agronomy

IMPACT FACTOR 3.7

CITESCORE 5.2

Article

Performance of Drift-Reducing Nozzles in Controlling Small Weed Seedlings with Contact Herbicides

Benny De Cauwer, Ilke De Meuter, Sander De Ryck, Donald Dekeyser, Ingrid Zwertvaegher and David Nuyttens

MDPI

https://doi.org/10.3390/agronomy13051342 agronomy

MDPI

Article

Performance of Drift-Reducing Nozzles in Controlling Small Weed Seedlings with Contact Herbicides

Benny De Cauwer [1,*], Ilke De Meuter [1], Sander De Ryck [1], Donald Dekeyser [2], Ingrid Zwertvaegher [2] and David Nuyttens [2]

[1] Weed Science Unit, Department of Plants and Crops, Faculty of Bioscience Engineering, Ghent University, 9000 Ghent, Belgium
[2] Technology & Food Science Unit, Flanders Research Institute for Agriculture, Fisheries and Food (ILVO), 9820 Merelbeke, Belgium
* Correspondence: benny.decauwer@ugent.be

Abstract: In many EU countries, spray applications should comply with increasingly stringent requirements regarding the drift reduction class of spray nozzles. Many farmers fear that the use of drift-reducing nozzles producing coarse droplet spectra may compromise the performance of contact herbicides on small weed targets. This study examined the effects of various ISO 03 drift-reducing flat-fan nozzles (pre-orifice and single and dual flat-fan air induction nozzles) differing in spray drift reduction class and spray pressure (2.5 bar, 5.0 bar) on (1) spray coverage, (2) droplet characteristics and (3) efficiency of contact herbicides bentazon and phenmedipham against cotyledon and 2-leaf stage plants of *Chenopodium album* and *Solanum nigrum*. Performance was compared to that of an ISO 03 standard flat-fan nozzle producing a finer droplet size spectrum. All sprayings were performed at a spray volume of 200 L ha^{-1}. In most dose–response experiments, several drift-reducing flat-fan nozzles performed equally well as standard flat-fan nozzles, regardless of herbicide, spray pressure, growth stage or weed species. However, droplet size spectra of air-induction nozzles were too coarse for an adequate spray coverage and efficient application of contact herbicides on cotyledon stage plants of *S. nigrum*. In addition, the performance of air-induction nozzles in controlling difficult-to-wet *C. album* weeds with phenmedipham was better at 5.0 bar than at 2.5 bar. In contrast with droplet size characteristics, spray coverage characteristics determined on water sensitive papers were not good proxies for estimating the biological efficiency of contact herbicides. Air induction nozzles at 5.0 bar allow efficient control of 2-leaf targets, but nozzles emitting finer droplet spectra, such as pre-orifice nozzles, should be preferred for controlling cotyledon stage weeds at low-herbicide doses.

Keywords: nozzle type; spray pressure; spray coverage; droplet characterisation; air induction nozzle; pre-orifice nozzle

Citation: De Cauwer, B.; De Meuter, I.; De Ryck, S.; Dekeyser, D.; Zwertvaegher, I.; Nuyttens, D. Performance of Drift-Reducing Nozzles in Controlling Small Weed Seedlings with Contact Herbicides. *Agronomy* **2023**, *13*, 1342. https://doi.org/10.3390/agronomy13051342

Academic Editor: Leslie A. Weston

Received: 30 March 2023
Revised: 5 May 2023
Accepted: 9 May 2023
Published: 10 May 2023

1. Introduction

In the EU, pesticide spray drift to non-target crops and areas, surface waters in particular, continues to be a major problem in applying agricultural pesticides [1]. Several indirect and direct drift mitigation measures have been introduced in many EU countries. Indirect measures such as fixed or variable buffer zones, no-spray zones and barriers aim to reduce exposure to spray drift, whereas direct measures such as drift-reducing spray application techniques including drift-reducing nozzle types, air support systems and shielded spray booms aim to reduce spray drift at the source [2,3]. This study focuses on drift-reducing nozzles typically producing a coarser droplet size spectrum. Nozzles play a decisive role in the process of liquid atomization, transfer and impact on the targets and deposition and drift characteristics of pesticide droplets [4,5]. As fine droplets below 150 µm have the greatest drift potential [6,7], nozzle types producing large droplets (air induction nozzles in particular) are increasingly used in many European and North American countries [8]. For air induction nozzles (also called air injector or air inclusion), air is drawn into the liquid channel through aspiration holes and mixed with the spray liquid [9]. Consequently, larger air-bubble-containing droplets are formed, which are scattered into smaller droplets when impacting on the target due to the splashing of the droplets [10]. Anti-drift flat-fan nozzles have a pre-orifice chamber aimed to increase the droplet size. More recently, some new compact anti-drift air induction nozzles and dual (twin) flat-fan air induction nozzles have come into use for herbicide spraying [11]. Herbicide efficacy is strongly linked to the extent of crop canopy penetration [12]. Air-induction dual flat-fan nozzles have forward- and backward-facing orifices that deposit droplets before and after the boom has passed over the target. These nozzles seek to increase spray coverage and improve crop canopy penetration. According to Gossen et al. [13], dual-fan nozzles lessen the plume angle to the target which can improve droplet deposition on target surfaces. In many spray coverage studies [14–16], dual-fan nozzles provided similar or improved deposition compared to single-fan nozzles with a similar droplet size classification and nominal flow rate.

In Belgium, pre-orifice nozzles and (twin flat-fan) air induction nozzles are increasingly used for herbicide applications triggered by recent and future legal obligations to realise a minimum of 50% (since 2017), 75% (since 2023) and 90% drift reduction (from 2026 onwards)—compared to an ISO 03 standard flat-fan application at 3.0 bar—in Flanders. For field crop treatments using horizontal boom sprayers, the drift reduction classification system is based on two variables: nozzle (type and size) and spray technique (conventional, air assisted, shielded, (shielded) row and bed spraying). The classification system includes drift reduction classes of 0%, 50%, 75% and 90% drift reduction, as also used in Germany.

A spray application is most effective when the optimal droplet size for the intended target is utilized. Wang et al. [11] recommend air induction nozzles for herbicide applications as they provide good biological efficacy while significantly reducing the amount of spray drift. Standard flat-fan nozzles and air induction flat-fan nozzles performed equally well in herbicide applications of acetochlor, atrazine and 2,4-D against a mixed weed flora in maize (*Zea mays* L.). However, the herbicides used in their study were tank-mixed, thus obscuring possible differential effects of nozzle types on the performance of individual herbicides. Moreover, the mixture was comprised of soil active herbicides (atrazine, acetochlor) and a systemic foliar active herbicide (2,4-D) for which uniform coverage and deposition are deemed less important for achieving good control efficacy than for contact herbicides [17]. Furthermore, maize is a major crop with a wide range of registered potent herbicides that are usually applied in herbicide mixture or sequences. In minor crops, the number of herbicides approved is very limited, and for some weed targets, control entirely relies on a single active substance. For example, phenmedipham and bentazon are crucial postemergence contact herbicides for controlling emerged poisonous solanaceous weeds, e.g., *Datura stramonium* L. (jimson weed), *Solanum nigrum* L. ssp. *nigrum* and *Chenopodium album* (fat hen) in processing spinach (*Spinacia oleracea* L.) and common bean (*Phaseolus vulgaris* L.) [18]. For satisfactory control, these weeds should be targeted no later than the 2-leaf stage. Growers and the industry fear unsatisfactory control of these small weed targets when contact herbicides are applied with coarse droplet nozzles. Indeed, control efficacy of contact herbicides largely depends on the amount and uniformity of spray coverage and deposition on the targeted weeds [17]. Usually, farmers have only one chance to control these weeds, as reapplication is not legally allowed or implementable because of too long minimum waiting periods required between herbicide application and harvest (for bentazon, the pre-harvest interval is 40 days in common bean, a crop with a short growing period of 2 months). Uncontrolled solanaceous weeds in these crops mean that the field cannot be harvested as it entrains a high risk of contamination of some end products with poisonous plant material.

This study seeks to examine pressure and nozzle type effects on spray coverage and droplet size characteristics and on the efficiency of contact herbicides on small weed targets of major weeds. There are two study objectives: (1) Do drift-reducing nozzles negatively affect the performance of contact herbicides on small weed targets, regardless of spray pressure? (2) Are spray coverage on horizontal water sensitive papers and spray droplet characteristics good predictors of the efficiency of contact herbicides?

2. Materials and Methods

2.1. Experiments

During the summer of 2020, dose–response pot experiments were conducted for two foliar-applied contact herbicides (bentazon, phenmedipham) at two different growth stages (BBCH10: cotyledon stage, BBCH12: 2-leaf stage) of two weed species (*C. album*, *S. nigrum*) to evaluate the performance of eight different nozzle type-spray pressure combinations. The nozzle-pressure combinations included 5 different ISO 03 flat-fan nozzles belonging to different drift reduction classes (standard nozzles used as reference and 4 drift-reducing nozzles comprising pre-orifice nozzles and single and dual air induction nozzles) and 2 spray pressures (2.5 and 5 bar) (Table 1). Contact herbicides tested were the photosystem II inhibitors bentazon (Basagran SG®, 87% bentazon L^{-1}, WP, BASF, Waterloo, Belgium) and phenmedipham (Astrix®, 160 g a.i. L^{-1}, EC, DuPont De Nemours, Wilmington, DE, USA). Bentazon and phenmedipham are key foliar contact herbicides for controlling *C. album* and *S. nigrum* in common bean and spinach fields in Belgium. The chosen weed growth stages correspond to the stages at which phenmedipham and bentazon are most commonly applied in these fields and are achieved by staggering sowing times to achieve simultaneous execution of herbicide applications.

Table 1. Flat-fan nozzles used in the study by full name and acronym, their spray angle, manufacturer and a description of the nozzle type. Nominal flow rate was 1.08 L min^{-1} at 2.5 bar and 1.52 L min^{-1} at 5.0 bar.

