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Determining the uniformity and consistency of droplet size across spray drift reducing nozzles in a wind tunnel

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A B S T R A C T

Spray drift is a consideration for growers and applicators who are increasingly selecting larger droplet producing nozzles to allay their concerns. As new technologies arrive on the market, the prices of individual nozzles have risen which puts a greater need for consistency among nozzles to be worth the investment. These nozzles, while effective at reducing spray drift, may not always be consistent at maintaining efficacy which can be a result of a lack of uniformity in the production of these nozzles. Twenty-one spray drift reducing nozzles were compared for droplet size distributions across three liquids of varying dynamic surface tensions in a wind tunnel at the University of Queensland. Research sought to identify the repeatability of each nozzle type by randomly selecting five units to test consistency of droplet size measurements across nozzle type. Results indicate that some nozzle types are consistent and repeatable while others are not. It was also observed that some nozzle types are relatively unaffected by liquid type, where others resulted in a droplet size change in volume median diameter (VMD) of 100 μm depending on liquid type at the same operating pressure. Research from this study will help growers and industry to select the best nozzle types to ensure uniformity of application, to maximize efficacy and to reduce pesticide spray drift.

1. Introduction

Reducing pesticide spray drift and maximising efficacy are the paramount considerations when selecting technologies and operating parameters prior to making an application. The number of herbicide applications are increasing each year, with the US alone increasing its herbicide use by 130% between 2002 and 2010 (Osteen and Fernandez-Cornejo, 2013). With the increasing number of applications each year the likelihood of off-target movement of the sprays is of great concern. Spray drift is defined by the US Environmental Protection Agency (EPA) as the "the physical movement of a pesticide through the air at the time of application or soon thereafter, to any site other than the one intended for application" (EPA, 1999). Spray drift increases with wind, in low humidity and when small droplets comprise the majority of the spray (Bouse et al., 1990), making nozzle selection of the utmost importance to any spray drift management procedure. Droplets below 100 μm in diameter are considered to be the most prone to spray drift (Byass and Lake, 1977; Grover et al., 1978); however, droplets of any size can drift when atomised in the wrong environmental conditions. Droplet size can also influence the rate of on-target deposition as well as canopy penetration (Spillman, 1984) with smaller droplets providing better deposition and canopy penetration than larger ones (Knoche, 1994).

The growing concern of spray drift has led to the adoption of nozzles with air-induction (AI) ports, pre-orifice chambers, and other design features that can increase droplet size to reduce spray drift. These design features can also allow for applications to be made in a wider range of environmental conditions. Many of these nozzle types use the Venturi process which introduces air into the

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liquid, forming droplets with air inclusions, which increases the spray droplet size. The design factors of AI nozzles are a significant component of what affects the atomisation performance of these nozzles (Butler-Ellis et al., 2002). In selecting AI and other larger droplet producing nozzles, it is useful to know how consistent each nozzle type is across multiple units of the same nozzle. AI and other newly produced nozzle types can cost ten-fold of a standard flat-fan nozzle ($35 USD each in Australia) (Croplands, 2015), making their performance and consistency of the utmost importance.

Droplet sizes are determined in each laboratory by following a standard testing method and a set of pre-determined nozzles at specific operating pressures to achieve droplet size curves (ASAE, 2009). This standard is based on previous standards of the Brighton Crop Protection Council (BCPC) (Southcombe et al., 1997) that also categorised sprays into classifications of Very Fine, Fine, Medium, Coarse, Very Coarse and Extra Coarse. This droplet size measurement technique involves the use of laser diffraction or other type of acceptable droplet measurement or imaging system (ASAE, 2009). Laser diffraction is a common method used to analyse and characterise sprays. The intricacies of laser diffraction are well explained by Ma et al. (2000). Laser diffraction is widely adopted given its repeatability and consistency of measurements, even across different laboratories with a similar set-up (Fritz et al., 2014).

