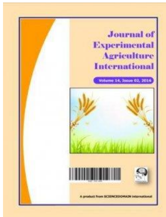

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Herbicide Formulation, Spray Nozzle Design, and Operating Pressure Affects the Droplet Size Spectra of Agricultural Sprays

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Authors' contributions

This work was carried out in collaboration among all authors. Author JAM designed the studies, performed the statistical analyses and wrote the first draft of the manuscript, while authors GDM, PAD and PAB assisted in designing the studies and reviewed the manuscript. All authors read and approved the final manuscript.

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ABSTRACT

Aims: Determine the droplet size spectra of agricultural sprays as affected by herbicide formulations, spray nozzle designs, and operating pressures.
Place and Duration of Study: This study was conducted in April 2014 at the United States Department of Agriculture Agricultural Research Service Aerial Application Technology Research Unit Facility in College Station, Texas.
Methodology: The spray droplet size spectra of six herbicide formulations as well as water alone and water with nonionic surfactant were evaluated in a low-speed wind tunnel. These spray solutions were conducted with five different flat-fan spray nozzle designs, producing a wide range of spray droplet sizes. The wind tunnel was equipped with a laser diffraction sensor to analyze spray

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droplet size. All combinations of spray solution and nozzle were operated at 207 and 414 kPa and replicated three times.
Results: Many differences in droplet size spectra were detected among the spray solutions, nozzle designs, and pressures tested. Solutions of Liberty 280 SL exhibited the smallest median droplet size and the greatest proportion of spray volume contained in droplets 100 μm or less in size. Solutions of Enlist Duo resulted in smaller median droplet size than many of the solutions tested, but also exhibited some of the smallest production of fine spray droplets. Median droplet size was found to vary greatly among nozzle designs, with the greatest droplet size and smallest drift-prone fine droplet production observed with air-inclusion designs utilizing a pre-orifice. Increasing the operating pressure from 207 to 414 kPa resulted in a decrease in median droplet size and an increase in the production of droplets 100 μm or less in size.
Conclusion: Herbicide formulations and spray nozzle designs tested varied widely in droplet size spectra and thus the potential for spray drift. Increasing operating pressure resulted in decreased droplet size and an increase in the production of drift-prone droplets. Additionally, median droplet size alone should not be used to compare spray drift potential among spray solutions but should include relative span and V100 values to better predict the potential for spray drift due to drift-prone spray droplets.

Keywords: Droplet size; spray drift; spray nozzles; herbicide formulation.

1. INTRODUCTION

The widespread adoption of glyphosate-, glufosinate-, 2,4-D-, and dicamba- tolerant crop technologies has increased the need for understanding the potential for off-target injury to susceptible crops due to physical spray drift. Droplet size highly influences the potential for spray drift to occur. Larger droplets have been shown to retain vertical exit velocity to a greater extent than smaller droplets, leading to a shorter duration of time between exiting the spray nozzle and deposition on the target (foliage, soil, or both.) [1]. The longer this duration of time, the greater the risk for off-target movement of the spray droplet [2]. Additionally, smaller droplets exhibit a greater surface area to volume ratio, which results in a greater rate of evaporation of water from the spray droplet [3]. This can further exacerbate the potential for spray drift due to a rapid decrease in droplet size after exiting the nozzle.

Properties of the spray solution such as viscosity, density, and surface tension have all been shown to influence spray droplet size; however, surface tension appears to have the greatest impact [4]. As the spray solution exits a flat-fan spray nozzle, it forms a sheet that breaks up as it expands due to oscillations produced by sinuous waves in the sheet [5]. As the sheet fragments, spray droplets are formed. Any material that reduces the surface tension of the spray solution will tend to delay the fragmentation of the sheet by suppressing these oscillations [4], which tends to decrease droplet size when sprayed through conventional hydraulic flat-fan nozzles. Air-inclusion nozzles appear to be sensitive to other changes in the properties of the spray solution and occasionally do not follow the same trend of sprays produced by conventional (non-air-inclusion) nozzles [6].