Nozzle Type	Manufacturer	Description of Nozzle Type	Drift Reduction Class (%) [2]	Spray Pressure (bar)	
				2.5	5.0
XR 110 03	TeeJet	Standard single 110° flat-fan	0	X	- [1]
DG 110 03	TeeJet	Pre-orifice single 110° flat-fan	50	X	- [1]
AI 110 03	TeeJet	Air induction single 110° flat-fan	50	X	X
AVI TWIN 110 03	Albuz	Symmetric air induction dual 110° flat-fan with 30° forward and backward angle	75	X	X
ID3 120 03	Lechler	Air induction single 120° flat-fan	90	X	X

[1] Not tested; [2] Drift reduction class according to Belgian legislation.

The experimental design was a randomised block with three replicates and one factor (nozzle-pressure combination). The experimental unit was 1 pot of 10 seedlings. Herbicides were applied with the 8 nozzle-pressure combinations at a constant spray volume of 200 L ha^{-1}. Each herbicide was tested in seven doses and compared with a control, as enumerated in Table 2. Dose ranges listed in Table 2 allowed successful fitting of dose–response curves in preliminary experiments. All herbicides were applied in an automated spray cabinet (Demtec, Moorslede, Belgium) with 1 single stationary nozzle mounted 50 cm above the pot surface and a conveyer belt speed of 4.80 (XR 110 03), 3.69 (DG 110 03), 3.90 (AI 110 03), 4.23 (AVI TWIN 110 03) and 4.91 (ID3 120 03) km h^{-1} at a spray pressure of 2.5 bar and 5.27 (AI 110 03), 5.41 (AVI TWIN 110 03) and 6.81(ID3 120 03) km h^{-1} at 5 bar. These belt speeds were required to obtain a spray volume of 200 L ha^{-1} in the central 10 cm zone beneath a nozzle (i.e., the position of the pot during spraying) as derived from spray distribution measurements with a distribution bench (ISO 5682-1) (Figure S1).

Table 2. Herbicides, their maximum authorised field dose and their doses examined in post-emergence dose–response bioassays.

Herbicide (Formulated Product)	Herbicide Mode of Action (HRAC/WSSA-Group/Legacy HRAC)	Max. Field Dose [2] (g a.i. ha^{-1})	Herbicide Doses (g a.i. ha^{-1})
Bentazon [1] (Basagran, 87%, SG, BASF, Waterloo, Belgium)	Photosystem II-inhibitor (6/C3)	960 (beans and peas)	0.0–18.6–41.0–90.2–198.3–436.4–960.0
Phenmedipham (Astrix, 160 g L^{-1}, EC, UPL Europe, Ltd., Warrington, UK)	Photoystem II-inhibitor (5/C1)	320 (spinach)	0–20–40–80–160–320–640

[1] 1 L ha^{-1} of triglyceride oil (Actirob B, 812 g a.i. L^{-1}, EC, Oleon NV), a methylated seed oil, was added to the herbicide spray solution to enhance foliar uptake and distribution; [2] Max. field dose authorised in this crop in Belgium.

All dose–response experiments were conducted using plastic pots filled with steamed sandy loam soil containing 2.6% organic matter, 10.0% clay, 46.7% silt and 43.4% sand with a pH_{KCl} of 5.5. Pots were kept under plastic rain shelters with open sides up to 1 m height for natural ventilation and were irrigated by overhead sprinklers as needed. Daytime and night-time mean temperature and humidity values and the mean light intensity during the experimental periods are given in Table 3. Experiments were conducted with seeds of local populations of *S. nigrum* and *C. album* collected from at least 100 plants scattered over an organic field. All pots were seeded with 25 seeds per pot at 2 mm depth. As soon as seedlings reached the cotyledon stage (BBCH10), they were thinned to 10 uniform plants per pot.

Table 3. Mean daytime and night-time temperatures, relative humidity and daytime light intensity during the dose–response experiment.

Experimental Period		Mean DayTime/Night-Time Temperature (°C) [3]	Mean Day/Night Relative Humidity (%)	Mean Daytime Light Intensity (lux)
Pre-application	10/07/20 [1]–19/07/20	24.3/13.8	56.2/84.6	7745.7
Day of application	19/07/20 11 h–12 h 30 (phenmedipham)	20.9/-	61.7/-	22,161.8
	19/07/20 13 h–15 h 20 (bentazon)	22.3/-	51.3/-	20,485.9
Post-application	19/07/20–01/08/20 [2] (phenmedipham)	29.8/16.7	50.9/85.8	7711.6
	19/07/20–31/07/20 [2] (bentazon)	30.4/17.0	50.1/85.6	7652.6

[1] Three days after the last sowing time (phenological stage BBCH10); [2] Cutting time; [3] Sunrise/sunset: 05:38/21:57 (10/07/20), 05:48/21:48 (19/07/20), 06:05/22:02 (31/07/20) and 06:06/22:01 (01/08/20).

2.2. Droplet Size and Velocity Characteristics

The droplet size characteristics of the eight nozzle type-pressure combinations (Table 1) were obtained at ILVO using a phase Doppler particle analyser (PDPA) laser-based measuring setup, as described by Nuyttens et al. [19,20]. The PDPA laser used was a PowerSight PDPA one-dimensional system (TSI, Minneapolis, MN, USA). Measurements were performed at a distance of 50 cm below the nozzle with pure water. Pure tap water was used to avoid any interference between formulation type and spray setting (nozzle type and spray pressure) [19]. Adjuvants in the herbicide formulation or added to the spray tank are indeed commonly used to improve liquid atomization and droplet impact characteristics by changing physical properties such as surface tension, density and viscosity of the liquid. However, unpublished work indicates that nozzle selection has a much larger effect on spray droplet and coverage characteristics than the addition of a tank-mix adjuvant and/or herbicide to the tap water. Moreover, it would not be feasible to perform these measurements for all spray solutions and herbicide concentrations tested in our dose–response experiments.

All measurements were carried out along the horizontal axis of the spray fan in the central 7 cm zone of the fan, as this is the zone that contributed to spray deposition on our pot plants passing right beneath the spray nozzle. For each nozzle-pressure combination, 3 measurements were performed as repetitions. The volumetric droplet size and distribution parameters selected for data interpretation were $D_{v0.1}$, $D_{v0.5}$, $D_{v0.9}$ and V_{150}. $D_{v0.1}$ and $D_{v0.9}$ are the diameters at which 10% and 90% of the droplet volume are contained in droplets at or below that diameter, respectively. $D_{v0.5}$, also called the volume median diameter (VMD), is the diameter at which 50% of the volume is contained in droplets of either larger or smaller diameters. The V_{150} is the percent of the spray volume contained in droplets with a diameter below 150 µm (so called driftable fines). The following droplet number-based characteristics were also determined: $D_{n0.1}$, $D_{n0.5}$ and $D_{n0.9}$ being the droplet diameters at which 10, 50 and 90% of the number of droplets have a diameter at or below these diameters, and N_{150} being the percentage (%) of droplets smaller than 150 µm. Finally, the average droplet velocity was also measured (m s^{-1}).

2.3. Spray Coverage Characteristics

To examine the relation between spray coverage characteristics and herbicide performance, spray coverage (%), impact number density (number of droplet impacts per cm^2) and mean droplet impact size (mm^2) were determined for each nozzle-pressure combination. Per nozzle-pressure combination, 5 water sensitive papers (WSP, 27.6 mm × 76.0 mm, *Syngenta* Crop Protection AG, Basel, Switzerland) were sprayed with pure tap water without herbicide addition at a fixed spray volume of 200 L ha^{-1}. Each WSP was positioned horizontally on top of a metal plate laid down on the pot surface. During spraying, the cards passed right under the position of the non-moving nozzle tip. Pots and cards were arranged 50 cm apart on the moving conveyor belt. After spraying, WSPs were allowed to dry and were then collected and digitized at 600 dpi. An image analysis system using Halcon software (MVTec Software GmbH, München, Germany) was used to calculate spray coverage characteristics.

2.4. Plant Response to Herbicide Application

In all experiments, foliage fresh biomass was determined per pot by clipping all living plants in a pot at the soil surface, pooling their biomass and weighing the pooled biomass, 28 days after treatment (DAT). Foliage dry biomass per pot was determined after drying for 16 h at 75 °C.

2.5. Data Analysis

All data (foliage dry biomass, spray coverage characteristics) were analysed in R version 4.0.3. [21]. The normality and homoscedasticity were checked with a Q–Q plot and a Levene test, respectively. No data transformation was required.

Foliage dry biomass data obtained from dose–response bioassays were analysed with the drc package [22]. Dose–response curves were calculated according to Streibig et al. [23] for each factorial combination of herbicide, weed species and growth stage separately. Within each factorial combination, dose–response curves for all nozzle type-pressure combinations (8 in total) were fitted simultaneously for each tested herbicide. Effective dosage ED_{90} (dose required for 90% biomass reduction) and selectivity indices (SI) as relative potencies between two dose–response curves were derived from the regression model utilising the delta method [24]. SI (90, 90), that is the ratio between ED_{90} for one dose–response curve, and ED_{90} for another dose–response curve were used to compare the relative differences of ED_{90} doses among curves and, hence, evaluate the performance of different nozzle-pressure combinations. Compared to an application with low ED_{90} response, an application with high ED_{90} response requires a higher dose to obtain the same efficacy level of 90% biomass reduction.

One-way ANOVAs were performed to assess the impact of nozzle-pressure combination on spray coverage characteristics. Differences between group means were analysed using the Tukey test at $p < 0.05$ (confidence level of 95%).

Regression analysis (line of best fit) was used to examine the relation between ED_{90} plant responses and droplet characteristics ($D_{n0.9}$, VMD, V_{150}) or coverage characteristics (spray coverage, impact number density, droplet impact size) for each combination of herbicide, weed species and growth stage. In preliminary studies, $D_{n0.9}$, VMD and V_{150} were the droplet characteristics that showed strongest association with herbicide performance. To find a model that predicts the ED_{90} well, several simple regressions (linear, power, quadratic, exponential and logistic) were performed. The best goodness of fit was obtained with quadratic regression, except for the V150 data of the bentazon–*S. nigrum*-BBCH12 combination and the phenmedipham–*C. album*-BBCH10 combination for which the best predictions were obtained with a power regression.