Previous research with non-AI reference nozzles found little difference across multiple units of the same nozzle type (Fritz et al., 2014, 2012; Womac et al., 1999). This result was less obvious when testing multiple units of non-certified ground nozzles (some of which were AI nozzles) where inconsistencies across multiple units of the same nozzle were observed (Fritz et al., 2014; Womac, 2000). The non-reference nozzles studied by Womac (2000) were pre-screened by their manufacturers, yet still resulted in an overall conclusion that more work needed to be conducted to guarantee consistency in nozzle production. Nozzle manufacturers publish nozzle patternation data about the uniformity of new nozzle spray patterns which are listed at or below 6% coefficient of variation (CV) (Teejet, 2011; Croplands, 2015). There is not data however, on the consistency of droplet size measurements across nozzle units published in these same catalogues. The research objectives of this study are therefore to 1) determine the uniformity of the droplet size spectra emitted from a given nozzle type by testing multiple representatives of the same nozzle (nozzle units) for droplet size in a wind tunnel, and 2) to compare the consistency of droplet size spectra of the given nozzle type across different spray solutions.

2. Materials and methods

2.1. The nozzles and spray solutions

A study to compare the consistency and uniformity of a given nozzle type's spray droplet size spectrum across multiple nozzle units was conducted at the Centre for Pesticide Application and Safety (CPAS) Wind Tunnel Research Facility at the University of Queensland in Gatton, Queensland, Australia. Twenty-one nozzle types commonly used under Australian cereal growing conditions and one reference nozzle were selected from seven manufacturers for comparison in the study. The nozzles were 015 and 02 orifice sizes [(0.15 and 0.2 gallons) or (0.57 and 0.76 L)] per minute flow rate at the reference spray pressure of 276 kPa (40 psi). This nomenclature and colour scheme for nozzle classification is based on an International Organization for Standardization (ISO) Standard 10625 (ISO, 2004). An extended range XR 11003VS (Spraying Systems Inc. Wheaton, Illinois USA) was included for comparison as it is the reference nozzle type used for most international DRT studies (van de Zande et al., 2002). Nozzle types used in the study are listed in Table 1. Five nozzle units from each of the 22 nozzle types were compared across three liquids: water alone, pinoxaden (Axial + Adigor, Syngenta Australia Pty Limited, Macquarie Park, NSW, Australia) at 0.2% v/v + methylated seed oil at 0.5% v/v, and clopyralid (Lontrel Advanced, Dow AgroSciences Australia Limited, Frenches Forest, NSW, Australia) at 0.25% v/v. Each treatment across all nozzles was applied at a pressure of 350 kPa, with the exception of the reference XRVS 11003 which was sprayed at 300 kPa (consistent with international DRT studies) (ISO, 2006, 2008; 2010). Nozzles were operated at this selected pressure as it falls within the manufacturer's recommended pressure operating range for all nozzles.

Each randomly selected nozzle unit from each nozzle type was assigned a number (1–5) to ensure repeatability of that given nozzle for the three liquids to allow for appropriate data comparisons. The two herbicides were selected as they are commonly used in cereal (pinoxaden) or oilseed crop (clopyralid) weed control in Australia. The rates selected were also the label rates for use in Queensland for each of the respective crops.

