Effect of spray angle and spray volume on deposition of a medium droplet spray with air support in ivy pot plants

Dieter Foqué, Jan G. Pieters and David Nuyttens

Abstract

BACKGROUND: Spray boom systems, an alternative to the predominantly-used spray guns, have the potential to considerably improve crop protection management in glasshouses. Based on earlier experiments, the further optimization of the deposits of a medium spray quality extended range flat fan nozzle type using easy adjustable spray boom settings was examined. Using mineral chelate tracers and water sensitive papers, the spray results were monitored at three plant levels, on the upper side and the underside of the leaves, and on some off-target collectors. In addition, the deposition datasets of all tree experiments were compared.

RESULTS: The data showed that the most efficient spray distribution with the medium spray quality flat fan nozzles was found with a 30° forward angled spray combined with air support and an application rate of 1000 L ha⁻¹. This technique resulted in a more uniform deposition in the dense canopy and increased spray deposition on the lower side of the leaves compared with the a standard spray boom application. Applying 1000 L ha⁻¹ in two subsequent runs instead of one did not seem to show any added value.

CONCLUSION: Spray deposition can be improved hugely simply by changing some spray boom settings like nozzle type, angling the spray, using air support and adjusting the spray volume to the crop.

Keywords: application technique; angling; air assistance; spray volume; passes; ornamental crops

1 INTRODUCTION

Most ornamental plant growers in Flanders still use knapsack sprayers and lances for crop protection purposes at high application rates (up to 6650 L ha⁻¹) and spray pressures (up to 50 bar). Similar observations by other authors illustrate that using handheld equipment with high application rates and spray pressures, is a common practice in ornamental and other production systems in other countries as well.

These hand held techniques are, however, often less effective than spray booms, are known for their heavy workload, inferior spray distribution and high operator exposure risks and have been reported to result in higher off-target depositions and losses to the ground.

Also, knowing that plant protection products (PPPs) authorized for the treatment of glasshouse ornamental plants in Belgium often express the dose as a concentration (e.g. 50 g 100 L⁻¹ spray volume; http://www.fytoweb.fgov.be/indexEn.asp), the high application rates result in a high amount of PPP applied to a certain surface. So, additional to the operator risks, there are also some potential environmental hazards (e.g. point source pollution, run-off) related to the common practices.

Several studies have already demonstrated that horizontal and vertical spray booms can improve spray distribution and reduce labour costs and operator exposure compared with traditional handheld techniques. However, most growers still lack an understanding of the optimal settings for spray boom equipment. This is especially true for ornamental growers due to the tremendous diversity of ornamental plants and production systems.

In 2006, a research project was started to investigate the (combined) effect of nozzle type, spray pressure, droplet characteristics, spray angle, spray volume and air support on spray deposition and biological efficacy of vertical and horizontal boom applications with a focus on obtaining good crop penetration and uniform spray liquid distribution on ornamental plants.

For the horizontal boom application, ivy pot plants were selected as a model crop because of their high crop density, their commercial importance and the current need for an effective treatment for the two-spotted spider mite. A first series of
experiments focused on the effect of nozzle type, spray pressure and droplet characteristics on the spray distribution in ivy pot plants. Additionally, the effect of spray angle was studied for the extended range flat fan TeeJet XR 80 03 nozzle. The experiments showed a significant variation of deposition and coverage in the crop. Spray deposition and coverage of the underside of the leaves was generally low, but could be improved with a factor of 3.0 to 4.9 using the appropriate application technique. Based on these tests, the coarse droplet air induction nozzle and the medium droplet extended range flat fan nozzle were selected for further examination. In a second series of tests the effect of air support and spray angle (−30°, 0°, 30°) was evaluated with the coarse droplet Lechler ID 90 02 air induction nozzle at 6.0 bar. The use of air support improved crop penetration and deposition on the underside of the leaves and reduced spray deposition in the top layer at the top side of the leaves. This effect was most pronounced with the standard 0° spray angle. Despite the significant effect of air support with this coarse spray, the spray distribution over the crop canopy was still far from uniform. Without air support, spray angling improved crop penetration but the deposition on the underside of the leaves was still low.

Many studies describe that angling the nozzles is an efficient, easily adjustable and inexpensive way to improve the deposition or penetration in the canopy, or a combination of both air support and an angled spray have also showed promising results in other studies. Finally, treating the crop from two directions has also been suggested to improve spray results, especially to overcome a lower deposition on the back side of the plants.

Based on the guidelines of manufacturers, the first two series of experiments were done at an application volume of 1000 L ha−1. This application rate is still quite high, particularly when compared with those used when spraying arable crops (25–200 L ha−1), fruit (50–500 L ha−1), field-grown vegetables (150–400 L ha−1), or ornamental liners (187–374 L ha−1). Many growers, however, argued that this application rate is far too low to obtain a good plant protection. Hence, the use of a better application technique could result in better spray results, a further reduction of the spray volume was also considered.

Using the information found earlier and the findings of Foqué and Nuyttens, the effect of spray angle, spray volume (500, 1000 and 2000 L ha−1) and the number of passes, were evaluated for extended range standard flat fan nozzles with a medium spray quality in combination with air support. The effects were studied for deposition as well as coverage, with particular attention for reaching the underside of the leaves and a better crop penetration. The aim was to evaluate whether further improvement in the uniformity of the spray distribution in ivy pot plants can be obtained.

In addition, spray results of all application techniques tested at 1000 L ha−1 and 2.7 km h−1 in current and previous experiments were compared to see if any of the tested technique could be pointed out as the optimal application technique.