3. Results

3.1. Droplet Characteristics and Spray Coverage

Volume-based and number-based droplet characteristics for all nozzle type-pressure combinations are summarized in Table S1. At 2.5 bar, the finest droplet size spectrum was obtained with the XR standard flat-fan nozzle followed by the DG pre-orifice flat-fan nozzle and the air induction flat-fan nozzles AI and AVI TWIN (VMD = 264 µm, 335 µm, 496 µm, 505 µm, respectively). The air induction flat-fan nozzle ID3 produced the coarsest droplet size spectrum (VMD = 533 µm). Increasing the spray pressure up to 5 bar resulted in a finer droplet size spectrum generated by the air induction nozzles with reductions in VMD from 10% (ID3) to 16% (AI) (Table S1). Overall, the XR standard nozzle produced the finest droplets as indicated by the lowest $D_{v0.1}$, VMD and $D_{v0.9}$ and the largest portion of driftable fines droplets (V_{150}) compared to the drift-reducing nozzles (Table S1, Figure 1).

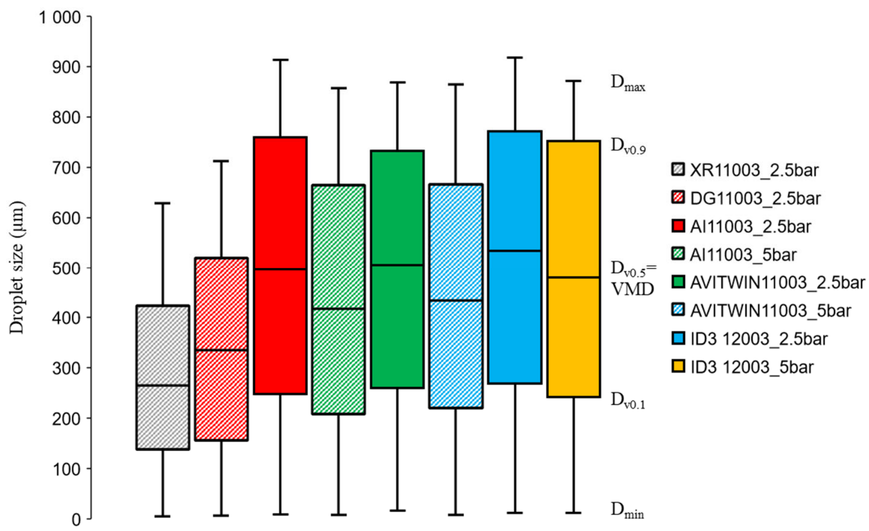

Figure 1. Droplet size spectrum characterised by minimum and maximum droplet size (D_{min} and D_{max}, respectively) and droplet diameters at which 10%, 50% or 90% of the spray volume is contained in droplets of smaller diameter ($D_{v0.1}$, $D_{v0.5}$ and $D_{v0.9}$, respectively). $D_{v0.5}$ is also known as volume median diameter (VMD).

Irrespective of spray pressure, the drift-reducing flat-fan nozzles resulted in significantly lower coverage (−22 to −40%) compared to the XR standard flat-fan nozzle at 2.5 bar (Figure 2). Air induction nozzles at 2.5 bar resulted in the lowest coverage. Doubling the spray pressure increased the coverage of the air induction nozzles (AI, AVI TWIN, ID3) by about 20%. The DG pre-orifice nozzle at 2.5 bar provided similar coverage as the air induction nozzles at 5 bar.

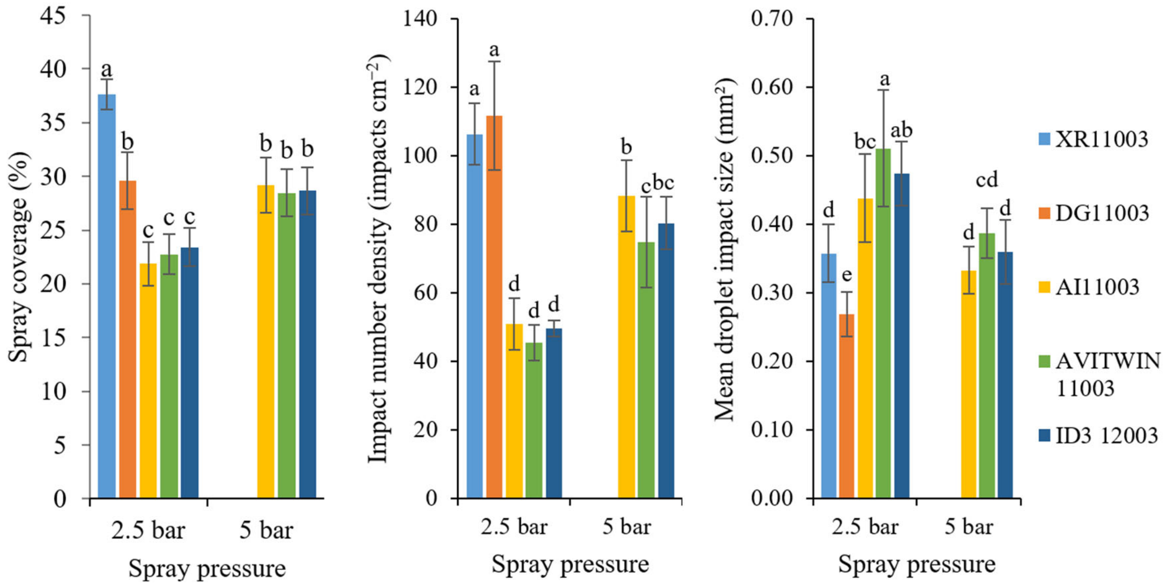

Figure 2. Spray coverage, impact number density and mean droplet impact size (mean ± SD) for the 8 tested nozzle type-pressure combinations all at 200 L ha^{-1}. Means without a common letter are significantly different ($p < 0.05$) according to the Tukey test.

The air induction flat-fan nozzles AI, AVI TWIN and ID3 resulted in 60 (at 2.5 bar) to 20% (at 5 bar) lower impact number densities relative to the XR standard flat-fan nozzle and DG pre-orifice flat-fan nozzle which showed similar impact number density (Figure 2). Air induction nozzles at a pressure of 2.5 bar significantly produced the lowest impact number density. Doubling the spray pressure increased the impact number density of the air induction nozzles by about 40%, up to about 80 droplet impacts cm^{-2} at higher forward speed advance to maintain the spray volume of 200 L ha^{-1}.

At 2.5 bar, all air induction nozzles produced up to 38% and 88% larger mean droplet impact sizes compared to the XR standard nozzle and DG pre-orifice nozzle, respectively (Figure 2). Increasing the spray pressure up to 5 bar significantly decreased the droplet impact size of the air induction nozzles by about 26%.

Overall, at 2.5 bar, the air induction nozzles resulted in the lowest spray coverage and impact number density despite producing the largest mean droplet impact size. Compared to the air induction nozzles at 5 bar, the DG pre-orifice nozzle gave similar spray coverage but with a significantly higher impact number density and significantly smaller mean droplet impact size.

3.2. Herbicide Performance with Different Nozzle-Pressure Combinations

Figures 3 and 4 provide ED_{90} responses to phenmedipham and bentazon for each nozzle-pressure combination within each species-growth stage combination. Overall, none of the drift-reducing nozzles performed significantly better than the XR standard flat-fan nozzle at 2.5 bar. However, in 6 out of 8 tested herbicide-species growth-stage combinations, several drift-reducing nozzle-pressure combinations performed equally well as the XR standard flat-fan nozzle at 2.5 bar. In some cases, ED_{90} responses exceeded the maximum field dose of phenmedipham (i.e., 320 g a.i. g ha^{-1}) and bentazon (960 g a.i. ha^{-1}) authorised in Belgium. For phenmedipham, this is true for BBCH12 stage plants of *S. nigrum* (Figure 3D) regardless of nozzle-pressure combination and for BBCH12 stage plants of *C. album* (Figure 3B) treated with air induction nozzles at 2.5 bar. For bentazon, this was the case for BBCH12 stage plants of *S. nigrum* (Figure 4D) treated with ID3 nozzles, regardless of spray pressure.

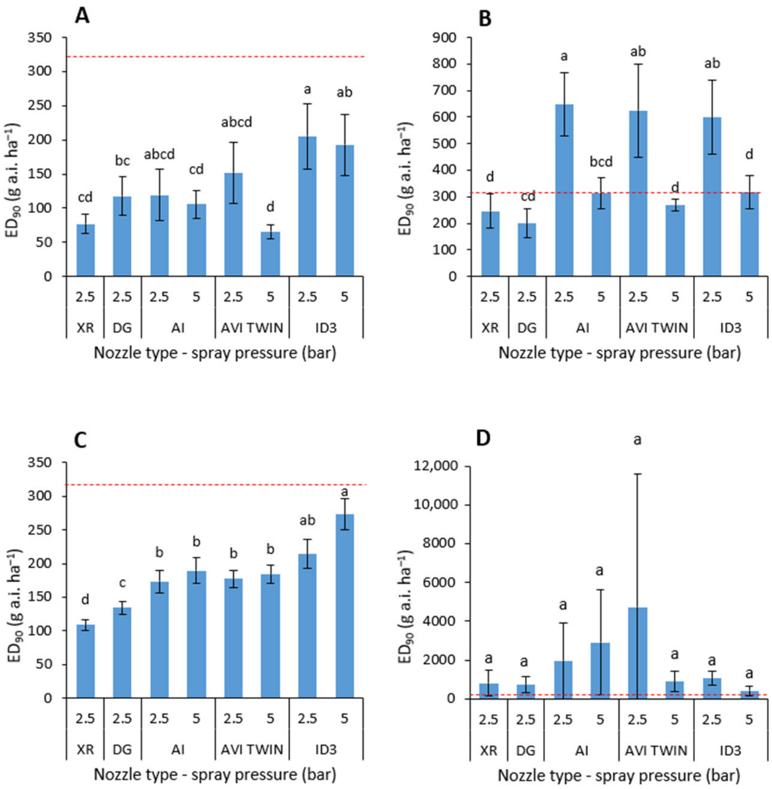

Figure 3. ED_{90} responses (with standard errors) of cotyledon and 2-leaf stage plants of *C. album* and *S. nigrum* to phenmedipham applied with various nozzle-pressure combinations: (**A**) *C. album* at BBCH10, (**B**) *C. album* at BBCH12, (**C**) *S. nigrum* at BBCH10 and (**D**) *S. nigrum* at BBCH12. Nozzle types used are standard flat-fan (XR), pre-orifice flat-fan (DG), air induction flat-fan (AI, ID3) and air induction dual flat-fan (AVI TWIN). No significant differences ($p < 0.05$) between bars with the same letter (based on computed selectivity indices and corresponding *p*-values). The red dotted line represents maximum authorised field dose.

