**This is the accepted version of the following article: Boom sprayer optimizations for bed-grown carrots at different growth stages based on spray distribution and droplet characteristics, which has been published in final form at https://onlinelibrary.wiley.com/doi/10.1002/ps.6792.**

**Running title: Sprayer optimizations for bed-grown carrots.**

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## ABSTRACT

BACKGROUND: Pesticide losses and uneven spray distribution should be avoided as much as possible as they reduce the effectiveness of spraying and increase environmental contamination as well as costs. Within the H2020-project OPTIMA the goal is to develop a smart sprayer for bed-grown carrots, including optimizations such as air support and variable nozzle spacing. This paper focuses on selecting the most optimal nozzle types, spacing and height for spraying bed-grown crops, while taking into account different target zone widths depending on the growth stage, based on spray distribution and droplet characterization measurements.

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

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

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

## 1 INTRODUCTION

Since January 2014, growers in the European Union are obliged to implement the principles of integrated pest management (IPM).[1] These principles aim to minimise environmental, economic and health risks due to the use of plant protection products (PPP), by combining various biological, physical, cultural and chemical techniques to manage all classes of pests. Within the H2020-project OPTIMA (*OPTimised Integrated pest MAnagement for precise detection and control of plant diseases in perennial crops and open-field vegetables*, www.optima-h2020.eu), an environmentally friendly IPM framework for Alternaria leaf blight in carrots, downy mildew in vineyards, and apple scab in orchards is developed by providing a holistic approach which includes major elements related to integrated disease management, such as precision spraying techniques, as well as the use of novel bio-PPPs, disease prediction models, and spectral disease detection systems. The overall goal is to integrate those elements and develop three prototype smart sprayers in collaboration with sprayer manufacturers.

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

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

## 2 MATERIALS AND METHODS

### *2.1 Planting system and crop characteristics*

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

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

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

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

### *2.3 Spray distribution*

Prior to the spray distribution and droplet characteristics experiments, the flow rate of the nozzles was determined using a nozzle test bench (ITEQ, Belgium) at the Spray Technology Laboratory of Flanders Research Institute for Agricultural, Fisheries and Food (ILVO, Belgium). Every nozzle was tested three times at a spray pressure of 300 kPa. The nozzles with the lowest mean deviation from the nominal flow rate were selected for further experiments. Per off-center nozzle type, 6 nozzles were tested and 2 were selected for further experiments, of the other nozzle types (i.e. XR and AI), 12 nozzles were tested and 4 were selected for further experiments.

To achieve maximal and uniform deposition on the canopy (i.e. target zone) and to have minimal losses between the beds, optimal nozzle spacings and heights for bed spray applications were determined using 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 range) were assessed for a distance between carrot beds of 2.33 m (Fig. 1).

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

The spray distribution measurements were performed indoor at ILVO's Spray Technology Laboratory, according to ISO 5682-2[15]. The spray scanner set-up consisted of a 0.8 m wide, channelled, sloping scanner with 0.1 m grooves and calibrated collecting tubes by AAMS-Salvarani (Maldegem, Belgium), running over a frame underneath a fixed 12 m 'ideal' spray boom. For this experiment, a short spray boom with variable nozzle spacing was constructed and mounted on the fixed spray boom. The center of the short spray boom was positioned above a channel partition, thus forming the zero-point position corresponding to the middle of the bed. The reciever-unit with 0.1 m wide grooves collected the liquid sprayed with the short spray boom during a known time interval, as described by Zwertvaegher et al.[16]. The flow rates (L min$^{-1}$) achieved from the spray scanner measurements, which are basically time measurements as also described by Višacki et al. [4], were recalculated to spray volume (L ha$^{-1}$) based on a driving speed of 12 km h$^{-1}$. For each target zone width and nozzle configuration, following variables were calculated, taking into account possible overlap between sprays of neighboring beds: minimum spray volume in target zone (L $ha^{-1}$), maximum spray volume in target zone (L $ha^{-1}$), average spray volume in target zone (L $ha^{-1}$), percentage of spray volume in target zone (%), percentage of losses outside the target zone (%), and Coefficient of variation (CV) of the spray distribution in the target zone (%).

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

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

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

### *2.4 Droplet size and velocity characteristics*

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

Based on the spray distribution measurements (see 2.3 Spray distribution), the 4 nozzle types of the most appropriate nozzle configurations, i.e. XR8004, XR8002, AI11004, and AI8004, were also tested with air support at 4 different settings (Table 1), using the Caffini Air Wing (Caffini s.p.a., Palù Verona, Italy) and ILVO fan (Ventomatic, Merelbeke, Belgium). Measurements were performed with the test set-up at fan frequencies corresponding to Caffini sprayer fan speeds of 0, 1400, 1750 and 2000 rpm 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 combinations (4 nozzle types x 4 air support settings) were tested. Following characteristics were calculated:

(1) BCPC – BCPC spray quality class based on droplet size;

(2) $D_{v0.5}$ – volume median diameter (VMD, µm) below which smaller droplets constitute 50% of the spray volume;

(3) $D_{v0.1}$, $D_{v0.9}$ – volume diameter (µm) below which smaller droplets constitute respectively 10% and 90% of the total volume;

(4) $V_{100}$ – proportion of total volume (%) of droplets smaller than 100 µm in diameter;

(5) $v_{v0.50}$ – droplet velocity (m $s^{-1}$) below which slower droplets constitute 50% of the total spray volume;

$v_{avg}$ – arithmetic average droplet velocity (m $s^{-1}$).