## 2 MATERIALS AND METHODS

### 2.1 Spray application techniques

The self-propelled aluminium spray unit with a horizontal spray boom, described by Foqué and Nuyttens, was equipped with an air support system that copies the Hardi Twin system. Seven different spray application techniques were tested to evaluate the combined effect of spray angle and spray volume on a medium droplet size application with air support (Table 1). An application volume of 1000 L ha−1 is often suggested by manufacturers of PPPs as the minimum spray volume for ornamental crops kept in glasshouse conditions. At this application volume, a forward (30°) as well as a downward (0°) and backward (−30°) spray angle were tested. In this experiment, the effects of a halved (500 L ha−1) and doubled (2000 L ha−1) application rate were investigated as well but only for a forward spray angle (30°) following the results of Foqué and Nuyttens. The application rates were adjusted by changing the speed of the automated spray boom. The 500 L ha−1 applications were made in two directions, namely, left (L) and right (R), which made it possible to evaluate the effect of applying 1000 L ha−1 in two passes with a different direction (L + R).

All sprayings were performed with a TeeJet XR 80 03 extended range flat fan nozzle (TeeJet Technologies, Wheaton, USA) at 3.0 bar with a nominal flow rate of 1.18 L min−1, a volume median diameter of 203.43 ± 8.37 µm and an average one-dimensional droplet velocity of 2.45 ± 0.19 m s−1. Droplet characteristics were measured at 0.50 m below the spray nozzle as described by Nuyttens et al. In agreement with Foqué and Nuyttens, spray passes were performed with a nozzle distance of 0.25 m, a boom height of 0.45 m and an intended speed of 1.35, 2.7 and 5.4 km h−1, resulting in application volumes of 2000, 1000 and 500 L ha−1 respectively. Each spray application was carried out in triplicate.

<table>
<thead>
<tr>
<th>Techniquea</th>
<th>Spray angle (deg)b</th>
<th>Air support</th>
<th>Speed (km h−1)</th>
<th>Application rate (ha−1)</th>
<th>Boom moving directionc</th>
</tr>
</thead>
<tbody>
<tr>
<td>XR 0° 1000 + Air</td>
<td>0</td>
<td>Yes</td>
<td>2.49 ± 0.01</td>
<td>1113 ± 4</td>
<td>L</td>
</tr>
<tr>
<td>XR −30° 1000 + Air</td>
<td>−30</td>
<td>Yes</td>
<td>2.48 ± 0.03</td>
<td>1138 ± 13</td>
<td>L</td>
</tr>
<tr>
<td>XR 30° 1000 + Air</td>
<td>30</td>
<td>Yes</td>
<td>2.47 ± 0.03</td>
<td>1144 ± 12</td>
<td>L</td>
</tr>
<tr>
<td>XR 30° 500 (L) + Air</td>
<td>30</td>
<td>Yes</td>
<td>5.59 ± 0.12</td>
<td>507 ± 11</td>
<td>L</td>
</tr>
<tr>
<td>XR 30° 500 (R) + Air</td>
<td>30</td>
<td>Yes</td>
<td>5.56 ± 0.06</td>
<td>509 ± 5</td>
<td>R</td>
</tr>
<tr>
<td>XR 30° 2 × 500 (L/R) + Aird</td>
<td>30</td>
<td>Yes</td>
<td>5.57 ± 0.09</td>
<td>1016 ± 19</td>
<td>L + R</td>
</tr>
<tr>
<td>XR 30° 2000 + Air</td>
<td>30</td>
<td>Yes</td>
<td>1.44 ± 0.00</td>
<td>1967 ± 8</td>
<td>L</td>
</tr>
</tbody>
</table>

a All sprayings with TeeJet XR 80 03 extended range flat fan nozzle at 3.0 bar and air support.
b Spray angle relative to the movement of the spray boom: forward (30°), downward (0°) or backward (−30°).
c L, left spray direction; R, right spray direction.
d Not run as an experiment; the addition of both 500 L ha−1 runs.
2.2 Experimental setup and crop characteristics

The experimental setup was very similar to the one described by Foqué and Nuyttens. Ivy pot plants (Hedera algeriensis var. Montgomery) were used to evaluate the effect of application technique on crop deposition and coverage. The plants were placed on a rolling bench (2.00 m × 3.50 m) in three rows of six plant pallets (0.53 m × 0.31 m) (Figs 1 and 2). Each pallet contained six ivy pot plants. Plant density was 32.6 plants per square metre. Because of the design of the tray, plant distances were 16 cm within the same pallet in the spray direction, 19 cm perpendicular to the spray direction and 21.5 cm for the distance between the first and the last plant of two consecutive pallets in the spray direction. This setup resulted in a closed and dense canopy with an average height of 18.9 ± 2.4 cm and with many shielded features caused by frequently overlapping foliage from different plants and the more or less horizontal position of the leaves. The leaf area index (LAI) of a similar ivy crop was reported before and increased from top to bottom: it measured 2.1 at the top, 5.5 in the middle and 6.9 at the bottom of the plants, corresponding to average heights of about 19.9, 9.0 and 3.4 cm above the pot.

2.3 Spray deposition and coverage

Spray deposition was evaluated using filter paper collectors (FPCs, 5.7 cm × 2.6 cm, Schleicher & Schuell, type 751, Filter Service NV, Eupen, Belgium) attached by small paper clips to six collector plants. Spray coverage was assessed by the use of water sensitive paper (WSP, 2.6 cm × 3.8 cm, Syngenta Crop Protection AG, Basel, Switzerland) attached to three collector plants zones on leaves at least as big as the collector (Figs 1 and 2). Spray coverage was only assessed in the first of three replicates. WSP has been used in many studies as a tool for providing quick and cheap evaluation of spray coverage. All spraying applications were done at a low relative humidity (51 ± 8%) to prevent the WSP turning blue because of high relative humidity. Because the XR 30° 2 × 500 (L/R) + Air technique resulted from two consecutive 500 L ha⁻¹ applications in an opposite direction and the plants were not allowed to dry between passes, spray coverage could not be assessed for this technique as well as for the XR 30° 500 (R) + Air technique. The WSP collector plants were replaced by normal plants within minutes after the XR 30° 500 (L) + Air application spray. Afterward, the XR 30° 500 (R) + Air spray was made.

