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2 **GROWN CARROTS AT DIFFERENT GROWTH STAGES BASED ON SPRAY DISTRIBUTION AND DROPLET**
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6 **Running title: Sprayer optimizations for bed-grown carrots.**

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21

22 **ABSTRACT**

23 **BACKGROUND:** Pesticide losses and uneven spray distribution should be avoided as much as possible
24 as they reduce the effectiveness of spraying and increase environmental contamination as well as costs.
25 Within the H2020-project OPTIMA the goal is to develop a smart sprayer for bed-grown carrots,
26 including optimizations such as air support and variable nozzle spacing. This paper focuses on selecting
27 the most optimal nozzle types, spacing and height for spraying bed-grown crops, while taking into

28 account different target zone widths depending on the growth stage, based on spray distribution and
29 droplet characterization measurements.

30 RESULTS: The results indicate that four bed spray configurations consisting of four nozzles per bed,
31 i.e. XR8004/XR8004/XR8004/XR8004, AIUB8504/AI11004/AI11004/AIUB8504,
32 AI8004/AI8004/AI8004/AI8004, and XR8002/XR8002/XR8002/XR8002, spraying at 300 kPa and
33 recalculated to 12.0 km h⁻¹ forward speed, are appropriate for spraying different target zone widths
34 (ranging from 1.2 to 2.2 m) with high uniformity (CV < 12%) and minimal losses out of the target zone
35 (< 17%), when applied at the most appropriate nozzle spacing and height (varying from 0.35 to 0.65 m).
36 Droplet characterization measurements showed that for the same nozzle size and spray pressure, air
37 inclusion nozzles produced larger but slower droplets than standard flat-fan nozzles. Air support
38 increased the droplet velocities but had only a very limited effect on droplet size.

39 CONCLUSION: Laboratory spray distribution and droplet characterization measurements allowed to
40 select the most optimal nozzle type, spacing and height for bed spray applications in terms of reduced
41 pesticide losses compared to conventional broadcast applications.

42

43 **Keywords:** bed spray application, nozzle configuration, nozzle type, droplet size, droplet velocity, air
44 support.

45

46 1 INTRODUCTION

47

48 Since January 2014, growers in the European Union are obliged to implement the principles of integrated
49 pest management (IPM).¹ These principles aim to minimise environmental, economic and health risks
50 due to the use of plant protection products (PPP), by combining various biological, physical, cultural
51 and chemical techniques to manage all classes of pests. Within the H2020-project OPTIMA (*OPTimised*
52 *Integrated pest MAnagement for precise detection and control of plant diseases in perennial crops and*
53 *open-field vegetables*, www.optima-h2020.eu), an environmentally friendly IPM framework for
54 Alternaria leaf blight in carrots, downy mildew in vineyards, and apple scab in orchards is developed by
55 providing a holistic approach which includes major elements related to integrated disease management,

56 such as precision spraying techniques, as well as the use of novel bio-PPPs, disease prediction models,
57 and spectral disease detection systems. The overall goal is to integrate those elements and develop three
58 prototype smart sprayers in collaboration with sprayer manufacturers.

59 The main goal in all spray applications is to obtain an adequate coverage and uniform pesticide
60 deposition on the target in order to provide sufficient efficacy against the target pest.² Pesticide losses
61 and unsatisfactory uniformity of distribution should be avoided as much as possible as they reduce the
62 effectiveness of spraying and increase environmental contamination as well as costs.³⁻⁵ For bed-grown
63 crops, ideally the spray is applied evenly to the bed, and in particular to the target zone width depending
64 on the crop growth stage, while no spray is applied to the paths in between the beds to avoid losses,⁶
65 unless herbicides are applied.

66 As spray deposition and drift are affected by the spray and droplet characteristics, including droplet size
67 and velocity distribution, the volume distribution pattern, and the entrained air characteristics,^{7, 8} and
68 droplet size determines the biological efficacy of the applied pesticide,⁹⁻¹⁴ the nozzle-pressure
69 combination greatly determines the efficacy of the application process. This paper therefore focuses on
70 the use of various nozzle types and configurations, and of variable nozzle spacing and height as possible
71 optimizations of a smart sprayer for bed-grown carrots. The goal is to define optimal settings, in terms
72 of spray distribution and reduced spray losses, of an air-assisted smart sprayer for bed-grown carrots
73 with variable nozzle spacing at different target zone widths (depending on the growth stage of the crop)
74 in comparison to the reference conventional horizontal boom sprayer.

75

76 **2 MATERIALS AND METHODS**

77

78 ***2.1 Planting system and crop characteristics***

79 Beds of 1.83 m wide, containing 3 rows of carrots per bed, and an inter-bed distance of 0.5 m, thus
80 resulting in a total distance of 2.33 m between carrot beds, were considered. This design matches the
81 pilot fields in the southwest of France where at a later stage of the OPTIMA project field trials will be
82 conducted using the developed smart sprayer. A schematic presentation of the design is given in Figure
83 1. In total, 9 beds of 2.33 m can be sprayed using a 21 m horizontal spray boom (holding 42 nozzles at

84 0.5 m nozzle spacing). In France, around four to five treatments against *Alternaria* are performed in
85 carrots during a growing season. The first treatment is generally applied around BBCH 14 - 16 (i.e. 4th
86 till 6th true leaf unfolded). At that time, about 50% of the inter-row is covered by foliage. By BBCH
87 18 - 19, the entire inter-row is covered by foliage (S. Bellalou, personal communication). Based on the
88 carrot plant design (Fig. 1) and growth stages (with more developed canopies at full growth stage
89 compared to early growth stage), target zone widths ranging from 1.2 to 2.2 m (at incremental steps of
90 0.2 m) were studied.

91

92 ***2.2 Sprayer configurations, nozzle types and spray settings***

93 A horizontal spray boom application with TeeJet XR 110 04 nozzles at a spray pressure of 300 kPa,
94 0.5 m spray boom height and 0.5 m nozzle spacing, without air support, at 12.0 km h⁻¹, corresponding
95 to 158 L ha⁻¹, was considered as reference condition. Studied possible carrot sprayer optimizations
96 included the use of reduced spray volume nozzles (ISO 02 vs ISO 04 nozzles), the use of drift reducing
97 nozzles (air inclusion AI vs standard XR nozzles), and bed spray applications instead of broadcast
98 applications, by using off-center and/or narrow angle nozzles (80° vs 110°). In addition, the use of air
99 support was also considered as optimization, and the effect of air support on the droplet characteristics
100 is described. An overview of the nozzles and settings selected and tested as possible optimizations is
101 given in Table 1. Theoretical application rates are expressed as L ha⁻¹ of total ground area. The total
102 ground area includes the carrot beds and the space between the beds.

103

104 ***2.3 Spray distribution***

105 Prior to the spray distribution and droplet characteristics experiments, the flow rate of the nozzles was
106 determined using a nozzle test bench (ITEQ, Belgium) at the Spray Technology Laboratory of Flanders
107 Research Institute for Agricultural, Fisheries and Food (ILVO, Belgium). Every nozzle was tested three
108 times at a spray pressure of 300 kPa. The nozzles with the lowest mean deviation from the nominal flow
109 rate were selected for further experiments. Per off-center nozzle type, 6 nozzles were tested and 2 were

110 selected for further experiments, of the other nozzle types (i.e. XR and AI), 12 nozzles were tested and
111 4 were selected for further experiments.

112 To achieve maximal and uniform deposition on the canopy (i.e. target zone) and to have minimal losses
113 between the beds, optimal nozzle spacings and heights for bed spray applications were determined using
114 a spray scanner. Spray depositions and losses for 6 target zone widths (1.2, 1.4, 1.6, 1.8, 2.0, 2.2 m
115 range) were assessed for a distance between carrot beds of 2.33 m (Fig. 1).

116 The spray distribution of 13 nozzle configurations, consisting of different nozzle types (standard flat
117 fan, air inclusion, off-center), nozzle size (ISO 02, 04), spray angle (80°, 110°), and number of nozzles
118 (3 or 4 nozzles per bed) was determined. An overview of the tested configurations is given in Table 2.
119 For every nozzle configuration, measurements were performed at several nozzle spacing and height
120 combinations, but within each test, nozzle spacing and height were kept equal as this is more practical
121 for the farmers in real field conditions. The configurations with four nozzles were tested in a range from
122 0.35 to 0.65 m nozzle spacing/height, while those with three nozzles were performed from 0.40 to
123 0.65 m, all at incremental steps of 50 mm. Heights of 0.7 m and higher were not considered due to
124 increased risk of drift. In addition, a broadcast application with XR 110 04 nozzles at 0.5 m spray height
125 and 0.5 m nozzle spacing was tested as reference. In total, 81 different combinations were tested.

