66		

3.3.1. Canopy Zone Level Coverage

There was no significant difference in spray coverage among canopy zones regardless of the SSCDS treatments (Table 5). Moreover, no significant interaction was reported between canopy zone and SSCDS treatment. The bottom zone coverage of modified irrigation micro-emitter treatment i.e., T1 (34.6 ± 5.3%) was highest followed by bottom zone coverage of hollow cone nozzle treatment i.e., T2 (26.0 ± 5.7%) (Figure 7a). Moreover, top zone coverage of T1 (15.5 ± 3.9%) was significantly lower than bottom zone coverage. The least canopy coverage was reported for mid zone canopy coverage of treatment T2

(15.3 ± 3.9%). Furthermore, unlike T1, the differences in bottom and top zone coverage (15.8 ± 4.0%) for T2 were statistically non-significant.

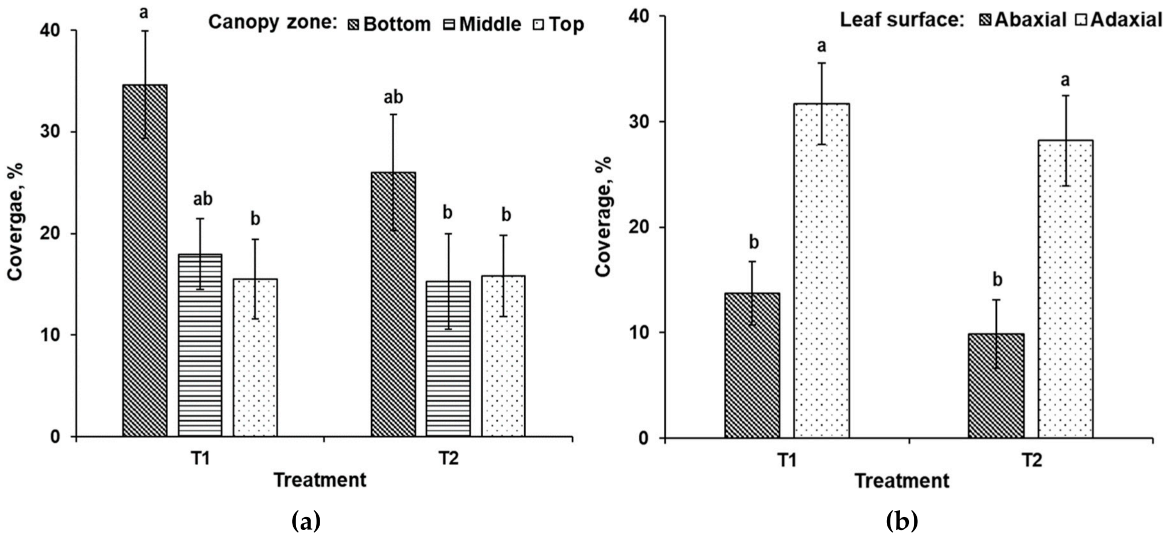


Figure 7. Mean spray coverage assessed at different (**a**) canopy zones and (**b**) leaf surfaces for modified irrigation micro-emitter (T1) and hollow cone nozzle (T2) treatments. The lowercase letters above individual bar plots indicate the significance of mean differences in transformed mean at 5% level and associated error bars indicate standard error; non-transformed coverage (%) values are presented.

3.3.2. Leaf Surface Level Coverage

There was a significant difference in abaxial and adaxial sample coverage for both SSCDS treatments (Figure 7b). However, interaction effect between treatment and surface was not significant (Table 5). The adaxial leaf surfaces of the canopies treated with modified irrigation micro-emitter (T1) received the highest spray coverage (31.7 ± 3.9%) followed by the adaxial leaf surfaces (28.2 ± 4.3%) of hollow cone nozzle SSCDS (T2) treated canopies. Moreover, abaxial coverage for T1 (13.7 ± 3.0%) and T2 (9.9 ± 3.2%) was significantly lower than corresponding adaxial coverage. Further analysis indicates that the CV in spray coverage among the leaf surfaces for T1 and T2 were 55.9% and 68.1%, respectively.