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

## 3 RESULTS AND DISCUSSION

### *3.1 Spray distribution*

The spray distribution results showed that the configurations with 3 nozzles did not meet the criteria, and were therefore not appropriate, not even for the smallest target zone width of 1.2 m, as either the CV and/or the losses were too high (criterion 1 and 2, respectively). In total, 4 nozzle configurations were appropriate for all target zone widths (from 1.2 to 2.2 m), i.e. XR8004/XR8004/XR8004/XR8004, AIUB8504/AI11004/AI11004/AIUB8504, AI8004/AI8004/AI8004/AI8004, and XR8002/XR8002/XR8002/XR8002. Table 3 tabulates the spray distribution characteristics of these configurations at the most appropriate nozzle spacing/height combinations for the different target zone widths. As an example, the spray distribution patterns and characteristics of AIUB8504/AI11004/AI11004/AIUB8504 and the broadcast application with XR11004 nozzles, both at 0.5 m nozzle spacing/height, for a target zone width of 1.6 m, are presented in Figure 2a and b, respectively. Per target zone, the losses outside the target zone (%) and the CV (%) and the average of the applied dose (%), i.e. the average spray volume in the target zone relative to the theoretical spray volume per ha of total ground area (Table 1), expressed as %, are given in Figure 3 for the reference broadcast application and the 4 most appropriate nozzle configurations, i.e. XR8004/XR8004/XR8004/XR8004, AIUB8504/AI11004/AI11004/AIUB8504, AI8004/AI8004/AI8004/AI8004, and XR8002/XR8002/XR8002/XR8002.

With lowest variation (CV) inside the target zone and lowest relative losses outside the target zone, while maintaining a high average spray volume in the target zone, the overall best ISO 04 configuration is AIUB8504/AI11004/AI11004/AIUB8504 for target zone widths from 1.2 to 1.6 m, as indicated by Table 3 and Figure 3. For a target zone width of 2.2 m, a nozzle spacing/height combination of 0.7 m might be more appropriate with this configuration, however, as reported earlier, this spacing/height combination was not tested due to increased risk of drift.[19] However, compared to AIUB8504/AI11004/AI11004/AIUB8504, configurations XR8004/XR8004/XR8004/XR8004, AI8004/AI8004/AI8004/AI8004, and XR8002/XR8002/XR8002/XR8002 have the advantage that only one nozzle type can be used along the spray boom, and as no off-center nozzles are needed, they are less expensive and less sensitive to deviations in spray line and boom movements. For target zones up to 1.8 m, losses were always highest for the broadcast application (10 to 36% higher than the bed spray configurations), thus denoting a clear advantage for bed spray applications at these target zones. However, the broadcast application losses decreased with increasing target zone and at 2.0 m target zone the losses were comparable to those of the bed spray applications (13 to 17%). Over a 2.2 m target zone, only configuration AIUB8504/AI11004/AI11004/AIUB8504 had lower losses than the broadcast application (7 *vs* 8%). The four bed spray applications had similar losses at all target zones, ranging from 16% at 1.2 m to 7% at 2.2 m. The CV, which is a measure of uniformity, was lowest for the broadcast application at all target zones (0.6 to 5.3% lower than the bed spray configurations), indicating that the most uniform spray applications were obtained with this configuration. However, this is at the expense of higher losses outside the target zone and lower applied doses in the target zone. Although the average applied dose (relative to the theoretical application rate, Table 1) in the target zone was always around 100% for the broadcast application, it was considerably lower (11 to 67%) than compared to the bed spray applications for target zones from 1.2 to 1.8 m, indicating lower depositions in those target zones for the broadcast application. This demonstrates the added value of the bed spray applications since potential dosage or application rate savings can be obtained. Considering the example from Figure 2, configuration AIUB8504/AI11004/AI11004/AIUB8504 resulted in an average spray volume of 173 L $ha^{-1}$ within the target zone of 1.6 m, whereas a theoretical application rate of 135 L $ha^{-1}$ ground area was determined for a boom sprayer with 36 ISO 04 nozzles (4 nozzles per bed) at 12 km $h^{-1}$ driving speed and a spray pressure of 300 kPa. The latter is already a 14% reduction in theoretical application rate compared to a broadcast application of 158 L $ha^{-1}$ with 42 XR11004 nozzles at the same driving speed and spray pressure. The increased on-target deposition of 173 L $ha^{-1}$ indicates that even lower spray volumes or dosages could be applied with the bed spray configurations at adjusted nozzle spacing/height while maintaining the same bio-efficacy as for the reference broadcast application. Indirectly these reductions would also result in lower losses and spray drift. Variable rate application methods could also be used to obtain the desired, reduced application rate or dosage. At target zones from 2.0 to 2.2 m, the average applied doses were comparable for all configurations, ranging from 99 to 105%. Configurations XR8004/XR8004/XR8004/XR8004 and AI8004/AI8004/AI8004/AI8004 had the highest CV (8.7 to 10.8%), i.e. lowest uniformity, followed by XR8002/XR8002/XR8002/XR8002 and AIUB8504/AI11004/AI11004/AIUB8504, except for the target zone of 2.2 m. For the 2.2 m target zone, AI8004/AI8004/AI8004/AI8004 and AIUB8504/AI11004/AI11004/AIUB8504 had the highest CV (over 8%). The CV in the target zone of the bed spray applications are almost always below the 10% threshold value stated in ISO 16122-2[17] and EN 13790-1[18], which should not be exceeded by standard horizontal boom sprayers. These values indicate a good uniformity within the target zone for the bed spray applications, especially considering the threshold value has primarily been defined for broadcast applications. As suggested by the overall low CV in the target zone and the lower losses outside the target zone, the broadcast application might still be the most suitable spray application at later crop stages, when the canopy is more developped and more closed and the bed is covered with foliage (target zone of 2.0 – 2.2 m).

