GUILHERME SOUSA ALVES

DICAMBA DRIFT AS AFFECTED BY NOZZLE TYPE, WIND SPEED AND SPRAY COMPOSITION

Tese apresentada à Universidade Federal de Uberlândia, como parte das exigências do Programa de Pós-graduação em Agronomia – Doutorado, área de concentração em Fitotecnia, para obtenção do título de "Doutor".

Orientador
Prof. Dr. João Paulo Arantes Rodrigues da Cunha

Co-orientador
Prof. Ph.D. Greg R. Kruger

UBERLÂNDIA
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“Seja quem você for, seja qual for a sua posição social que você tenha na vida, a mais alta ou a mais baixa, tenha sempre como meta muita força, muita determinação e sempre faça tudo com muito amor e com muita fé em Deus, que algum dia você chega lá. De alguma forma você chega lá. *Whoever you are, no matter what social position you have, rich or poor, always show great strength and determination, and do everything with love and deep faith in God. One day you will reach your goals.*”

Ayrton Senna da Silva

“It ain’t about how hard you hit, it’s about how hard you can get hit and keep moving forward. *Não importa o quão duro você pode bater, mas sim o quanto você pode apanhar e ainda continuar em frente.*”

Rocky Balboa

Talvez esta obra seja a mais importante de minha vida.

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SUMARY

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ABSTRACT

SOUSA ALVES, GUILHERME. **Dicamba drift as affected by nozzle type, wind speed and spray composition.** 2017. 68 p. Dissertation (Doctorate in Agronomy/Crop Science) – Federal University of Uberlândia, Uberlândia[1] and University of Nebraska-Lincoln, North Platte[2].

With new releases of dicamba-tolerant crops, it is necessary to understand how technical and environmental conditions affects its application. This dissertation was developed at the West Central Research and Extension Center of the University of Nebraska-Lincoln in North Platte, Nebraska, USA. It was divided in three studies to evaluate dicamba spray drift. The first study evaluated dicamba drift from applications under four wind speeds (0.9; 2.2; 3.6; and 4.9 m s^{-1}). The second and third studies evaluated droplet spectrum and drift from applications of dicamba tank-mixed with drift-reducing adjuvants and glyphosate, conducted at 3.5 and 2.2 m s^{-1} wind speeds, respectively. The adjuvants used were polymer, ammonium sulfate, vegetable oil and phosphatidylcholine. All applications were performed in a wind tunnel using two standard (XR and TT) and two air induction (AIXR and TTI) 110015 nozzles at 276 kPa pressure. The nozzles were positioned 60 cm above the tunnel floor. Drift potential was determined using a fluorescent tracer added to solutions, quantified by fluorimetry. Round strings were used as drift collectors, positioned 10 cm above the tunnel floor and perpendicular to the wind direction from 2 to 12 m downwind from the nozzle. Each replication consisted of a continuous 10-second application. Droplet spectrum was measured at 6.7 m s^{-1} using a laser diffraction system. The air induction TTI nozzle produced the lowest percentage of dicamba drift at 2.2, 3.6 and 4.9 m s^{-1} wind speeds until 12 m, which increased linearly as wind speed increased. Dicamba spray drift from the XR, TT, and AIXR nozzles increased exponentially as wind speed increased. Non-air induction nozzles, in special XR, are not adequated to be used in dicamba applications. Droplet spectrum and dicamba drift depended on the interaction between spray composition and nozzle type. Dicamba associated with vegetable oil and phosphatidylcholine produced finer droplets than dicamba alone when sprayed through the TTI nozzle. The polymer and ammonium sulfate increased the droplet size for all nozzle types. At 12 m from theTTI nozzle, dicamba solutions with or without any adjuvant produced similar drift. Dicamba alone produced coarser droplets than dicamba + glyphosate when sprayed through air induction nozzles. Dicamba tank-mixed with glyphosate reduced the drift if sprayed through the XR, TT, and AIXR nozzles. If sprayed through the TTI nozzle, dicamba alone produced less drift. In general, drift decreased exponentially as downwind distance increased for all spray compositions.

Keywords: herbicide application technology, flat-fan nozzles, environmental contamination, wind tunnel.

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[1] Advisor: João Paulo A. R. da Cunha – UFU.
[2] Co-advisor: Greg R. Kruger – UNL.

RESUMO

SOUSA ALVES, GUILHERME. **Deriva de dicamba influenciada por ponta de pulverização, velocidade do vento e composição da calda.** 2017. 68 f. Tese (Doutorado em Agronomia/Fitotecnia) – Universidade Federal de Uberlândia, Uberlândia[3] e University of Nebraska-Lincoln, North Platte[4].

Com o desenvolvimento de culturas tolerantes ao dicamba, torna-se necessário entender como condições técnicas e ambientais afetam a aplicação deste herbicida. Esta tese foi desenvolvida no Centro de Extensão e Pesquisa do Centro-Oeste da Universidade de Nebraska-Lincoln em North Platte, Nebraska, EUA. A tese foi dividida em três estudos para avaliar a deriva de dicamba. O primeiro estudo avaliou a deriva de dicamba em aplicações sob quatro velocidades do vento (0,9; 2,2; 3,6 e 4,9 m s^{-1}). O segundo e o terceiro estudos avaliaram o espectro de gotas e a deriva em aplicações de dicamba em mistura com adjuvantes redutores de deriva e glifosato, conduzidos a 3,6 e 2,2 m s^{-1}, respectivamente. Os adjuvantes usados foram polímero, sulfato de amônio, óleo vegetal e fosfatidilcoline. Todas as aplicações foram realizadas em um túnel de vento, usando pontas padrão (XR e TT) e com indução de ar (AIXR e TTI) 110015 na pressão de trabalho de 276 kPa. As pontas foram posicionadas 60 cm acima do piso do túnel. O potencial de deriva foi determinado quantificando-se um traçador por fluorimetria previamente adicionado às caldas. Fios de nylon circulares foram usados como coletores de deriva, posicionados 10 cm acima do piso do túnel, perpendiculares à direção do vento, de 2 a 12 m de distância da ponta de pulverização. Cada repetição consistiu em uma aplicação contínua de 10 s. O espectro de gotas foi medido por um sistema de difração a laser, na velocidade do vento de 6,7 m s^{-1}. A ponta com indução de ar TTI produziu a menor porcentagem de deriva nas velocidades do vento de 2,2; 3,6 e 4,9 m s^{-1} até 12 m de distância, tendo aumento linear à medida em que a velocidade do vento aumentou. Pontas sem indução de ar, especialmente do tipo XR, não são adequadas para aplicações de dicamba. O espectro de gotas e deriva de dicamba dependeram da interação entre composição de calda e tipo de ponta. As soluções de dicamba com óleo vegetal e fosfatidilcoline produziram gotas mais finas do que a solução apenas com dicamba aplicadas pela ponta TTI. O polímero e sulfato de amônio aumentaram o tamanho das gotas quando aplicados por todas as pontas. A 12 m da ponta TTI, soluções de dicamba com e sem qualquer adjuvante produziram derivas similares. A solução apenas com dicamba produziu gotas mais grossas do que a solução de dicamba com glifosato usando-se as pontas com indução de ar. Dicamba associado ao glifosato reduziu a deriva se aplicado pelas pontas XR, TT e AIXR. Se aplicado pela ponta TTI, dicamba sem glifosato produziu menos deriva. Para todas as composições de calda, em geral, a deriva reduziu exponencialmente à medida em que a distância da ponta de pulverização aumentou.

Palavras-chave: tecnologia de aplicação de herbicidas, pontas de jato plano, contaminação ambiental, túnel de vento.

[3] Orientador: João Paulo A. R. da Cunha – UFU.
[4] Co-orientador: Greg R. Kruger – UNL.

CHAPTER I: HERBICIDE APPLICATION TECHNOLOGY – A SPRAY DRIFT APPROACH

1 GENERAL INTRODUCTION

Spray application has changed more in the past ten years than in the previous fifty. Not only we are spraying a greater diversity of crops with more types of crop protection agents and larger, more efficient machines, we are also under the scrutiny of a public that is increasingly interested in what they think are sound agricultural practices (WOLF, 2009). As a result, regulations that protect public spaces, especially air and water, have been emerging and will continue to force change in the industry (KUCHNICKI et al., 2004). Public awareness and concern about agricultural herbicide use has increased creating the need to regularly re-evaluate weed control and herbicide application practices (WALLACE; BELLINDER, 1992).

Herbicides continue to play a critical role in weed control for many growers in the world. Once it is totally impossible to eliminate drift in agricultural pesticide applications, herbicide drift is a source of environmental contamination which has potential human health impacts, and can cause damage to non-target plants, animals, and other natural resources. Herbicides should technically only be used when cultural management practices cannot provide effective weed control. If their use are needed, their efficacy has to be balanced with getting the job done quickly and ensure that we do not harm non-target areas (HISLOP, 1987).