3.4. Off-Target Drift Losses

3.4.1. Ground Run-Off and Drift Losses

There was no significant difference in deposition for sub-tree run-off obtained from modified irrigation micro-emitter i.e., T1 (1720.6 ± 289.3 ng cm^{-2}) and hollow cone nozzle treatment i.e., T2 (1785.3 ± 435.6 ng cm^{-2}) (Table 6). Moreover, the percent of applied active ingredient lost underneath the tree for T1 (45.3%) was marginally lower than T2 (47.4%). The analysis of coverage samplers exhibited similar results. The treatment T1 and T2 had a coverage of 36.9 ± 5.7% and 35.3 ± 7.6%, respectively.

Mid-row ground drift deposition data collected at 1.5, 4.5 and 7.5 m downwind indicate that mean ground deposition for modified irrigation micro-emitter treatment, i.e., T1 (121.8 ± 43.4 ng cm^{-2}), was numerically lower than hollow cone nozzle SSCDS, i.e., T2 (447.4 ± 190.9 ng cm^{-2}) (Table 7). However, the difference among them were non-significant. Additionally, the percent of applied active ingredient lost to the ground drift for T1 (3.2 %) was considerably lower than T2 (20.8%). Furthermore, T1 had significantly lower mid-row ground deposition (364.4 ± 85.3 ng cm^{-2}) at 1.5 m downwind distance compared to T2 (1306.9 ± 465.3 ng cm^{-2}) (Figure 8a). The measured mid-row ground deposition at 4.5 and 7.5 m downwind for treatment T1 was also lower than T2; however, the difference was not significant. Similar trends were observed for the analysis of coverage samplers. The mean coverage corresponding to T1 (4.8 ± 1.7%) was lower than T2 (20.5 ± 6.2%); however, the difference was not significant (Table 7). Likewise, the coverage observed at

1.5 m downwind distance for treatment T1 (14.3 ± 3.3%) was significantly lower than T2 (61.0 ± 8.0%) (Figure 8b).

Table 6. Mean sub-tree run-off evaluated for tested treatments.

Off-Target Loss	Treatment	Deposition (ng cm^{-2}) * [Run-Off (%)] #	Coverage (%) *
Run-off	T1	1720.6 ± 289.3 ^{a} [45.3]	36.9 ± 5.7 ^{A}
	T2	1785.3 ± 435.6 ^{a} [47.4]	35.3 ± 7.6 ^{A}

* Transformed data were used for statistical analysis; presented data are non-transformed values in (mean ± SEM) format; different lowercase and uppercase letters represent the differences (significant or not significant) in transformed mean at α = 0.05; # The values in the square bracket represents the percent of applied active ingredient lost underneath the tree.

Table 7. Mean mid-row ground drift losses evaluated for tested treatments.

Off-Target Losses	Treatment	Deposition (ng cm^{-2}) * [Ground Drift (%)] #	Coverage (%) *
Mid-row ground drift	T1	121.8 ± 43.4 ^{a} [3.2]	4.8 ± 1.7 ^{A}
	T2	447.4 ± 190.9 ^{a} [20.8]	20.5 ± 6.2 ^{A}

* Transformed data was used for statistical analysis; presented data are non-transformed values in (mean ± SEM) format; different lowercase and uppercase letters represent the differences (significant or not significant) in transformed mean at α = 0.05; # The values in the square bracket represents the percent of applied active ingredient drifted on the ground. The lowercase and uppercase letters in superscript indicates the significant differences in transformed mean at α = 0.05.