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

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

### *3.2 Droplet size and velocity characteristics*

3.2.1 Droplet characteristics without air support

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

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

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

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

### 3.2.2 Droplet characteristics with air support

The cumulative volumetric droplet size and velocity distribution of the nozzles AI 80 04, AI 110 04, XR 80 02, and XR 80 04 spraying at 300 kPa, 0.5 m spray boom height, without (0 rpm) and with air support (1400, 1750, 2000 rpm) are presented in Figure 6, respectively. An overview of the most important droplet size and velocity characteristics is given in Table S2. As for the measurements with a single nozzle without air support, air inclusion nozzles generated the coarsest droplet size spectrum, followed by the standard ISO 04 nozzle, and the standard ISO 02 nozzle. Within nozzle type, VMD was slightly higher with air support compared to without air support, except for XR 80 02, but no clear trends were visible (VMD = 457, 473, 472, 467 µm for AI 80 04, 445, 456, 455, 456 µm for AI11004, 320, 337, 336, 337 µm for XR 80 04, and 262, 264, 261, 263 µm for XR 80 02 at 0, 1400, 1750, and 2000 rpm, respectively). Nuyttens *et al.*[33] also reported only a limited effect of air support on droplet size, but they found a more important and significant increase in droplet velocities with air support. In addition, the effect of air support on droplet velocity was found to be more important for larger nozzle heights.[33] In this study, the volumetric median droplet velocity increased with increasing air support within nozzle type, except for XR 80 04, although even than velocities were considerably higher with than without air 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, 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, respectively). Although these measurements were more or less static, and therefore the air stream would interact less with the spray fan than compared to field conditions where the sprayer drives at larger speeds, a similar trend of increased droplet velocities with increased air support is to be expected in the field. An increase in vertical droplet velocity induced by air support on boom sprayers reduces the time of flight and thus the risk of drift. In addition, the forced airstream under the spray boom directs the spray towards the target and blows the spray droplets into the crops, thus resulting in drift reduction,[20, 33] and improved deposition on the target.[34] The increase in droplet velocity by means of air support was found to have the highest impact on the amount of spray drift for finer sprays, as especially small droplets quickly lose momentum imparted by the nozzle system and tend to quickly adopt the speed and direction of the ambient airflow in situations without air support.[33] However, drift reducing techniques, such as air support, can also lead to increased soil deposition underneath the crop canopy and consequently shift the risk to water contamination by leaching through the soil.[34] It is therefore important to also consider soil deposition when studying the effect of air support. A combination of air support and adjusted spray boom height depending on the canopy growth stage and target zone, as discussed above, could result in even better drift reduction on bed-grown crops, as lower spray boom height generally reduces spray drift and the effect of air support on drift reduction increased when sprayer boom height was reduced.[20, 35] The effect of air support and adjusted nozzle spacing and boom height on potential spray drift reduction and canopy and soil deposition on early stage and full grown carrots in lab trials is discussed in Douzals *et al.*[23]

**4 CONCLUSION**

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

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## REFERENCES


1. *EC. Directive 2009/128/EC.* European Commission, Brussels, Belgium (2009).

2. Gil E, Llorens J, Landers A, Llop J and Giralt L, Field validation of DOSAVINA, a decision support system to determine the optimal volume rate for pesticide application in vineyards. *Eur J Agron* **35**:33-46 (2011).

3. Vercruysse F, Steurbaut W, Drieghe S and Dejonckheere W, Off target ground deposits from spraying a semi-dwarf orchard. *Crop Prot* **18**:565-570 (1999).

4. Višacki VV, Sedlar AD, Gil E, Bugarin RM, Turan JJ, Janic TV, et al., Effects of sprayer boom height and operating pressure on the spray uniformity and distribution model development. *Applied Engineering in Agriculture* **32**:341-346 (2016).

5. Forney SH, Luck JD, Kocher MF and Pitla SK, Laboratory and full boom-based investigation of nozzle setup error effects on flow, pressure, and spray pattern distribution. *Applied Engineering in Agriculture* **33**:641-653 (2017).

6. Holterman H, van de Zande J and Van Velde P, Optimizing sprayer boom design for bed-grown crops. *Aspects of Applied Biology* **137**:123-130 (2018).

7. Miller PCH and Butler Ellis MC, Effects of formulation on spray nozzle performance for applications from ground-based boom sprayers. *Crop Prot* **19**:609-615 (2000).

8. Nuyttens D, De Schampheleire M, Verboven P and Sonck B, Comparison between indirect and direct spray drift assessment methods. *Biosyst Eng* **105**:2-12 (2010).

9. Jensen PK, Jorgensen LN and Kirknel E, Biological efficacy of herbicides and fungicides applied with low-drift and twin-fluid nozzles. *Crop Prot* **20**:57-64 (2001).

10. Brown L, Soltani N, Shropshire C, Spieser H and Sikkema PH, Efficacy of four corn (Zea mays L.) herbicides when applied with flat fan and air induction nozzles. *Weed Biol Manage* **7**:55-61 (2007).

11. Nuyttens D, Baetens K, De Schampheleire M and Sonck B, Effect of nozzle type, size and pressure on spray droplet characteristics. *Biosyst Eng* **97**:333-345 (2007).

12. Vajs S, Leskosek G, Simoncic A and Lesnik M, Comparison of the effectiveness of standard and drift-reducing nozzles for control of some winter wheat diseases. *J Plant Dis Prot* **115**:23-31 (2008).

13. De Cock N, Massinon M, Salah SOT and Lebeau F, Investigation on optimal spray properties for ground based agricultural applications using deposition and retention models. *Biosyst Eng* **162**:99-111 (2017).