The introduction of herbicide-tolerant crops was promoted as a way to simplify weed management and increase weed control (MARTINEZ-GHERSA et al., 2003). This includes development of dicamba-, 2,4-D-, and 4-Hydroxyphenylpyruvate dioxygenase (HPPD) inhibitor-tolerant soybeans that are being developed by some companies and will soon be available to growers pending regulatory approval. Once approved, that technology will enable the use of those products with glyphosate tank-mixtures for preplant burndown, at planting, and in-season applications (DAVIS, 2012). It explains why it is so important to study what happens in terms of efficacy and drift when those herbicides are sprayed in tank-mixtures with glyphosate and other products such as adjuvants, which will be the tendency in the next few years.

The integration of herbicide-tolerant crops has resulted in increased usage of nonselective herbicides allowing growers to use more options later in the growing season, thereby increasing the chances that off-target movement of herbicides could damage non-tolerant crops and other sensitive vegetation, decreasing their yields (CREECH, 2015; REDDY et al., 2010). Besides, spray drift may also contribute to herbicide resistance in some weeds (LONDO et al., 2010; MANALIL et al., 2011).

Many efforts have been made to minimize herbicide spray drift using drift reduction techniques (DRT's), associated with best management practices for application technology. The DRT's include spray nozzles that minimize the production of droplets finer than 100 μm, sprayer modifications such as hoods or shields, spray delivery assistance such as air booms, spray liquid physical-property modifiers such as drift-reducing adjuvants, and/or landscape modifications (EPA, 2016; REICHARD et al., 1996; UCAR; HALL, 2001; WOLF et al., 1993).

Among the good agricultural practices for pesticide applications, Food and Agriculture Organization of the United Nations (FAO) reports that wind speeds between 1 and 2 m s^{-1} are generally considered ideal for hydraulic nozzle treatments during an application (FAO, 2001). However, it is well known that pesticide applications in the field are not always performed under ideal meteorological conditions. As wind speed is one of the most important environmental features that affect the distance that a sprayed droplet can reach, it is necessary research showing its effects on drift.

Given this general approach focused on factors that affect spray drift, as well as new releases of herbicide-tolerant crops, which will increase the use of nonselective herbicides, this dissertation was divided in three chapters to better discuss about dicamba spray drift. All applications were performed in a wind tunnel using standard and air-induction flat-fan nozzles commonly used in herbicide applications. The studies were separated according to their respective objectives, evaluating dicamba drift as affected by wind speed (Chapter II), drift-reducing adjuvants (Chapter III), and tank-mixed with glyphosate (Chapter IV).

2 OBJECTIVES

2.1 General objectives

The general objective of this dissertation was to evaluate dicamba spray drift from different application conditions in a wind tunnel, varying nozzle type, wind speed, and spray composition.

2.2 Specific objectives

- Quantify the drift from dicamba applications using standard and air induction flat-fan nozzles;
- Evaluate the effects of wind speed on dicamba spray drift;
- Determine a prediction drift model for dicamba applications as a function of driftable droplets and wind speed;
- Evaluate the effects of drift-reducing adjuvants on drift reduction and droplet spectrum in dicamba applications;
- Determine if the addition of glyphosate in tank-mixtures with dicamba has any influence on droplet spectrum and spray drift.

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CHAPTER II

DICAMBA SPRAY DRIFT AS INFLUENCED BY WIND SPEED AND NOZZLE TYPE[5]

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DICAMBA SPRAY DRIFT AS INFLUENCED BY WIND SPEED AND NOZZLE TYPE

ABSTRACT

With new releases of dicamba-tolerant crops, it is necessary to understand how technical and environmental conditions affect its application. This study sought to evaluate drift from dicamba applications through flat-fan nozzles, under several wind speeds in a wind tunnel. Dicamba applications were performed through two standard (XR and TT) and two air induction (AIXR and TTI) 110015 nozzles at 0.9, 2.2, 3.6 and 4.9 m s^{-1} wind speeds. The applications were made at 276 kPa pressure and the dicamba rate was 561 g ae ha^{-1} (0.6% v v^{-1}). The droplet spectrum was measured using a laser diffraction system. Artificial targets were used as drift collectors, positioned in a wind tunnel from 2 to 12 m downwind from the nozzles. Drift potential was determined using a fluorescent tracer added to solutions, quantified by fluorimetry. The air induction TTI nozzle produced the lowest percentage of dicamba drift at 2.2, 3.6 and 4.9 m s^{-1} wind speeds at all distances. Dicamba spray drift from the XR, TT and AIXR nozzles increased exponentially as wind speed increased, whereas from the TTI nozzle drift increased linearly as wind speed increased. Drift did not increase linearly as the volume percentage of droplets smaller than 100 µm and wind speed increased.

Keywords: herbicide application technology, air induction nozzles, percent fines.

DERIVA DE DICAMBA EM TÚNEL DE VENTO INFLUENCIADA PELA VELOCIDADE DO VENTO E PONTAS DE PULVERIZAÇÃO

RESUMO

Devido à expectativa do uso em larga escala de culturas tolerantes ao herbicida dicamba, é necessário entender como fatores técnicos e ambientais afetam a sua aplicação. O objetivo deste trabalho foi avaliar a deriva em aplicações de dicamba em túnel de vento usando-se pontas de jato plano. As aplicações foram realizadas através de duas pontas padrão (XR e TT) e duas pontas com indução de ar (AIXR e TTI) nas velocidades do vento de 0,9; 2,2; 3,6 e 4,9 m s^{-1}. A pressão utilizada foi de 276 kPa e a dose de dicamba foi de 561 g ea ha^{-1} (0,6% v v^{-1}). O espectro de gotas foi avaliado usando um sistema de difração a laser. Alvos artificiais foram usados como coletores e posicionados perpendicularmente à direção do vento, de 2 a 12 m de distância em relação à ponta de aplicação. A deriva foi determinada quantificando-se por fluorimetria um traçador adicionado à calda. A ponta TTI produziu a menor porcentagem de deriva em todas as distâncias nas velocidades do vento 2,2; 3,6 e 4,9 m s^{-1}. A deriva de dicamba proveniente das pontas XR, TT e AIXR aumentou exponencialmente, enquanto que para a ponta TTI aumentou linearmente à medida que se aumentou a velocidade do vento. A deriva em túnel de vento em aplicações de dicamba aumentou não linearmente à medida que a porcentagem do volume de gotas menores que 100 μm e a velocidade do vento aumentaram.

Palavras-chave: tecnologia de aplicação de herbicidas, pontas com indução de ar, porcentagem de gotas finas.

1 INTRODUCTION

Spray drift could be defined as the quantity of pesticide that is dissipated out from the treated area due to climatic conditions during the application process (GIL; SINFORT, 2005), primarily the wind (van PUL et al., 1999). It has caused concerns about the use of pesticides, specifically on herbicide dicamba due to new releases of genetically-engineered dicamba-tolerant cotton and soybean crops, being a new use for the previously approved herbicide dicamba. Hewitt (1997) described the paradox encountered in agricultural spraying. Smaller droplets are often the most efficacious and may offer better coverage, but also are generally more prone to drift under unfavorable conditions. There is lack of studies evaluating the impact of spray droplet size on the pesticide efficacy. Specifically for dicamba, Creech et al. (2016) observed a 17% better control of common lambsquarter using medium droplets compared with fine droplets. Besides providing safer applications, larger droplets may also provide better efficacy in some situations.

Dicamba is a selective herbicide in the Benzoic Acid family of chemicals which has been used to control many broadleaf weeds and woody plants. Its use will likely increase in the near future to help farmers manage weeds that have become resistant to other herbicides (EPA, 2016), as new dicamba-tolerant cotton and soybean varieties are now commercially available. However, there is little research showing how technical and environmental conditions, such as nozzle type and wind speed, could affect dicamba movement during application. By knowing these points, its recommendation would be much safer.

Among the factors which affect drift, equipment, application techniques and weather conditions are the most important (GANZELMEIER et al., 1995; HAPEMAN et al., 2003; HOFMAN; SOLSENG, 2001; THREADGILL; SMITH, 1975). Many studies have been reported in literature related to equipment and application techniques (FERGUSON et al., 2015; PHILLIPS; MILLER, 1999; ROTEN et al., 2014; SCHRÜBBERS et al., 2014); however, few of them are related to environmental factors including wind speed. Miller et al. (2000) found that atmospheric stability was the major determinant of the amount of deposition in adjacent areas to treated fields. Wind speed and direction have a significant effect on drift values (NUYTTENS et al., 2011). However, many drift prediction models do not consider atmospheric stability effects on displacement. Experiments are necessary under real conditions, which include velocity and temperature measurements (GIL; SINFORT, 2005).