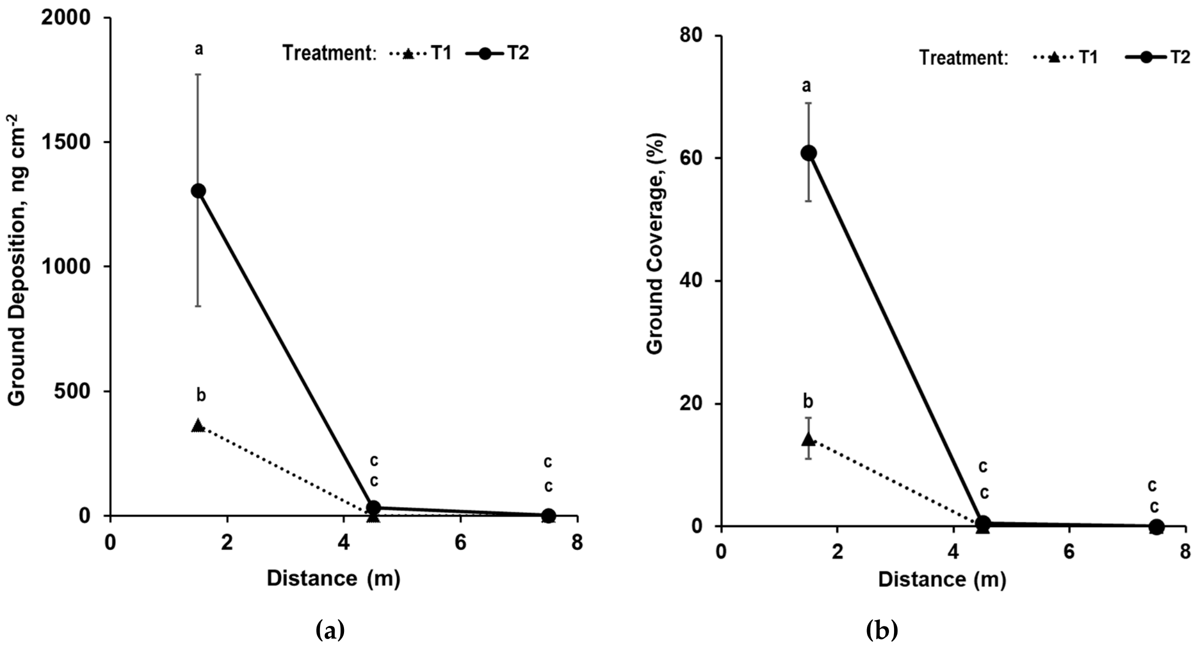


Figure 8. Mean mid-row ground (**a**) deposition and (**b**) coverage assessed at 1.5 m, 4.5 m and 7.5 m downwind for tested SSCDS treatments (i.e., T1 and T2). The lowercase letters above the line markers indicate the significant differences in transformed mean at α = 0.05 and associated error bars indicate standard error; presented values are non-transformed mid-row ground deposition (ng cm^{-2}) and coverage (%).

3.4.2. Aerial Drift Losses

Mean aerial deposition for modified irrigation micro-emitter i.e., T1 (0.7 ± 0.1 ng cm^{-2}) was significantly lower than hollow cone nozzle SSCDS treatment, i.e., T2 (3.2 ± 0.4 ng cm^{-2}) (Table 8). Additionally, the percent of applied active ingredient lost to the aerial drift was negligible for both treatments (0.02, and 0.08% for T1 and T2, respectively). Similar aerial deposition trends were observed at 3 and 6 m downwind (Figure 9a). Additionally, the deposition evaluated at various sampling heights (i.e., 3.3, 3.6, and 3.9 m above ground level) for treatment T1 (1.0 ± 0.5, 0.6 ± 0.3, 0.4 ± 0.2 ng cm^{-2}, respectively) was significantly lower than T2 (3.9 ± 1.0, 2.8 ± 0.9, 2.9 ± 0.9 ng cm^{-2}, respectively) (Figure 9b). However, the sampling height did not significantly affect the aerial deposition for a particular SSCDS treatment. Analysis of coverage samplers indicated that there was negligible mean aerial coverage (<0.1%) for both the treatments.

Table 8. Mean aerial drift losses evaluated for tested treatments.

Off-Target Loss	Treatment	Deposition (ng cm^{-2}) * [Aerial Drift (%)] #	Coverage (%) *
Aerial drift	T1	0.7 ± 0.1 ^{b} [0.02]	0.0 ± 0.0 ^{A}
	T2	3.2 ± 0.4 ^{a} [0.08]	0.0 ± 0.0 ^{A}

* Transformed data was used for statistical analysis; presented data are non-transformed values in (mean ± SEM) format; different lowercase and uppercase letters represent the differences (significant or not significant) in transformed mean at α = 0.05; # The values in the square bracket represent the percent of applied active ingredient drifted into the air; The lowercase and uppercase letters in superscript indicates the significant differences in transformed mean at α = 0.05.