Commercial herbicide and adjuvant formulations are often highly complex and may contain proprietary inert ingredients. As a result, most studies on the impact of formulations on spray characteristics are conducted on a case-by-case basis [7,8,9]. The objectives of this study were to determine the droplet size spectra of agricultural sprays as affected by herbicide formulations, spray nozzle designs, and operating pressures commonly utilized with modern herbicide-tolerant corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), and soybean (*Glycine max* (L.) Merr.) varieties.

2. METHODOLOGY

A low-speed wind tunnel operated by the United States Department of Agriculture, Agricultural Research Service in College Station, TX was used to investigate the effect of various herbicide formulations, spray nozzle designs, and operating pressures on droplet size spectra. A fan at the upstream end of a 1.2 by 1.2 m tunnel 14.6 m in length pushes air at 6.7 m sec^{-1} through flow straighteners to produce a laminar flow of air. The size of the spray droplets was measured with a Helos/KR laser diffraction sensor (Sympatec GmbH, Clausthal, Germany). This sensor is made up of an emitter and a receiver. The emitter houses a 623 nm helium-neon laser aligned with the receiver. Fitted to the receiver is a lens with 32 sizing bins that can measure droplets from 0.5 to 3500 µm (denoted as an R7 lens by the manufacturer). The laser diffraction sensor is placed so that the laser fires horizontally across the center of the downstream end of the tunnel. A single spray nozzle was attached to a vertically-mounted traverse system that allows the nozzle to travel from the top to the bottom of the tunnel while spraying. This traverse system is positioned so that the nozzle is 30.5 cm from the laser diffraction sensor. Three replications of each combination of spray nozzle, operating pressure and herbicide formulation were conducted. Each replication consisted of traversing the vertically aligned flat-fan spray nozzle from the top to the bottom of the tunnel so that the entire spray plume moves across the laser. Spray solutions were prepared in 11 L samples and placed into a 19 L stainless steel container pressurized by a regulated supply of compressed air. A valve on the container was used to start and stop the flow of the pressurized solution to the spray nozzle. Airborne spray solution was captured at the end of the tunnel with a portable air scrubber.

Spray solutions were prepared with several herbicide formulations with a total spray volume of 140 L ha^{-1} to simulate a ground broadcast application. Herbicide formulations included Enlist Duo™ (choline salt of 2,4-D, 192 g ae (acid equivalent) L^{-1} + dimethylamine salt of glyphosate, 205 g ae L^{-1} at a product rate of 5.55 L ha^{-1}), Clarity® (diglycolamine salt of dicamba, 480 g ae L^{-1} at a product rate of 1.17 L ha^{-1}), 2,4-D Amine 4 (dimethylamine salt of 2,4-D, 455 g ae L^{-1} at a product rate of 2.34 L ha^{-1}, Roundup PowerMAX® (potassium salt of glyphosate, 540 g ae L^{-1} at a product rate of 1.61 L ha^{-1}), Durango® DMA (dimethylamine salt of glyphosate, 480 g ae L^{-1} at a product rate of 1.75 L ha^{-1}), and Liberty® 280 SL (glufosinate ammonium, 280 g ai (active ingredient) L^{-1} at a product rate of 2.12 L ha^{-1}). The products Enlist Duo, Roundup PowerMAX, Durango DMA, and Liberty 280 SL do not require the addition of a surfactant. A non-ionic surfactant (NIS), Activator 90, was included at a rate of 0.25% v/v to Clarity and 2,4-D Amine 4 as recommended by the product labels. In addition to the herbicide solutions listed above, solutions of water alone and water + 0.25% v/v Activator 90 were included for comparison purposes.

Spray nozzles included in this study were the TeeJet XR 11002 Extended Range, DG 11002 Drift Guard, AIXR 11002 Air Induction XR, AI 11002 Air Induction, and TTI 11002 Turbo TeeJet Induction flat-fan spray tips (TeeJet Technologies, Wheaton, Illinois). These nozzle designs represent a wide range of droplet size spectra of commonly used agricultural spray nozzles of both conventional hydraulic and air-inclusion designs. The XR nozzle is a conventional hydraulic design with a single orifice. The DG nozzle is also a conventional hydraulic design with the addition of a pre-orifice, which regulates the flow of the spray solution before exiting a larger final orifice. The AIXR, AI, and TTI nozzles are all air-inclusion designs that also utilize a pre-orifice. These nozzles are all designed to produce a 110° spray plume and flow 0.757 L min^{-1} and were tested prior to the study to verify that their flow rate was within the manufacturer's specifications. TeeJet 8079 strainers were used to prevent contaminants from altering spray characteristics. All combinations of herbicide formulations and spray nozzles were operated at 207 and 414 kPa.