14. Ferguson J, Chechetto R, Adkins S, Hewitt A, Chauhan B, Kruger G, et al., Effect of spray droplet size on herbicide efficacy on four winter annual grasses. *Crop Prot* **112**:118-124 (2018).

15. *ISO 5682-2 - Equipment for crop protection - Spraying equipment - Part 2: Test methods to assess the horizontal transverse distribution for hydraulic sprayers.* ISO, Geneva, Switzerland (2017).

16. Zwertvaegher I, Van Daele I, Verheesen P, Peferoen M and Nuyttens D, Development and implementation of a laboratory spray device and rainfall simulator for retention research using small amounts of agroformulations. *Pest Manage Sci* **73**:123-129 (2017).

17. *ISO 16122-2 - Agricultural and forestry machinery - Inspection of sprayers in use - Part 2: Horizontal boom sprayers.* ISO, Geneva, Switzerland (2015).

18. *EN 13790-1 - Agricultural machinery - Sprayers - Inspection of sprayers in use - Part 1: Field crop sprayers.* European Committee for Standardization, Brussels, Belgium (2003).

19. Nuyttens D, De Schampheleire M, Baetens K and Sonck B, The influence of operator-controlled variables on spray drift from field crop sprayers. *Trans ASABE* **50**:1129-1140 (2007).

20. De Jong A, Michielsen J, Stallinga H and van de Zande J, Effect of sprayer boom height on spray drift. *Meded - Fac Landbouwkd Toegepaste Biol Wet (Univ Gent)* **62**:919-930 (2000).

21. Balsari P, Gil E, Marucco P, van de Zande J, Nuyttens D, Herbst A, et al., Field-crop-sprayer potential drift measured using test bench: Effects of boom height and nozzle type. *Biosyst Eng* **154**:3-13 (2017).

22. Azimi AH, Carpenter TG and Reichard DL, Nozzle spray distribution for pesticide application. *Trans ASAE* **28**:1410-1414 (1985).

23. Douzals J-P, Lamare A, Fountas S, Athanasakos L, Mylonas N, Zwertvaegher I, et al., Optimization of spray application on bed-grown vegetables - On-going developments within OPTIMA project. [Manuscript submitted for publication]. *Aspects of Applied Biology* **147** (2022).

24. Southcombe ESE, Miller PCH, Ganzelmeier H, van de Zande J, Miralles A and Hewitt A. The international (BCPC) spray classification system including a drift potential factor (The Brighton Crop Protection Conference - Weeds 1997). p. 371-380.

25. Etheridge R, Womac A and Mueller TA, Characterization of the spray droplet spectra and patterns of four Venturi-type drift reduction nozzles. *Weed Technol* **13**:765-770 (1999).

26. Nuyttens D, De Schampheleire M, Verboven P, Brusselman E and Dekeyser D, Droplet size and velocity characteristics of agricultural sprays. *Trans ASABE* **52**:1471-1480 (2009).

27. Zwertvaegher I, Verhaeghe M, Brusselman E, Verboven P, Lebeau F, Massinon M, et al., The impact and retention of spray droplets on a horizontal hydrophobic surface. *Biosyst Eng* **126**:82-91 (2014).

28. Creech C, Henry R, Fritz B and Kruger G, Influence of herbicide active ingredient, nozzle type, orifice size, spray pressure, and carrier volume rate on spray droplet size characteristics. *Weed Technol* **29**:298-310 (2015).

29. Vulgarakis Minov S, Cointault F, Vangeyte J, Pieters JG and Nuyttens D, Spray droplet characterization from a single nozzle by high speed image analysis using an in-focus droplet criterion. *Sensors* **16**:218-237 (2016).

30. Matthews GA, Pesticide application methods. Third ed. Oxford: Blackwell Science Ltd, pp. 432 (2000).

31. Massinon M, De Cock N, Forster WA, Nairn JJ, McCue SW, Zabkiewicz J, et al., Spray droplet impaction outcomes for different plant species and spray formulations. *Crop Prot* **99**:65-75 (2017).

32. Spilman JJ, Spray impaction, retention and adhesion: an introduction to basic characteristics. *Pestic Sci* **15**:97-106 (1984).

33. Nuyttens D, Dekeyser D, De Schampheleire M, Baetens K and Sonck B, The effect of air support on droplet characteristics and spray drift. *Commun Agric Appl Biol Sci* **72**:71-79 (2007).

34. van de Zande J, Michielsen J, Stallinga H, Porskamp H, Holterman H and Huijsmans J. Spray distribution when spraying potatoes with a conventional or an air-assisted field boom sprayer (ASAE 2002), Chicago, Illinois, USA, July 28-31, 2002.

35. van de Zande J, Porskamp H, Michielsen J, Holterman H and Huijsmans J, Classification of spray applications for driftability, to protect surface water. *Aspects of Applied Biology* **57**:57-64 (2000).