126 The spray distribution measurements were performed indoor at ILVO's Spray Technology Laboratory,
127 according to ISO 5682-2¹⁵. The spray scanner set-up consisted of a 0.8 m wide, channelled, sloping
128 scanner with 0.1 m grooves and calibrated collecting tubes by AAMS-Salvarani (Maldegem, Belgium),
129 running over a frame underneath a fixed 12 m 'ideal' spray boom. For this experiment, a short spray
130 boom with variable nozzle spacing was constructed and mounted on the fixed spray boom. The center
131 of the short spray boom was positioned above a channel partition, thus forming the zero-point position
132 corresponding to the middle of the bed. The receiver-unit with 0.1 m wide grooves collected the liquid
133 sprayed with the short spray boom during a known time interval, as described by Zwervaegher et al.¹⁶.
134 The flow rates ($L \text{ min}^{-1}$) achieved from the spray scanner measurements, which are basically time
135 measurements as also described by Višacki et al.⁴, were recalculated to spray volume ($L \text{ ha}^{-1}$) based on
136 a driving speed of 12 km h^{-1} . For each target zone width and nozzle configuration, following variables
137 were calculated, taking into account possible overlap between sprays of neighboring beds: minimum

138 spray volume in target zone (L ha^{-1}), maximum spray volume in target zone (L ha^{-1}), average spray
139 volume in target zone (L ha^{-1}), percentage of spray volume in target zone (%), percentage of losses
140 outside the target zone (%), and Coefficient of variation (CV) of the spray distribution in the target zone
141 (%).

142 The following criteria were used to select appropriate spray configurations and nozzle spacing/height
143 combinations for the different target zone widths:

- 144 – Criterion 1: CV in target zone $< 12\%$, to guarantee a uniform deposition in the target zone,
- 145 – Criterion 2: Losses outside target zone $< 17\%$, to minimise losses out of the target zone.

146 If both criteria were fulfilled, the configuration at this nozzle spacing and height was considered
147 appropriate for that target zone width. Provided that multiple combinations were appropriate for the
148 same target zone width, the combination with the highest minimum spray volume (L ha^{-1}) in the target
149 zone was selected. The thresholds were selected as such so that at least one spray configuration per
150 target zone width met the criteria. Although chosen arbitrary, the uniformity threshold is close to those
151 specified by the inspection of sprayers in use, i.e. the CV of the transverse distribution should not exceed
152 10% for broadcast spray applications.^{17, 18}

153

154 ***2.4 Droplet size and velocity characteristics***

155 Droplet size and velocity characteristics were obtained at ILVO using a Phase Doppler Particle Analyser
156 (PDPA) laser-based measuring set-up, as described by Nuyttens et al.¹¹. The used PDPA laser was a
157 PowersSight PDPA one dimensional system (TSI, Minneapolis). With this one-dimensional system,
158 velocity measurements were limited to the dominant vertical direction. When a droplet passes through
159 a small sampling volume, formed by two intersecting laser beams, light is scattered by refraction. From
160 the light scattering characteristics, droplet sizes and velocities are obtained. All measurements were
161 performed at a distance of 0.5 m below the nozzle(s), and repeated three times. Rectangular scan profiles
162 were used. All measurements were carried out along the horizontal long axis of the spray fan. All nozzles
163 (Table 1) were tested without air support using a single nozzle set-up.

164 Based on the spray distribution measurements (see 2.3 Spray distribution), the 4 nozzle types of the most
165 appropriate nozzle configurations, i.e. XR8004, XR8002, AI11004, and AI8004, were also tested with

166 air support at 4 different settings (Table 1), using the Caffini Air Wing (Caffini s.p.a., Palù Verona,
167 Italy) and ILVO fan (Ventomatic, Merelbeke, Belgium). Measurements were performed with the test
168 set-up at fan frequencies corresponding to Caffini sprayer fan speeds of 0, 1400, 1750 and 2000 rpm
169 and air speeds 0, 1.2, 1.6, and 1.9 m s⁻¹ at 0.5 m below the air outlet. So in total, 16 nozzle-air support
170 combinations (4 nozzle types x 4 air support settings) were tested. Following characteristics were
171 calculated:

- 172 (1) BCPC – BCPC spray quality class based on droplet size;
- 173 (2) $D_{v0.5}$ – volume median diameter (VMD, μm) below which smaller droplets constitute 50% of
174 the spray volume;
- 175 (3) $D_{v0.1}$, $D_{v0.9}$ – volume diameter (μm) below which smaller droplets constitute respectively 10%
176 and 90% of the total volume;
- 177 (4) V_{100} – proportion of total volume (%) of droplets smaller than 100 μm in diameter;
- 178 (5) $v_{v0.50}$ – droplet velocity (m s⁻¹) below which slower droplets constitute 50% of the total spray
179 volume;
- 180 v_{avg} – arithmetic average droplet velocity (m s⁻¹).

181

182 To test the effect of air support on the droplet characteristics, a short spray boom with multiple nozzles
183 was used in order to sample droplets at different positions in the spray fan, as the position of the nozzles
184 relative to the air holes should be fixed and comparable to in-field conditions for realistic measurements.
185 Due to the restricted movement of the air support system, using a single mobile nozzle would result in
186 a misalignment between nozzle position and air hole, leading to incorrect results.

187

188 **3 RESULTS AND DISCUSSION**

189

190 ***3.1 Spray distribution***

191 The spray distribution results showed that the configurations with 3 nozzles did not meet the criteria,
192 and were therefore not appropriate, not even for the smallest target zone width of 1.2 m, as either the
193 CV and/or the losses were too high (criterion 1 and 2, respectively). In total, 4 nozzle configurations

194 were appropriate for all target zone widths (from 1.2 to 2.2 m), i.e. XR8004/XR8004/XR8004/XR8004,
195 AIUB8504/AI11004/AI11004/AIUB8504, AI8004/AI8004/AI8004/AI8004, and
196 XR8002/XR8002/XR8002/XR8002. Table 3 tabulates the spray distribution characteristics of these
197 configurations at the most appropriate nozzle spacing/height combinations for the different target zone
198 widths. As an example, the spray distribution patterns and characteristics of
199 AIUB8504/AI11004/AI11004/AIUB8504 and the broadcast application with XR11004 nozzles, both at
200 0.5 m nozzle spacing/height, for a target zone width of 1.6 m, are presented in Figure 2a and b,
201 respectively. Per target zone, the losses outside the target zone (%) and the CV (%) and the average of
202 the applied dose (%), i.e. the average spray volume in the target zone relative to the theoretical spray
203 volume per ha of total ground area (Table 1), expressed as %, are given in Figure 3 for the reference
204 broadcast application and the 4 most appropriate nozzle configurations, i.e.
205 XR8004/XR8004/XR8004/XR8004, AIUB8504/AI11004/AI11004/AIUB8504,
206 AI8004/AI8004/AI8004/AI8004, and XR8002/XR8002/XR8002/XR8002.