For each sampled plant, six collectors were equally distributed between three crop zones, i.e. the uppermost foliage layer, the zone between the middle of the plant and the soil and the soil area (Fig. 2). Two collectors were positioned in the upper layer at an average height of 18.1 ± 2.7 cm. Two other collectors were placed in the middle layer on leaves at an average height of 6.4 ± 2.0 cm above the pot. In both crop zones, one collector was on the upper surface of a leaf and one on the bottom surface of another leaf. The two remaining collectors were placed at the bottom of the plants. One was placed on a small Petri dish, parallel to the soil, while the other was attached to the plant’s stem, perpendicular to the soil but without touching it. The latter two collectors gave an indication of crop penetration and possible differences in run-off. The height of each collector was measured during the experimental setup. The collector plants were randomly distributed between the other ivy plants.

To measure off-target spray deposition, six FPCs were placed at 0.225 m from the crop’s edge and six others were randomly placed within the crop between the pots (Fig. 1).

While the WSP strips were replaced for every spray application, the same FPCs were used during six subsequent spray events with a different technique using a different mineral chelate (Fe, Co, Cu, Mn, Mo and Zn, Chelal®, BMS Micro-Nutrients NV, Bornem, Belgium) at a targeted concentration of 1.0 g L⁻¹ in a randomized order to obtain a direct comparison between the different techniques as described by Braekman et al. and Nuyttens et al. The crop and collectors were allowed to dry completely between successive applications. Drying time ranged from two to four hours depending on ambient conditions. After spraying with all six techniques, the FPCs were gathered and analysed using inductively coupled plasma (ICP) analysis (VISTAPRO, Varian, Palo Alto, CA, USA).

The spray deposition (in L ha⁻¹) on every collector was calculated with the actual concentration in the tank, the calculated application rate, the quantity of 0.16 M nitric acid (HNO₃) (66-%, p.a., Acros organics, Geel, Belgium) used for extraction, and the analysis of the blank samples taken into account. For a comparative assessment...
of the different techniques, the results were normalized to the targeted application rate (500, 1000 and 2000 L ha\(^{-1}\)) and a tank concentration of 1.0 g L\(^{-1}\). Because different spray application rates were used, the deposition results were also expressed as a relative spray deposition (%) in relation to the application rate used as suggested by Braekman et al.\(^{23}\) After each application, the WSPs were gathered and digitized at 600 dpi. An image analysis system using Halcon 8.0 software (MVTec Software GmbH, München, Germany), was used to calculate spray coverage.

2.4 Statistical analysis

Statistica 7.1 (Statsoft Inc., Tulsa, Oklahoma, USA) was used for all statistical analyses. A \(P\)-value < 0.05 was considered to be statistically significant. Deposition and coverage data were analysed using a non-parametrical Kruskal–Wallis test because no adequate way was found to transform the data into a normally distributed dataset. The effect of the different application techniques was tested for the different collector positions. This Kruskal–Wallis test is based on the comparison of mean ranks and is less powerful than a one-way analysis of variance (ANOVA). Nevertheless, it has been used by Foquè and Nuyttens\(^{1,2}\) for the same reason.

The coefficient of variation (CV) can be used as an indicator for the uniformity of the spray deposition in the canopy.\(^{10,13,46,70–72}\) Because our dataset did not show a normal distribution, we could not calculate the overall CVs in the usual way, as was done in the studies mentioned. However, to get an idea of the spray uniformity, the statistics shown in Tables 2 and 3 were calculated based on the values of the median per collector position per technique, which were then grouped per collector position (Table 2) or technique (Table 3). For example, the CV of the deposition (Table 3) expresses the uniformity of the median spray deposition values measured on the FPS at six different sampling positions. The Kruskal–Wallis analyses for these tables were done on the raw datasets of the different parameters.

Afterward, depositions (in L ha\(^{-1}\)) of all application techniques tested at 1000 L ha\(^{-1}\) and 2.7 km h\(^{-1}\) in current and previous experiments\(^{1,2}\) were compared to see if one of the tested techniques could be pointed out as the optimal application technique.

3 RESULTS

3.1 Spray application parameters and environmental conditions

The average measured flow rate of the used nozzles\(^2\) was 1.178 ± 0.003 L min\(^{-1}\). The application rate and speed of the spray boom as observed during spraying (Table 1) were statistically analysed. For the applications with a recommended application rate of 1000 L ha\(^{-1}\) in a single pass, the actual application rate varied from 1133 to 1144 L ha\(^{-1}\) corresponding with an actual speed of 2.49 and 2.47 km h\(^{-1}\) (Table 1). For the 500 L ha\(^{-1}\) applications, actual application rates were 507 and 509 L ha\(^{-1}\) resulting in an application volume of 1016 L ha\(^{-1}\) for the 1000 L ha\(^{-1}\) application in two passes. The spray volume that was effectively used for the 2000 L ha\(^{-1}\) application was 1967 L ha\(^{-1}\). For the different application rates, no significant differences were found between the replicates. With a boom height of 0.45 m and a downward spray, a CV of 8.9% was found using a spray distribution bench (ISO 5682–1) in the ILVO Spray Tech Laboratory.\(^2\) This value fulfils the European standard EN 12761–2 (CV < 9%).

During the experiments, the ambient temperature (20.0 ± 1.3 °C) and relative humidity (51.2 ± 8.1%) were relatively constant and in the same range as during the experiments performed by Foqué and Nuyttens.\(^{1,2}\)

3.2 Canopy spray deposition

For each of the six collector locations (numbered 1–6), spray depositions (in L ha\(^{-1}\)) for the different techniques are shown in Fig. 3 [mean ± standard error (SE), median]. These collector numbers refer to a specific collector position as follows: 1, upper layer, upper side of leaves; 2, upper layer, bottom side of leaves; 3, middle layer, upper side of leaves; 4, middle layer, bottom side of leaves; 5, ground level, attached to stem; 6, ground level, horizontal to soil. Only at collector position 2 (upper layer, bottom side of leaves), no significant differences in mean spray deposition rank were found between the different techniques. Significant differences were found at all other collector positions.