Drift reduction techniques (DRTs) have come to the forefront of application research in the past few years, and these include new spray nozzles, sprayer modifications, spray delivery assistance, spray property modifiers (adjuvants), and/or landscape modifications (HOFFMANN et al., 2010). Among these factors, spray droplet size has long been recognized as one of the most important variables to be considered to mitigate spray drift (BIRD et al., 1996). Low-drift nozzle selection is essential to reduce spray drift (CELEN, 2010), as these nozzles produce coarser droplets compared to ordinary flat-fan nozzles (COOPER; TAYLOR, 1999; MILLER, 1999).

Another attempt to minimize the effects of drift are buffer zones, which are unsprayed strips between the edge of the application and neighboring areas. No general agreement exists among researchers on whether or not buffer zones will offer enough protection to surrounding areas (CARLSEN et al., 2006). Snoo and Wit (1998) stated that a zone of 5 to 10 m wide reduces drift considerably.

Drift management requirements will be specified on several new dicamba-containing herbicide labels, including guidelines for boom height, buffer zones, tank-mix partners, nozzle selection, operating pressure, wind speed and air temperature at time of application (HEWITT, 2000). If the applicators do not follow label guidelines, they may be penalized. Therefore, the objective of this research was to evaluate drift from dicamba applications through air induction and non-air induction flat-fan nozzles, under several wind speeds in a wind tunnel. From these observations, a prediction drift model was created as a function of driftable fine droplets and wind speed.

2 MATERIALS AND METHODS

This study was conducted at the Pesticide Application Technology Laboratory (PAT Lab) at the West Central Research and Extension Center of the University of Nebraska-Lincoln in North Platte, Nebraska, USA, in 2015.

2.1 Experimental designs

Four studies were conducted separately, characterized by different wind speeds. However, experimental design and configuration were the same in all studies. The wind speeds used were 0.9, 2.2, 3.6 and 4.9 m s^{-1} (3.2, 7.9, 13.0, and 17.6 km h^{-1}) and were measured using a portable anemometer (Nielsen-Kellerman Inc., Kestrel® 4000, Boothwyn, PA, USA) placed upwind of the boom at the nozzle height. Within each wind speed, the experimental design was a 4 x 7 split-plot arranged in a complete random design with four replications. Main plots and sub-plots consisted of four nozzle types, and seven downwind distances from the nozzles (2, 3, 4, 5, 6, 7, and 12 m), respectively. These four experiments were conducted twice in time, representing two experimental runs. All conditions (treatments, wind tunnel set up, procedures, etc.) were the same for both runs.

Another study was conducted in a complete random factorial scheme with four nozzle types (and different droplet spectrum) and four wind speeds. However, drift was only measured at 12 m downwind from the nozzles. The nozzle types and wind speeds were the same in all studies.

Dicamba (Clarity®, BASF, Research Triangle Park, NC, USA) was used at rate of 1.17 L ha^{-1} (561 g ae ha^{-1}) of commercial product, and applied at 200 L ha^{-1} (0.6% v v^{-1}) through a single and static nozzle. In addition, a PTSA fluorescent tracer (1,3,6,8-pyrenetetrasulfonic acid tetrasodium salt) (Spectra Colors Corp., Kearny, NJ, USA) was added to the solution at 1 g L^{-1} to be detected using fluorimetry (HOFFMANN et al., 2014; ROTEN et al., 2014). Nozzles types included Extended Range (XR), Turbo TeeJet (TT), Air-Induction Extended Range (AIXR), and Turbo TeeJet Induction (TTI) (Spraying Systems Co., Wheaton, IL, USA). All nozzles were 110015 flat-fan nozzles and were evaluated at a pressure of 276 kPa. A digital manometer was fixed next to each nozzle to ensure that the pressure was the same for all nozzles. Each replication consisted of a continuous 10-second application, controlled by a digital auto shut-off timer switch (Intermatic Inc., EI 400C, Spring Grove, IL, USA). All distances were sprayed at the same time and each set was considered one replication.

2.2 Determination of drift

Applications were performed in a wind tunnel with a working section of 1.2 m wide, 1.2 m high, and 15 m long. This wind tunnel used an axial fan (Hartzell Inc., Piqua, OH, USA) to generate and move air flow from the fan into an expansion chamber located in front of the tunnel. Environmental conditions during applications were kept at 20ºC (± 2ºC) and 60 to 70% relative humidity.

The drift was determined in accordance to the ISO 22856 Standard (ISO 22856, 2008) with a few modifications, calculated as function of the amount of tracer deposited on collectors. This methodology has also been used by many other researchers (COSTA et al., 2006; LUND, 2000; QI et al., 2008; WALKLATE et al., 2000). The uniformity of the artificial wind was also measured as recommended by ISO Standard, obtaining a degree of turbulence of 7.2%, being lower than the maximum tolerate value (8%).

Prior to each application, artificial collectors composed of colorless round strings 2 mm in diameter (Blount Inc., Magnum Gatorline^{TM}, Portland, OR, USA) and 1.0 m length were positioned at each distance, parallel and perpendicular to the tunnel floor and its length, respectively. Herbst and Molnar (2002) concluded that cylindrical collectors with a diameter of 2 mm and with a smooth and well-defined surface were the most suitable collectors for airborne drift. The collectors and nozzle were placed at 0.1 m and 0.6 m above the tunnel floor and in the longitudinal center of the wind tunnel, respectively. A 1.2 m x 0.5 m rug with polyethylene blades 1 cm tall (GrassWorx LLC., St. Louis, MO, USA) was positioned on the sprayed area to absorb droplets, simulating a leaf area (Figure 2.1).

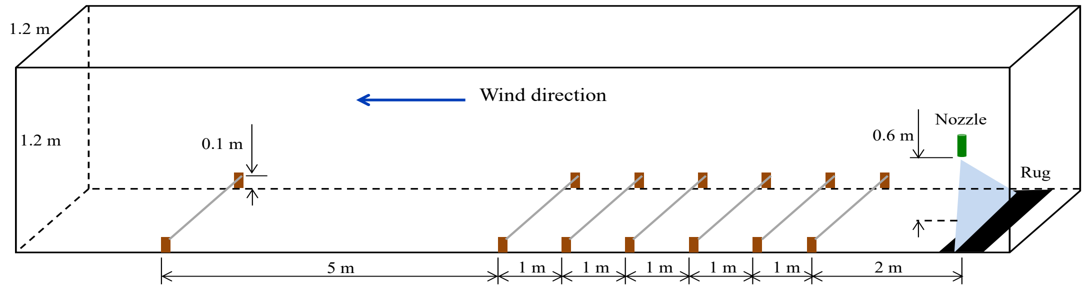


FIGURE 2.1. Schematic drawing detailing the positions of nozzle and drift collectors in a wind tunnel.

2.3 Sampling process

Once the application was performed, strings were collected and placed individually into pre-labeled plastic bags and then placed into a dark container to prevent photodegradation of the tracer. Samples were kept in the dark until fluorimetric analysis could be conducted. In the laboratory, a similar technique described by Roten et al. (2014) was used to extract the tracer from the collectors. A 50 mL of 1:9 isopropyl alcohol:distilled water solution was added to each plastic bag using a bottle top dispenser (LabSciences Inc., 60000-BTR, Reno, NV, USA). Samples were then swirled and shaken to release fluorescent material. After the tracer was suspended in solution, a 1.5 mL aliquot from each sample bag was drawn to fill a glass cuvette. The cuvette was placed in a PTSA module inside a fluorimeter (Turner Designs, Trilogy 7200.000, Sunnyvale, CA, USA) using ultra-violet light to collect fluorescence data. The fluorimeter was initially calibrated to Relative Fluorescence Unit (RFU), which was converted into mg L^{-1} using a calibration curve for the tracer (Figure 2.2).

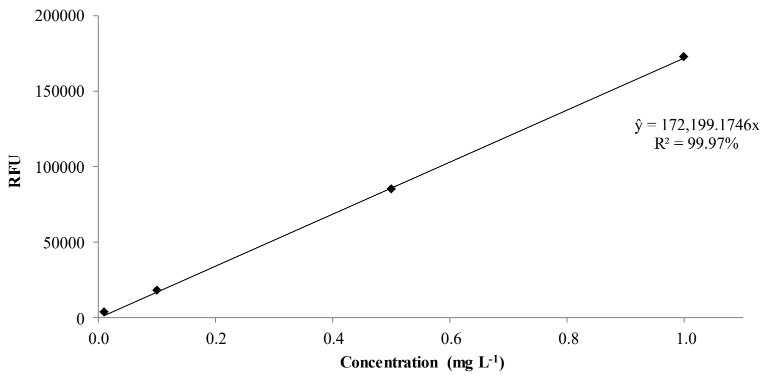


FIGURE 2.2. Calibration curve for the PTSA tracer showing the relationship of concentration of dye to relative fluorescence units (RFU).