For each traverse of a spray plume across the sensor, the Helos system calculates $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ values, which are the droplet sizes in µm for which 10, 50, and 90% of the spray volume is made up of droplets less than or equal to that size. Relative span (RS) is dimensionless measure of the spread of the droplet size distribution of the spray volume and is calculated by the following equation: $(D_{v0.9} - D_{v0.1}) / D_{v0.5}$. The percentage of the total spray volume consisting of droplets less than 100 µm (V100) was recorded to provide an indicator of the highly susceptible portion of the spray to drift. All data were subjected to ANOVA using JMP 12 to test for the main effects of spray solution, nozzle design, and operating pressure as well as all possible interactions on $Dv_{0.5}$, RS, and V100. Treatment means were separated using Fisher's LSD at the 0.05 level of significance [10].

3. RESULTS AND DISCUSSION

An interaction of spray solution, spray nozzle, and operating pressure was observed for $D_{v0.5}$ and V100 (*P* <.0001), and all two-way interactions and main effects were significant (*P* <.0001) for $Dv_{0.5}$, RS, and V100. Due to a large number of treatment combinations (80), the models were simplified to run each main effect separately, with all other main effects pooled to better facilitate the interpretation and discussion of these results (Table 1).

Averaged over other variables, water alone provided the greatest $D_{v0.5}$ (556 µm), followed by Clarity, water + NIS, Roundup PowerMAX, and 2,4-D Amine 4 (509, 504, 502, and 500 µm, respectively), Durango DMA (498 µm), Enlist Duo (468 µm), and Liberty 280 SL (445 µm). All other solutions contained a surfactant either included in the formulated product or manually added as in the case of the water + NIS, 2,4-D Amine 4, and Clarity solutions. The inclusion of a surfactant decreases the surface tension of the solution, likely resulting in a delay in the breakage of the fluid sheet produced by flat fan spray nozzles [4]. Delayed breakage of this sheet tends to produce droplets of smaller size and mass, which will have greater susceptibility to spray drift. The smallest droplet size was recorded with sprays of Liberty 280 SL, potentially indicating a stronger surfactant load in this product as prepared by the manufacturer. Sprays of Liberty 280 SL exhibited the greatest RS (1.35), followed by Durango DMA and Roundup PowerMAX (1.25 and 1.22, respectively), and water alone (1.17). Larger RS indicates a less uniform droplet size spectra with these spray solutions. Spray solutions ranked in order of V100 values from smallest to largest are water + NIS, Clarity, Enlist Duo, water, Durango DMA, Roundup PowerMAX, and Liberty 280 SL. Solutions of Enlist Duo resulted in smaller median droplet size than many other solutions; however, sprays with this product also resulted in one of the smallest V100 values in the trial. This indicates that although droplet size decreased with solutions of Enlist Duo, the width of the droplet size distribution decreased as well (as indicated by small RS values), resulting in decreased production of droplets at either end of the extreme of the distribution. These results are similar to the results of field studies where a similar formulation of a choline salt of 2,4-D alone compared to 2,4-D DMA [11].

Nozzle designs ranked from smallest to largest in terms of Dv0.5 averaged over spray solution and pressure were XR, DG, AIXR, AI, and TTI. This trend in nozzles for $D_{v0.5}$ was inversely correlated with V100. As has been previously found, air-inclusion designs provided the greatest reductions in spray drift potential [12,13,14]. The XR nozzle exhibited the largest RS (1.22), followed by the DG nozzles (1.19), and all other designs (1.13 to 1.15). As pressure was increased from 207 to 414 kPa, $D_{v0.5}$ decreased from 598 to 397 µm, along with increases in RS

Table 1. Effect of spray solutions, spray nozzles, and operating pressure on droplet size spectra when pooled across all other variables