In Fig. 4, the relative spray deposition results (%, mean ± SE, median) are presented. Although some trends can be observed,
no statistically significant differences were observed between the different techniques at the different positions.

Table 2 shows the means, medians, standard deviations (SD) and CVs of deposition (in L ha\(^{-1}\)) and relative deposition for the different sampling positions averaged across the different application techniques. Similarly, Table 3 presents the means, medians, SD and CVs of deposition and relative deposition for the different spray application techniques averaged across the different sampling positions. The CVs can be used as an indicator for the uniformity of the spray deposition in the canopy.\(^{10,13,46,70–72}\)

### 3.3 Canopy spray coverage and the number of spots
For each of the six collector locations (numbered 1–6 below), spray coverage results (%) and the number of spots (spots cm\(^{-2}\)) for the different techniques are shown in Figs 5 and 6 (mean ± SE, median). In both cases, significant differences in mean

**Table 2.** Means, medians, standard deviation (SD) and coefficients of variation (CV) of the medians of the deposition (in L ha\(^{-1}\)), relative deposition (%), coverage (%) and number of droplets for the different sampling positions, calculated across the different techniques

<table>
<thead>
<tr>
<th>Technique</th>
<th>Upper layer, upper side of leaves</th>
<th>Upper layer, underside of leaves</th>
<th>Middle layer, upper side of leaves</th>
<th>Middle layer, underside of leaves</th>
<th>Ground level, attached to stem</th>
<th>Ground level; horizontal to soil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deposition Mean (L ha(^{-1}))</td>
<td>114</td>
<td>53</td>
<td>59</td>
<td>7</td>
<td>45</td>
<td>24</td>
</tr>
<tr>
<td>Median (L ha(^{-1}))</td>
<td>87a</td>
<td>46ab</td>
<td>54ab</td>
<td>6c</td>
<td>37ab</td>
<td>15b</td>
</tr>
<tr>
<td>SD (L ha(^{-1}))</td>
<td>70</td>
<td>33</td>
<td>36</td>
<td>4</td>
<td>31</td>
<td>21</td>
</tr>
<tr>
<td>CV (%)</td>
<td>60</td>
<td>63</td>
<td>61</td>
<td>65</td>
<td>70</td>
<td>87</td>
</tr>
<tr>
<td>Relative deposition Mean (%)</td>
<td>12.1</td>
<td>5.9</td>
<td>5.7</td>
<td>0.6</td>
<td>4.2</td>
<td>2.1</td>
</tr>
<tr>
<td>Median (%)</td>
<td>8.5a</td>
<td>4.1ab</td>
<td>5.4ab</td>
<td>0.6c</td>
<td>4.4a</td>
<td>1.6b</td>
</tr>
<tr>
<td>SD (%)</td>
<td>6.5</td>
<td>4.4</td>
<td>2.0</td>
<td>0.2</td>
<td>1.3</td>
<td>1.1</td>
</tr>
<tr>
<td>CV (%)</td>
<td>53</td>
<td>74</td>
<td>35</td>
<td>40</td>
<td>31</td>
<td>52</td>
</tr>
<tr>
<td>Coveragea Mean (%)</td>
<td>37.1</td>
<td>14.2</td>
<td>17.2</td>
<td>1.3</td>
<td>10.7</td>
<td>13.7</td>
</tr>
<tr>
<td>Median (%)</td>
<td>33.1a</td>
<td>7.7a</td>
<td>9.8ab</td>
<td>0.5c</td>
<td>0.9bc</td>
<td>9.3a</td>
</tr>
<tr>
<td>SD (%)</td>
<td>11.8</td>
<td>13.5</td>
<td>21.8</td>
<td>1.6</td>
<td>5.9</td>
<td>6.1</td>
</tr>
<tr>
<td>CV (%)</td>
<td>32</td>
<td>95</td>
<td>126</td>
<td>124</td>
<td>55</td>
<td>44</td>
</tr>
<tr>
<td>Number of spotsa Mean (Spots cm(^{-2}))</td>
<td>53</td>
<td>65</td>
<td>58</td>
<td>28</td>
<td>15</td>
<td>51</td>
</tr>
<tr>
<td>Median (Spots cm(^{-2}))</td>
<td>42a</td>
<td>40a</td>
<td>53a</td>
<td>17a</td>
<td>8a</td>
<td>32a</td>
</tr>
<tr>
<td>SD (Spots cm(^{-2}))</td>
<td>33</td>
<td>46</td>
<td>42</td>
<td>28</td>
<td>13</td>
<td>53</td>
</tr>
<tr>
<td>CV (%)</td>
<td>62</td>
<td>71</td>
<td>73</td>
<td>100</td>
<td>89</td>
<td>105</td>
</tr>
</tbody>
</table>

Note: Medians in the same row with the same letter do not differ significantly (P < 0.05, Kruskal–Wallis test).

a Based on experiments with XR 0° 1000 + Air, XR −30° 1000 + Air, XR 30° 1000 + Air, XR 30° 500 (L) + Air and XR 30° 2000 + Air.

**Table 3.** Means, medians, standard deviation (SD) and coefficients of variation (CV) of the medians of the deposition (L ha\(^{-1}\)), relative deposition (%), coverage (%) and number of droplets for the different techniques, calculated across the different sampling positions