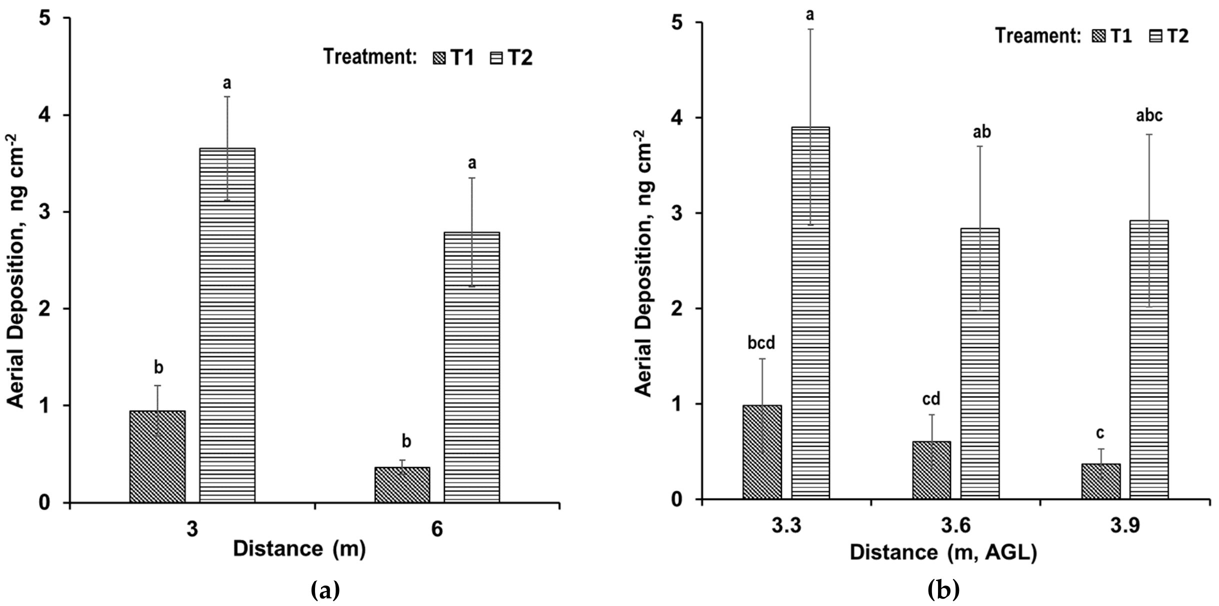


Figure 9. Mean aerial deposition observed at (**a**) 3 m and 6 m downwind and (**b**) 3.3 m, 3.6 m and 3.9 m above ground level for tested SSCDS treatments (i.e., T1 and T2). Different lowercase letters above individual bar plots indicate the differences (significant or not significant) in transformed mean at α = 0.05 and associated error bars indicate standard error; presented values are non-transformed mean ground deposition (ng cm^{-2}).

4. Discussion

The study results indicate that the SSCDS configured modified irrigation micro-emitters resulted in comparable canopy deposition and coverage against that of hollow cone nozzles. The modified irrigation micro-emitter configured treatment resulted in 28.0%

and 19.5% higher mean spray deposition and coverage, respectively, compared to hollow cone nozzle configured SSCDS treatment. Despite a considerable numerical difference in deposition and coverage between the modified irrigation micro-emitter and hollow cone nozzle SSCDS treatment, the corresponding difference was statistically non-significant, perhaps due to high variability in deposition and coverage data and a relatively small number of samples. Such variability is very typical in agrochemical application scenarios [20,31,32] and could be reduced by increasing the number of replicates in the experiment. The bottom zone deposition and coverage for both the tested treatments were highest compared to the other sampling zones. The spray droplets that missed the target and spray run-off from the top and mid canopy zone, settled to the bottom, would have resulted in a higher deposition in later zone. The modified irrigation micro-emitter treatment resulted in 59.4% and 33.1% higher bottom zone deposition and coverage, respectively, compared to the hollow cone nozzle treatment. Similarly, mid zone deposition and coverage was higher than the hollow cone nozzle treatment.