207 With lowest variation (CV) inside the target zone and lowest relative losses outside the target zone,
208 while maintaining a high average spray volume in the target zone, the overall best ISO 04 configuration
209 is AIUB8504/AI11004/AI11004/AIUB8504 for target zone widths from 1.2 to 1.6 m, as indicated by
210 Table 3 and Figure 3. For a target zone width of 2.2 m, a nozzle spacing/height combination of 0.7 m
211 might be more appropriate with this configuration, however, as reported earlier, this spacing/height
212 combination was not tested due to increased risk of drift.¹⁹ However, compared to
213 AIUB8504/AI11004/AI11004/AIUB8504, configurations XR8004/XR8004/XR8004/XR8004,
214 AI8004/AI8004/AI8004/AI8004, and XR8002/XR8002/XR8002/XR8002 have the advantage that only
215 one nozzle type can be used along the spray boom, and as no off-center nozzles are needed, they are less
216 expensive and less sensitive to deviations in spray line and boom movements. For target zones up to
217 1.8 m, losses were always highest for the broadcast application (10 to 36% higher than the bed spray
218 configurations), thus denoting a clear advantage for bed spray applications at these target zones.
219 However, the broadcast application losses decreased with increasing target zone and at 2.0 m target zone
220 the losses were comparable to those of the bed spray applications (13 to 17%). Over a 2.2 m target zone,
221 only configuration AIUB8504/AI11004/AI11004/AIUB8504 had lower losses than the broadcast

222 application (7 vs 8%). The four bed spray applications had similar losses at all target zones, ranging
223 from 16% at 1.2 m to 7% at 2.2 m. The CV, which is a measure of uniformity, was lowest for the
224 broadcast application at all target zones (0.6 to 5.3% lower than the bed spray configurations), indicating
225 that the most uniform spray applications were obtained with this configuration. However, this is at the
226 expense of higher losses outside the target zone and lower applied doses in the target zone. Although
227 the average applied dose (relative to the theoretical application rate, Table 1) in the target zone was
228 always around 100% for the broadcast application, it was considerably lower (11 to 67%) than compared
229 to the bed spray applications for target zones from 1.2 to 1.8 m, indicating lower depositions in those
230 target zones for the broadcast application. This demonstrates the added value of the bed spray
231 applications since potential dosage or application rate savings can be obtained. Considering the example
232 from Figure 2, configuration AIUB8504/AI11004/AI11004/AIUB8504 resulted in an average spray
233 volume of 173 L ha⁻¹ within the target zone of 1.6 m, whereas a theoretical application rate of 135 L ha⁻¹
234 ground area was determined for a boom sprayer with 36 ISO 04 nozzles (4 nozzles per bed) at 12 km h⁻¹
235 driving speed and a spray pressure of 300 kPa. The latter is already a 14% reduction in theoretical
236 application rate compared to a broadcast application of 158 L ha⁻¹ with 42 XR11004 nozzles at the same
237 driving speed and spray pressure. The increased on-target deposition of 173 L ha⁻¹ indicates that even
238 lower spray volumes or dosages could be applied with the bed spray configurations at adjusted nozzle
239 spacing/height while maintaining the same bio-efficacy as for the reference broadcast application.
240 Indirectly these reductions would also result in lower losses and spray drift. Variable rate application
241 methods could also be used to obtain the desired, reduced application rate or dosage. At target zones
242 from 2.0 to 2.2 m, the average applied doses were comparable for all configurations, ranging from 99 to
243 105%. Configurations XR8004/XR8004/XR8004/XR8004 and AI8004/AI8004/AI8004/AI8004 had
244 the highest CV (8.7 to 10.8%), i.e. lowest uniformity, followed by XR8002/XR8002/XR8002/XR8002
245 and AIUB8504/AI11004/AI11004/AIUB8504, except for the target zone of 2.2 m. For the 2.2 m target
246 zone, AI8004/AI8004/AI8004/AI8004 and AIUB8504/AI11004/AI11004/AIUB8504 had the highest
247 CV (over 8%). The CV in the target zone of the bed spray applications are almost always below the 10%
248 threshold value stated in ISO 16122-2¹⁷ and EN 13790-1¹⁸, which should not be exceeded by standard
249 horizontal boom sprayers. These values indicate a good uniformity within the target zone for the bed

250 spray applications, especially considering the threshold value has primarily been defined for broadcast
251 applications. As suggested by the overall low CV in the target zone and the lower losses outside the
252 target zone, the broadcast application might still be the most suitable spray application at later crop
253 stages, when the canopy is more developed and more closed and the bed is covered with foliage (target
254 zone of 2.0 – 2.2 m).

255 Depending on the canopy growth stage and thus the target zone width, the bed spray configurations at
256 their most appropriate nozzle spacing/height combinations may also reduce spray drift because lower
257 spray boom heights also reduce spray drift.^{20, 21} Reducing boom height generally results in less uniform
258 spray distributions, but this negative effect was buffered by the narrower nozzle spacings used in this
259 study, as also reported by Azimi *et al.*²². The four most optimal bed spray configurations and the
260 reference broadcast application were further tested for spray deposition and potential spray drift in the
261 OPTIMA project, as described in Douzals *et al.*²³

262 Based on the spray distribution patterns of single nozzles at different boom heights, models could be
263 build to design and select the most optimal set-ups of nozzles on a sprayer boom for bed-grown crops,
264 as illustrated by Holterman *et al.*⁶ Their model simulated spray patterns while varying nozzle types,
265 nozzle spacing and the position and angling of end nozzles based on single nozzle spray patterns. The
266 authors concluded that, although the number of possible designs is extremely large, relatively few met
267 the user definable criteria concerning bed width, edge width and uniformity of depositions.

268

269 **3.2 Droplet size and velocity characteristics**

270 3.2.1 Droplet characteristics without air support

271 The cumulative volumetric droplet size and velocity distribution of the different nozzles spraying at
272 300 kPa, 0.5 m spray boom height, and without air support are presented in Figure 4. An overview of
273 the most important droplet size and velocity characteristics, as well as the BCPC spray quality class,²⁴
274 is given in Table S1. The PDPA measurements indicate that the air inclusion nozzles generated the
275 coarsest droplet size spectrums (VMD = 460, 445, 443 μm for AIUB 85 04, AI 80 04, and AI 110 04),
276 followed by the standard ISO 04 nozzles (VMD = 338, 314, 300 μm for UB 85 04, XR 80 04, and XR
277 110 04), and the standard ISO 02 nozzles (VMD = 286, 260, 240 μm for UB 85 02, XR 80 02, XR 110

278 02). These findings are in agreement with those of other authors who also reported the coarsest droplet
279 size spectrum for air injection nozzles, followed by standard flat-fan nozzles, and who reported generally
280 coarser droplet size spectra with larger ISO nozzle sizes.^{11, 14, 25-29}

281 With regard to droplet velocity (Figure 4b and Table S1), the standard ISO 02 nozzles showed the lowest
282 volumetric median droplet velocity ($v_{v0.5} = 2.7, 2.9, \text{ and } 4.8 \text{ m/s}$ for UB 85 02, XR 110 02, and
283 XR 80 02). Within the ISO 04 nozzles, the standard nozzle type always generated higher volumetric
284 median droplet velocities than the air inclusion type, in increasing order of AI 110 04, XR 110 04, AIUB
285 85 04, UB 85 04, AI 80 04, and XR 80 04 ($v_{v0.5} = 5.1, 5.5, 5.8, 6.0, 6.5, \text{ and } 8.3 \text{ m s}^{-1}$). Nuyttens *et al.*²⁶
286 also found that bigger ISO nozzle sizes correspond with significantly higher droplet velocity
287 characteristics for all nozzle types. Vulgarakis Minov *et al.*²⁹ also observed higher droplet velocities
288 with standard flat fan nozzles compared to air inclusion nozzles measured using a high speed image
289 system. For the same droplet size, flat-fan nozzles produced higher average vertical droplet velocities
290 than air inclusion nozzles, for the same ISO nozzle size and spray pressure, as can be seen in Figure 5,
291 and as also reported by Nuyttens *et al.*²⁶. The results furthermore show a clear effect of spray angle with
292 higher average velocities for 80° nozzles compared to 110° nozzles.

293 Droplet characteristics, in particular droplet size, are very important factors related to spray drift and
294 biological efficacy. Smaller droplets are more sensitive to evaporation and drift, because, due to their
295 lower velocity, they remain in the air longer before deposition.^{13, 30} A common approach to reduce drift
296 is to shift the droplet size spectrum towards coarser droplets. However, coarser droplets can result in
297 relatively low degree of target surface coverage and may shatter or bounce off the target.^{13, 31} On the other
298 hand, larger droplets are more likely to collide with the target surface as they are less likely to deviate
299 from their initial path when there are changes in the direction of air due to an object. By contrast, very
300 small droplets follow almost exactly the streamlines of air flowing around an encountered object.³² The
301 trade-off between spray deposition and drift, emphasizes the need for optimal droplet size distribution
302 and effective drift control practices, such as the use of air support.