<table>
<thead>
<tr>
<th>Technique</th>
<th>XR 0° 1000</th>
<th>XR −30° 1000</th>
<th>XR 30° 1000</th>
<th>XR 30° 500 (L)</th>
<th>XR 30° 500 (R)</th>
<th>2 × 500 (L/R) 2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ Air</td>
<td>Air</td>
<td>+ Air</td>
<td>+ Air</td>
<td>+ Air</td>
<td>+ Air</td>
<td>+ Air</td>
</tr>
</tbody>
</table>

| Deposition Mean (L ha\(^{-1}\)) | 48.21 | 60.30 | 41.48 | 17.66 | 31.71 | 66.10 | 85.22 |
| Median (L ha\(^{-1}\)) | 43.10a | 33.70ab | 46.57ab | 14.73c | 16.52bc | 55.76ab | 84.84a |
| SD (L ha\(^{-1}\)) | 29.91 | 82.66 | 24.36 | 15.58 | 34.64 | 57.40 | 55.45 |
| CV (%) | 62 | 137 | 59 | 88 | 109 | 87 | 65 |
| Relative deposition Mean (%) | 4.82 | 6.03 | 4.15 | 3.53 | 6.34 | 6.61 | 4.26 |
| Median (%) | 4.31a | 3.37ab | 4.66ab | 2.95b | 3.30ab | 5.58ab | 4.24ab |
| SD (%) | 2.99 | 8.27 | 2.44 | 3.12 | 6.93 | 5.74 | 2.77 |
| CV (%) | 62 | 137 | 59 | 88 | 109 | 87 | 65 |
| Coveragea Mean (%) | 10.81 | 15.58 | 11.23 | 7.57 | — | — | 23.27 |
| Median (%) | 8.78ab | 11.39ab | 5.76ab | 3.48b | — | — | 20.45a |
| SD (%) | 10.70 | 19.37 | 17.23 | 12.69 | — | — | 20.30 |
| CV (%) | 99 | 124 | 153 | 168 | — | — | 87 |
| Number of spotsa Mean (Spots cm\(^{-2}\)) | 29 | 41 | 52 | 34 | — | — | 63 |
| Median (Spots cm\(^{-2}\)) | 35a | 22a | 26a | 36a | — | — | 61a |
| SD (Spots cm\(^{-2}\)) | 15 | 39 | 51 | 29 | — | — | 47 |
| CV (%) | 51 | 95 | 98 | 85 | — | — | 75 |

Note: Medians in the same row with the same letter do not differ significantly (P < 0.05, Kruskal–Wallis test).

a Based on experiments with XR 0° 1000 + Air, XR −30° 1000 + Air, XR 30° 1000 + Air, XR 30° 500 (L) + Air and XR 30° 2000 + Air.
Figure 3. Spray deposition (in L ha⁻¹) at different collector positions (mean ± SE, median) for the different application techniques: 1, upper layer, upper side of leaves; 2, upper layer, bottom side of leaves; 3, middle layer, upper side of leaves; 4, middle layer, bottom side of leaves; 5, ground level, attached to stem; 6, ground level, horizontal. Bars carrying the same label are not statistically different.

Figure 4. Relative spray deposition (%) at different collector positions (mean ± SE, median) for the different application techniques: 1, upper layer, upper side of leaves; 2, upper layer, bottom side of leaves; 3, middle layer, upper side of leaves; 4, middle layer, bottom side of leaves; 5, ground level, attached to stem; 6, ground level, horizontal.

Spray coverage rank between techniques were only observed at position 4 also because of the limited number of replicates and the high variability between measurements. In general, there is a good correspondence between spray deposition, coverage results and the number of spots although there are some differences as discussed later.

Again, the means, medians, SD and CVs of the relative coverage and the number of spots for the different sampling positions averaged across the different application techniques and averaged across the different sampling positions are shown in Tables 2 and 3.

3.4 Off-target spray deposition

The off-target depositions were evaluated as mentioned earlier and presented in Fig. 7. On average, off-target positions outside of the crop (OT Outside) were found to capture a significantly higher amount of spraying liquid than collectors placed between plant...
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Figure 5. Spray coverage (%) at different collector positions (mean ± SE, median) for the different application techniques: 1, upper layer, upper side of leaves; 2, upper layer, bottom side of leaves; 3, middle layer, upper side of leaves; 4, middle layer, bottom side of leaves; 5, ground level, attached to stem; 6, ground level, horizontal. Bars carrying the same label are not statistically different.

Figure 6. Number of spots (in spots cm⁻²) at different collector positions (mean ± SE, median) for the different application techniques: 1, upper layer, upper side of leaves; 2, upper layer, bottom side of leaves; 3, middle layer, upper side of leaves; 4, middle layer, bottom side of leaves; 5, ground level, attached to stem; 6, ground level, horizontal. Bars carrying the same label are not statistically different.

pot (OTₚ) caused by some direct spray deposition from the outer spray nozzles as illustrated in Fig. 1 \( H_{(2, N = 252)} = 136.80; P < 0.01 \).

Inside \( H_{(6, N = 49)} = 7.03; P = 0.32 \) as well as outside \( H_{(6, N = 126)} = 78.58; P < 0.001 \) the crop, statistically significant difference in off-target deposition were found between the different techniques.

Outside the crop, highest off-target deposition was found for the 2000 L ha⁻¹ application while lowest off-target depositions were measured for both 500 L ha⁻¹ applications. This is caused by the effect of spray volume. No significant effect of spray angle for the 1000 L ha⁻¹ applications was found on off-target
deposition outside the crop. Similar results were found inside the crop where lowest off-target depositions were found for both 500 L ha\(^{-1}\) applications. The highest values were measured with the XR 0°1000 + Air technique and the XR 0°2000 + Air technique. No significant differences between the 1000 L ha\(^{-1}\) applications were found.

3.5 Comparing depositions in current and previous experiment

In Table 4, the median deposition values of all the techniques tested at 1000 L ha\(^{-1}\) in current and previous experiments\(^{1,2}\) are compared per collector position. Apart from the median depositions and their statistical relevance, a factor of improvement relative to the reference technique is shown. As it is often used in practice, the extended range flat fan nozzle, used without air assistance and with a standard spray direction (XR 0°), was considered to be the reference. Similar to Table 3, for each technique the CVs calculated based on the median deposition values on all collector positions are shown. In addition, the CVs calculated only based on the leaf collectors (positions 1–4) are included.

4 DISCUSSION

4.1 Influence of sampling position

The experiments show a significant effect of sampling position on mean spray deposition, relative spray deposition and coverage (Table 2).