The ED_{90} response levels of *C. album* and *S. nigrum* treated with phenmedipham at BBCH10 were significantly higher for the coarsest ID3 nozzle than for the XR and DG nozzles, except for the ED_{90} of *C. album* for the ID3 nozzle at 5.0 bar compared to the DG nozzle (Figure 3A,C). For *C. album* at BBCH10 sprayed at 2.5 bar, the ED_{90} levels obtained by the ID3 nozzle were 166% and 73% higher than the ED_{90} levels for the XR and DG nozzles, respectively (Figure 3A). The ED_{90} for the ID3 nozzle at 5.0 bar was 151% higher than that for the XR nozzle. For *S. nigrum* sprayed at 2.5 bar, the ED_{90} for the ID3 nozzle was 97% and 60% higher than the ED_{90} for the XR and DG nozzles, respectively (Figure 3C). The ED_{90} for the ID3 nozzle at 5.0 bar was 150% and 104% higher than that for the XR and DG nozzle, respectively. Compared to the XR nozzle, phenmedipham applications with drift-reducing nozzles (DG, AI, AVI TWIN, ID3) showed significantly higher (23 to 151%) ED_{90} values of BBCH10 stage plants of *S. nigrum*, regardless of their spray pressure (Figure 3C). Among drift-reducing nozzles, all air induction nozzles (AI, AVI TWIN, ID3) showed significantly higher (from 29 to 104%) ED_{90} values than the DG pre-orifice nozzle at 2.5 bar, regardless of their spray pressure (Figure 3C).

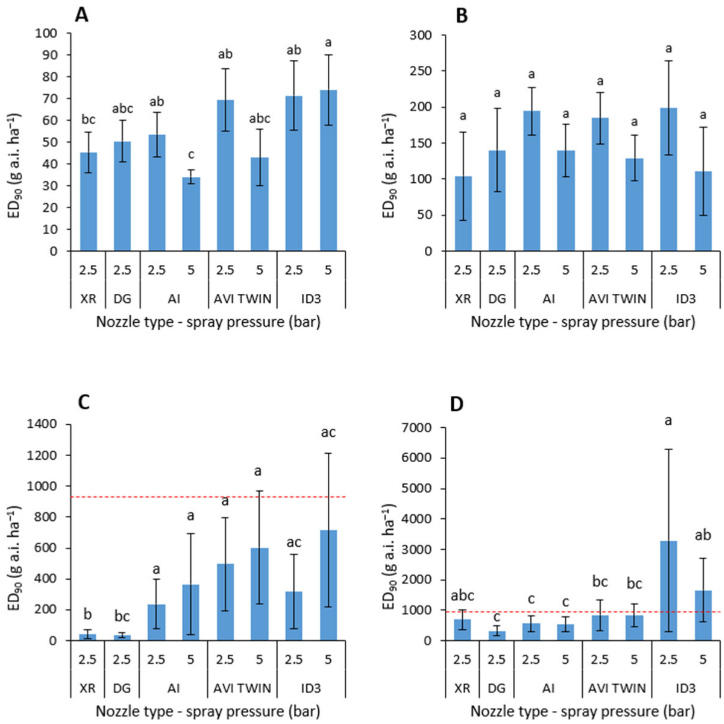

Figure 4. ED_{90} responses (with standard errors) of cotyledon and 2-leaf stage plants of *C. album* and *S. nigrum* to bentazon applied with various nozzle type-pressure combinations: (**A**) *C. album* at BBCH10, (**B**) *C. album* at BBCH12, (**C**) *S. nigrum* at BBCH10 and (**D**) *S. nigrum* at BBCH12. Nozzle types used are standard flat-fan (XR), pre-orifice flat-fan (DG), air induction flat-fan (AI, ID3) and air induction dual flat-fan (AVI TWIN). No significant differences ($p < 0.05$) between bars with the same letter (based on computed selectivity indices and corresponding *p*-values). The red dotted line represents maximum authorised field dose.

For BBCH10 plants treated with bentazon, fewer significant differences were found (Figure 4A,C). The ED_{90} response of *C. album* was 63% higher for ID3 nozzles at 5.0 bar than for XR nozzles at 2.5 bar (Figure 4A). For *S. nigrum*, ID3 nozzles at 2.5 bar and 5.0 bar resulted in 595% and 1472% higher ED_{90} responses relative to the XR nozzle at 2.5 bar (Figure 4C). There were no significant differences in ED_{90} between the ID3 and DG nozzles.

Contrary to BBCH10 stage plants, BBCH12 stage plants of *C. album* treated with phenmedipham showed no significant differences in ED_{90} values between the air induction nozzles (AI, AVI TWIN, ID3) at 5.0 bar and the DG pre-orifice nozzle and the XR standard nozzle (Figure 3B). However, at 2.5 bar, the ED_{90} values for the air induction nozzles (AI, AVI TWIN, ID3) were significantly higher than those of the XR nozzle (+144 to 164%) and the DG nozzle (+199 to 223%). Increasing the spray pressure to 5.0 bar significantly reduced the ED_{90} values of the air induction nozzles (AI, AVI TWIN and ID3) by 51, 57 and 47%, respectively. For BBCH12 plants of *C. album* treated with bentazon (Figure 4B), no significant differences in ED_{90} response levels were found among nozzle type-pressure combinations despite the systematically higher ED_{90} values obtained with the air induction nozzles at 2.5 bar. For BBCH12 plants of *S. nigrum*, no significant differences in ED_{90} values were found among XR, DG, AI and AVI TWIN nozzles, regardless of spray pressure and herbicide (Figures 3D and 4D).

3.3. Relation between Herbicide Performance and Coverage/Droplet Characteristics

Quadratic relations between the ED_{90} values and spray coverage and between the ED_{90} values and impact number density are provided for each species-stage combination in Figure 5 (phenmedipham) and Figure 6 (bentazon). Model parameters are provided in Table S2. Relations between the ED_{90} responses and the mean droplet impact size are not shown as the determination coefficients were rather low, namely 0.22, 0.81, 0.14 and 0.45 for phenmedipham and 0.37, 0.65, 0.21 and 0.23 for bentazon, for *C. album* BBCH10 and BBCH12 and *S. nigrum* BBCH10 and BBCH12, respectively. Overall, ED_{90} responses decreased with increasing spray coverage and impact number density. Unfortunately, due to poor determination coefficients, no critical threshold for a bio-efficient herbicide application could be defined based on spray coverage characteristics, irrespective of combination of herbicide, species and growth stage, except for 2-leaf stage plants of *C. album* treated with phenmedipham for which spray coverage and impact number density should be minimally 28.8% (Figure 5A) and 81.2 (Figure 5D) (average of all air induction nozzles at 5 bar). Nozzle-pressure combinations equalling or exceeding these thresholds performed equally well as a XR standard flat-fan nozzles at 2.5 bar, indeed.

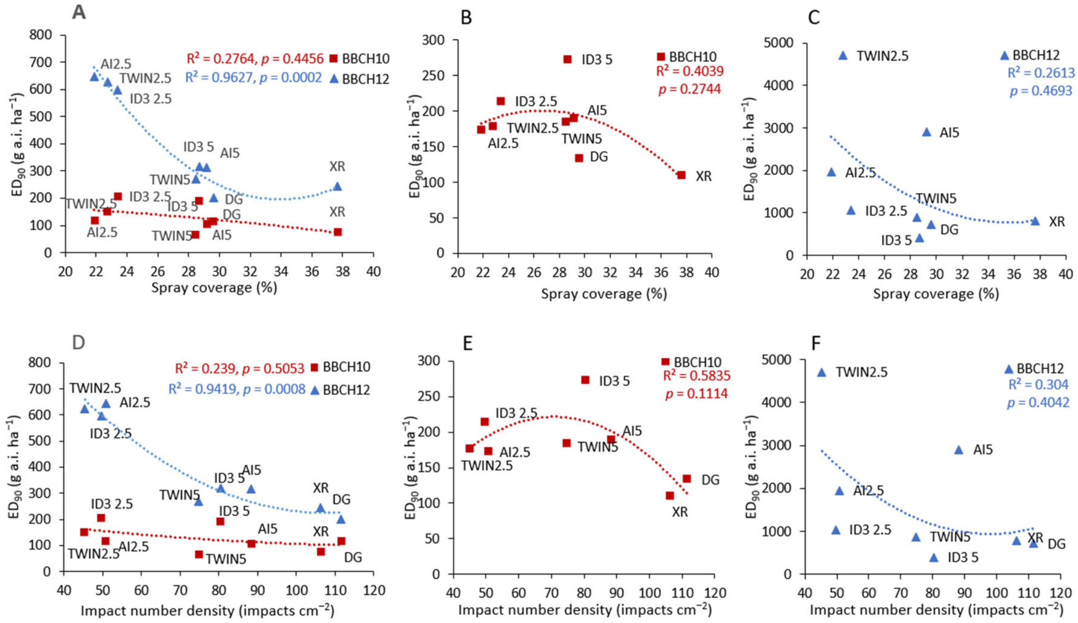

Figure 5. Quadratic regressions (with R^2-values) between spray coverage (**A**–**C**) or impact number density (**D**–**F**) and the ED_{90}-responses of 2 growth stages (BBCH10, BBCH12) of *C. album* (**A**,**D**) and *S. nigrum* (**B**,**C**,**E**,**F**) treated with phenmedipham using various nozzle type-spray pressure combinations. Nozzle types used are standard flat-fan at 2.5 bar (XR), pre-orifice flat-fan at 2.5 bar (DG), air induction flat-fan at 2.5 and 5 bar (AI2.5, AI5, ID3 2.5, ID3 5) and air induction dual flat-fan at 2.5 and 5 bar (TWIN2.5, TWIN5). Model parameters are provided in Table S2.