303

304 3.2.2 Droplet characteristics with air support

305 The cumulative volumetric droplet size and velocity distribution of the nozzles AI 80 04, AI 110 04,
306 XR 80 02, and XR 80 04 spraying at 300 kPa, 0.5 m spray boom height, without (0 rpm) and with air
307 support (1400, 1750, 2000 rpm) are presented in Figure 6, respectively. An overview of the most
308 important droplet size and velocity characteristics is given in Table S2. As for the measurements with a
309 single nozzle without air support, air inclusion nozzles generated the coarsest droplet size spectrum,
310 followed by the standard ISO 04 nozzle, and the standard ISO 02 nozzle. Within nozzle type, VMD was
311 slightly higher with air support compared to without air support, except for XR 80 02, but no clear trends
312 were visible (VMD = 457, 473, 472, 467 μm for AI 80 04, 445, 456, 455, 456 μm for AI11004, 320,
313 337, 336, 337 μm for XR 80 04, and 262, 264, 261, 263 μm for XR 80 02 at 0, 1400, 1750, and 2000
314 rpm, respectively). Nuyttens *et al.*³³ also reported only a limited effect of air support on droplet size, but
315 they found a more important and significant increase in droplet velocities with air support. In addition,
316 the effect of air support on droplet velocity was found to be more important for larger nozzle heights.³³
317 In this study, the volumetric median droplet velocity increased with increasing air support within nozzle
318 type, except for XR 80 04, although even than velocities were considerably higher with than without air
319 support ($v_{v0.5}$ = 6.9, 7.1, 7.9, 8.4 m s^{-1} for AI 80 04, 5.5, 6.2, 7.1, 7.4 m s^{-1} for AI 110 04, 5.5, 6.4, 7.2,
320 7.9 m s^{-1} for XR 80 02, and 8.4, 11.2, 11.0, 11.4 m s^{-1} for XR 80 04 at 0, 1400, 1750, and 2000 rpm,
321 respectively). Although these measurements were more or less static, and therefore the air stream would
322 interact less with the spray fan than compared to field conditions where the sprayer drives at larger
323 speeds, a similar trend of increased droplet velocities with increased air support is to be expected in the
324 field. An increase in vertical droplet velocity induced by air support on boom sprayers reduces the time
325 of flight and thus the risk of drift. In addition, the forced airstream under the spray boom directs the
326 spray towards the target and blows the spray droplets into the crops, thus resulting in drift reduction,²⁰
327 ³³ and improved deposition on the target.³⁴ The increase in droplet velocity by means of air support was
328 found to have the highest impact on the amount of spray drift for finer sprays, as especially small droplets
329 quickly lose momentum imparted by the nozzle system and tend to quickly adopt the speed and direction
330 of the ambient airflow in situations without air support.³³ However, drift reducing techniques, such as
331 air support, can also lead to increased soil deposition underneath the crop canopy and consequently shift
332 the risk to water contamination by leaching through the soil.³⁴ It is therefore important to also consider

333 soil deposition when studying the effect of air support. A combination of air support and adjusted spray
334 boom height depending on the canopy growth stage and target zone, as discussed above, could result in
335 even better drift reduction on bed-grown crops, as lower spray boom height generally reduces spray drift
336 and the effect of air support on drift reduction increased when sprayer boom height was reduced.^{20, 35}
337 The effect of air support and adjusted nozzle spacing and boom height on potential spray drift reduction
338 and canopy and soil deposition on early stage and full grown carrots in lab trials is discussed in Douzals
339 *et al.*²³

340

341 **4 CONCLUSION**

342 In light of the optimization of a smart sprayer for bed-grown carrots within the H2020-project OPTIMA,
343 the use of various nozzle types and configurations, variable nozzle spacing and height, and air-support
344 was presented in this study. Four bed spray configurations, i.e. XR8004/XR8004/XR8004/XR8004,
345 AIUB8504/AI11004/AI11004/AIUB8504, AI8004/AI8004/AI8004/AI8004, and
346 XR8002/XR8002/XR8002/XR8002, were identified that clearly show an added value compared to a
347 standard broadcast application for spraying different target zone widths (1.2 to 1.8 m) with high
348 uniformity (CV < 12%) and minimal losses out of the target zone (< 17%), using the correct nozzle
349 spacing/height depending on the carrot growth stage. At later crop stages, when the canopy is more
350 closed and the bed is covered with foliage (target zone of 2.0 – 2.2 m), the broadcast application might
351 still be the most suitable spray application. Bed spraying and adjusting the target zone width to the leaf
352 foliage (cultivar, growth stage, planting system) can thus reduce the use of PPP's by reductions in
353 application volume or dosage compared to broadcast applications up to a certain target zone width. In
354 general, reducing the boom height in combination with narrower nozzle spacing, as done in this study
355 with the bed spray applications for smaller target zone widths, may aid in decreasing spray drift. Nozzle
356 type had an important effect on the droplet size and velocity spectra. For the same nozzle size and spray
357 pressure, air inclusion nozzles produced larger but slower droplets than standard flat-fan nozzles,
358 potentially reducing spray drift. Air support increased the droplet velocities but only had a very limited
359 effect on droplet size. This paper shows that laboratory measurements of spray distribution and droplet

360 characteristics can aid in selecting the most optimal spray settings for bed spray applications of different
361 target zone widths.

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447

448 Table 1. Overview of nozzles and settings selected and tested as possible optimizations.

Technique	Nozzle type + size	Spray pressure (kPa)	Nozzle flow rate (L min ⁻¹)	Appl. rate (L ha ⁻¹) [†]	Air support ^{††}
Reference nozzle	TeeJet XR 110 04	300	1.58	158 [‡]	No
Reduced volume nozzle	TeeJet XR 110 02	300	0.79	79 [‡]	No
Drift reducing nozzle	TeeJet AI 110 04	300	1.58	158 [‡]	No / Yes
Off-center reference nozzle	TeeJet UB 85 04	300	1.58	135 [§]	No
Off-center reduced volume nozzle	TeeJet UB 85 02	300	0.79	101 [§]	No
Off-center drift reducing nozzle	TeeJet AIUB 85 04	300	1.58	135 [§]	No
Narrow angle, reference nozzle	TeeJet XR 80 04	300	1.58	135 [¶]	No / Yes
Narrow angle, reduced volume nozzle	TeeJet XR 80 02	300	0.79	68 [¶]	No / Yes
Narrow angle, drift reducing nozzle	TeeJet AI 80 04	300	1.58	135 [¶]	No / Yes

[†] Theoretical application rate at 12 km h⁻¹, expressed as L ha⁻¹ of total ground area

[‡] Broadcast application with 42 nozzles on a 21 m spray boom

[§] Bed spray application with 36 nozzles (4 nozzles per bed, incl. 2 off-centre nozzles) on a 21 m spray boom

[¶] Bed spray application with 36 nozzles (4 nozzles per bed) on a 21 m spray boom

^{††} No / Yes = tested without air support and with air support set at 0, 1400, 1750, 2000 rpm

450 Table 2. Nozzle configurations tested for spray distributions.

Configuration	Spray pressure (kPa)	Nozzle spacing & height (m)
XR 110 04 [†]	300	0.5
UB 85 04 / XR 110 04 / UB 85 04	300	0.4 – 0.45 – 0.5 – 0.55 – 0.6 – 0.65
UB 85 04 / XR 80 04 / UB 85 04	300	0.4 – 0.45 – 0.5 – 0.55 – 0.6 – 0.65
XR 80 04 / XR 80 04 / XR 80 04	300	0.4 – 0.45 – 0.5 – 0.55 – 0.6 – 0.65
UB 85 04 / XR 110 04 / XR 110 04 / UB 85 04	300	0.35 – 0.4 – 0.45 – 0.5 – 0.55 – 0.6 – 0.65
UB 85 04 / XR 80 04 / XR 80 04 / UB 85 04	300	0.35 – 0.4 – 0.45 – 0.5 – 0.55 – 0.6 – 0.65
XR 80 04 / XR 80 04 / XR 80 04 / XR 80 04	300	0.35 – 0.4 – 0.45 – 0.5 – 0.55 – 0.6 – 0.65
AI UB 85 04 / AI 110 04 / AI 110 04 / AI UB 85 04	300	0.35 – 0.4 – 0.45 – 0.5 – 0.55 – 0.6 – 0.65
AI UB 85 04 / AI 80 04 / AI 80 04 / AI UB 85 04	300	0.35 – 0.4 – 0.45 – 0.5 – 0.55 – 0.6 – 0.65
AI 80 04 / AI 80 04 / AI 80 04 / AI 80 04	300	0.35 – 0.4 – 0.45 – 0.5 – 0.55 – 0.6 – 0.65
XR 110 04 / XR 110 04 / XR 110 04 / XR 110 04	300	0.35 – 0.4 – 0.45 – 0.5 – 0.55 – 0.6 – 0.65
AI 110 04 / AI 110 04 / AI 110 04 / AI 110 04	300	0.35 – 0.4 – 0.45 – 0.5 – 0.55 – 0.6 – 0.65
XR 80 02 / XR 80 02 / XR 80 02 / XR 80 02	300	0.35 – 0.4 – 0.45 – 0.5 – 0.55 – 0.6 – 0.65