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

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

Table 3. Spray distribution characteristics of the broadcast application (XR 110 04) and the 4 most appropriate bed spray configurations at the most optimal 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 |

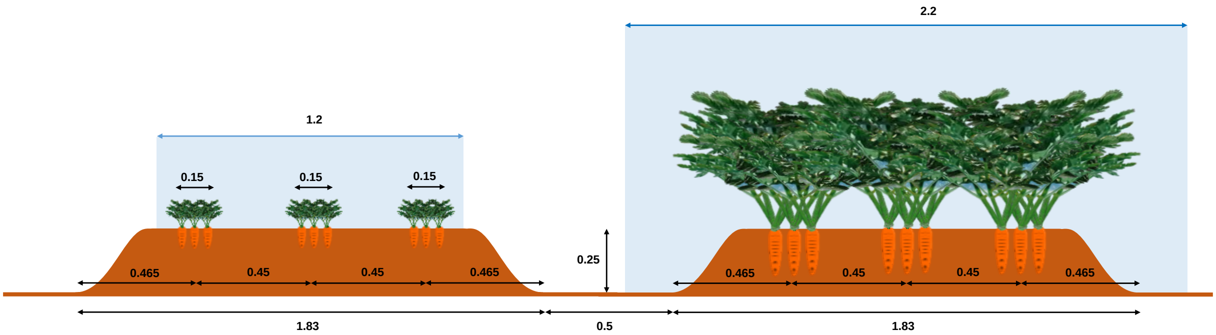


Figure 1. Schematic of the carrot bed design at early (left) and full growth stage (right), with indication of respectively the 1.2 m and the 2.2 m target zone in blue (dimensions given in m).

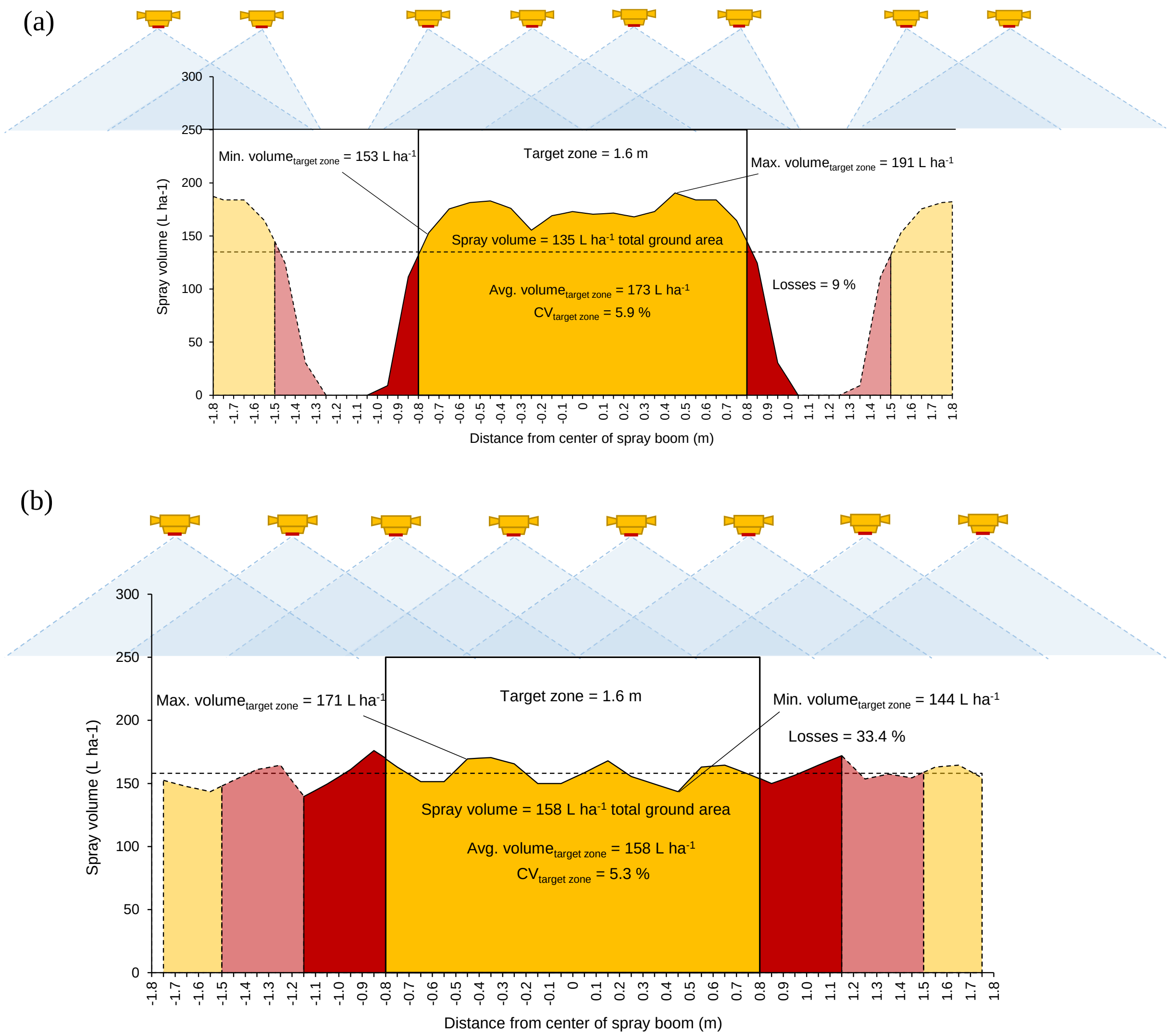


Figure 2. Spray distribution pattern of (a) AIUB8504/AI11004/AI11004/AIUB8504 and (b) a broadcast application with XR11004 nozzles, at nozzle spacing/height of 0.5 m (for the bed spray configuration, only above the carrot beds, not between the beds), with indication of spray volume within (yellow) and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