Micro-emitter modification also improved the leaf surface deposition and coverage. The abaxial and adaxial deposition of modified irrigation micro-emitter treatment were 38% and 21.6% higher than hollow cone nozzle treatment, respectively. Likewise, the modified treatment had 38.3% and 12.4% higher abaxial and adaxial coverage compared to hollow cone nozzle treatments. Additionally, modified SSCDS treatment resulted in lower CV in spray deposition and coverage between the abaxial and adaxial leaf surfaces. Results indicate that the micro-emitter modification also augmented the leaf level spray uniformity. Previous SSCDS configuration test studies have reported that shower down arrangement with only one nozzle/micro-emitter atop tree canopy was the simplest and the most economical SSCDS configuration [20,22]. However, poor bottom zone and abaxial leaf surface deposition were perceived as a major constraint with such configuration [33]. The presented 3-tier configured SSCDS with modified emitters indicates a substantial increase in the bottom zone and abaxial leaf surface deposition and coverage. Furthermore, the modified SSCDS configuration uses a low-cost micro-emitter (1.5 $/unit) (Table 1) that assisted in reducing the system installation cost by ~12 times, compared to expensive off-the-shelf hollow cone nozzles (20 $/unit) configured SSCDS. Such cost savings is expected to improve its economic viability.

The off-target drift data trends indicate that the modified irrigation micro-emitter treatment (T1) had numerically lower aerial, ground run-off and drift losses compared to treatment configured with hollow cone nozzle (T2). The adjacent mid-row ground deposition and coverage evaluated at 1.5 m downwind were, respectively, 258.5% and 326.5% lower for the modified micro-emitter treatment. Likewise, overall mean mid-row ground deposition and coverage in the modified treatment were 267.3% and 327% lower than hollow cone nozzle treatment. A similar trend was observed for downwind aerial drift. The aerial deposition for T1 recorded at 3 m and 6 m downwind was, respectively, 298% and 373% lower than T2. The overall mean aerial deposition of modified treatment was 395% lower compared to hollow cone nozzle SSCDS treatment. Furthermore, the ground spray coverage at 4.5 m and 7.5 m and aerial coverage at 3 m and 6 m downwind for modified treatment were almost negligible (<0.1%). The hollow cone nozzles produced fine size droplets (Table 3) that are highly susceptible to drift due to longer air suspension time and lighter weight [34–36]. In contrast, the modified micro-emitter produced medium sized droplets (Table 3) that would have reduced the off-target drift potential [37]. Additionally, wind speed during the modified micro-emitter trials was 1.5 times higher than hollow cone nozzle treatment trials (Table 2). With similar wind direction trend during both treatments, higher wind speed would cause higher off-target drift for spray with modified irrigation micro-emitters. Nonetheless, modification in droplet size spectrum would have curtailed pertinent off-target drift losses. This might be one of the reasons why modified micro-emitter configured treatments would have resulted in lesser ground and aerial drift. Therefore, pertinent modification could assist in minimizing the environmental contamination and subsequent hazards [6–8]. Furthermore, the reduced drift for modified

SSCDS treatment would have resulted in improved overall as well as zone and leaf specific canopy deposition and coverage [38].

While a modified irrigation micro-emitter provided a low-cost alternative to the hollow cone nozzles in SSCDS configuration, existing pneumatic spray delivery reservoir drains the residual spray mix onto the soil through auto drain valve for cleaning. During pesticide application, such residues can contaminate the soil [39] and can cause up to 25% pesticide losses to the ground. To overcome this problem, our lab is working on the modification of the existing pneumatic spray delivery reservoirs, which allows partial passage of the air to the nozzle feed line towards the end of the spray cycle so that residues can be sprayed into the canopy instead of draining onto the soil. Pertinent self-cleaning ability would eliminate the need of the auto-drain valve in the reservoir and ground chemical losses.

5. Conclusions

1. The 3-tier SSCDS treatment configured with modified micro-emitters had comparable spray performance with numerically higher spray deposition, coverage and lower off-target drift losses compared to that of a SSCDS configured using off-the-shelf hollow cone nozzles.
2. The modified micro-emitters facilitated the uniform distribution of spray material on upper and lower leaf surfaces. The micro-emitter refinement was thus successful and assisted in improving spray performance.

Our future research will focus on exploring the biological efficacy of the modified SSCDS configuration. These data are needed to support the further development and eventual commercial adaptation of this system.

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