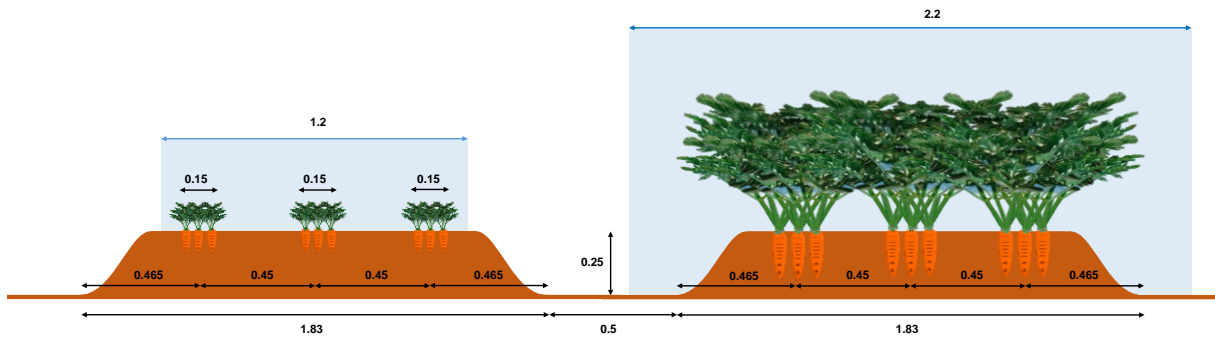
[†] Reference broadcast application, spray distribution of 12 nozzles measured

452 Table 3. Spray distribution characteristics of the broadcast application (XR 110 04) and the 4 most appropriate bed spray configurations at the most optimal
 453 nozzle spacing/height combinations for different target zone widths of 1.2, 1.4 , 1.6, 1.8, 2.0, and 2.2 m.

Configuration	Spray distribution characteristic	Target zone width (m)					
		1.2	1.4	1.6	1.8	2.0	2.2
Broadcast application – XR 110 04	Nozzle spacing/height (m)	0.5	0.5	0.5	0.5	0.5	0.5
	Min. spray volume (L ha ⁻¹)	144	144	144	144	144	144
	Max. spray volume (L ha ⁻¹)	171	171	171	176	176	176
	Avg. spray volume (L ha ⁻¹)	158	158	158	159	159	159
	Spray volume in target zone (%)	49.9	58.2	66.6	75.2	83.5	91.8
	Losses (%)	50.1	41.8	33.4	24.8	16.5	8.2
	CV (%)	5.8	5.6	5.3	5.8	5.5	5.4
XR 80 04/XR 80 04/XR 80 04/XR 80 04	Nozzle spacing/height (m)	0.35	0.4	0.45	0.5	0.55	0.6
	Min. spray volume (L ha ⁻¹)	181	147	132	115	96	121
	Max. spray volume (L ha ⁻¹)	247	214	184	176	158	161
	Avg. spray volume (L ha ⁻¹)	220	189	166	150	138	135
	Spray volume in target zone (%)	84.5	85.9	87.0	87.8	84.9	91.0
	Losses (%)	15.5	14.1	13.0	14.0	15.1	9.0
	CV (%)	9.2	9.4	8.7	10.2	10.8	6.2
AIUB 85 04/AI 110 04/AI 110 04/AIUB 85 04	Nozzle spacing/height (m)	0.4	0.45	0.5	0.6	0.65	0.65
	Min. spray volume (L ha ⁻¹)	206	180	153	129	123	118
	Max. spray volume (L ha ⁻¹)	252	222	191	169	157	157
	Avg. spray volume (L ha ⁻¹)	225	200	173	151	140	139
	Spray volume in target zone (%)	85.5	88.5	91.0	85.5	85.5	92.9
	Losses (%)	14.5	11.5	9.0	14.5	14.5	7.1
	CV (%)	6.6	6.2	5.9	7.0	7.1	8.0
AI 80 04/AI 80 04/AI 80 04/AI 80 04	Nozzle spacing/height (m)	0.35	0.4	0.45	0.5	0.55	0.6
	Min. spray volume (L ha ⁻¹)	197	160	148	126	104	117
	Max. spray volume (L ha ⁻¹)	252	220	194	176	165	155
	Avg. spray volume (L ha ⁻¹)	224	191	172	152	141	135
	Spray volume in target zone (%)	85.5	86.6	88.2	89.1	87.3	90.5
	Losses (%)	14.5	13.4	11.8	11.5	12.7	9.5
	CV (%)	9.4	9.8	9.6	9.4	10.8	8.2
XR 80 02/XR 80 02/XR 80 02/XR 80 02	Nozzle spacing/height (m)	0.35	0.4	0.45	0.5	0.55	0.6

Min. spray volume (L ha ⁻¹)	90	77	70	63	57	63
Max. spray volume (L ha ⁻¹)	117	107	92	87	77	79
Avg. spray volume (L ha ⁻¹)	107	95	85	77	70	67
Spray volume in target zone (%)	85.0	86.5	87.9	87.9	87.5	91.0
Losses (%)	15.0	13.5	12.1	12.1	12.5	9.0
CV (%)	6.8	7.5	7.4	7.3	7.6	5.9

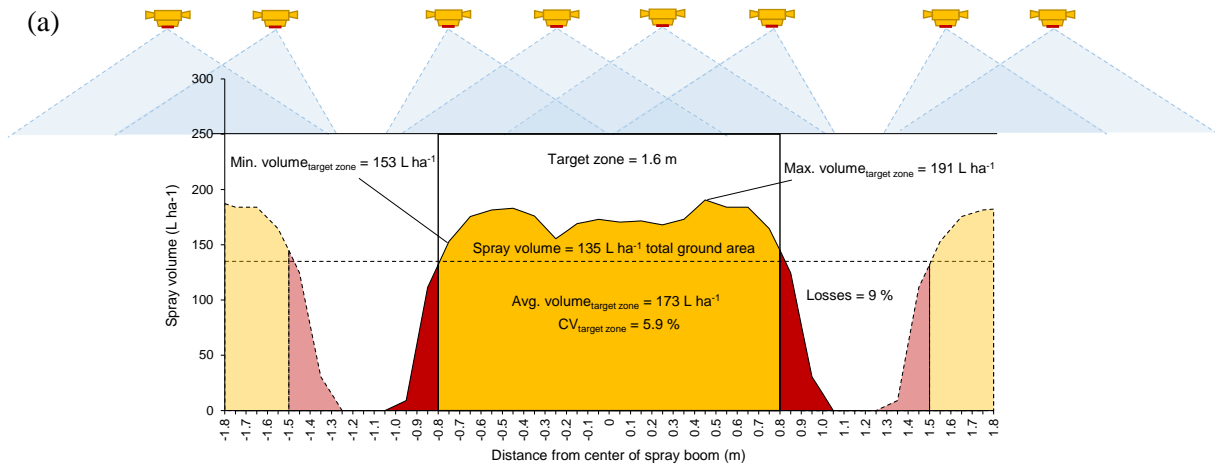
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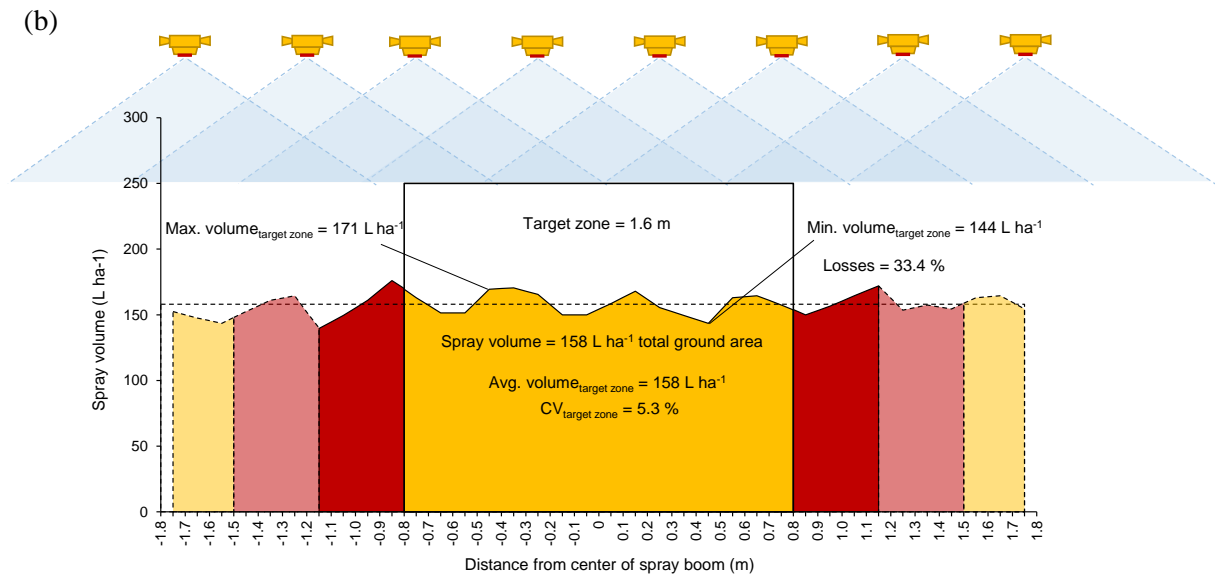
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456 Figure 1. Schematic of the carrot bed design at early (left) and full growth stage (right), with indication