Finally, percentage of drift for each distance was calculated in accordance to the ISO Standard using Equations 1 and 2:

$$\beta_{dep} = \frac{(\rho_{sample} - \rho_{blank}) \times f_{flow} \times f_{conc} \times V_{dil}}{\rho_{spray}} \qquad \text{(Equation 1)}$$

$$\%Drift = \frac{\beta_{dep} \times C_{lenght}}{C_{diameter} \times A_{time} \times R_{flow}} \times 6 \qquad \text{(Equation 2)}$$

Where:

β_{dep}: spray drift deposit (mL);

ρ_{sample}: fluorimeter reading of the sample (mg L^{-1});

ρ_{blank}: fluorimeter reading of the blanks (collector + extractor solution) (mg L^{-1});

ρ_{spray}: concentration of referential solution (g L^{-1});

f_{flow}: adjustment factor for flow rate (dimensionless);

f_{conc}: adjustment factor for tracer concentration from solution (dimensionless);

V_{dil}: volume of dilution liquid used to solute tracer from collector (L);

C_{lenght}: drift collector length (mm);

$C_{diameter}$: drift collector diameter (mm);

A_{time}: application time (s);

R_{flow}: flow rate of referential nozzle (L min^{-1})

2.4 Droplet spectrum

The droplet spectrum produced by each nozzle type was measured using a Sympatec HELOS-VARIO K/R laser diffraction droplet sizing system (Sympatec Inc., Clausthal, Germany) set up with a R7 lens with a dynamic size range of 9 to 3700 µm. This system was integrated into the wind tunnel and the wind speed was maintained at 6.7 m s^{-1} during data acquisition, following methodology proposed by Fritz et al. (2014). The pressure was the same used at drift determination, 276 kPa, and the distance from the nozzle tip to the laser was 0.3 m. Three replicated measurements were made for each treatment, with each replication consisting of a complete vertical traverse of the spray plume. Spray parameters of interest were volumetric median diameter (VMD) and volume percentage of droplets smaller than 100 µm (driftable fine droplets - V_{100}).

2.5 Statistical analysis

Normality of residuals and homogeneity of variance of drift data were analysed by Kolmogorov-Smirnov and Levene's tests, respectively, using SPSS Statistical Software, version 17.0 (SPSS Inc., Chicago, IL, USA). In cases that the assumptions were significant at $\alpha = 0.01$, the data were transformed by arc sine [$(x/100)^{0.5}$] and subjected to a new analysis. The data (original and transformed) were subjected to analysis of variance (ANOVA) using Sisvar Statistical Software, version 5.6 (FERREIRA, 2011). Nozzles were compared to each other within each distance by Tukey's multiple comparison test, whereas regression analysis was performed for the distances, both at $\alpha = 0.05$. All adjustments of the regressions were made using SigmaPlot Software, version 11.0 (Systat Software Inc., Chicago, IL, USA). Joint analysis was performed to make comparisons between wind speed experiments and proceeded when the ratio between the greatest and lowest mean square error (MSE) of ANOVA from each experiment was not over to 3, as described by Box (1954) and Pimentel-Gomes and Guimarães (1958).

For the study conducted in a factorial scheme, comparisons between nozzles were made using Tukey's test and regression analysis was applied to wind speed. With droplet spectrum analysis, percentage of drift at 12 m downwind was subjected to a multiple regression analysis, being the drift as result of driftable fine droplets and wind speed. This analysis, as well as response surface graph based on multiple regression, were made using Statistica Software (Dell Inc., Tulsa, OK, USA).

3 RESULTS AND DISCUSSION

The VMDs generated by XR, TT, AIXR and TTI nozzles were 172, 248, 372 and 774 µm, while V_{100} were 19, 7, 2 and 0.3%, respectively. These four nozzles had a wide range of droplet spectra with 4.5-fold difference between the largest and smallest VMD and 64-fold difference between the highest and lowest V_{100}. Comparisons between wind speeds were not possible because the ratio between the highest and lowest MSE was over 3. In this case, joint analysis could not be applied to the data and the analysis was performed separately within each wind speed.

In general, the highest and lowest percentage of drift with dicamba applications occured with XR and TTI nozzles, respectively, across distances at wind speeds over 0.9 m s^{-1} in both experimental runs (Table 2.1). At 0.9 m s^{-1}, standard nozzles (non-air induction - XR and TT) produced similar drift at 7 m and 12 m as compared with air induction nozzles. In run 2, air induction nozzles produced similar drift at distances over 5 m. At 12 m, TT, AIXR and TTI nozzles produced similar drift, varying from 0 to 0.1% in run 1 and from 0.1 to 0.3% in run 2.

At the closest sampling point (2 m), the XR nozzle produced 25 times more drift than TTI nozzle at 0.9 m s^{-1}, 16 times at 2.2 m s^{-1}, 7 times at 3.6 m s^{-1} and 4 times at 4.9 m s^{-1}. At 12 m the differences were 6, 31, 24 and 24 times, respectively. Even under high wind speeds, ultra-coarse droplets (produced through the TTI nozzle) had a tendency to be deposited on areas closer to the nozzle. On the other hand, low wind speeds are enough to carry fine droplets (produced through the XR nozzle) at further distances from nozzle.

Drift decreased exponentially as the downwind distance increased for all nozzle types and wind speed, except for the TTI nozzle at 0.9 m s^{-1}, where no significant regression model could be calculated (Figure 2.3; Table 2.2). All significant regression models for drift data had coefficient of determination values over 99.7% for both experimental runs. For the XR nozzle in run 1, the estimated drift data at 4.9 m s^{-1} was below to the estimated drift data at 3.6 m s^{-1} until the 4 m distance; however, beyond 5 m, the opposite was observed. This same response was not observed in run 2, which suggests that there was an unknown factor causing overestimated drift at closer distances in run 1. At lower wind speeds, drift curves generally had larger and narrower numerical curvature angles for non-air induction and air induction nozzles, respectively, at distances less than 5 m. The opposite was observed at higher wind speeds. At further distances, finer droplets sprayed at higher wind speeds, such as those produced through XR and TT nozzles, had a tendency to have less inclined drift curves.

Bueno et al. (2016) and Carlsen et al. (2006) evaluated pesticide drift from a boom sprayer with flat-fan and low-drift nozzles in field experiments and observed that the deposits declined exponentially as the distance from the sprayed area increased, as observed in this study. It shows that drift measured in wind tunnels and in the fields has similar behavior.

Considering that the base of the wind tunnel is smooth, the drift collected could be even lower than the drift collected from applications where there are surfaces capable to absorb droplets, as happens in field situations. Thus, experiments in wind tunnels may overestimate the drift observed in the field under similar conditions of temperature, wind speed, etc. Miller (1999) observed 50% less drift at 3 m when vegetative strips at field boundaries were used in comparison with cut stubble.

TABLE 2.1. Percentage of drift in dicamba applications at wind speeds of 0.9, 2.2, 3.6, and 4.9 m s^{-1} through four flat-fan nozzles in two experimental runs

Nozzle	Distance (Run 1)[a] m							Distance (Run 2) m						
	Wind speed = 0.9 m s^{-1}													
	2	3	4	5	6	7	12	2	3	4	5	6	7	12
	%													
XR	10.3 c	3.5 c	2.2 c	1.3 d	0.9 d	0.6 b	0.1 b	18.7 d	6.6 d	3.2 d	1.9 c	1.2 c	0.8 c	0.3 b
TT	9.1 c	3.3 c	1.6 c	0.9 c	0.6 c	0.5 b	0.1 ab	9.5 c	3.5 c	1.7 c	1.2 b	0.7 b	0.5 b	0.3 ab
AIXR	2.8 b	1.3 b	0.6 b	0.3 b	0.2 b	0.1 a	0.0 ab	2.9 b	1.3 b	0.6 b	0.4 a	0.3 a	0.3 a	0.1 ab
TTI	0.5 a	0.3 a	0.1 a	0.1 a	0.1 a	0.1 a	0.0 a	0.6 a	0.3 a	0.2 a	0.2 a	0.2 a	0.1 a	0.2 a
	Wind speed = 2.2 m s^{-1}													
XR	65.9 d	40.4 d	25.3 d	16.6 d	12.1 d	8.9 d	3.0 c	56.1 d	31.7 d	19.3 d	13.0 d	9.3 d	6.5 d	2.0 d
TT	40.1 c	23.3 c	14.0 c	9.6 c	6.9 c	5.3 c	2.7 c	35.8 c	18.8 c	10.7 c	6.6 c	4.3 c	3.4 c	0.9 c
AIXR	15.6 b	8.1 b	4.8 b	3.6 b	2.9 b	2.6 b	1.9 b	14.7 b	6.7 b	3.7 b	2.4 b	1.5 b	1.2 b	0.4 b
TTI	4.5 a	1.8 a	0.8 a	0.5 a	0.3 a	0.2 a	0.1 a	3.3 a	1.2 a	0.8 a	0.5 a	0.4 a	0.4 a	0.1 a
	Wind speed = 3.6 m s^{-1}													
XR	87.4 d	66.0 d	50.4 d	38.6 d	30.1 d	23.9 d	9.3 d	71.4 d	53.7 d	39.7 d	29.9 d	23.4 d	18.5 d	6.8 c
TT	54.0 c	40.6 c	28.7 c	21.1 c	16.4 c	12.4 c	4.4 c	47.3 c	34.8 c	25.5 c	18.3 c	13.8 c	10.7 c	3.7 bc
AIXR	33.3 b	19.9 b	12.6 b	8.6 b	6.3 b	4.5 b	1.6 b	32.3 b	18.7 b	11.5 b	7.8 b	5.4 b	4.1 b	1.3 ab
TTI	12.0 a	6.0 a	3.5 a	1.9 a	1.2 a	0.8 a	0.3 a	10.8 a	5.4 a	3.0 a	1.9 a	1.1 a	0.9 a	0.4 a
	Wind speed = 4.9 m s^{-1}													
XR	71.5 d	59.2 d	47.3 d	40.1 d	33.2 d	28.2 d	13.2 d	70.9 c	59.6 d	49.4 d	41.7 d	34.2 d	29.1 d	13.8 d
TT	51.5 c	42.0 c	32.9 c	26.6 c	21.2 c	17.5 c	6.5 c	48.5 b	40.8 c	32.1 c	25.6 c	20.9 c	16.9 c	6.6 c
AIXR	41.4 b	28.0 b	20.8 b	15.3 b	11.8 b	9.2 b	3.2 b	42.0 b	28.1 b	19.6 b	14.6 b	10.7 b	8.4 b	3.3 b
TTI	18.2 a	11.2 a	6.7 a	4.3 a	2.8 a	2.0 a	0.5 a	17.9 a	10.9 a	6.9 a	4.5 a	3.2 a	2.2 a	0.6 a