Calculated across the different techniques, highest median deposition values were found on the upper side of the leaves in the upper layer (position 1: 87 L ha\(^{-1}\)) which were significantly higher than the median depositions at the underside of the leaves in the middle layer (position 4: 6 L ha\(^{-1}\)) and at the ground level, parallel to the soil (position 6: 15 L ha\(^{-1}\)). Median deposition values at the other sampling positions (position 2, 3 and 5) ranged from 37 to 54 L ha\(^{-1}\) and were not statistically different from the depositions on positions 1 and 6. Similar results were found for the median relative deposition where the significantly highest values were found at the upper side of the leaves in the upper layer (9%) as well as at ground level attached to the stem (4.4%) and lowest values at the underside of the leaves in the middle layer (0.6%). The significantly lowest coverage values were found in the middle layer, at the underside of the leaves (0.5%). When comparing the underside to the upper side of the leaves, deposition, relative deposition as well as coverage values were always significantly higher at the upper side of the leaves in the middle plant layer, while no significant differences were found in the upper plant layer.

Considering the number of spots, no significant effect was observed probably because of the high variation in combination with the limited number of replicates. The median number of spots ranged from 8 spots cm\(^{-2}\) at ground level attached to the stem up to 53 spots cm\(^{-2}\) in the middle layer on the upper side of the leaves.

The difference in application techniques, the not perfectly uniform spray distribution (CV = 8.9%) and the variations in plant architecture and the positioning of the collectors in the canopy are all factors contributing to the high variability of the deposits and coverage measured at each sampling position across application techniques as indicated by the high CV values in Table 2. The effect of the variation in plant architecture and sampling position on the variability of the spray results is even more pronounced for the parameters measured with WSP (coverage and number of spots cm\(^{-2}\)) because collector plants equipped with WSP were replaced after each spraying.

4.2 Influence of spray application technique

Besides sampling position, spray application technique also affects spray deposition and coverage results. The effect of spray angle (section 4.2.1), application rate (section 4.2.2), spray direction and the number of passes (section 4.2.3) for a medium droplet size application with air support is discussed here.
leaves in the upper layer.

The forward spray angle also increased spray deposition on the underside of the leaves, resulting in slightly higher depositions on the underside of the leaves. In the middle layer at the underside of the leaves, higher coverage values were found for the 30° spray angle followed by the 30° and the 0° spray angles. This discrepancy between deposition and coverage might be caused by droplet size effects as for the same spray deposition, smaller droplets produce a higher coverage. In turn, this finding suggests that larger droplets reached position 4 with a 0° or 30° spray angle than with a 30° spray angle. At the upper side of the leaves in the middle layer, the median coverage for the 30° spray angle was highest. In turn, this finding suggests that larger droplets reached position 4 with a 0° or 30° spray angle than with a 30° spray angle. At the upper side of the leaves in the middle layer, the median coverage for the 30° spray angle was highest.

Comparing the median depositions (in L ha^{-1}) at the different collector positions between all application techniques tested at 1000 L ha^{-1} and 2.7 km h^{-1} in current and previous experiments together with the CV values based on all leaf sampling positions and based on all collector positions are given in Table 4. Across the different sampling positions, no statistically significant effect of spray angle was found on deposition, relative deposition and coverage at the different collector positions although some trends can be observed (Figs 3–6).

### Table 4. Comparison of the median depositions (in L ha^{-1}) at the different collector positions between all application techniques tested at 1000 L ha^{-1} and 2.7 km h^{-1} in current and previous experiments together with the CV values based on all leaf sampling positions and based on all collector positions

<table>
<thead>
<tr>
<th>Collector Position</th>
<th>Median Deposition L ha^{-1}</th>
<th>CV %</th>
</tr>
</thead>
<tbody>
<tr>
<td>TVI b, d</td>
<td>271 abc</td>
<td>90</td>
</tr>
<tr>
<td>ID 30° b, e</td>
<td>279 abc</td>
<td>93</td>
</tr>
<tr>
<td>ID −30° b, e</td>
<td>230 abc</td>
<td>97</td>
</tr>
<tr>
<td>ID 30° − Air b, e</td>
<td>208 abc</td>
<td>97</td>
</tr>
<tr>
<td>ID −30° + Air b, e</td>
<td>292 abc</td>
<td>97</td>
</tr>
<tr>
<td>TVI 0° b, c, e</td>
<td>317 a</td>
<td>105</td>
</tr>
<tr>
<td>ID 0° + Air b, e</td>
<td>193 cd</td>
<td>64</td>
</tr>
<tr>
<td>XR 30° + Air f</td>
<td>63 d</td>
<td>21</td>
</tr>
<tr>
<td>XR 0° + Air f</td>
<td>57 cd</td>
<td>19</td>
</tr>
<tr>
<td>XR 30° − Air f</td>
<td>226 abc</td>
<td>75</td>
</tr>
<tr>
<td>XR 30° 2 x 500 f</td>
<td>154 abc</td>
<td>51</td>
</tr>
<tr>
<td>TXA 9° b, g</td>
<td>331 ab</td>
<td>11</td>
</tr>
<tr>
<td>XR 30° b, f</td>
<td>224 cd</td>
<td>74</td>
</tr>
<tr>
<td>XR −30° b, f</td>
<td>248 bcd</td>
<td>82</td>
</tr>
<tr>
<td>XR 0° b, f</td>
<td>301 abc</td>
<td>89</td>
</tr>
</tbody>
</table>

4.2.1 Effect of spray angle

Across the different sampling positions, no statistically significant effect of spray angle was found on the deposition, relative deposition, coverage and number of spots for the XR 0° 1000 + Air, XR −30° 1000 + Air and the XR 30° 1000 + Air (Table 3). Similarly, no significant effect of spray angle was found on deposition, relative deposition and coverage at the different sampling positions although some trends can be observed (Figs 3–6).

Although they were not significantly different, certain trends can be observed for deposition (Fig. 3). In the upper plant layer, a backward (−30°) spray angle tended to favour deposition on the upper side of the leaves when compared with a standard (0°) and a forward (30°) spray angle. The latter two resulted in a more even distribution between the upper side and the underside. The forward spray angle also increased spray deposition on the underside of the leaves, resulting in slightly higher depositions on the underside of the leaves compared with the upper side of the leaves in the upper layer.