457 of respectively the 1.2 m and the 2.2 m target zone in blue (dimensions given in m).

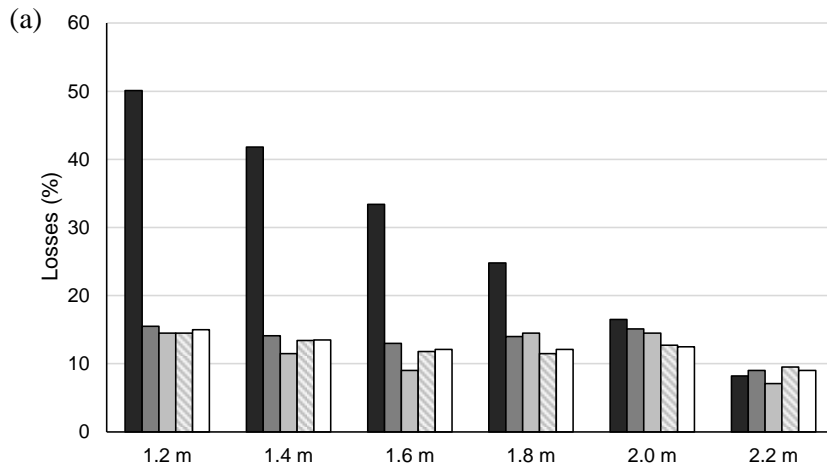


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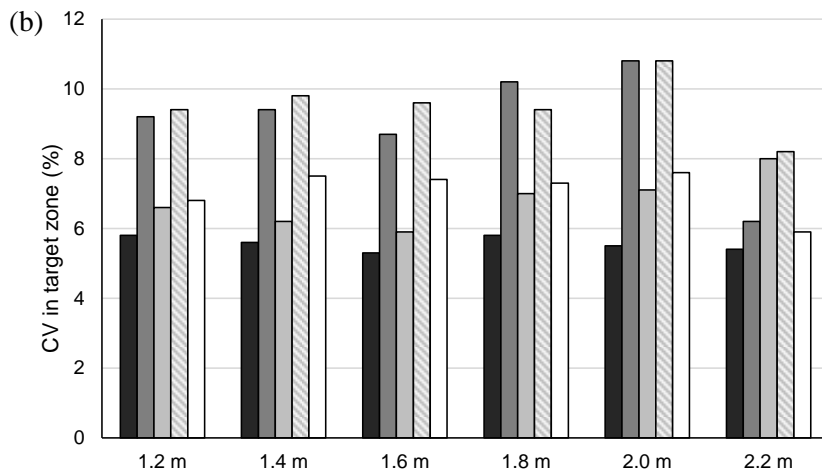


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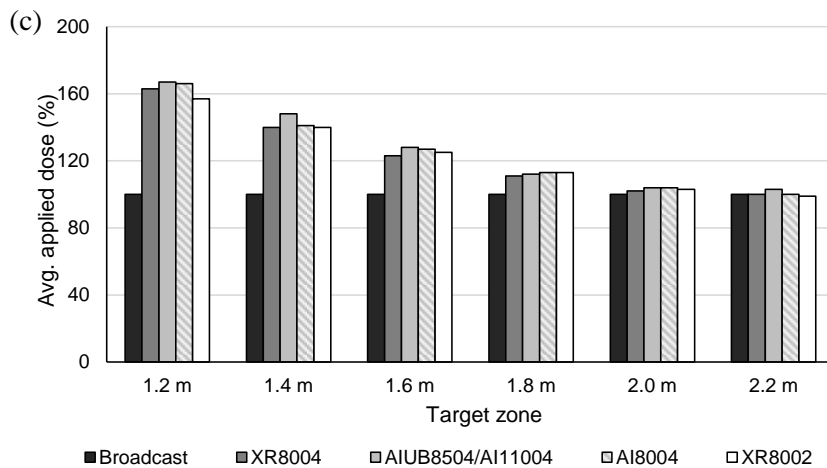
460 Figure 2. Spray distribution pattern of (a) AIUB8504/AI11004/AI11004/AIUB8504 and (b) a broadcast
 461 application with XR11004 nozzles, at nozzle spacing/height of 0.5 m (for the bed spray configuration,
 462 only above the carrot beds, not between the beds), with indication of spray volume within (yellow) and
 463 outside (red) the 1.6 m target zone.



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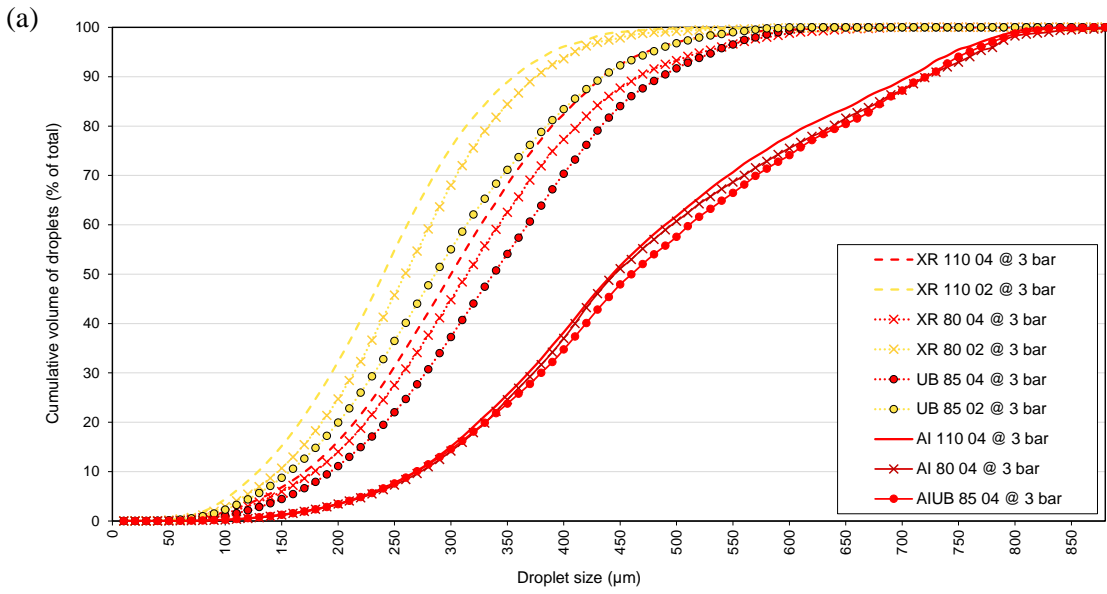