Volume median diameter (Figure 7, Table S3) and $D_{n0.9}$ (Figure 8, Table S3) were strongly associated ($R^2 > 0.5$) with ED_{90}, irrespective of considered combination of herbicide, species and growth stage, except for 2-leaf stage plants of *S. nigrum* treated with phenmedipham ($R^2 < 0.2$). Additionally, V_{150} (Figure 9, Table S3) showed a good association with ED_{90} (mean R^2 of 0.5) across all tested combinations, except for 2-leaf stage plants of *S. nigrum* treated with phenmedipham (Figure 9D). For example, the ED_{90} of cotyledon stage plants of *S. nigrum* treated with phenmedipham generally increased with increasing VMD (Figure 7C) and $D_{n0.9}$ (Figure 8C) and with decreasing V_{150} (Figure 9C). The critical thresholds in droplet characteristics required for a bio-efficient application are around a maximum of 264.3 µm for VMD, a maximum of 227.1 µm for $D_{n0.9}$ and a minimum of 13.4% for V_{150}. The droplet spectrum produced by a XR standard flat-fan nozzle at 2.5 bar largely complies to these thresholds. The ED_{90} of 2-leaf stage plants of *C. album* treated with phenmedipham generally increased with increasing VMD (Figure 7B) and $D_{n0.9}$ (Figure 8B) and decreasing V_{150} (Figure 9B). Air induction nozzles closely clustered together according to spray pressure. The critical thresholds in droplet characteristics required for a bio-efficient application are around a maximum of 443.2 µm for VMD, a maximum of 355.2 µm for $D_{n0.9}$ and a minimum of 3.4% for V_{150}. These thresholds correspond to the average values for air induction nozzles at 5 bar showing no significant difference in ED_{90} with the XR standard nozzle at 2.5 bar (Figure 3B).

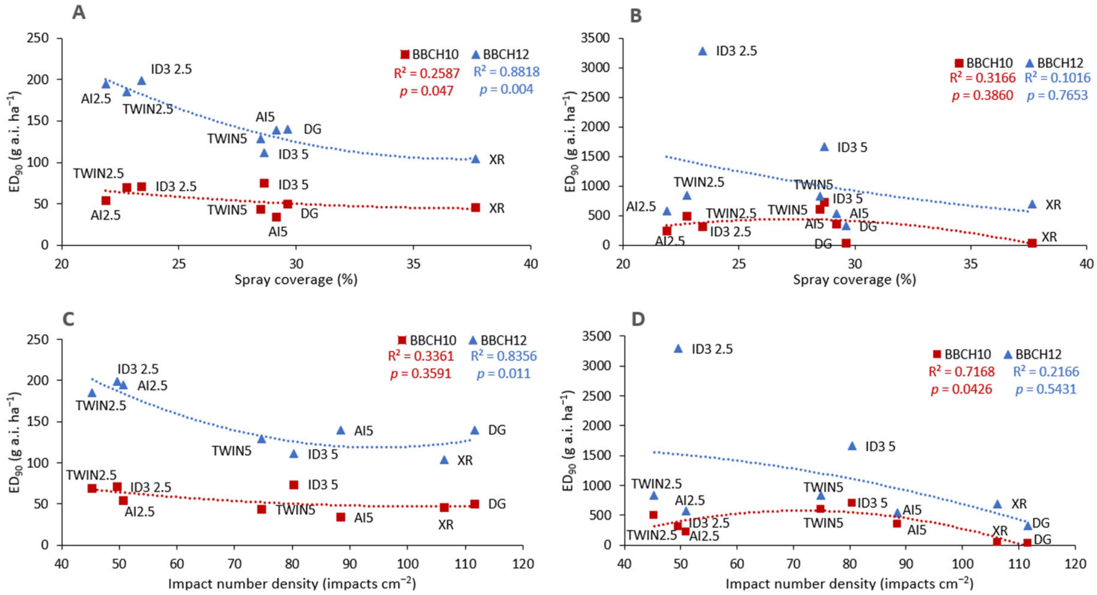

Figure 6. Quadratic regressions (with R^2-values) between spray coverage (**A**,**B**) or impact number density (**C**,**D**) and the ED_{90}-responses of 2 growth stages (BBCH10, BBCH12) of *C. album* (**A**,**C**) and *S. nigrum* (**B**,**D**) treated with bentazon using various nozzle type-spray pressure combinations. Nozzle types used are standard flat-fan at 2.5 bar (XR), pre-orifice flat-fan at 2.5 bar (DG), air induction flat-fan at 2.5 and 5 bar (AI2.5, AI5, ID3 2.5, ID3 5) and air induction dual flat-fan at 2.5 and 5 bar (TWIN2.5, TWIN5). Model parameters are provided in Table S2.

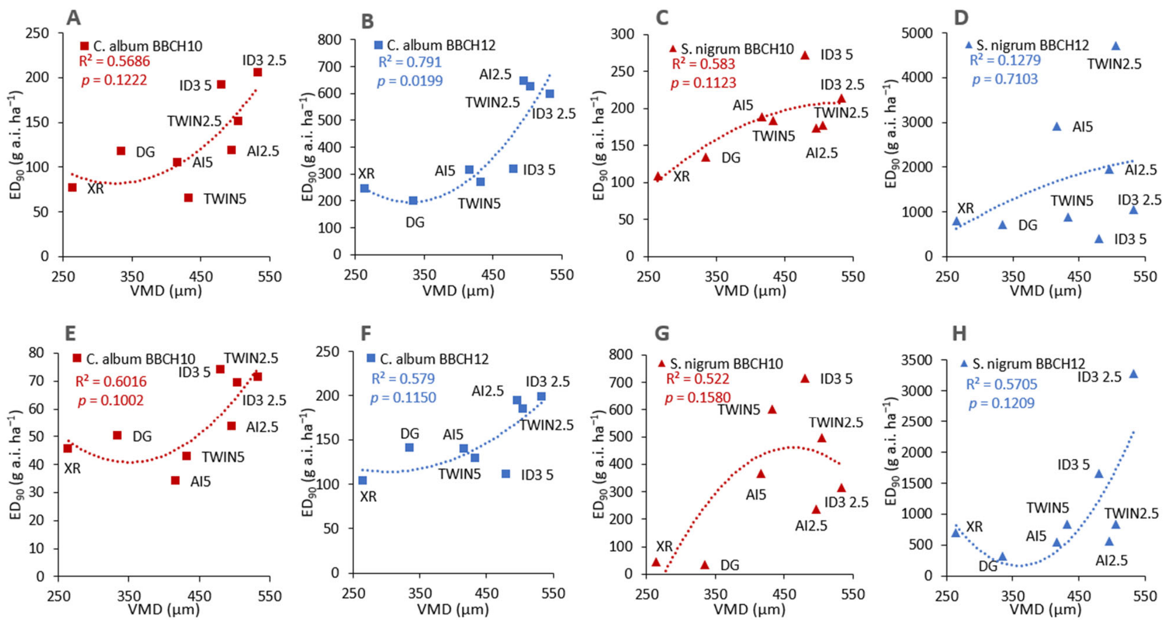

Figure 7. Quadratic regressions (with R^2-values) between the volume median diameter (VMD) and the ED_{90}-responses of 2 growth stages (BBCH10, BBCH12) of *C. album* (**A**,**B**,**E**,**F**) and *S. nigrum* (**C**,**D**,**G**,**H**) treated with phenmedipham (**A**–**D**) and bentazon (**E**–**H**) using various nozzle type-spray pressure combinations. Nozzle types used are standard flat-fan at 2.5 bar (XR), pre-orifice flat-fan at 2.5 bar (DG), air induction flat-fan at 2.5 and 5 bar (AI2.5, AI5, ID3 2.5, ID3 5) and air induction dual flat-fan at 2.5 and 5 bar (TWIN2.5, TWIN5). Model parameters are provided in Table S3.

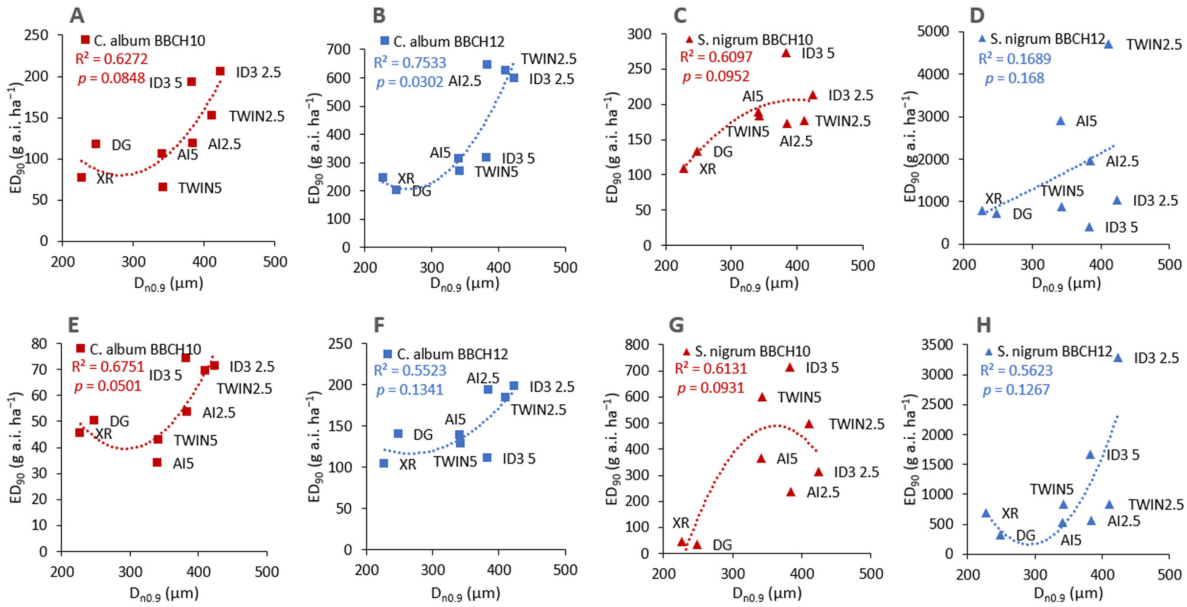

Figure 8. Quadratic regressions (with R^2-values) between the droplet diameter at which 90 percent of the droplets are smaller than that diameter (Dn0.9) and the ED_{90}-responses of 2 growth stages (BBCH10, BBCH12) of *C. album* (**A**,**B**,**E**,**F**) and *S. nigrum* (**C**,**D**,**G**,**H**) treated with phenmedipham (**A**–**D**) and bentazon (**E**–**H**) using various nozzle type-spray pressure combinations. Nozzle types used are standard flat-fan at 2.5 bar (XR), pre-orifice flat-fan at 2.5 bar (DG), air induction flat-fan at 2.5 and 5 bar (AI2.5, AI5, ID3 2.5, ID3 5) and air induction dual flat-fan at 2.5 and 5 bar (TWIN2.5, TWIN5). Model parameters are provided in Table S3.