In the middle plant layer, the forward and standard spray angle gave slightly higher deposition values compared with the −30° spray angle on the top as well as on the underside of the leaves.

Considering spray coverage (Fig. 5), other trends are observed. In the upper layer, the effect of spray angle was less pronounced and highest coverage was found for the 0° spray angle followed by the −30° and the 30° spray angle on the topside as well as on the underside of the leaves. In the middle layer at the underside of the leaves, higher coverage values were found for the −30° spray angle than for the 0° and the 30° spray angles. This discrepancy between deposition and coverage might be caused by droplet size effects as for the same spray deposition, smaller droplets produce a higher coverage. In turn, this finding suggests that larger droplets reached position 4 with a 0° or 30° spray angle than with a −30° spray angle. At the upper side of the leaves in the middle layer, the median coverage for the −30° backward spray angle was very low, however.

In the middle layer of the crop, the number of spots (Fig. 6) showed similar trends as observed for coverage. At the top layer and at ground level, however, different trends can be seen than the ones observed for coverage. In the upper layer at the upper side of leaves, the highest number of spots was found for the 30° spray angle followed by the −30° and the 0° spray angle. In contrast, on the underside of the leaves, the highest number of spots was found for the −30° spray angle followed by the 30° and the 0° spray angle. At ground level, the highest number of droplets on the collectors attached to the stem was found for the 0° spray angle followed by the −30° and the 30° spray angles. At position 6, the number of spots was highest for the 30° spray angle.

These results illustrate that the optimum spray angle depends on the part of the canopy to be protected. They also suggest that the 30° and the 0° angle are more likely to result in a more even distribution of the spray. This is further discussed in section 4.2.4 later.
4.2.2 Effect of application rate

Three spray volumes were tested with a 30° forward spray angle, air support and a medium droplet size spray, namely, 500 (XR 30° 500 (L) + Air), 1000 (XR 30° 1000 + Air) and 2000 L ha⁻¹ (XR 30° 2000 + Air).

Calculated across the different sampling positions, median deposition at 500 L ha⁻¹ was significantly lower than these of both other spray volumes tested and coverage at 500 L ha⁻¹ was significantly lower than at 2000 L ha⁻¹ (Table 3). Table 3 also shows that doubling the spray volume from 500 L ha⁻¹ to 1000 L ha⁻¹ resulted in a significant increase of the median deposition with a factor of 3.16. A further increase of the spray volume to 2000 L ha⁻¹ did not significantly improve deposition and relative deposition which indicates a less efficient application. However, the increase from 500 L ha⁻¹ to 1000 L ha⁻¹ had no significant effect on coverage while a further rise to 2000 L ha⁻¹ significantly improved coverage compared with 500 L ha⁻¹. The higher coverage of the 2000 L ha⁻¹ application, however, could very well be the effect of run-off as well. This statement is supported by the trend of this technique towards higher spray losses to the ground (Figs 3 and 5).

On the upper side of the leaves in the top layer, the 2000 L ha⁻¹ application resulted in significantly higher deposition values compared with the 500 L ha⁻¹ application (Fig. 3) but there was no significant effect on relative deposition (Fig. 4), coverage (Fig. 5) and number of spots (Fig. 6). At the underside of the leaves in the top layer, no significant effects of application volume were found for any of the observed parameters. Except for coverage (0.26), good ratios between medians for the top and bottom side of the leaves were reached for the 1000 L ha⁻¹ application [1.04 for (relative) deposition, 0.84 for number of spots]. This was not the case for the 500 L ha⁻¹ (0.13, 0.14, 0.59) and the 2000 L ha⁻¹ (0.28, 1.53, 0.93) application.

In the middle plant layer, deposition on the underside of the leaves with the 500 L ha⁻¹ application was significantly lower compared with the 2000 L ha⁻¹ (Fig. 3). Although no other significant differences were observed in the middle plant layer, probably because of the variability in measuring results, some interesting trends are observed. From the three spray volumes, 1000 L ha⁻¹ tended to give higher relative deposition values than the 500 L ha⁻¹ application and comparable relative deposition values with the 2000 L ha⁻¹ application on the top as well as on the underside of the leaves, indicating good penetration capacity. This is in agreement with Derksen et al., who observed that spray volume had little effect on underside leaf surface deposition.

In summary, of the tested spray volumes, the 1000 L ha⁻¹ spray volume gave the most uniform spray deposition in the crop with a CV value of 59% of the medians of the deposition values across the different sampling positions (Table 3). This is also reflected in the median relative deposition values of 6.3, 6.6, 5.6 and 0.8% for the 1000 L ha⁻¹ application at positions 1, 2, 3, and 4, respectively (Fig. 4). These values were 8.5, 1.1, 4.4 and 0.4% for 500 L ha⁻¹ application and 8.4, 2.3, 5.7 and 0.7% for 2000 L ha⁻¹ application.

4.2.3 Effect of spray direction and the number of passes

Two 500 L ha⁻¹ applications were made in an opposite direction (L and R). As expected, no significant differences can be found between the two applications although some small differences can be observed. For example, the XR 30° 500 (R) + Air application seems to have resulted in somewhat higher median depositions in the top layer, while the same is true for the XR 30° 500 (L) + Air application at ground level. These results indicate that changing the direction between applications could have a positive impact on the pest control because different parts of the plants are targeted.