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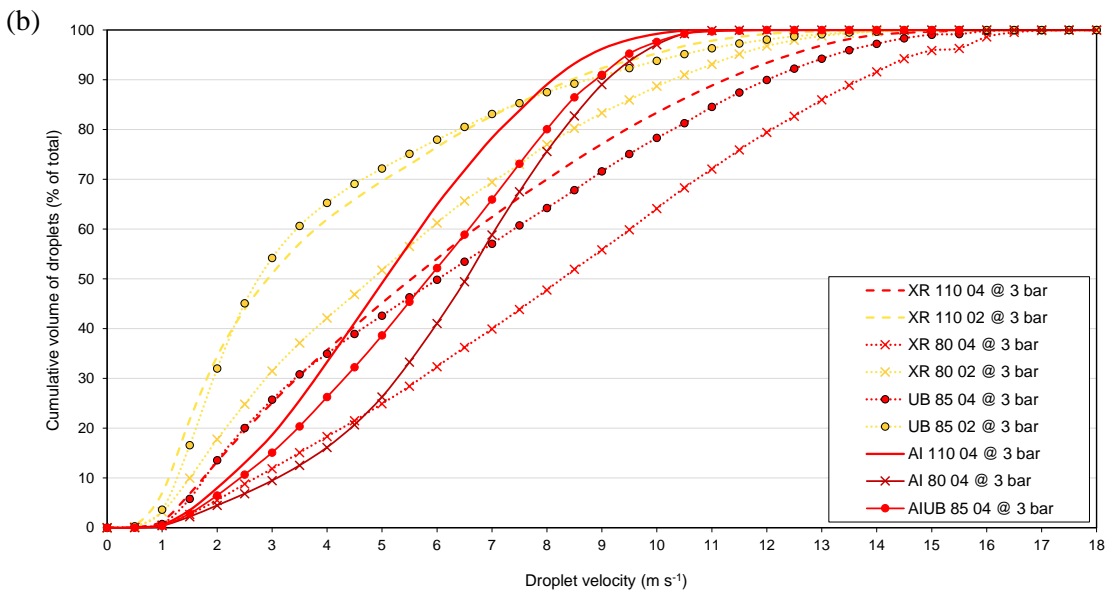


466

467 Figure 3. (a) Losses outside the target zone (%), (b) CV in the target zone (%), and (c) average applied
 468 dose in the target zone for the reference broadcast application (■) and the 4 most appropriate nozzle
 469 configurations per target zone (■ XR8004/XR8004/XR8004/XR8004, ■ AIUB8504/AI11004/AI11004/AIUB8504,
 470 ■ AI8004/AI8004/AI8004/AI8004, ■ XR8002/XR8002/XR8002/XR8002).

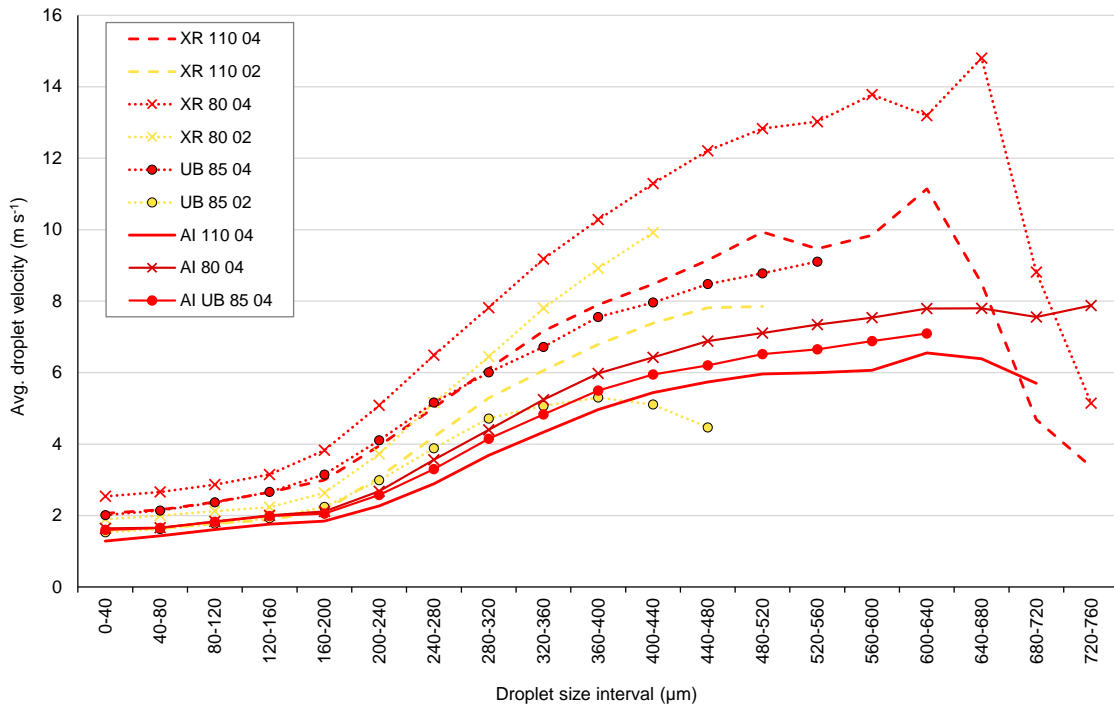


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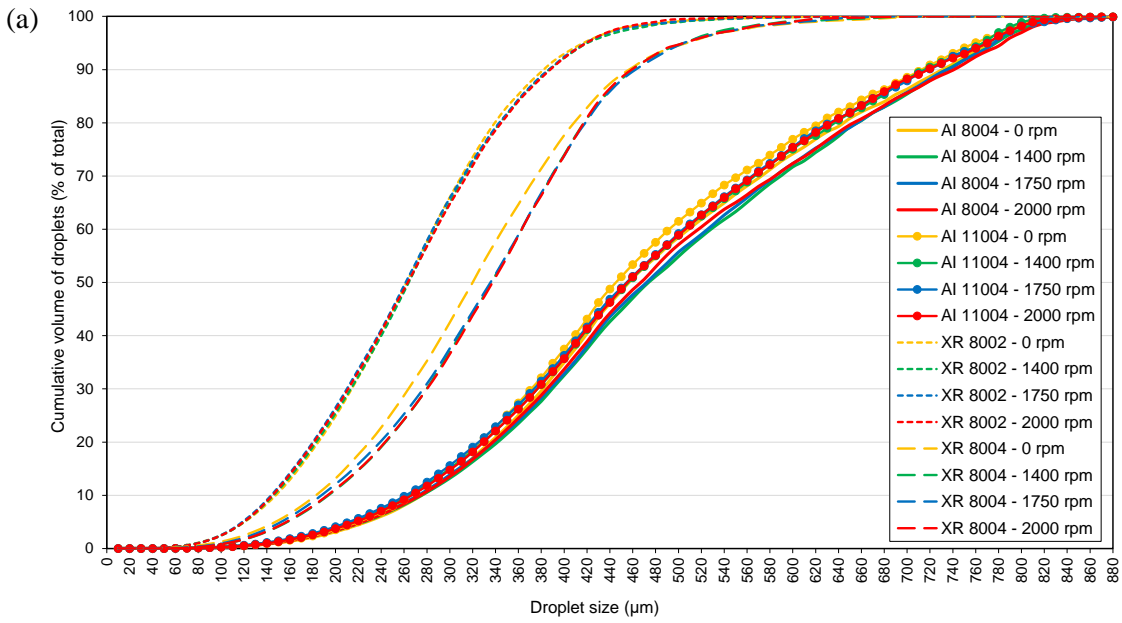
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474 Figure 4. (a) Cumulative volumetric droplet size distribution and (b) cumulative volumetric droplet
 475 velocity distribution for different nozzles spraying at 300 kPa, 0.5 m spray height and without air support
 476 (measured with PDPA; TSI).