[a] Averages followed by the same letter in the columns, within wind speed, do not differ using Tukey's test at $\alpha = 0.05$.

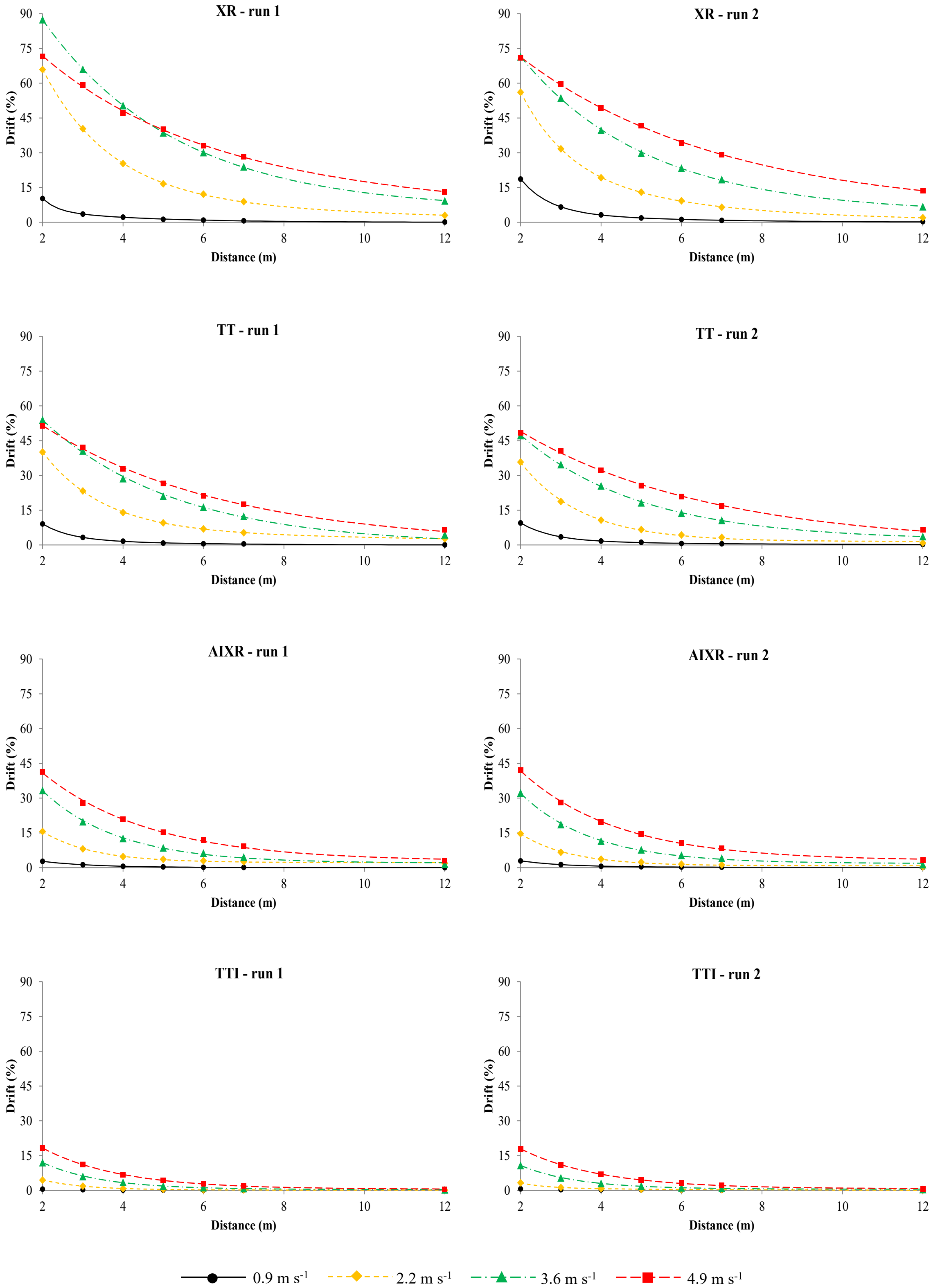


FIGURE 2.3. Drift curves from dicamba applications through four flat-fan nozzles in a wind tunnel operating at wind speeds of 0.9, 2.2, 3.6, and 4.9 m s^{-1} in two experimental runs.

TABLE 2.2. Functions, R^2 and F_c generated by regression analysis of wind speed effect on dicamba drift using flat-fan nozzles in two experimental runs

Nozzle	Wind speed	Run 1			Run 2		
		Function ($\hat{y}$ =)	R^2	[a]F_c	Function ($\hat{y}$ =)	R^2	F_c
	$m\ s^{-1}$		%			%	
XR	0.9	$11.19e^{-0.4118x} + 1570.01e^{-2.8373x}$	99.98	153.1**	$8.65e^{-0.3263x} + 246.29e^{-1.4275x}$	99.99	823.1**
	2.2	$17.63e^{-0.1488x} + 177.53e^{-0.6057x}$	99.99	5948.0**	$31.13e^{-0.2320x} + 187.27e^{-0.8173x}$	99.99	6791.2**
	3.6	$5.26 + 149.16e^{-0.2956x}$	100.00	3073.4**	$4.03 + 126.39e^{-0.3140x}$	99.98	445.2**
	4.9	$73.25e^{-0.2861x} + 37.38e^{-0.1030x}$	99.94	527.7**	$4.39 + 99.32e^{-0.1978x}$	99.97	884.2**
TT	0.9	$5.60e^{-0.3744x} + 127.56e^{-1.4895x}$	99.98	126.7**	$2.43e^{-0.2053x} + 99.00e^{-1.2647x}$	99.94	208.3**
	2.2	$7.84e^{-0.0897x} + 128.41e^{-0.6704x}$	99.99	2140.8**	$1.52 + 125.28e^{-0.6510x}$	99.88	4336.5**
	3.6	$98.33e^{-0.3005x}$	99.70	2559.0**	$2.02 + 88.65e^{-0.3345x}$	99.96	206.9**
	4.9	$79.66e^{-0.2177x}$	99.92	1575.8**	$74.60e^{-0.2104x}$	99.82	978.9**
AIXR	0.9	$0.08 + 13.09e^{-0.7922x}$	99.91	17.6**	$0.19 + 15.73e^{-0.8700x}$	99.86	29.2**
	2.2	$2.22 + 65.91e^{-0.7975x}$	99.82	436.4**	$0.84 + 67.90e^{-0.7990x}$	99.69	719.3**
	3.6	$1.98 + 89.08e^{-0.5259x}$	99.86	525.0**	$1.80 + 90.31e^{-0.5578x}$	99.86	105.3**
	4.9	$2.73 + 79.99e^{-0.3707x}$	99.80	562.7**	$3.08 + 88.31e^{-0.4134x}$	99.90	419.0**
TTI	0.9	$1.57e^{-0.5498x}$	-	1.24[ns]	$1.07e^{-0.3181x}$	-	1.32[ns]
	2.2	$0.14 + 27.71e^{-0.9303x}$	99.95	48.8**	$60.88e^{-1.6555x} + 1.69e^{-0.2351x}$	99.86	23.0**
	3.6	$0.39 + 45.48e^{-0.6832x}$	99.88	75.9**	$0.54 + 41.92e^{-0.7063x}$	99.91	12.4**
	4.9	$0.51 + 49.51e^{-0.5136x}$	99.97	132.5**	$0.70 + 47.09e^{-0.5034x}$	99.95	87.2**

[a] F_c: Calculated F-value. **Significant at $\alpha = 0.01$. [ns]Non-significant.