Comparing the 1000 L ha⁻¹ application in a single pass (XR 30° 1000 + Air) with the application in two passes (XR 30° 2 × 500 (L/R) + Air), no significant differences were found between (relative) deposition across the different sampling positions (Table 3). Although not statistically different, there were some important site-specific differences in deposition results (Fig. 3). In the middle plant layer, applying 1000 L ha⁻¹ in a single pass gave higher deposition values compared with the double pass application. This increase was most pronounced at the underside of the leaves with a factor of 1.25. In the upper layer, opposite results were found. This confirms the better penetration capacity of a 1000 L ha⁻¹ application compared to a 500 L ha⁻¹ application. The results show no added value of applying 1000 L ha⁻¹ in two passes with an opposite direction compared to applying the same volume in a single pass. This observation does not agree with the findings of Derksen et al., who observed that treating the crop in two directions is a good way to improve the homogeneity of a spray. The difference could be the result of the higher spray boom speed that was used to achieve the 500 L ha⁻¹ spray volume in our experiments, which may reduce the spray penetration capacity. As an alternative, smaller nozzle sizes could be used to reduce the application rate down to 500 L ha⁻¹. A smaller nozzle size, however, will most likely produce smaller droplets as well, which could also have a lower penetration capacity.

4.2.4 Comparing current and previous experiment

Table 4 shows the median deposition results of all the performed experiments in the considered ivy crop at 1000 L ha⁻¹. In general, the spray deposition (Table 4) and coverage (see earlier and previous papers) was high on the upper leaf surface in the top layer and potentially high enough for an adequate pest control irrespective of spray application technique. However, as emphasized by several growers, reaching the underside of the leaves (abaxial; positions 2 and 4), the level of penetration in the crop and the uniformity of the spray distribution are important factors determining the bio-efficacy of a treatment. This opinion is supported by many authors. Based on this conclusion, special attention is given to the abaxial deposition, penetration and uniformity of the spray deposition in subsequent discussion.

Table 4 shows that the deposition results can be optimized in several ways. Without the use of air support, the results of the hollow cone (TXA) and Venturi flat fan (ID 0°) show that using a different nozzle type can have a positive effect on the lower leaf deposition and penetration. Compared to the frequently used reference technique (XR 0°), the deposition at the lower side of the leaves was improved by a factor 2.10 or 2.95 in the upper plant layer and a factor 3.0 or 4.1 in the middle plant layer. Using a Venturi hollow cone (TVI), however, always lead to lower deposits than the reference technique. These findings are in agreement with Foqué and Nuyttens and prove the importance of a well-considered nozzle choice, as shown by Braekman et al.

Table 4 also shows that the deposition on the lower side of the leaves with the frequently used reference technique can be optimized without using air support by using an adjusted spray angle. In our experiment, the 30° forward angle had the highest effect on depositions at the lower side of the leaves and of uniformity of the spray. Although this spray angle only lead to a significant higher deposition on position 2, the deposition on the lower side of the leaves in both the upper plant layer
and the middle plant layer was increased, by a factor 1.98 and 1.47, respectively. In contrast to the two other angles used, the depositions of the XR 30° technique on position 2 are statistically comparable to some of the higher scoring techniques and are no longer statistically comparable to the weaker performing TVI nozzle. The overall CV and the CV for the leaf collectors only are also lower. This confirms the positive trend of using a forward spray angle for the considered ivy crop with a horizontal leaf positioning, as discussed before in Foqué and Nuyttens.² This positive effect of a forward spray angle was not found for a coarser air inclusion which seemed to benefit more from a normal 0° spray. For this nozzle type, angled sprays only lead to higher CVs and make the deposition results more comparable to the ones the TVI nozzle.

The fact that spray angling, without air support, does not improve the deposition on the bottom sides of the leaves for the Venturi flat fan was argued before in Foqué and Nuyttens.¹

Air support, however, had a much bigger impact on the lower leaf depositions, penetration and spray uniformity. However, because of the much lower CVs and high abaxial depositions, the best results were found for the medium droplet spray (XR) when compared to the coarse air inclusion spray (ID). Interestingly, the same effects of spray angle as for the non-air assisted spray applications can be seen for the XR air supported techniques with the best results with a 30° forward (XR 30° + Air) or a normal 0° spray angle (XR0° + Air). The coarser air-supported sprays (namely, ID 0° + Air, ID 30° + Air and ID −30° + Air) seemed to benefit more from a normal 0° or −30° backward spray. Although never statistically different from the non-air supported ID 0° technique, the deposition at the lower side of the leaves and the uniformity of the spray also increased substantially using air support with the coarser spray. Again, this confirms conclusions made in previous work.¹

Based on all the results discussed, the XR 30° 1000 + Air and XR 0° 1000 + Air application showed the most promising results of all the applications tested in three series of laboratory experiments. These findings agree with Scudeler and Reatano who drew similar conclusions for hollow cone nozzles. They concluded that the 30° forward angle with and without air assistance, and the 0° angle with air assistance favoured deposition on the lower positions on potato plants, in contrast to the −30° angle (with and without air assistance) and the 0° angle without air assistance. Compared with the reference technique, the XR 30° 1000 + Air and XR 0° 1000 + Air techniques improved median spray deposition results at the lower side of the leaves by a factor of respectively 21.7 or 11.6 in the upper plant layer and by a factor 19.0 or 25.2 in the middle plant layer. This is probably the combined effect of the horizontal leaves of the ivy crop and the more horizontal droplet trajectory that is produced by these techniques. As these are the most difficult plant zones to reach, these techniques also gave the best spray uniformity in the plant.

5 CONCLUSIONS

In general, our experiments showed that air support resulted in substantial improvement of the spray results. The positive effect was most pronounced for the extended range flat fan considered in this paper, with a medium droplet spray (XR 80 03, TeeJet), with a standard 0° or a 30° forward angled spray. These techniques dramatically improved spray uniformity in the plant by increasing median spray deposition results on the lower side of the leaves by a factor of respectively 11.6 or 21.7 in the upper plant layer and by a factor 25.2 or 19.0 in the middle plant layer compared with the reference technique. Of the three application rates tested, the spray volume of 1000 L ha⁻¹ proved to be most appropriate for our ivy crop. The less favourable results observed for the 500 L ha⁻¹ applications could be the result of the higher application speed used.

Spraying 1000 L ha⁻¹ in two passes with an opposite direction did not improve the spray uniformity but this again could be an effect of the higher application speed.

In future, long-term bio-efficacy trials will have to verify whether these optimized spray boom configurations indeed result in higher plant protection product efficacies than the traditionally used lance spray applications.

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