2.2. Description of the wind tunnel testing method

The nozzle types were tested in the CPAS Wind Tunnel Research Facility at the University of Queensland. A detailed description of the research facility can be found in Fritz et al. (2014). Wind speed in the study was constant at 8.0 m s^{-1}, a necessary wind speed to significantly mitigate spatial sampling biases (SDTF, 1997). Each treatment was analysed on a laser diffraction instrument (Sympatec Helos Sympatec Inc., Clausthal, Germany) to measure droplet size and compare each nozzle type by treatment. The laser diffraction instruments was 30 cm from the nozzle, a distance that allows for sufficient breakup of the liquid sheet. The nozzles were operated on an actuated arm in a downward direction with their spray plume passing through the beam for 9 s per measurement. The volumetric droplet size spectra parameters selected for data interpretation were the $D_{v0.1}$, $D_{v0.5}$, $D_{v0.9}$, relative span (RS), and the percentage of the spray volume contained in droplets with a diameter below 150 μm. The volume median diameter ($D_{v0.5}$) is the diameter at which half of the volume of droplets are contained in droplets of larger or smaller diameter to help classify sprays, and understand the size classification of each. The $D_{v0.1}$ is the diameter at which ten percent of the volume of droplets are contained in droplets at or below that diameter the $D_{v0.9}$ is the diameter at which ninety percent of the droplets are contained in droplets at or below that diameter. The RS was calculated using Equation 1.

$$\boldsymbol{RS} = \frac{\boldsymbol{D_{v\ 0.9} - D_{v\ 0.1}}}{\boldsymbol{D_{v\ 0.5}}}$$

These parameters were selected because they are widely used to assess spray drift potential ($D_{v0.1}$ and % < 150 μm), efficacy potential ($D_{v0.5}$), and evenness of the spray droplet size spectrum (RS). Droplet size measurements for each nozzle type by nozzle unit by spray solution were replicated to provide three measurements within ± 5 μm of the mean of the $D_{v0.1}$, a standard operating procedure in the CPAS laboratory managing data quality. Spray solutions were maintained between 23 °C and 25 °C. The study was conducted in March and May 2014.

2.3. Definitions of uniformity and consistency

Uniformity in this study is determined by the coefficient of variation for each nozzle type by spray solution $D_{v0.5}$. The coefficient of variation (CV) is calculated as the standard deviation (σ) of the $D_{v0.5}$ divided by the mean of the $D_{v0.5}$. Uniformity across a nozzle type will result in a CV at or below 4%, and non-uniformity

Table 1
Nozzles used in the study classified by their manufacturer, spray drift reduction technology feature and manufacturer listed operating pressure range.

Common name	Nozzle type	Angle and flow rate	Manufacturer	DRT feature	Operating pressures
Extended Range	XR (reference)	11003	Teejet	None	100–400
Air-induction Extended Range	AIXR	110015	Teejet	Venturi, pre-orifice	100–600
Air-induction Extended Range	AIXR	11002	Teejet	Venturi, pre-orifice	100–600
Air-induction Turbo TwinJet	AITTJ60	11002	Teejet	Venturi, pre-orifice, twin-fan	150–600
Turbo TeeJet Induction	TTI	110015	Teejet	Venturi, pre-orifice, anvil shaped	100–700
Turbo TeeJet Induction	TTI	11002	Teejet	Venturi, pre-orifice, anvil shaped	100–700
Turbo TwinJet	TTJ60	11002	Teejet	Twin-fan	150–600
Air BubbleJet	ABJ	110015	Billericay Farm Services	Venturi, pre-orifice	200–600
Air BubbleJet	ABJ	11002	Billericay Farm Services	Venturi, pre-orifice	200–600
Guardian Air	GA	110015	Hypro	Venturi, pre-orifice, off-set angle	100–600
Guardian Air	GA	11002	Hypro	Venturi, pre-orifice, off-set angle	100–600
Ultra-low Drift	ULD	120015	Hypro	Venturi, pre-orifice	200–800
Ultra-low Drift	ULD	12002	Hypro	Venturi, pre-orifice	200–800
Air-injector	ID	120015	Lechler GmbH	Venturi, pre-orifice	300–800
Air-injector	ID	12002	Lechler GmbH	Venturi, pre-orifice	300–800
Air-injector compact	IDK	12002	Lechler GmbH	Venturi, pre-orifice	150–600
Air-injector compact-twin	IDKT	120015	Lechler GmbH	Venturi, pre-orifice, twin-fan	150–600
MiniDrift	MD	11002	Hardi	Venturi, pre-orifice	100–500
MiniDrift Duo	MD Duo	11002	Hardi	Venturi, pre-orifice, twin-fan	150–600
TurboDrop Asymmetrical Dual-fan	TDADF	11002	Agrotop GmbH	Dual cap, Venturi, pre-orifice, asymmetric twin-fan	150–800
TurboDrop High Speed	TDHS	11002	Agrotop GmbH	Dual cap, Venturi, pre-orifice, twin-fan	200–1000
TurboDrop	TDXL	11002	Agrotop GmbH	Dual cap, Venturi, pre-orifice	100–800