At 0.9 m s^{-1}, nozzles produced similar drift at 12 m, varying from 0.1 to 0.2% (Table 2.3). At 3.6 and 4.9 m s^{-1}, the highest percentage of drift was observed for the XR, followed by the TT, AIXR, and TTI nozzles. At 2.2 m s^{-1}, the TTI nozzle produced the lowest drift (0.1%), while the greatest drift was produced through XR, and TT nozzles, 2.5% and 1.8%, respectively. At 2.2 m s^{-1}, the TT produced similar drift when compared with the AIXR even though the AIXR generated 124 μm coarser VMD than the TT nozzle. These results reinforced the idea that wind speed has a stronger effect on drift than droplet size.

TABLE 2.3. Percentage of dicamba drift at 12 m downwind from flat-fan nozzles in applications at different wind speeds

Wind speed	Nozzle[a]			
	XR	TT	AIXR	TTI
m s^{-1}	------------------------------%------------------------------			
0.9	0.2 a	0.2 a	0.1 a	0.1 a
2.2	2.5 c	1.8 bc	1.1 b	0.1 a
3.6	8.0 d	4.1 c	1.5 b	0.3 a
4.9	13.5 d	6.6 c	3.2 b	0.6 a
[b]CV (%)	26.48			
[b]LSD	0.95			
[d]$F_{ws\ x\ noz}$	94.6**			
[e]OD: F_{Levene} = 11.357**; K-S = 0.176**				
TD: F_{Levene} = 11.850**; K-S = 0.103**				

[a] Averages followed by the same letter in the rows do not differ using Tukey's test at α = 0.05.
[b] Abbreviations: CV: coefficient of variation; LSD: least significant difference.
[d] $F_{ws\ x\ noz}$: Calculated F-value for interaction between wind speed and nozzle. **Significant at α = 0.01.
[e] F_{Levene} and K-S values of the F statistic for the Levene's test and K-S for the Kolmogorov-Smirnov's test, respectively. Original data (OD). Data transformed (TD) by arc sine [$(x/100)^{0.5}$]. **Significant at α = 0.01.

As expected, when wind speed increased, higher drift was observed across nozzle types (Figure 2.4). For the XR, TT, and AIXR nozzles, drift increased exponentially following a stirling model while for the TTI nozzle, the increase was linear (Table 2.4). The smaller the droplet size, the greater the drift potential. The least drift was occured with the TTI nozzle. It is expected that the drift at 12 m for this nozzle will be 0.03% higher for each 0.28 m s^{-1} (1 km h^{-1}) increase in wind speed. The difference in drift between nozzle types increased as the wind speed increased, reaching the highest amount of 13.5% at 4.9 m s^{-1} with the XR nozzle (finest droplets). Differently than observed in this study, drift data collected by Combellack et al. (1996) was better fit to a sigmoidal curve as wind speed increased, and a maximum amount of drift did not increase as wind speed increased, starting around 4 m s^{-1}. However, the authors did not described clearly which distance from the nozzle the collectors were positioned.

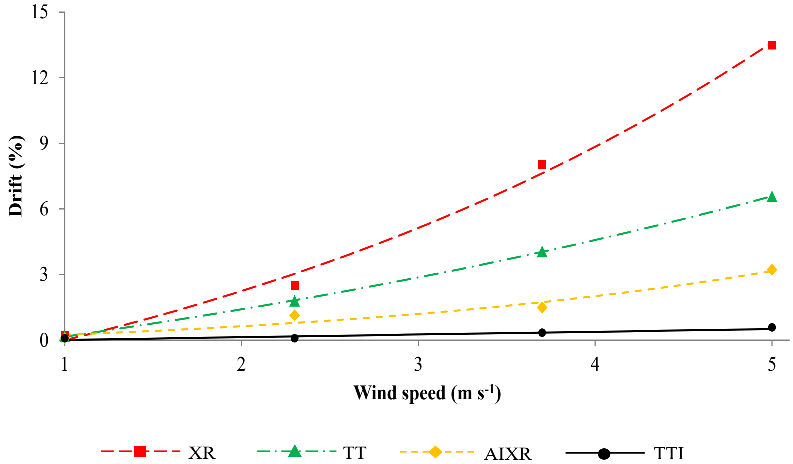


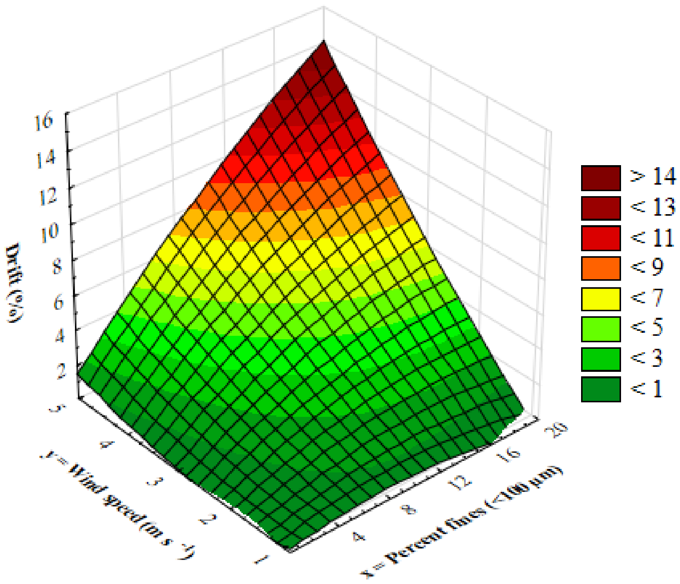
FIGURE 2.4. Effect of wind speed on dicamba drift collected at 12 m downwind from flat-fan nozzles in a wind tunnel.

TABLE 2.4. Functions, R^2 and F_c generated by regression analysis of wind speed effect on dicamba drift collected at 12 m downwind from flat-fan nozzles

Nozzle	Function	R^2	^aF_c
		%	
XR	$\hat{y} = -1.5930 + 1.57*(e^{0.2511x} - 1)/0.2511$	99.51	99.9*
TT	$\hat{y} = -0.8036 + 0.99*(e^{0.1585x} - 1)/0.1585$	99.99	22.1*
AIXR	$\hat{y} = -0.0119 + 1.57*(e^{0.2389x} - 1)/0.2389$	95.83	4.6*
TTI	$\hat{y} = -0.1019 + 0.1239x$	91.30	2.3*

[a] F_c: Calculated F-value. *Significant at $\alpha = 0.05$.

Percentage of drift at 12 m downwind was expressed as a function of driftable fine droplets and wind speed, using a multiple polynomial regression (Figure 2.5). Negative values of drift were observed when the highest values of driftable fine droplets were combined with the lowest values of wind speed. In those cases, the drift was considered null. Combellack et al. (1996) also observed that the treatments that created large volumes of small droplets generally produced more drift. Antuniassi et al. (2014) correlated drift and droplet spectra generated by flat-fan nozzles (XR 8003 and XR 11002) spraying pesticides with different formulations and adjuvants. The authors found that higher V_{100} and VMD produced greater and lower drift, respectively. Stainier et al. (2006) also have reported a similar tendency. However, none of these authors expressed drift using multiple regression as function of driftable fine droplets and wind speed.



$$\text{Drift (\%)} = 0.5867 - 0.0007x - 0.7503y + 0.1655xy - 0.0093x^2 + 0.1774y^2$$
$$R^2 = 98.52\%$$
$$F_c = 133.5^{**}$$

FIGURE 2.5. Graphic representation of dicamba drift collected at 12 m downwind from nozzle, as result of combination between percent fines and wind speed. F_c: Calculated F-value. **Significant at $\alpha = 0.01$.

Table 2.5 represents several predictions of percentage of drift in dicamba applications, in a range from 1 to 19% of volume percentage of droplets smaller than 100 µm from 1.5 to 4.5 m s^{-1} wind speeds. When knowing the amount of driftable fine doplets produced through a given nozzle and wind speed condition during an application, it is possible to predict drift at 12 m from the nozzle in dicamba applications. Obviously, the highest percentage of drift is expected in conditions of high wind speeds and with nozzles that produce high amount of driftable fine droplets. Although Holterman et al. (1997) reported that field trials have an agreement with model results since field trials are averaged over several replications, further trials are needed to investigate dicamba spray drift in the field under different weather conditions, using nozzles that are recommended on the new dicamba labels.