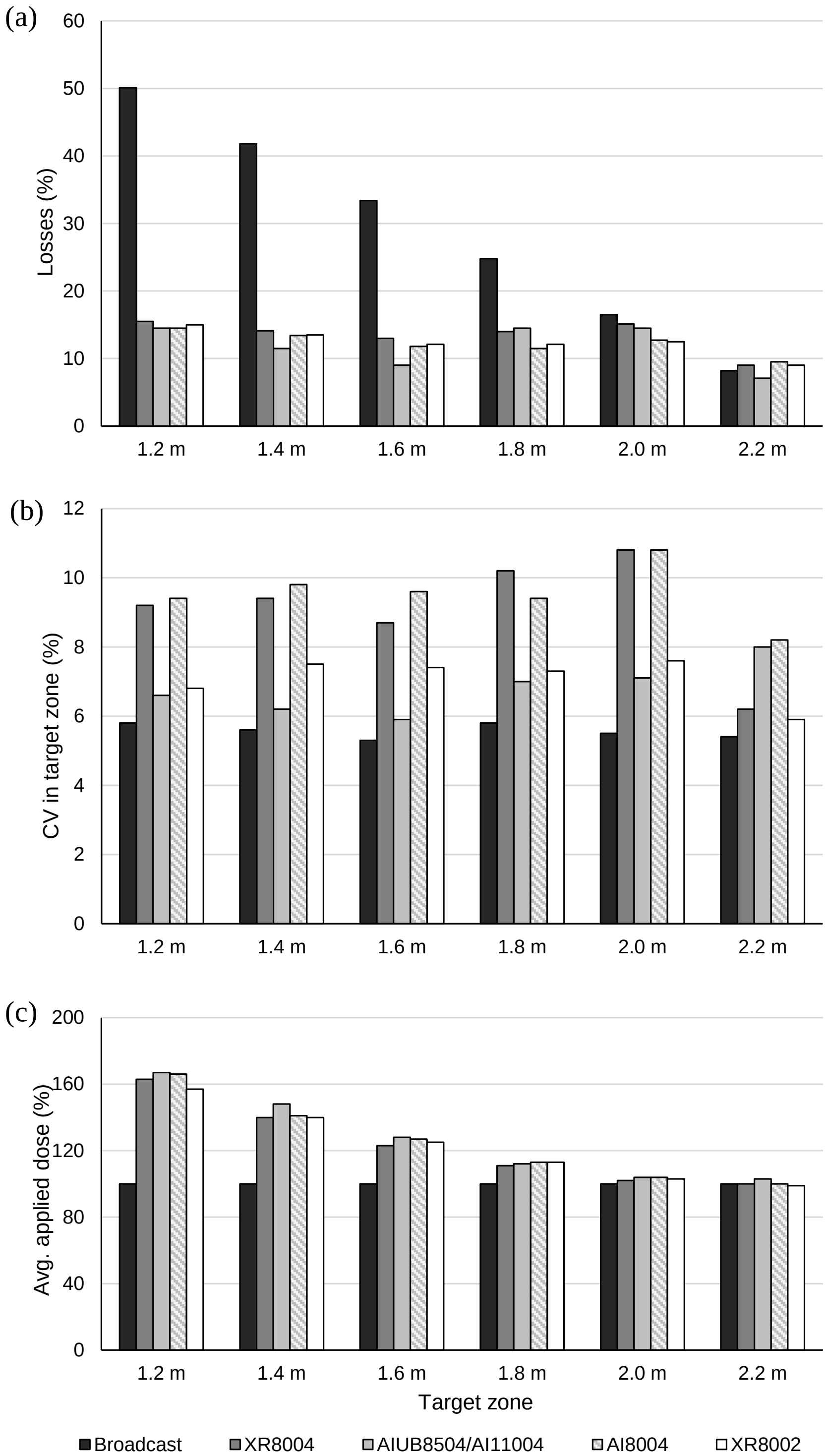


Figure 3. (a) Losses outside the target zone (%), (b) CV in the target zone (%), and (c) average applied dose in the target zone for the reference broadcast application ( ) and the 4 most appropriate nozzle configurations per target zone ( XR8004/XR8004/XR8004/XR8004, AIUB8504/AI11004/AI11004/AIUB8504,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