would be observed as a CV greater than 4%. Consistency in this study is defined as the similarity of a given nozzle type CV across spray solution. Consistency of a nozzle type will result if the CV across solutions is ± 2% of each other.

2.4. Dynamic surface tension measurements

Liquids were quantified for dynamic surface tension (DST) using a bubble pressure tensiometer (Kruss BP-2 Bubble Pressure Tensiometer, Kruss GmbH, Hamburg, Germany). DST was measured in the Cooper–White Laboratory at the Australian Institute of Bioengineering and Nanotechnology (AIBN) at the University of Queensland, St. Lucia, Australia. DST was recorded at 20 ms and 25 °C, a time and temperature consistent of agricultural hydraulic nozzle atomisation (Hewitt et al., 2002). Each liquid was measured twice to produce a composite DST for each liquid.

2.5. Statistical analyses

Data were analysed using a generalised linear mixed model (PROC GLIMMIX) in SAS (Statistical Analysis Software, version 9.4, Cary, North Carolina, USA) with means separations made at the $\alpha = 0.05$ level. The model for each nozzle set (e.g., within all five AIXR 11002s) was: *spray droplet spectrum variable* = nozzle unit × spray solution (e.g. $D_{v0.5}$ = nozzle unit × spray solution). Each nozzle type was analysed separately across the three spray solutions for each of the categories of droplet spectrum characterisation ($D_{v0.1}$, $D_{v0.5}$, and percentage of the spray volume contained in droplets with a diameter below 150 μm and the RS). Tukey–Kramer's Honestly Significant Difference (HSD) adjustment was applied to means separation for the data (Kramer, 1957). Nozzle types were analysed in this manner since the study was focused on differences within a nozzle type, not differences between nozzle types which would be expected given the size class of nozzles selected for the study. The replicate was random, as conditions were tightly controlled and would not have impacted the outcome. This model isolated the two main variables of focus – nozzle unit by spray solution.

3. Results

CV values ranged from 0.5 to 7.6 %, but most nozzles had CV values below 3% (Table 2). Nozzles that were not different across $D_{v0.5}$ (Table 3) had an average CV below 2, (Table 2). Water resulted in the most erratic standard deviations and CVs across nozzle type with some at or above ± 30 μm and CVs over 5% (ABJ 110015 and ID 12002). The pinoxaden + methylated oil spray solution showed the lowest standard deviations and CVs across the nozzle types.

Nozzle unit effects were not significantly different for four nozzle types (IDKT 120015, MD11002, MD Duo 11002, and ULD 12002) for each of the respective droplet size parameters measured (Table 3). Two nozzle types (AITTJ60 11002 and ID 12002) had nozzle unit differences for each droplet size parameter measured (Table 3). Most nozzle types tested had nozzle unit differences across each respective size parameter, but had a similar relative span (RS). With the exception of five nozzle types, (AITTJ60 11002, ID 12002, IDK 12002, TDADF 11002, and TTI 11002), other types had a similar RS regardless of the response of other droplet size parameters (Table 3).