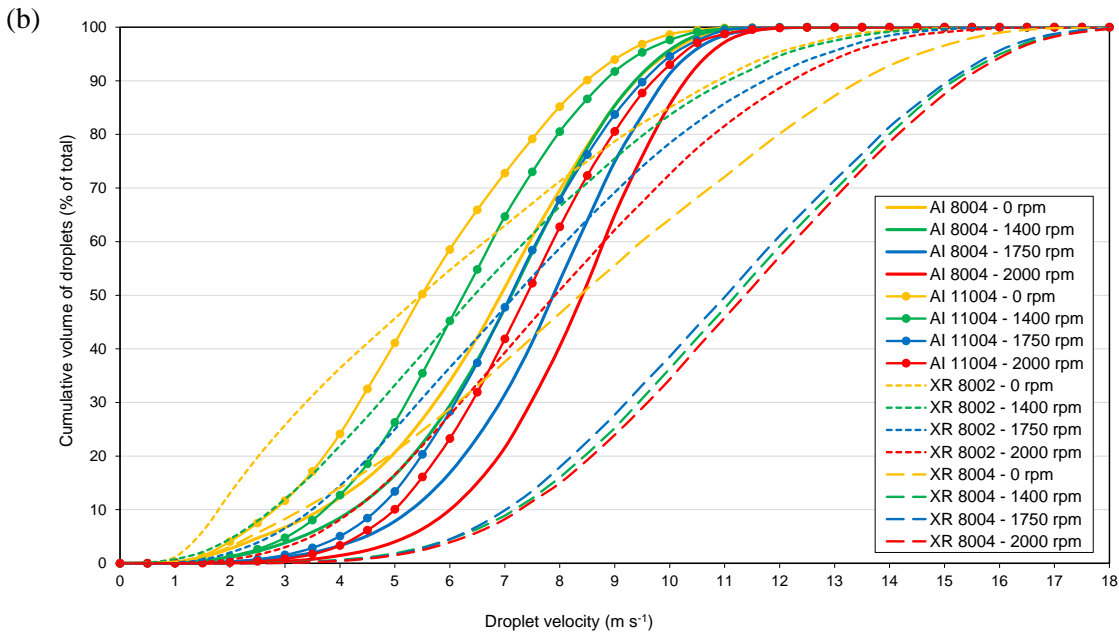


477

478 Figure 5. Average droplet velocities (m s^{-1}) for the different droplet size classes (μm) of the different
 479 nozzles spraying at 300 kPa, 0.5 m spray height, without air support.



480



481

482 Figure 6. (a) Cumulative volumetric droplet size distribution and (b) cumulative volumetric droplet

483 velocity distribution for AI 80 04, AI 110 04, XR 80 02, and XR 80 04 spraying at 300 kPa, 0.5 m

484 spray height, without (0 rpm) and with air support (1400, 1750, 2000 rpm).

Supporting information

Table S1. BCPC class and droplet size and velocity characteristics $D_{v0.1}$, $D_{v0.5}$, $D_{v0.9}$, V_{100} , $v_{v0.50}$, v_{avg} (average \pm SD) of the 9 nozzle types tested without air support.

Nozzle type	Pressure (kPa)	BCPC class [†]	$D_{v0.1}$ (μm)	$D_{v0.5}$ (μm)	$D_{v0.9}$ (μm)	V_{100} (%)	$v_{v0.50}$ (m s^{-1})	v_{avg} (m s^{-1})
XR 110 04	300	Medium	170.8 \pm 5.6	300.0 \pm 1.6	434.2 \pm 0.8	1.8 \pm 0.2	5.5 \pm 0.2	3.2 \pm 0.0
XR 110 02	300	Fine	129.3 \pm 4.3	240.1 \pm 4.7	355.2 \pm 5.1	4.4 \pm 0.3	2.9 \pm 0.1	2.1 \pm 0.0
AI 110 04	300	Very Coarse	268.8 \pm 1.0	443.3 \pm 3.7	706.1 \pm 11.6	0.2 \pm 0.0	5.1 \pm 0.1	3.0 \pm 0.1
UB 85 04	300	Medium	193.8 \pm 6.6	337.7 \pm 4.0	486.3 \pm 1.9	1.1 \pm 0.1	6.0 \pm 0.3	3.5 \pm 0.1
UB 85 02	300	Medium	157.3 \pm 6.0	286.4 \pm 6.9	434.2 \pm 9.4	2.3 \pm 0.3	2.7 \pm 0.1	2.3 \pm 0.0
AIUB 85 04	300	Very Coarse	269.3 \pm 4.0	460.3 \pm 2.1	718.6 \pm 6.1	0.3 \pm 0.0	5.8 \pm 0.1	3.3 \pm 0.0
XR 80 04	300	Medium	178.9 \pm 6.3	314.1 \pm 3.5	466.0 \pm 3.0	1.6 \pm 0.2	8.3 \pm 0.1	4.2 \pm 0.1
XR 80 02	300	Medium	146.9 \pm 4.4	259.6 \pm 4.7	374.5 \pm 1.2	2.9 \pm 0.2	4.8 \pm 0.2	2.8 \pm 0.0
AI 80 04	300	Very Coarse	273.1 \pm 8.0	445.4 \pm 5.2	721.1 \pm 4.9	0.2 \pm 0.1	6.5 \pm 0.1	3.5 \pm 0.1

[†] BCPC Spray quality class (Southcombe et al., 1997)

Table S2. Droplet size and velocity characteristics $D_{v0.1}$, $D_{v0.5}$, $D_{v0.9}$, V_{100} , $v_{v0.50}$, v_{avg} (average \pm SD) of the 4 nozzle types tested with air support (0, 1400, 1750, 2000 rpm).

Nozzle type	Air support (rpm)	Pressure (kPa)	$D_{v0.1}$ (μm)	$D_{v0.5}$ (μm)	$D_{v0.9}$ (μm)	V_{100} (%)	$v_{v0.50}$ (m s^{-1})	v_{avg} (m s^{-1})
AI 80 04	0	300	275.2 ± 2.5	456.7 ± 6.0	731.1 ± 6.3	0.2 ± 0.0	6.9 ± 0.1	3.9 ± 0.1
AI 80 04	1400	300	275.4 ± 2.5	473.9 ± 3.9	734.7 ± 4.8	0.2 ± 0.0	7.1 ± 0.2	4.9 ± 0.2
AI 80 04	1750	300	272.7 ± 4.5	471.5 ± 7.9	733.9 ± 13.0	0.2 ± 0.0	7.9 ± 0.0	6.1 ± 0.1
AI 80 04	2000	300	273.7 ± 8.3	466.9 ± 2.8	740.4 ± 4.1	0.2 ± 0.1	8.4 ± 0.1	6.9 ± 0.1
AI 110 04	0	300	266.6 ± 4.9	445.4 ± 7.2	712.9 ± 4.0	0.2 ± 0.0	5.5 ± 0.1	3.3 ± 0.1
AI 110 04	1400	300	264.6 ± 1.2	456.2 ± 0.8	714.9 ± 4.8	0.3 ± 0.0	6.2 ± 0.3	4.9 ± 0.4
AI 110 04	1750	300	261.6 ± 0.9	454.8 ± 4.1	717.9 ± 10.8	0.3 ± 0.0	7.1 ± 0.0	6.1 ± 0.0
AI 110 04	2000	300	267.4 ± 10.3	455.8 ± 10.5	718.0 ± 5.0	0.2 ± 0.1	7.4 ± 0.1	6.5 ± 0.1
XR 80 02	0	300	147.6 ± 2.9	262.0 ± 0.5	381.6 ± 2.6	2.5 ± 0.2	5.5 ± 0.0	3.0 ± 0.0
XR 80 02	1400	300	145.9 ± 3.0	264.0 ± 1.3	386.5 ± 3.5	2.4 ± 0.2	6.4 ± 0.3	4.9 ± 0.3
XR 80 02	1750	300	143.7 ± 1.7	261.3 ± 3.4	386.4 ± 3.6	2.5 ± 0.1	7.2 ± 0.0	5.7 ± 0.1
XR 80 02	2000	300	144.9 ± 1.5	263.4 ± 3.3	387.5 ± 3.9	2.5 ± 0.1	7.9 ± 0.2	6.4 ± 0.1
XR 80 04	0	300	182.7 ± 1.9	319.9 ± 0.4	456.8 ± 1.0	1.3 ± 0.1	8.4 ± 0.1	4.4 ± 0.1
XR 80 04	1400	300	194.1 ± 2.7	336.8 ± 4.3	459.4 ± 5.2	0.8 ± 0.1	11.2 ± 0.2	8.3 ± 0.4
XR 80 04	1750	300	187.8 ± 1.0	335.8 ± 3.0	463.1 ± 9.4	1.0 ± 0.1	11.0 ± 0.0	8.3 ± 0.1
XR 80 04	2000	300	193.1 ± 2.3	337.4 ± 0.8	459.2 ± 2.1	0.8 ± 0.1	11.4 ± 0.5	8.7 ± 0.3