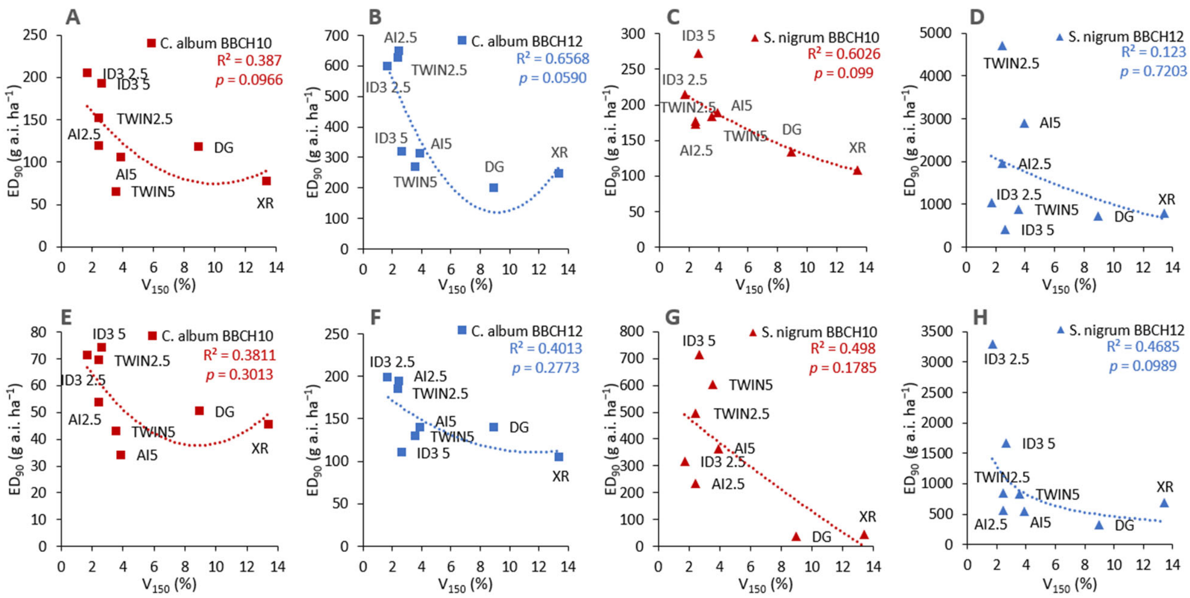

Figure 9. Quadratic regressions (with R^2-values) between the percentage of spray volume contained in droplets smaller than 150 µm (V150) and the ED_{90}-responses of 2 growth stages (BBCH10, BBCH12) of *C. album* (**A**,**B**,**E**,**F**) and *S. nigrum* (**C**,**D**,**G**,**H**) treated with phenmedipham (**A**–**D**) and bentazon (**E**–**H**) using various nozzle type-spray pressure combinations. Nozzle types used are standard flat-fan at 2.5 bar (XR), pre-orifice flat-fan at 2.5 bar (DG), air induction flat-fan at 2.5 and 5 bar (AI2.5, AI5, ID3 2.5, ID3 5) and air induction dual flat-fan at 2.5 and 5 bar (TWIN2.5, TWIN5). Model parameters are provided in Table S3.

4. Discussion

The impact of nozzle type and spray pressure on herbicide performance depended on the type of contact herbicide. In contrast with phenmedipham applications, the efficiency of the bentazon applications was hardly affected by nozzle type and spray pressure, as indicated by the small number of significant differences between the tested nozzle type–pressure combinations. Unlike phenmedipham spray solutions, bentazon spray solutions contained a tank mix adjuvant, namely methylated seed oil. The addition of this adjuvant is recommended in practice to improve the control of bentazon against *S. nigrum* and *C. album* in common bean and pea. Most likely, poor coverage associated with nozzles producing coarse droplet spectra was avoided by the beneficial effect of this adjuvant on retention and spreading on the leaf surface. Indeed, Creech [25] and Ramsdale and Messersmith [26] reported a 4.5- and 3-fold increase in retention after addition of methylated seed oil to the spray solution. In bentazon efficacy trials performed by Antoons [27] on 2-leaf stage plants of *M. chamomilla,* a species with numerous, linear, narrowly lobed leaflets, the performance of air induction nozzles was only inferior to that obtained with standard flat-fan nozzles when no oil was added to the spray solution. The different performance of nozzles in trials of bentazon and phenmedipham may also be due to different effects of the adjuvants on the droplet spectrum. Apart from nozzle type and spray pressure, built-in adjuvants in the formulated product (EC formulation of phenmedipham) and added tank-mix adjuvants (wettable powder formulation of bentazon) may indeed affect the droplet size spectrum and droplet impact behaviour. However, the effect of adjuvants on droplet characteristics is deemed largely inferior to the effect of nozzle type or spray pressure. Indeed, Miller et al. [28] and Stainier et al. [29] found that the addition of methylated vegetable oil to an EC formulation had a smaller effect on the droplet size spectrum than a change in nozzle type from a conventional flat-fan nozzle to an air induction nozzle.

The efficiency of the bentazon and phenmedipham applications depended on targeted growth stage. Both *S. nigrum* and *C. album* were more sensitive to bentazon and phenmedipham (as indicated by the lower ED_{90} response levels) at the cotyledon stage than at the 2-leaf stage, irrespective of nozzle–pressure combination. Relative to 2-leaf stage seedlings, cotyledon stage seedlings have a thinner and less waxy cuticle, lower herbicide metabolism and more exposed leaves (no umbrella effect).

The efficiency of phenmedipham and bentazon applications on cotyledon stage plants of *C. album* and *S. nigrum* largely depended on the droplet characteristics of the nozzle–pressure combinations and on nozzle type in particular as the nozzle effect was independent of spray pressure. Efficiencies of bentazon and phenmedipham applications were lowest for the coarse droplet ID3 air induction nozzles exhibiting increases in ED_{90} of 97–166% and 57–595% at a spray pressure of 2.5 bar and 150–151% and 63–1472% at a spray pressure of 5 bar, relative to the XR standard flat-fan nozzle at 2.5 bar. Except for the bentazon applications on *C. album* seedlings at 2.5 bar, these increases were all significant. At a spray pressure of 2.5 bar and 5.0 bar, this nozzle produced the coarsest and second coarsest droplet spectrum with a 2- and 1.8-fold higher VMD compared to the standard flat-fan nozzle at 2.5 bar. Earlier, Miller et al. [28] also found the greatest increase in ED_{90} level for applications with ISO 02 air induction nozzles producing the coarsest droplet sizes.

Nozzle effects were more pronounced for *S. nigrum* plants treated with phenmedipham than for *C. album* plants treated with phenmedipham and bentazon showing no significant differences among nozzle–pressure combinations except for the aforementioned ID3 nozzle. The XR standard flat-fan at 2.5 bar, i.e., the nozzle type–pressure combination with the largest portion of fine droplets (V_{150}, $D_{v0.1}$, $D_{v0.5}$ and $D_{v0.9}$) and highest spray coverage on water sensitive paper, showed superior phenmedipham performance on cotyledon stage plants of *S. nigrum,* with 19–60% lower ED_{90} values relative to the drift-reducing flat-fan nozzles (DG, AI, AVI TWIN, ID3) at 2.5 and 5 bar. Among the drift-reducing flat-fan nozzles, the DG pre-orifice nozzle at 2.5 bar, i.e., the nozzle type–pressure combination with the finest droplet spectrum of all drift reducing nozzles, showed the best performance with 23–51% lower ED_{90} response levels relative to the air induction nozzles (AI, AVI TWIN, ID3) operating at 2.5 and 5.0 bar. These results are in contrast to the findings of Jensen et al. [30] who found no effect of nozzle type (standard flat-fan and anti-drift nozzles) and droplet size spectrum on the efficiency of phenmedipham against cotyledon stage plants of *Brassica napus* L. Miller et al. [28] also found no minimum target size for application of contact herbicides using air induction nozzles but nevertheless stated that these nozzles should not be preferred on small targets.

Aforementioned significant nozzle type effects on herbicide performance against cotyledon stage plants suggest that adequate and uniform spray coverage of weed leaves and apical and axillary meristems is critical to obtain an efficient application of contact herbicides (as also illustrated in Figure 5B). Spray interception, retention, coverage and deposition highly depend on droplet size and droplet size spectrum [10]. Because of the very coarse droplets and low impact number density, air induction nozzles are less suitable for application of contact herbicides to cotyledon stage plants. Droplets produced by air inclusion nozzles are assumed to break up on contact with the weeds, and spray retention is assumed to be higher than is indicated by droplet size [10], particularly when droplets hit the leaf surface at high speed (>2.8 m s^{-1}) as is the case when single fans operate at high spray pressure (Table S1). However, this is only true when cotyledons are able to intercept these droplets in adequate number. The risk of droplets missing their intended target is higher for a spray plume consisting predominantly of a few large droplets than for a spray plume consisting predominantly of many small droplets. Furthermore, the risk of droplet rebound and runoff is higher for a large droplet than for a small droplet [20,31,32].