TABLE 2.5. Percentage of predicted drift at 12 m downwind from the nozzle in dicamba applications, considering percent fines (<100 µm) and wind speed

Percent fines (<100 µm)	Wind speed						
	m s^{-1}						
	1.5	2.0	2.5	3.0	3.5	4.0	4.5
	--------------------%	--------------------					
1	0.10	0.12	0.22	0.42	0.70	1.08	1.54
2	0.32	0.42	0.61	0.89	1.25	1.71	2.25
3	0.52	0.70	0.98	1.34	1.79	2.32	2.95
4	0.70	0.97	1.32	1.77	2.30	2.92	3.63
5	0.87	1.21	1.65	2.18	2.79	3.50	4.29
6	1.01	1.44	1.96	2.57	3.27	4.06	4.93
7	1.14	1.65	2.26	2.95	3.73	4.60	5.56
8	1.25	1.84	2.53	3.30	4.17	5.12	6.16
9	1.34	2.02	2.78	3.64	4.59	5.62	6.75
10	1.41	2.17	3.02	3.96	4.99	6.11	7.31
11	1.46	2.30	3.24	4.26	5.37	6.57	7.86
12	1.49	2.42	3.44	4.54	5.74	7.02	8.39
13	1.51	2.52	3.62	4.81	6.08	7.45	8.90
14	1.50	2.60	3.78	5.05	6.41	7.86	9.40
15	1.48	2.66	3.92	5.28	6.72	8.25	9.87
16	1.44	2.70	4.05	5.48	7.01	8.62	10.33
17	1.38	2.72	4.15	5.67	7.28	8.98	10.76
18	1.30	2.73	4.24	5.84	7.53	9.31	11.18
19	1.21	2.71	4.31	6.00	7.77	9.63	11.58

Each crop has different levels of tolerance to dicamba, and it is impossible to estipulate a standard buffer zone for all of them. The determination of buffer zones should also consider, within other characteristics such as nozzle type and DRTs, the wind speed during the application. Considering Table 2.1 and a case study where a certain crop tolerates at maximum 2% of dicamba rate, a buffer zone 5 m wide could be safely adopted in dicamba applications at 0.9 m s^{-1} using any of the evaluated nozzles; 12 m wide at 2.2 m s^{-1} and 3.6 m s^{-1} if using AIXR and TTI nozzles; and 12 m or wider in applications using TTI nozzles at wind speeds over 4.9 m s^{-1}. These results support the general consensus that buffer zones from 5 to 10 m wide would reduce damages to sensitive crops (LONGLEY et al. 1997; SNOO; WIT, 1998), but further distances may be necessary depending on nozzle type and wind speed during applications. Kruger et al. (2012) found that only 1% drift caused 10% losses in marketable red fruits of tomato when the plant was at the first bloom stage.

4 CONCLUSIONS

Air induction TTI nozzle produced the lowest percentage of dicamba spray drift at 2.2, 3.6 and 4.9 m s^{-1} wind speeds, from 2 to 12 m downwind. Drift decreased exponentially as distance from nozzle increased across nozzle type and wind speed, except for TTI nozzle at 0.9 m s^{-1}. Increasing wind speeds resulted in exponential increases in dicamba spray drift for the XR, TT, and AIXR nozzles, whereas drift from the TTI nozzle increased linearly. Dicamba spray drift increased non-linearly as volume percentage of droplets smaller than 100 µm and wind speed increased. Definitely, non-air induction nozzles, in special XR, should not be used in dicamba applications as they produced drift from 1.8% to 13.4% at 12 m in wind speeds over 2.2 m s^{-1}.

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CHAPTER III

SPRAY DRIFT AND DROPLET SPECTRUM FROM DICAMBA ALONE AND TANK-MIXED WITH ADJUVANTS[6]

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SPRAY DRIFT AND DROPLET SPECTRUM FROM DICAMBA ALONE AND TANK-MIXED WITH ADJUVANTS

ABSTRACT

This study aimed to evaluate the spray drift and droplet spectrum from dicamba alone and tank mixed with four potential drift-reducing adjuvants sprayed through flat-fan nozzles in a wind tunnel. Two standard (XR and TT) and two air induction (AIXR and TTI) nozzles were used. The adjuvants used were polymer, ammonium sulfate, vegetable oil and phosphatidylcholine. The applications were conducted at 276 kPa pressure and 3.6 m s^{-1} wind speed. The droplet spectrum was measured using a laser diffraction system. Round strings were used as drift collectors, positioned parallel to the tunnel floor and perpendicular to the wind direction from 2 to 12 m downwind from the nozzle. Drift was calculated quantifying a fluorescent tracer by fluorimetry added to each solution at concentration of 1 g L^{-1}. Droplet spectrum and dicamba drift depended on the interaction between spray composition and nozzle type. The air induction nozzles produced less droplets prone to drift and lower percentage of drift from 2 to 12 m than non-air induction. At 12 m downwind from TTI nozzle, dicamba solutions with or without any adjuvant produced similar drift. The polymer and ammonium sulfate increased the droplet size for all nozzle types.

Keywords: drift-reducing techniques, flat-fan nozzles, wind tunnel.

DERIVA E ESPECTRO DE GOTAS EM APLICAÇÕES DE DICAMBA COM E SEM ADJUVANTES

RESUMO

Este trabalho objetivou avaliar a deriva e o espectro de gotas provenientes de aplicações de dicamba com e sem quatro adjuvantes com potential de redução de deriva aplicados por pontas de jato plano em um túnel de vento. Foram usadas duas pontas padrão (XR e TT) e duas pontas com indução de ar (AIXR e TTI). As aplicações foram feitas na pressão de 276 kPa e na velocidade do vento de 3,6 m s^{-1}. Os adjuvantes utilizados foram polímero, sulfato de amônio, óleo vegetal e fosfatidilcoline. O espectro de gotas foi avaliado por um sistema de difração a laser. Fios de nylon foram usados como coletores de deriva, posicionados de 2 a 12 m de distância da ponta de pulverização. A deriva foi calculada quantificando-se por fluorimetria um corante fluorescente adicionado à calda na concentração de 1 g L^{-1}. O espectro de gotas e a deriva de dicamba dependeram da interação entre composição da calda e o tipo de ponta de pulverização. As pontas com indução de ar produziram menos gotas propensas à deriva e menor porcentagem de deriva do que as pontas padrão de 2 até 12 m de distância. Aos 12 m da ponta TTI, soluções de dicamba com ou sem adjuvantes produziram similar deriva. O polímero e sulfato de amônio aumentaram o tamanho das gotas para todas as pontas de pulverização.

Palavras-chave: técnicas para redução de deriva, pontas de jato plano, túnel de vento.

1 INTRODUCTION

Dicamba is an “auxin”-type herbicide that mimics the effects of excess quantities of this natural plant hormone when applied to dicotyledonous plants. It has been used for more than 40 years to efficiently control most broadleaf weeds (BEHRENS et al., 2007), and in the last two decades its use has increased due to the expanding problem of glyphosate-resistant weeds. Currently, 21 broadleaf weed species are known to be resistant to glyphosate, 18 of these species have biotypes that are resistant to glyphosate and other herbicide types in the world (HEAP, 2017), what confirms the importance in rotating the mechanism of action of herbicides.

Additionally, recent introductions of soybean and cotton varieties genetically modified with tolerance to the growth regulator herbicides including dicamba will allow this compound to be used with greater flexibility. However, it may expose susceptible crops to non-target herbicide drift. From past experience, it is well known that soybean and cotton are both naturally and highly sensitive to low-dose exposures of dicamba (EGAN et al., 2014). A meta-analysis performed by those authors showed that soybean is more susceptible to dicamba than cotton in the flowering stage. Andersen et al. (2004) applied 11 and 56 g ae ha^{-1} on soybean at V3 stage and observed 14% and 71% of yield reduction, respectively.

Several studies have demonstrated that dicamba spray drift is phytotoxic to a number of broadleaf crops, including potato, sunflower and soybean (DERKSEN, 1989; HADERLIE et al., 1986; WEIDENHAMER et al., 1989). Besides, Behrens et al. (2007) have shown that dicamba damage symptoms were pronounced after spraying on nontransgenic tobacco plants even at low level of 17 g ha^{-1}. Symptoms were quite severe at 560 g ha^{-1}, a common rate used for weed control in agricultural applications.

Many tools can be used to reduce drift, named drift reduction technologies (DRTs). According to Hoffmann et al. (2010), DRTs can be spray nozzles, sprayer modifications, spray delivery assistance, spray property modifiers (adjuvants), and/or landscape modifications. Spanoghe et al. (2007) have mentioned that the nozzle performance is likely to be strongly affected by liquid properties and hence by the addition of adjuvants. Similarly, the way in which an individual adjuvant acts will be nozzle dependent, and so it is difficult to generalize the effect of adjuvants on the formation of sprays. In this case, it is important to evaluate each application condition, considering that the results do not follow a standard.

As few studies have been developed to evaluate dicamba drift, even using DRTs such as air induction nozzles and drift retardant adjuvants, the objectives of this study were to evaluate the drift and droplet spectrum from dicamba tank-mixed with four potential drift-reducing adjuvants sprayed through standard and air induction flat-fan nozzles in a wind tunnel.