Nozzle types in this study that were classified as uniform were: XR, ABJ 11002, AITTJ60, AIXR 110015, GA 11002, ID 120015, IDK, IDKT, MD, MD Duo, TDADF, TDXL, TTI 110015 and 11002, TTJ60, and ULD 110015 and 11002. Each of these nozzle types had an average CV at or below 4%. Non-uniform nozzle types were: ABJ 110015, AIXR 11002, GA 110015, and the TDHS. All of the non-uniform nozzles were consistent except the ABJ 110015. All nozzles were consistent except for the ABJ 110015, IDKT, TDADF, and the TTJ60.

The DST was different across spray solutions tested (Table 4). The effect of the DST was mostly linear with respect to $D_{v0.5}$ across nozzle type (Table 2). Where the DST decreased, so did the value of the $D_{v0.5}$ (Table 2). The spray solution effect was significant for $D_{v0.5}$ across all nozzle types except the MD Duo 11002. This nozzle type did not have any differences across the whole droplet size spectrum (Table 3) and no differences across all three spray solutions. The MD Duo 11002 was least affected with respect to changes in spray solution across each size parameter.

The GA 11002 and XR 11003 resulted in a reverse of the overall trend where lower DST values led to an increase in droplet $D_{v0.5}$ (Table 2). This trend was also similar with the GA 110015 where the

Table 2
Mean $D_{v0.5}$, standard deviation (σ) and coefficient of variation (CV) by spray solution across nozzle units per nozzle type.

Nozzle	Water			Clopyralid			Pinoxaden + methylated oil			Across spray solution
	Mean $D_{v0.5}$	σ +/−	CV	Mean $D_{v0.5}$	σ +/−	CV	Mean $D_{v0.5}$	σ +/−	CV	CV
	μm		%	μm		%	μm		%	%
XR 11003 (reference)	221	7.3	3.3	227	4.7	2.1	252	4.4	1.8	2.4
ABJ 110015	375	28.6	7.6	362	26.0	7.2	348	14.5	4.2	6.3
ABJ 11002	377	9.6	2.5	369	5.1	1.4	361	3.5	1.0	1.6
AITTJ60 11002	436	8.4	1.9	435	8.7	2.0	362	11.2	3.1	2.3
AIXR 110015	346	3.9	1.1	338	10.3	3.0	342	9.1	2.6	2.2
AIXR 11002	389	19.6	5.0	376	16.4	4.4	375	12.8	3.4	4.3
GA 110015	341	15.9	4.7	336	15.5	4.6	344	10.6	3.1	4.1
GA 11002	339	6.1	1.8	352	8.2	2.3	365	8.7	2.4	2.2
ID 120015	597	19.4	3.2	552	6.9	1.2	502	12.7	2.5	2.3
ID 12002	511	29.7	6.1	474	21.3	4.5	436	23.8	5.5	5.4
IDK 12002	411	4.6	1.1	393	6.4	1.6	384	4.8	1.3	1.3
IDKT 120015	511	16.4	3.2	508	8.2	1.6	481	4.4	0.9	1.9
MD 11002	383	4.2	1.1	367	3.7	1.0	368	3.1	0.8	1.0
MD Duo 11002	466	4.8	1.0	463	2.3	0.5	462	3.5	0.8	0.8
TDADF 11002	374	7.8	2.1	364	14.8	4.1	345	15.2	4.4	3.5
TDHS 11002	518	28.5	5.5	507	27.5	5.4	493	28.8	5.8	5.6
TDXL 11002	402	5.1	1.3	408	8.7	2.1	383	12.0	3.1	2.2
TTI 110015	773	13.0	1.7	650	10.5	1.6	630	14.0	2.2	1.8
TTI 11002	732	5.4	0.7	656	8.7	1.3	625	12.2	2.0	1.3
TTJ60 11002	270	5.4	2.0	262	11.7	4.5	211	5.8	2.8	3.1
ULD 120015	401	7.7	1.9	411	14.1	3.4	379	8.5	2.3	2.5
ULD 12002	424	7.6	1.8	430	3.4	0.8	406	3.9	1.0	1.2