For 2-leaf stage plants of *C. album* treated with phenmedipham, no significant differences in ED_{90} were found between XR standard flat-fan nozzle at 2.5 bar, DG pre-orifice flat-fan nozzle at 2.5 bar and the air induction flat-fan nozzles at 5 bar, despite their differences in droplet size spectra (VMD of 264, 335 and 417 to 480 μm, respectively). Brown et al. [33] also found similar performance of the contact herbicide glufosinate-ammonium on six-leaf stage plants of *C. album* with an XR standard flat-fan nozzle at 2.8 bar and air induction nozzles at 4.9 bar. However, Jensen et al. [30] found inferior performance of phenmedipham on 2-leaf stage plants of *B. napus* when applications were performed with anti-drift nozzles with medium and coarse droplets compared to standard nozzles with fine droplets. Additionally, Antoons [27] observed that bentazon was 21% less active on 2- and 4-leaf stage plants of *M. chamomilla* when applied with an air induction nozzle at 4 bar instead of a standard nozzle at 3 bar. However, when spray pressure of air induction nozzles was decreased from 5.0 to 2.5 bar, their performance was roughly halved with ED_{90} responses that were significantly higher than air induction nozzles at 5 bar (+88–132%) and XR standard nozzles at 2.5 bar (+144–164%). The spray pressure effect on the performance of phenmedipham on 2-leaf stage plants of *C. album* can most likely be explained via the inverse relation between spray pressure and droplet diameter [25,34]. Decreasing the spray pressure of the air induction nozzles AI 11003, AVI TWIN 11003 and ID3 12003 from 5.0 to 2.5 bar increased the VMD by 16, 14 and 10%, $D_{v0.1}$ by 16, 16 and 10% and $D_{v0.9}$ by 13, 10 and 2%, respectively. Apparently, the droplet size spectrum of air induction nozzles operating at a pressure of 2.5 bar is too coarse for an adequate interception, retention and coverage, especially on difficult-to-wet *C. album* leaves. Consequently, higher ED_{90} doses (exceeding maximum authorised field dose of phenmedipham) are needed for air induction nozzles at 2.5 bar to compensate for the significantly lower average spray coverage (22.7%) and impact number density (48.5 droplets cm^{-2}) relative to the DG pre-orifice nozzle at 2.5 bar (29.6% and 111.6 droplets cm^{-2}) and air induction nozzles at 5.0 bar (28.8% and 81.2 droplets cm^{-2}). Adverse effects of decreasing spray pressure on the performance of air induction nozzles were also partially found by Brown et al. [33]. In their study, decreasing the spray pressure of air induction nozzles (TeeJet AI) from 4.9 to 2.8 bar significantly reduced the performance of the contact herbicides bromoxynil and bentazon on 6-leaf stage plans of *C. album* by 7 and 4%, respectively, but did not affect the performance of glufosinate-ammonium.

Contrary to 2-leaf stage plants of *C. album* treated with phenmedipham, no spray pressure effects on herbicide performance were found for cotyledon stage plants of *C. album* treated with phenmedipham, nor for *S. nigrum* plants, regardless of stage or herbicide used. Most likely, these different responses to spray pressure can be attributed to differences in leaf surface hydrophobicity of the targeted weeds. Within species, leaf surface hydrophobicity is higher for true leaves than for cotyledons [35]. Hydrophobicity is also much higher for *C. album* than for *S. nigrum* leaves [36]. Since fine droplets spread and adhere easier to hydrophobic surfaces than coarse droplets [10,32], difficult-to-wet weed targets, such as 2-leaf stage plants of *C. album*, may, indeed, be most sensitive to pressure-mediated droplet spectrum alterations.

Water sensitive papers are very appropriate to determine the quality of the application and the relative effect of nozzle type and pressure on spray coverage. However, they are not good proxies for estimating the performance of contact herbicides on young *C. album* and *S. nigrum* seedlings and, thus, for determining critical thresholds for bio-efficient herbicide application. Spray coverage characteristics (spray coverage, impact number density and mean droplet impact size) were indeed poorly associated with ED_{90} responses as indicated by the low determination coefficients of the regression curves for cotyledon stage plants of *C. album* to bentazon and phenmedipham, cotyledon stage plants of *S. nigrum* to phenmedipham and for both growth stages of *S. nigrum* to bentazon (0.3, 0.4 and 0.2 on average for spray coverage, impact number density and mean droplet impact size, respectively). Ramsdale et al. [37] also found poor or inconsistent associations between spray coverage and herbicide performance. The low determination coefficients indicate that spray coverage determined on WSP is not a good proxy of the real spray coverage on leaf surfaces. In contrast with a wettable paper with a constant chemical composition and shape, a leaf surface is waxy and exhibits a spatio-temporal variation in leaf shape, chemical composition and hydrophilicity. Hence, spreading, retention, rebound and run-off of droplets may be quite different for a leaf surface than for a paper surface [38]. Putative effects of leaf angle on spray coverage (e.g., leaf run-off) or umbrella effects (e.g., by overlapping leaves) were also not accounted for as WSP were laid down in a horizontal position in absence of plants. Finally, as pure tap water was used in the spray coverage tests, impact of formulation components on surface tension of spray droplets could not be accounted for either. According to Nansen et al. [38] and Peters et al. [31], spray coverage obtained with WSP should therefore be considered as maximum attainable spray coverage at the pre-set spray pressure and nozzle type setting. Among droplet coverage characteristics, impact number density was the best predictor of phenmedipham and bentazon efficiency. In five out of eight tested factorial combinations of herbicide, species and growth stage, herbicide performance was best predicted by impact number density (R^2 values between 0.2 and 0.9). The stronger association between herbicide performance and impact number density points to the importance of obtaining a uniform coverage of the leaf surface. Clearly, in line with Ferguson et al. [39], spray coverage does not take into account droplet size and droplet impact size. For example, pre-orifice nozzles (finer droplets) at 2.5 bar and air induction nozzles at 5 bar (coarser droplets) showed similar spray coverages but differed significantly in impact number density and mean impact size. Aside from impact number density, average distance between droplets (not determined in this study) may also be a better characteristic for estimating herbicide efficiency of contact herbicides.

In contrast with spray coverage characteristics based on WSP, PDPA-based spray droplet characteristics were good predictors for herbicide efficiency across all combinations of herbicides, weed species and growth stages tested in this study. ED_{90} values were stronger associated with volume- and droplet number-based droplet characteristics (D_{min}, $D_{v0.1}$, VMD, $D_{v0.9}$, V_{150}, NMD, $D_{n0.9}$ and N_{150}) than with spray coverage characteristics, particularly for cotyledon stage of *C. album* treated with phenmedipham and bentazon, cotyledon stage plant of *S. nigrum* treated with phenmedipham and both growth stages of *S. nigrum* treated with bentazon. Nuyttens et al. [19] mentioned that characterisation of the spray emitted by a nozzle is important in explaining and predicting spray deposition, retention, coverage and biological efficiency, indeed.

5. Conclusions

In many herbicide–species combinations, several coarser droplet drift-reducing nozzles showed similar performance in controlling small *C. album* and *S. nigrum* targets with the contact herbicides bentazon and phenmedipham, compared to the XR standard flat-fan nozzle with a finer droplet spectrum. However, the effect of nozzle choice on herbicide efficiency was more important for cotyledon stage plants than for 2-leaf stage plants. Air induction flat-fan nozzles applied at 5.0 bar can be used for applications of contact herbicides on 2-leaf stage plants without loss of efficiency relative to the standard flat-fan nozzles at 2.5 bar, but other nozzles (e.g., pre-orifice flat-fan nozzles or standard flat-fan nozzles) producing a finer droplet size spectrum (VMD of about 264 µm) should be preferred when applying contact herbicides to cotyledon stage plants if (wind) conditions and regulations allow. Indeed, nozzles with finer droplet spectra allow to reduce herbicide doses required for satisfactory control of cotyledon stage plants. However, air induction nozzles producing coarse droplet spectra should always be preferred over standard flat-fan nozzles, regardless of weed target size when contact herbicides are applied under weather conditions fostering droplet evaporation rate (e.g., low relative humidity and high ambient temperature, in particular) or spray drift (high wind speed in particular). The performance of air induction nozzles in controlling difficult-to-wet weeds (2-leaf stage plants of *C. album*) is better at 5.0 bar than at 2.5 bar. In contrast with spray coverage characteristics based on WSP, PDPA-based spray droplet characteristics were very useful in predicting herbicide efficiency and defining critical thresholds for bio-efficient herbicide applications.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy13051342/s1, Table S1: Volume- and number-based droplet characteristics (mean ± SD) for all tested nozzle type-pressure combinations. D_{min}, D_{max}: minimum and maximum droplet diameter (µm); $D_{v0.1}$, $D_{v0.5}$ and $D_{v0.9}$: droplet diameter (µm) at which 10, 50 and 90% of the spray volume is contained in droplets at or below that diameter; $D_{v0.5}$ = VMD ('Volume Median Diameter'); V_{150}: percentage (%) of the spray volume contained in droplets with a diameter <150 µm; v_{avg}: average droplet velocity (m s^{-1}), RSF: 'Relative span factor, i.e.,' a measure of uniformity of droplet sizes in a spray, calculated as $[(D_{v0.9} - D_{v0.1})/D_{v0.5}]$; $D_{n0.1}$, $D_{n0.5}$ and $D_{n0.9}$: droplet diameter (µm) at which 10, 50 and 90 percent of the droplets have a diameter at or below that diameter; $D_{n0.5}$ = NMD ('Number Median Diameter'). N_{150}: percentage (%) of droplets smaller than 150 µm. Table S2: Model parameters and determination coefficients (R^2) of quadratic regressions $y = a * x^2 + b * x + c$ between ED_{90} and spray coverage characteristics for all factorial combinations of herbicide, species and growth stage. Table S3: Model parameters and determination coefficients (R^2) of quadratic regressions $y = a * x^2 + b * x + c$ between ED_{90} and droplet characteristics for all factorial combinations of herbicide, species and growth stage. VMD: volume median diameter. $D_{n0.9}$: droplet diameter (µm) at which 90% of the droplets have a diameter at or below that diameter. V_{150}: percentage (%) of the spray volume contained in droplets with a diameter <150 µm. Figure S1: Spray distribution (mean flow rate ± standard deviation) of a single nozzle at a given spray pressure, off set angle (7°) and height (50 cm) for 8 nozzle–pressure combinations: (A) standard flat-fan Teejet XR 110 03 at 2.5 bar, (B) pre-orifice flat-fan Teejet DG 110 03 at 2.5 bar (DG), (C) air induction flat-fan Teejet AI 110 03 at 2.5 bar, (D) air induction flat-fan Teejet AI 110 03 at 5 bar, (E) air induction dual flat-fan Albuz AVITWIN 110 03 at 2.5 bar, (F) air induction dual flat-fan Albuz AVITWIN 110 03 at 5 bar, (G) air induction flat-fan Lechler ID3 120 03 at 2.5 bar and (H) air induction flat-fan Lechler ID3 120 03 at 5 bar. Numbers on the X-axis depict groove numbers of the spray distribution bench (ISO 5682-1); each collector groove (i.e., one bar) is 5 cm wide; grooves −1 and 1 (gray bars) delineate the central 10-cm zone beneath the nozzle.