Variable	$D_{v0.5}$[a]		RS		V100	
	µm				%	
Spray solution						
Water	556	a[b]	1.17	c	3.87	d
Water + NIS	504	bc	1.08	d	2.27	f
Roundup PowerMAX	502	bc	1.22	b	5.19	b
Durango DMA	498	c	1.25	b	4.78	c
Liberty 280 SL	445	e	1.35	a	7.04	a
Clarity	509	bc	1.09	d	2.36	f
2,4-D Amine 4	500	bc	1.11	d	3.21	e
Enlist Duo	468	d	1.08	d	2.51	f
Nozzle						
XR	206	e	1.22	a	12.06	a
DG	302	d	1.19	b	4.84	b
AIXR	424	c	1.13	c	1.83	c
AI	703	b	1.15	c	0.56	d
TTI	852	a	1.14	c	0.22	e
Pressure						
207	598	a	1.12	b	2.07	b
414	397	b	1.21	a	5.73	a

[a]*Abbreviations: $D_{v0.5}$ represents the droplet size in µm at which 50% of the spray volume is comprised of droplets equal to or lesser in size. Relative span (RS) is a measure of the relative span of the droplet size distribution. The volume of the spray contained in droplets less than 100 µm in size is represented by V100.*
[b]*Within a column, means followed by different letters are significantly (P<0.0.5) different*

from 1.12 to 1.21 and V100 from 2.07 to 5.73%. When pressure was increased from 207 to 414 kPa, $D_{v0.5}$ decreased by 33.6%, RS increased by 8%, and V100 increased 177%, indicating an increased risk for physical spray drift when operating pressure is increased as has been previously observed [12].

When the interaction between nozzle design and spray solution on $D_{v0.5}$ was examined (Table 2), solutions of Liberty 280 SL produced the smallest median droplet size for all nozzles except for the TTI, where the Enlist Duo solution produced the smallest droplet size. When NIS was added to water, droplet size increased for the standard hydraulic nozzle designs tested (XR and DG); however, droplet size decreased for the air-inclusion designs (AIXR, AI, and TTI). Although a decrease in droplet size would be expected with the addition of a surfactant [4], these results indicate a difference in the effect of surfactant on droplet size depending on the nozzle design, which has been previously noted [6]. This same trend (larger size than water with hydraulic nozzles, smaller size than water with air-inclusion nozzles) was seen with solutions of Clarity and Enlist Duo. Solutions of Roundup PowerMAX, Durango DMA, Liberty 280 SL, and 2,4-D Amine 4 exhibited smaller droplet size than water alone with all nozzle designs, though not always significant.

Solutions of Liberty 280 SL resulted in the largest RS values for the XR, DG, and TTI nozzles; however, water + NIS and Durango DMA resulted in the largest RS values for the AIXR and AI nozzles, respectively (Table 3). The addition of NIS to water resulted in smaller RS values for the XR, DG, and AI nozzles when compared to water alone; however, an increase in RS relative to water alone was seen with the AIXR nozzle and no difference was observed with the TTI nozzle. Solutions of Clarity and Enlist Duo consistently provided RS values among the smallest in the trial, indicating a high level of uniformity in droplet size spectra with these sprays.

No differences among spray solutions for V100 were observed when sprayed through the TTI nozzle; however, many differences were detected for the other nozzle designs (Table 4). Solutions of Liberty 280 SL produced the largest V100 values among all spray solutions for all nozzles other than the TTI. The addition of NIS to water resulted in a significant decrease in V100 compared to water alone for the standard hydraulic nozzles but no change in V100 was observed for the air-inclusion designs. This differential response of nozzle designs to changes in spray solution has been previously noted by [6], where changes in spray characteristics with air-inclusion designs in response to changes in spray solution often did not follow the trend observed with conventional hydraulic nozzle designs. The smallest V100 values for the XR nozzle were observed with solutions of water + NIS and Clarity. Solutions of water + NIS, Clarity, and Enlist Duo resulted in the smallest V100 values for the DG and AIXR nozzles.