Standard deviations were calculated across nozzle type by subtracting the mean nozzle type Dv0.5 from the mean Dv0.5 values from each nozzle unit.

pinoxaden/methylated oil solution resulted in the largest droplet $D_{v0.5}$. Spray solution effects were apparent in some cases, where a change in solution affected droplet size by as much as ± 40 μm across five nozzles (AITTJ60 11002, ID 120015 and 12002, TTI 110015 and 11002) which had the largest Dv0.5 of those tested. The spray solution can alter the droplet size classification as is evident with some nozzles in this study (Table 5). Values for the droplet size classifications were previously recorded in 2008 (Hewitt, 2008), prior to the development of the current ASAE droplet size classification system, but they are still relevant for defining the curves for each size classification. Most of the nozzles in this study did not have that type of effect (Table 5), but this is worth noting as labels and best management practices increasingly support the use of specific droplet size classes for specific efficacy and/or spray drift management end-points.

Table 3
Statistical analysis for each spray droplet spectrum component across spray solutions by nozzle type across nozzle units.

Nozzle	$D_{v0.1}$	$D_{v0.5}$	<150 μm	RS
	μm	μm	%	
XR 11003 (reference)	NS	0.0002	0.0067	NS
ABJ 110015	<0.0001	<0.0001	<0.0001	NS
ABJ 11002	0.0017	0.0189	0.0041	NS
AITTJ 11002	<0.0001	0.0050	<0.0001	0.0090
AIXR 110015	0.0073	0.0010	0.0059	NS
AIXR 11002	<0.0001	<0.0001	<0.0001	NS
GA 110015	<0.0001	<0.0001	<0.0001	NS
GA 11002	0.0002	<0.0001	0.0015	NS
ID 120015	<0.0001	<0.0001	<0.0001	NS
ID 12002	<0.0001	<0.0001	<0.0001	0.0140
IDK 12002	NS	0.0256	0.0204	0.0165
IDKT 120015	NS	NS	NS	NS
MD 11002	NS	NS	NS	NS
MD Duo 11002	NS	NS	NS	NS
TDADF 11002	0.0160	<0.0001	0.0018	<0.0001
TDHS 11002	<0.0001	<0.0001	<0.0001	NS
TDXL 11002	0.0389	0.0367	NS	NS
TTI 110015	0.0010	0.0444	0.0119	NS
TTI 11002	0.0134	NS	NS	0.0145
TTJ60 11002	0.0338	<0.0001	0.0006	NS
ULD 120015	0.0009	<0.0001	0.0002	NS
ULD 12002	NS	NS	NS	NS

Each column includes the statistical significance across nozzle units and solutions for each respective droplet spectrum classification component. Data were separated using Tukey's HSD at $\alpha = 0.05$ and each nozzle was analysed separately. P values are listed if there was significance. NS (non-significant) indicates that there was not a nozzle effect across spray solutions.

4. Discussion

This study aimed to look at the effects of several common spray variables on the repeatability or variance impacting droplet size spectra applied in agricultural spray applications. These variables were as follows: 1) the nozzle unit (replicate unit of a given nozzle type) and 2) the applied spray solution (because different solutions have different physical properties such as dynamic surface tension which can impact the atomisation process differently through different nozzle types and units). The results from this study indicate that there is a clear difference in nozzle uniformity across nozzle types with as much as 7.6% CV in droplet size across units (Table 2). Results support the findings of Fritz et al. (2014) who observed less difference in the droplet size results across the respective wind tunnel laboratories at the CPAS Wind Tunnel Research Facility at The University of Queensland in Gatton QLD; the United States Department of Agriculture Agricultural Research

Table 4
Dynamic surface tension (DST) measurements from each spray solution measured at 20 ms and 25 °C.

Solution	DST
	mN/m
Water	72 a
Clopyralid	69 b
Pinoxaden + methylated oil	54 c

Each DST was recorded twice and averaged in the table. Data were analysed using Tukey's HSD at $\alpha = 0.05$. Different letters indicate significance.