Author Contributions: B.D.C.: Conceptualization (equal); methodology (equal); investigation (lead); formal analysis (lead); writing—original draft (lead); writing—review and editing (lead). I.D.M.: Investigation; formal analysis; writing—review and editing. S.D.R.: Methodology (equal); investigation; writing—review and editing. D.D.: Methodology (equal); investigation; writing—review and editing. I.Z.: Methodology (equal); writing—review and editing. D.N.: Conceptualization (equal); methodology (equal); writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare that there are no conflict of interest.

References

1. De Schampheleire, M.; Baetens, K.; Nuyttens, D.; Spanoghe, P. Spray drift measurements to evaluate the Belgian drift mitigation measures in field crops. *Crop Prot.* **2008**, *27*, 577–589. [CrossRef]
2. Nuyttens, D.; De Schampheleire, M.; Baetens, K.; Brusselman, E.; Dekeyser, D.; Verboven, P. Drift from field crop sprayers using an integrated approach: Results of a five-year study. *Trans. ASABE* **2011**, *54*, 403–408. [CrossRef]
3. De Schampheleire, M.; Nuyttens, D.; Dekeyser, D.; Verboven, P.; Spanoghe, P.; Cornelis, W.; Gabriels, D.; Steurbaut, W. Deposition of spray drift behind border structures. *Crop Prot.* **2009**, *28*, 1061–1075. [CrossRef]
4. Machado, W.A.; Silva, S.M.; Carvalho, S.M.; Cunha, J.P.A.R. da Effect of nozzles, application rates, and adjuvants on spray deposition in wheat crops. *Eng. Agríc.* **2019**, *39*, 83–88. [CrossRef]
5. Chen, P.; Douzals, J.P.; Lan, Y.; Cotteux, E.; Delpuech, X.; Pouxviel, G.; Zhan, Y. Characteristics of unmanned aerial spraying systems and related spray drift: A review. *Front. Plant Sci.* **2022**, *13*, 870956. [CrossRef] [PubMed]
6. Grover, R.; Kerr, L.A.; Maybank, J.; Yoshida, K. Field measurement of droplet drift from ground sprayers. I. Sampling, analytical, and data integration techniques. *Can. J. Plant Sci.* **1978**, *58*, 611–622. [CrossRef]
7. Nuyttens, D.; De Schampheleire, M.; Verboven, P.; Sonck, B. Comparison between indirect and direct spray drift assessment methods. *Biosyst. Eng.* **2010**, *105*, 2–12. [CrossRef]
8. Sousa Alves, G.; Kruger, G.R.; da Cunha, J.P.A.R.; de Santana, D.G.; Pinto, L.A.T.; Guimarães, F.; Zaric, M. Dicamba spray drift as influenced by wind speed and nozzle type. *Weed Technol.* **2017**, *31*, 724–731. [CrossRef]
9. Da Cunha, J.P.A.R.; França, J.A.L.; de Alvarenga, C.B.; Alves, G.S.; Antuniassi, U.R. Performance of air induction spray nozzle models under different operating conditions. *Eng. Agríc.* **2020**, *40*, 711–718. [CrossRef]
10. Zwertvaegher, I.K.; Verhaeghe, M.; Brusselman, E.; Verboven, P.; Lebeau, F.; Massinon, M.; Nicolaï, B.M.; Nuyttens, D. The impact and retention of spray droplets on a horizontal hydrophobic surface. *Biosyst. Eng.* **2014**, *126*, 82–91. [CrossRef]
11. Wang, S.; Li, X.; Nuyttens, D.; Zhang, L.; Liu, Y.; Li, X. Evaluation of compact air-induction flat fan nozzles for herbicide applications: Spray drift and biological efficacy. *Front. Plant Sci.* **2023**, *14*, 1018626. [CrossRef] [PubMed]
12. Knoche, M. Effect of droplet size and carrier volume on performance of foliage-applied herbicides. *Crop Prot.* **1994**, *13*, 163–178. [CrossRef]
13. Gossen, B.D.; Peng, G.; Wolf, T.M.; McDonald, M.R. Improving spray retention to enhance the efficacy of foliar-applied disease- and pest-management products in field and row crops. *Can. J. Plant Pathol.* **2008**, *30*, 505–516. [CrossRef]
14. Wolf, R.; Daggupati, N. Nozzle type effect on soybean canopy penetration. *Appl. Eng. Agric.* **2009**, *25*, 23–30. [CrossRef]
15. Guler, H.; Zhu, H.; Ozkan, H.E.; Ling, P. Characterization of hydraulic nozzles for droplet size and spray coverage. *Atomiz. Spr.* **2012**, *22*, 627–645. [CrossRef]
16. Ferguson, J.C.; Chechetto, R.G.; Hewitt, A.J.; Chauhan, B.S.; Adkins, S.W.; Kruger, G.R.; O'Donnell, C.C. Assessing the deposition and canopy penetration of nozzles with different spray qualities in an oat (*Avena sativa* L.) canopy. *Crop Prot.* **2016**, *81*, 14–19. [CrossRef]
17. Kudsk, P. Optimising herbicide performance. In *Weed Management Handbook*, 9th ed.; Naylor, R., Ed.; Blackwell Science: Oxford, UK, 2002; pp. 323–344.
18. Lauwers, M.; Nuyttens, D.; De Cauwer, B.; Pieters, J. Hyperspectral classification of poisonous solanaceous weeds in processing *Phaseolus vulgaris* L. and *Spinacia oleracea* L. *Comput. Electron. Agr.* **2022**, *196*, 106908. [CrossRef]
19. Nuyttens, D.; Baetens, K.; De Schampheleire, M.; Sonck, B. PDPA laser-based characterisation of agricultural spray nozzles. *Agric. Eng. Int. CIGR Ejournal* **2006**, *8*, 1–18.
20. Nuyttens, D.; Baetens, K.; De Schampheleire, M.; Sonck, B. Effect of nozzle type, size and pressure on spray droplet characteristics. *Biosyst. Eng.* **2007**, *97*, 333–345. [CrossRef]
21. *R Core Team R: A Language and Eironment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2021; ISBN 3-900051-07-0.

22. Ritz, C.; Streibig, J.C. Bioassay analysis using R. *J. Stat. Softw.* **2005**, *12*. [CrossRef]
23. Streibig, J.C.; Rudemo, M.; Jensen, J.E. Dose-response curves and statistical models. In *Herbicide Bioassays*; Streibig, J.C., Kudsk, P., Eds.; CRC Press: Boca Raton, FL, USA, 1993; pp. 29–55.
24. Van Der Vaart, A. *Asymptotic Statistics*; Cambridge University Press: Cambridge, UK, 1998; 439p.
25. Creech, C.F. Herbicide Application Technology Impacts on Herbicide Spray Characteristics and Performance. Ph.D. Thesis, University of Nebraska, Lincoln, NE, USA, 2015.
26. Ramsdale, B.K.; Messersmith, C.G. Nozzle, spray volume, and adjuvant effects on carfentrazone and imazamox efficacy. *Weed Technol.* **2001**, *15*, 485–491. [CrossRef]
27. Antoons, S. *Invloed van Tank-Mix Hulpstoffen Op Effectiviteit van Bladherbiciden, Faculteit Bio-Ingenieurswetenschappen*; Universiteit Gent: Gent, België, 2017.
28. Miller, P.; Powell, E.; Orson, J.; Kudsk, P.; Mathiassen, S. *Defining the size of target for air induction nozzles (Project Report 317)*; British Crop Protection Council: Hampshire, UK, 2003; 35p.
29. Stainier, C.; Destain, M.-F.; Schiffers, B.; Lebeau, F. Droplet size spectra and drift effect of two phenmedipham formulations and four adjuvants mixtures. *Crop Prot.* **2006**, *25*, 1238–1243. [CrossRef]
30. Jensen, P.K.; Jorgensen, L.N.; Kirknel, E. Biological efficacy of herbicides and fungicides applied with low-drift and twin-fluid nozzles. *Crop Prot.* **2001**, *20*, 57–64. [CrossRef]
31. Peters, T.; Thostenson, A.; Nowatzki, J.; Hofman, V.; Wilson, J. *Selecting Spray Nozzles to Reduce Particle Drift*; North Dakota State University: Fargo, ND, USA, 2017.
32. Spanoghe, P. *Effect van Additieven en Adjuvantia op de Efficiëntie van de Spuittoepassing van Gewasbeschermingsmiddelen*; Universiteit Gent: Gent, België, 2005.
33. Brown, L.; Soltani, N.; Shropshire, C.; Spieser, H.; Sikkema, P.H. Efficacy of four corn (*Zea mays* L.) herbicides when applied with flat fan and air induction nozzles. *Weed Biol. Manag.* **2007**, *7*, 55–61. [CrossRef]
34. Liao, J.; Luo, X.; Wang, P.; Zhou, Z.; O'Donnell, C.C.; Zang, Y.; Hewitt, A.J. Analysis of the influence of different parameters on droplet characteristics and droplet size classification categories for air induction nozzle. *Agronomy* **2020**, *10*, 256. [CrossRef]
35. Fogg, G.E.; Pearsall, W.H. Quantitative studies on the wetting of leaves by water. *Proc. R. Soc. London. Ser. B Biol. Sci.* **1947**, *134*, 503–522. [CrossRef]
36. Harr, J.; Guggenheim, R.; Schulke, G.; Falk, R.H. *The Leaf Surface of Major Weeds*; Sandoz Agro, Ltd.: Greensboro, NC, USA, 1991; 11p.
37. Ramsdale, B.K.; Messersmith, C.G. Drift-reducing nozzle effects on herbicide performance. *Weed Technol.* **2001**, *15*, 453–460. [CrossRef]
38. Nansen, C.; Ferguson, J.C.; Moore, J.; Groves, L.; Emery, R.; Garel, N.; Hewitt, A. Optimizing pesticide spray coverage using a novel web and smartphone tool, SnapCard. *Agron. Sustain. Dev.* **2015**, *35*, 1075–1085. [CrossRef]
39. Ferguson, J.C.; Hewitt, A.J.; O'Donnell, C.C. Pressure, droplet size classification, and nozzle arrangement effects on coverage and droplet number density using air-inclusion dual fan nozzles for pesticide applications. *Crop Prot.* **2016**, *89*, 231–238. [CrossRef]