Table 2. Interaction between nozzle design and spray solution, pooled across operating pressure, on droplet size at which 50% of the spray volume is comprised of droplets equal to or lesser in size ($D_{v0.5}$)

Spray solution	Nozzle design				
	XR[a]	DG	AIXR	AI	TTI
			µm		
Water	213	316	465	832	948
Water + NIS	230	339	454	687	813
Roundup PowerMAX	191	276	425	726	892
Durango DMA	194	285	417	711	884
Liberty 280 SL	176	252	368	610	819
Clarity	223	328	441	697	854
2,4-D Amine 4	208	289	389	731	882
Enlist Duo	217	329	432	633	728
LSD[b]			19.5		
Mean	207	302	424	703	853

[a]Abbreviations: XR, TeeJet 11002 Extended Range; DG, TeeJet 11002 Drift Guard; AIXR, TeeJet 11002 Air Induction XR; AI, TeeJet 11002 Air Induction, TTI, TeeJet 11002 Turbo TeeJet Induction

[b]Fisher's least significant difference (LSD) at the 0.05 level of significance for all combinations of spray solution and nozzle design

Table 3. Interaction between nozzle design and spray solution, pooled across operating pressure, on the relative span of droplet size distribution (RS), calculated by: $(D_{v0.9}-D_{v0.1})/D_{v0.5}$

Spray solution	Nozzle design				
	XR[a]	DG	AIXR	AI	TTI
Water	1.23	1.18	1.15	1.18	1.12
Water + NIS	1.13	1.08	1.30	1.04	1.13
Roundup PowerMAX	1.32	1.27	1.22	1.13	1.15
Durango DMA	1.25	1.25	1.19	1.40	1.14
Liberty 280 SL	1.49	1.38	1.28	1.28	1.31
Clarity	1.11	1.10	1.07	1.09	1.10
2,4-D Amine 4	1.10	1.15	1.09	1.10	1.12
Enlist Duo	1.15	1.09	1.04	1.01	1.08
LSD[b]			0.09		
Mean	1.22	1.19	1.17	1.15	1.14

[a]Abbreviations: XR, TeeJet 11002 Extended Range; DG, TeeJet 11002 Drift Guard; AIXR, TeeJet 11002 Air Induction XR; AI, TeeJet 11002 Air Induction, TTI, TeeJet 11002 Turbo TeeJet Induction

[b]Fisher's least significant difference (LSD) at the 0.05 level of significance for all combinations of spray solution and nozzle design

Table 4. Interaction between nozzle design and spray solution, pooled across operating pressure, on the percentage of spray volume contained in droplets less than 100 µm in size (V100)

Spray solution	Nozzle				
	XR[a]	DG	AIXR	AI	TTI
			%		
Water	12.3	4.8	1.5	0.5	0.3
Water + NIS	7.7	2.3	1.0	0.2	0.1
Roundup PowerMAX	16.2	6.8	2.3	0.5	0.2
Durango DMA	14.7	6.3	1.9	0.7	0.2
Liberty 280 SL	19.5	9.3	4.4	1.6	0.5
Clarity	7.9	2.5	1.1	0.2	0.1
2,4-D Amine 4	9.4	4.3	1.7	0.4	0.2
Enlist Duo	8.9	2.4	0.8	0.3	0.2
LSD[a]			0.69		
Mean	12.1	4.8	1.8	0.6	0.2

[a]Abbreviations: XR, TeeJet 11002 Extended Range; DG, TeeJet 11002 Drift Guard; AIXR, TeeJet 11002 Air Induction XR; AI, TeeJet 11002 Air Induction, TTI, TeeJet 11002 Turbo TeeJet Induction

[b]Fisher's least significant difference (LSD) at the 0.05 level of significance for all combinations of spray solution and nozzle design

4. CONCLUSION

The results of this study indicate great variability in spray droplet size spectra and potential for spray drift among common herbicide formulations, likely owing to differences in properties of the spray solution such as viscosity, density, and surface tension These results also indicated that median droplet size alone should not be used as an indicator for spray drift susceptibility, as RS and Qi100 values can provide additional insight into the width of droplet size distribution and portion of the spray consisting of highly drift-prone droplets. Additionally, spray nozzle designs were found to vary greatly in droplet size spectra across the spray solutions and pressures tested. Improved nozzle models that utilize a pre-orifice and air-inclusion design were found to greatly increase median droplet size and thus reduce the potential for physical spray drift to occur versus nozzles without these features.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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