Table 5
Selected nozzles by spray solution and the respective ASAE droplet size classification based on $D_{v0.5}$ with droplet size classification determined from Hewitt (2008) at the CPAS Wind Tunnel Research Facility at the University of Queensland.

Nozzle	Water		Clopyralid		Pinoxaden + methylated oil	
	$D_{v0.5}$					
	μm		μm		μm	
XR 11003 (reference)	221	F	227	F	252	M
GA 11002	336	M	352	C	365	C
ID 12002	511	VC	474	VC	436	C
TTI 110015	773	UC	650	XC	630	XC
TTI 11002	732	UC	656	UC	625	XC
TTJ60 11002	270	M	262	M	211	F

F = Fine; M = Medium; C = Coarse; VC = Very Coarse XC = Extra Coarse; UC = Ultra Coarse.

Service (ARS) Aerial Application Technology Lab in College Station, TX; and the University of Nebraska Pesticide Application Technology Laboratory in North Platte, NE than across the non-reference ground nozzle types used in their study. The certified reference nozzle sets for each lab were consistent (Fritz et al., 2014), but this is not surprising given the greater degree of scrutiny to individual nozzles selected for the set.

With three-quarters of all nozzles tested having a CV below 4% across spray solution, this seems an acceptable standard to meet. This study has shown some examples of nozzles that are consistent and uniform, supporting their recommendation for a high level of confidence in droplet size performance consistency based on low variability.

Effects on efficacy or spray drift potential are not presented here. It is well known that nozzles respond differently to changes in fluid physical properties (Miller and Butler-Ellis, 2000; Butler-Ellis et al., 2001), but the degree to which each nozzle responds can also vary. Eight nozzles had a CV below 2%, and five nozzles had a CV above 4% which supports previous research that reported venturi nozzles responding differently to changes in spray solution (Miller and Tuck, 2005). It is well established that fluid physical properties influence the atomisation process and driftability of the spray (Dombrowski and Fraser, 1954; Lefebvre, 1989; Ferguson et al., 1992). The TTI 11002 $D_{v0.5}$ varied by more than ± 50 μm across spray solution (Table 2) yet across the three spray solutions the nozzle CV was 1.3%. The TTI 11002 produces an Ultra-Coarse droplet size spray [$D_{v0.5}$ generally > 650 μm (ASAE, 2009)], but the CV of 1.3% across nozzles and spray solutions indicates a consistent and uniform response (Table 2). This is countered by the ID 12002 which also varied by 100 μm across spray solution, but had a CV of 5.4% – a 4x increase against the TTI. The dynamic surface tension measurements help explain the differences observed in the overall droplet size results across nozzle type. Dombrowski and Fraser (1954) and Butler-Ellis et al. (2001) explained that dynamic surface tension affects sheet break-up which may explain why the nozzles responded differently to a change in surface tension in this study. Miller and Butler-Ellis (2000) observed that while DST is a key factor affecting droplet production, there appears to be other physical property factors at play. It was not clear why the XR 11003 and the GA 11002 resulted in an increase in the $D_{v0.5}$ with decreasing DST – an anomaly with respect to accepted fluid mechanics. Both nozzles though had consistent results across CVs and solution type, which would indicate that this result is not of great importance.

The comparison across spray solution types here is useful for the end user, as product catalogues from nozzle companies publish droplet size data using water alone (Croplands, 2015; Teejet, 2011; Hardi, 2011). While the comparison is useful to understand differences among a given company's nozzle types, it does not present the full scope as nozzles can change droplet size based on spray solution. The IDKT 120015 had a CV of 3% with water, 1.6% with pinoxaden + methylated oil and 0.9% for clopyralid – a threefold change in CV based on spray solution (Table 2). Work conducted by Etheridge et al. (1999) and Creech et al. (2015) likewise found that water alone did not properly characterise the droplet size classifications of several nozzles which varied by spray solution type. AI nozzles showed had a greater variability in their patterns compared to flat-fan nozzles, which could result in reduced efficacy (Etheridge et al., 1999).