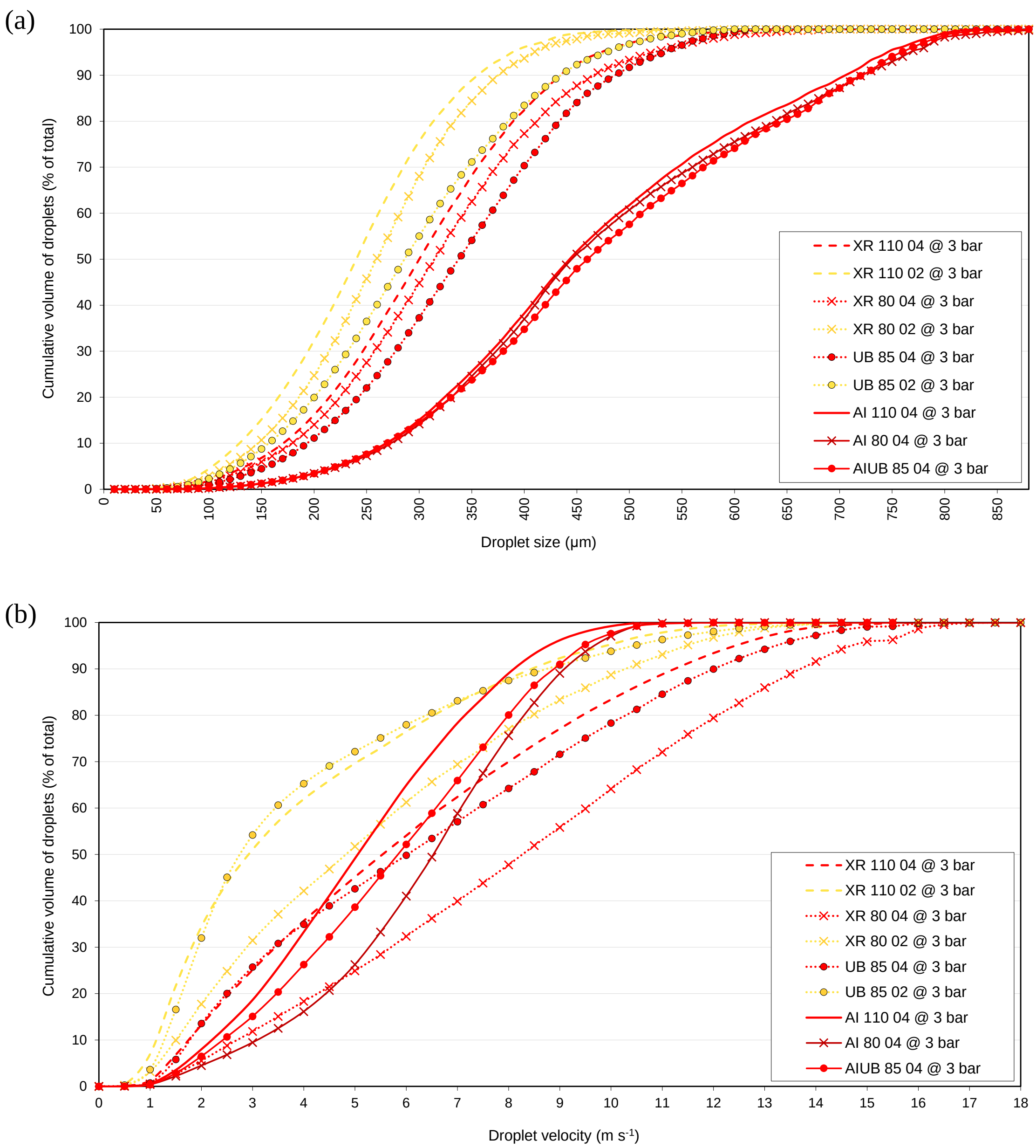


Figure 4. (a) Cumulative volumetric droplet size distribution and (b) cumulative volumetric droplet velocity distribution for different nozzles spraying at 300 kPa, 0.5 m spray height and without air support (measured with PDPA; TSI).

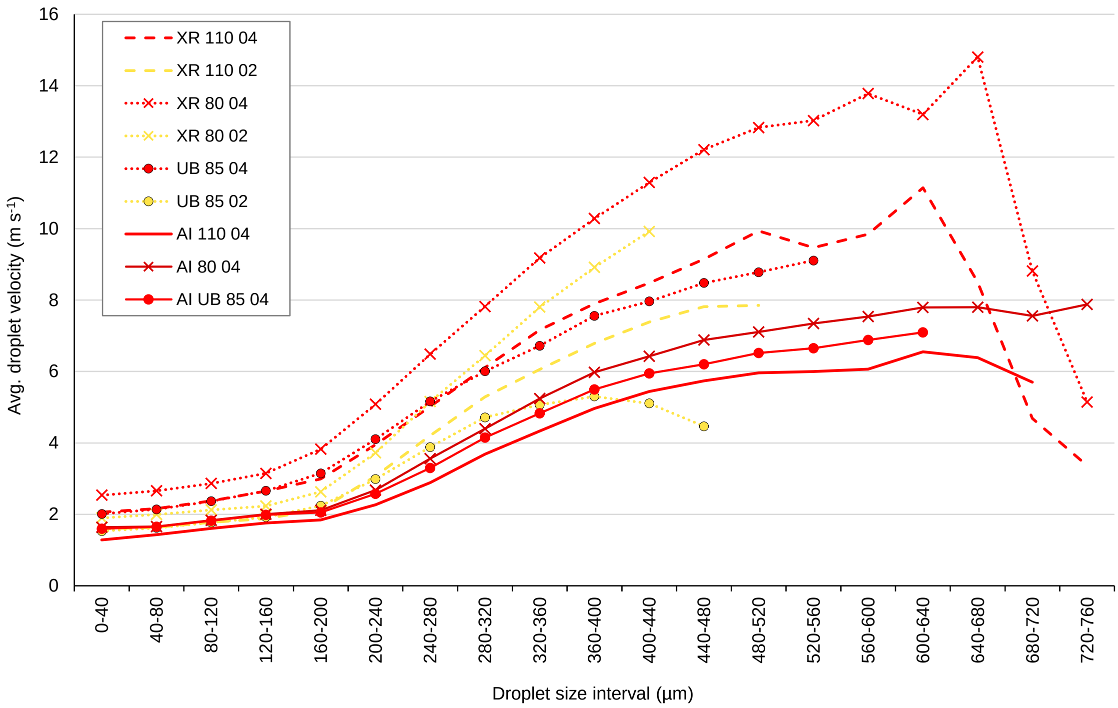


Figure 5. Averge droplet velocities ($m\ s^{-1}$) for the different droplet size classes (µm) of the different nozzles spraying at 300 kPa, 0.5 m spray height, without air support.

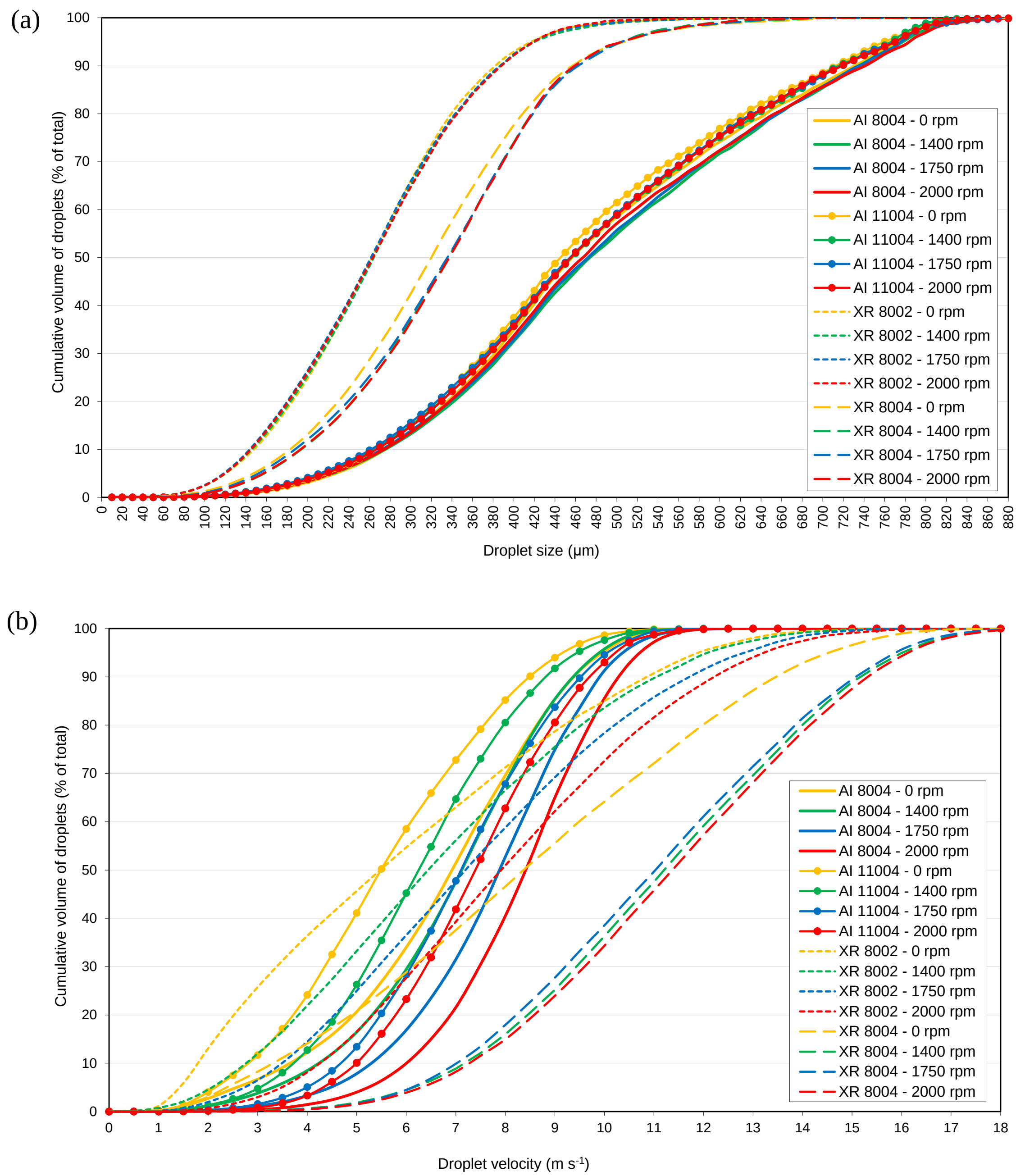


Figure 6. (a) Cumulative volumetric droplet size distribution and (b) cumulative volumetric droplet velocity distribution for AI 80 04, AI 110 04, XR 80 02, and XR 80 04 spraying at 300 kPa, 0.5 m spray height, without (0 rpm) and with air support (1400, 1750, 2000 rpm).

**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 ± 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 ± 5.6 | 300.0 ± 1.6 | 434.2 ± 0.8 | 1.8 ± 0.2 | 5.5 ± 0.2 | 3.2 ± 0.0 |
| XR 110 02 | 300 | Fine | 129.3 ± 4.3 | 240.1 ± 4.7 | 355.2 ± 5.1 | 4.4 ± 0.3 | 2.9 ± 0.1 | 2.1 ± 0.0 |
| AI 110 04 | 300 | Very Coarse | 268.8 ± 1.0 | 443.3 ± 3.7 | 706.1 ± 11.6 | 0.2 ± 0.0 | 5.1 ± 0.1 | 3.0 ± 0.1 |
| UB 85 04 | 300 | Medium | 193.8 ± 6.6 | 337.7 ±4.0 | 486.3 ± 1.9 | 1.1 ± 0.1 | 6.0 ± 0.3 | 3.5 ± 0.1 |
| UB 85 02 | 300 | Medium | 157.3 ± 6.0 | 286.4 ± 6.9 | 434.2 ± 9.4 | 2.3 ± 0.3 | 2.7 ± 0.1 | 2.3 ± 0.0 |
| AIUB 85 04 | 300 | Very Coarse | 269.3 ± 4.0 | 460.3 ± 2.1 | 718.6 ± 6.1 | 0.3 ± 0.0 | 5.8 ± 0.1 | 3.3 ± 0.0 |
| XR 80 04 | 300 | Medium | 178.9 ± 6.3 | 314.1 ± 3.5 | 466.0 ± 3.0 | 1.6 ± 0.2 | 8.3 ± 0.1 | 4.2 ± 0.1 |
| XR 80 02 | 300 | Medium | 146.9 ± 4.4 | 259.6 ± 4.7 | 374.5 ± 1.2 | 2.9 ± 0.2 | 4.8 ± 0.2 | 2.8 ± 0.0 |
| AI 80 04 | 300 | Very Coarse | 273.1 ± 8.0 | 445.4 ± 5.2 | 721.1 ± 4.9 | 0.2 ± 0.1 | 6.5 ± 0.1 | 3.5 ± 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 ± 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 |