The change in droplet size classification based on the change in the spray solution is of great importance, as the liquid properties could cause a spray application event to become off-label if poor nozzle selections are made. The droplet size classification from the TTJ60 11002 changed for the three spray solutions where it was Medium with water, Medium with clopyralid and Fine with pinoxaden (Table 5).

Performance variability implications are also worth noting as the new DRT programmes released by the US EPA and previous ones from Canada, the UK, and Europe (DEFRA, 2001; Health Canada, 2011) should be based on a sufficiently large and representative sample of nozzle tip and tank mixture combinations, which typically should favour the inclusion of reasonable worst case (i.e. highest spray drift potential) scenarios. In determining the DRT classification through the UK DRT scheme (Local Environmental Risk Assessment for Pesticides, or LERAP) or star method as selected for use in the USA, a nozzle that has a wide range of spray drift reduction outcomes may not give a comprehensive or even accurate indication of actual spray drift potential. This is a consideration with respect to nozzles that may be readily affected by a change in fluid physical properties as certain DRT adjuvants may inadvertently make a DRT nozzle show decreased spray drift reduction. The discussion is particularly germane when many DRT programmes and proposed programmes only take into account droplet size which can only present part of the picture of the usefulness of a given DRT treatment (Ferguson et al., 2014).

The nozzle with the lowest variability in the entire study was the MD Duo 11002. This nozzle was similar across the five nozzles for each of the droplet size parameters (Table 1) and had a standard deviation of ± 2.3 μm and a CV of 0.8% across spray solutions tested (Table 2). The MD Duo 11002 produced almost identical $D_{v0.5}$ values across the five replicates for each spray solution – 465 μm, 463 μm, and 462 μm for water, clopyralid, and pinoxaden, respectively (Table 3). The MD Duo 11002 was also the only nozzle which resulted in no difference in spray solution across the study. The droplet size and spray drift potential response of candidate DRT nozzles to tank mixture physical properties and the variability in performance across individual tips of a given nozzle type is an important consideration in DRT evaluation testing.

The nozzles in the present study with a dual fan were uniform but often not consistent. Of the nozzles that were uniform but not consistent, all but one were twin fan nozzles (IDKT 120015, TDADF 11002 and TTJ60 11002). The asymmetric flat-fan nozzle tested in this study, TDADF 11002 was uniform across nozzle replicates for the $D_{v0.5}$ (Table 3). This nozzle has two separate flat-fan inserts, which means that each individual nozzle is really a composite of two single fan nozzles.

In conclusion, the results from this study highlight the differences that exist in nozzle unit uniformity and repeatability of droplet size by nozzle type. Results also support prior studies showing that nozzle type can influence the sensitivity or tolerance to changes in liquid physical properties. Ongoing research is being conducted to determine further differences in these nozzles with respect to efficacy, coverage, and canopy penetration as these ultimately determine nozzle performance for their intended purpose of pest control. Results from this work will be used to support future field research examining biological effects with varying droplet size characteristics. Overall, most nozzles tested were uniform across nozzle units and showed little difference across solution type. Not all nozzles are created equally, and given the cost of some newer technologies, a greater impetus for consistency of performance ought to help drive markets resulting in a greater uniformity of nozzles off the shelf. Spray drift reduction is only possible if sprayers are equipped with the most uniform spray drift reducing technologies to ensure efficacy and coverage are maintained to best combat pests that seek to reduce viability of agricultural cropping systems.

Finally, it should be noted that it was not possible to test every available nozzle type in this study. The mention of certain nozzle and tank mixtures in this study is not intended to imply that these are the only ones or superior to other nozzles and types, nor to endorse their use over other nozzles.

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