2 MATERIALS AND METHODS

Experiment was conducted at the Pesticide Application Technology Laboratory (PAT Lab) at the West Central Research and Extension Center of the University of Nebraska-Lincoln in North Platte, Nebraska in 2015. The experimental design was in a completely random design 5 x 4 x 7 split-plot arrangement with four replications. Main plot, sub-plot, and sub-sub-plot consisted of five spray compositions, four nozzle types, and seven downwind distances from the nozzle, respectively. The spray compositions were: dicamba, dicamba + polymer, dicamba + ammonium sulfate, dicamba + vegetable oil and dicamba + phosphatidylcholine. Clarity® (BASF, Research Triangle Park, NC, USA) was used as source of dicamba at rate of 1.2 L ha^{-1} (561 g ae ha^{-1}). The adjuvants used and their respective rates are described in Table 3.1 The rates were based on the manufacturer's recommendation. In addition, a PTSA fluorescent tracer (1,3,6,8-pyrenetetrasulfonic acid tetrasodium salt) (Spectra Colors Corp., Kearny, NJ, USA) was added to the solutions at 1 g L^{-1} to be detected by fluorimetry afterwards (HOFFMANN et al., 2014).

TABLE 3.1. Adjuvants used and their respective recommended rates according to the manufacturer

Adjuvant	Trade name	Rate ($v\ v^{-1}$)	Manufacturer
polymer	Affect GC®	0.03	United Suppliers Inc., Eldora, IA, USA
ammonium sulfate	Border™ Xtra 8L	2.50	Precision Laboratories LLC., Waukegan, IL, USA
vegetable oil	In-Place®	0.69	Wilbur-Ellis, Fresno, CL, USA
phosphatidylcholine	LI 700®	0.50	Loveland Products Inc., Greeley, CO, USA

Solutions were sprayed through a single and static ISO 110015 flat-fan nozzle (Spraying Systems Co., Wheaton, IL, USA): standard (XR-Extended Range; TT-Turbo Teejet) and air induction (AIXR-Air Induction Extended Range; TTI-Turbo Teejet Induction). The pressure used was 276 kPa and solutions were applied at 200 L ha^{-1} carrier volume. Environmental conditions during the applications were kept at 20ºC (± 2ºC) and 60 to 70% relative air humidity.

2.1 Determination of drift

Drift was determined in accordance to the ISO 22856 Standard (ISO 22856, 2008), with few modifications. This study was conducted twice, separated temporally to represent two experimental runs. All conditions such as treatments, wind tunnel set up and procedures were the same in both runs.

A wind tunnel with acrylic glass walls and square working section of 1.2 m wide, 1.2 m high and 15 m long was used. There is an axial fan (Hartzell Inc., Piqua, OH, USA) to generate and move air flow from the fan into an expansion chamber located in front of the tunnel. Applications were performed at 3.6 m s^{-1} wind speed, and each replication consisted in a continuous 10-second application, controlled by a digital auto shut-off timer switch (Intermatic Inc., EI 400C, Spring Grove, IL, USA). Besides, all distances were sprayed at the same time and each set was considered as one replication.

Prior to each application, drift collectors composed of colourless round strings 2 mm diameter (Blount Inc., Magnum Gatorline™, Portland, OR, USA) and 1.0 m length were positioned at 2, 3, 4, 5, 6, 7, and 12 m from nozzle, parallel to the tunnel floor and perpendicular to the wind direction (Figure 2.1, Chapter II). Collectors and nozzle were placed at 0.1 m and 0.6 m above the tunnel floor and in the longitudinal center of the wind tunnel, respectively. A 1.2 m x 0.5 m rug with polyethylene blades 1 cm tall (GrassWorx LLC., St. Louis, MO, USA) was positioned on the sprayed area to absorb droplets.

Once the application was performed, the strings were collected and placed individually into pre-labeled plastic bags and then placed into a dark container to prevent photodegradation of the tracer. In the laboratory, 50 mL of 1:9 isopropyl alcohol:destilled water solution was added to each plastic bag using a bottle top dispenser (LabSciences Inc., 60000-BTR, Reno, NV, USA). Samples were then swirled and shaken to release fluorescent material. After the tracer was suspended in solution, a 1.5 mL aliquot from each sample bag was drawn to fill a glass cuvette, which was placed in a fluorimeter

(Turner Designs, Trilogy 7200.000, Sunnyvale, CA, USA) using ultra-violet light to collect fluorescence data. The fluorimeter was initially calibrated to Relative Fluorescence Unit (RFU), which was converted into mg L^{-1} using a calibration curve for the tracer (Figure 2.2, Chapter II). The percentage of drift for each distance was calculated using the Equations 1 and 2 shown in Chapter II.

2.2 Droplet spectrum

The droplet spectrum produced by each nozzle type was measured using a Sympatec HELOS-VARIO K/R laser diffraction droplet sizing system (Sympatec Inc., Clausthal, Germany) set up with a R7 lens with a dynamic size range of 9 to 3700 µm. This system was integrated into the wind tunnel and the wind speed was maintained at 6.7 m s^{-1} during data acquisition, following methodology proposed by Fritz et al. (2014). The pressure was the same used at drift determination, 276 kPa, and the distance from the nozzle tip to the laser was 0.3 m. Three replicated measurements were made for each treatment, with each replication consisting of a complete vertical traverse of the spray plume. Spray parameters of interest were the droplet diameter (µm) for which 10%, 50%, and 90% ($D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$, respectively), relative span (RS), and volume percentage of droplets smaller than 100 µm (V_{100}).

2.3 Statistical analysis

Normality of residuals and homogeneity of variance of drift data were analysed by Kolmogorov-Smirnov and Levene's tests, respectively, using SPSS Statistical Software, version 17.0 (SPSS Inc., Chicago, IL, USA). In cases that the assumptions were significant at $\alpha = 0.01$, drift and V_{100} data were transformed by arc sine $[(x/100)^{0.5}]$ whilst $D_{v0.1}$, $D_{v0.5}$, $D_{v0.9}$, and RS data were transformed by $(x + 0.5)^{0.5}$. Drift, RS, and V_{100} data (original and transformed) were subjected to analysis of variance (ANOVA) using Sisvar Statistical Software, version 5.6 (FERREIRA, 2011). Nozzles and solutions were compared to each other within each distance by Tukey's multiple comparison test, whereas regression analysis was performed for the distances, both at $\alpha = 0.05$. All regressions were adjusted using SigmaPlot Software, version 11.0 (Systat Software Inc., Chicago, IL, USA). Confidence interval at 95% was used for $D_{v0.1}$, $D_{v0.5}$ and $D_{v0.9}$

comparisons to produce a graphical representation of cumulative volume fraction using SigmaPlot, version 11.0.

3 RESULTS AND DISCUSSION

Assumptions from the original drift, RS, and V_{100} data were not reached at $\alpha = 0.01$; therefore, data were transformed proceeding all comparisons between treatments to improve the analysis. It was applicable to both runs. For the other variables, ANOVA was conducted using the original data.

The adjuvants polymer and ammonium sulfate increased the droplet size across nozzle types (Figure 3.1). However, for TT and TTI nozzles, these two adjuvants had different behavior, once sprayed through TT nozzle the polymer produced higher $D_{v0.5}$ (396 µm-very coarse) whilst on TTI it was noticed by ammonium sulfate (1015 µm-ultra coarse). Through AIXR nozzle, dicamba alone and dicamba + phosphatidylcholine produced similar $D_{v0.5}$. When sprayed through XR nozzle, which produced the finest droplets, the adjuvants increased the droplet size in relation to dicamba alone. When sprayed through TTI nozzle, which produced the coarsest droplets, vegetable oil and phosphatidylcholine reduced the $D_{v0.5}$ by 18% and 23%, respectively, in comparison with dicamba alone. These adjuvants showed to lose their drift-reducing effect as droplet size was increased using air induction nozzles, which means that these adjuvants may be more efficient when finer droplets are used. Miller and Butler Ellis (2000) demonstrated that surfactants such as phosphatidylcholine increase the droplet size when sprayed through air induction nozzles, differently than observed in this study. However, according to those authors, not all air induction nozzles respond in the same way.

In general, the TTI air induction nozzle produced the lowest V_{100} values in comparison with the other nozzles across solutions, ranging from 0.04 to 0.33% (Figure 3.2). Oppositely, the XR nozzle produced the highest amount of droplets prone to drift, followed by TT and AIXR nozzles, with V_{100} values up to 19%, 7%, and 2%, respectively, when dicamba alone was sprayed. Both air induction nozzles (AIXR and TTI) produced similar V_{100} values when polymer and ammonium sulfate were combined with dicamba. Comparisons between XR and AIXR nozzles, and between TT and TTI nozzles, showed a reduction of 89% and 95%, respectively, on potential risk of drift only for using the air induction nozzles in applications of dicamba alone.

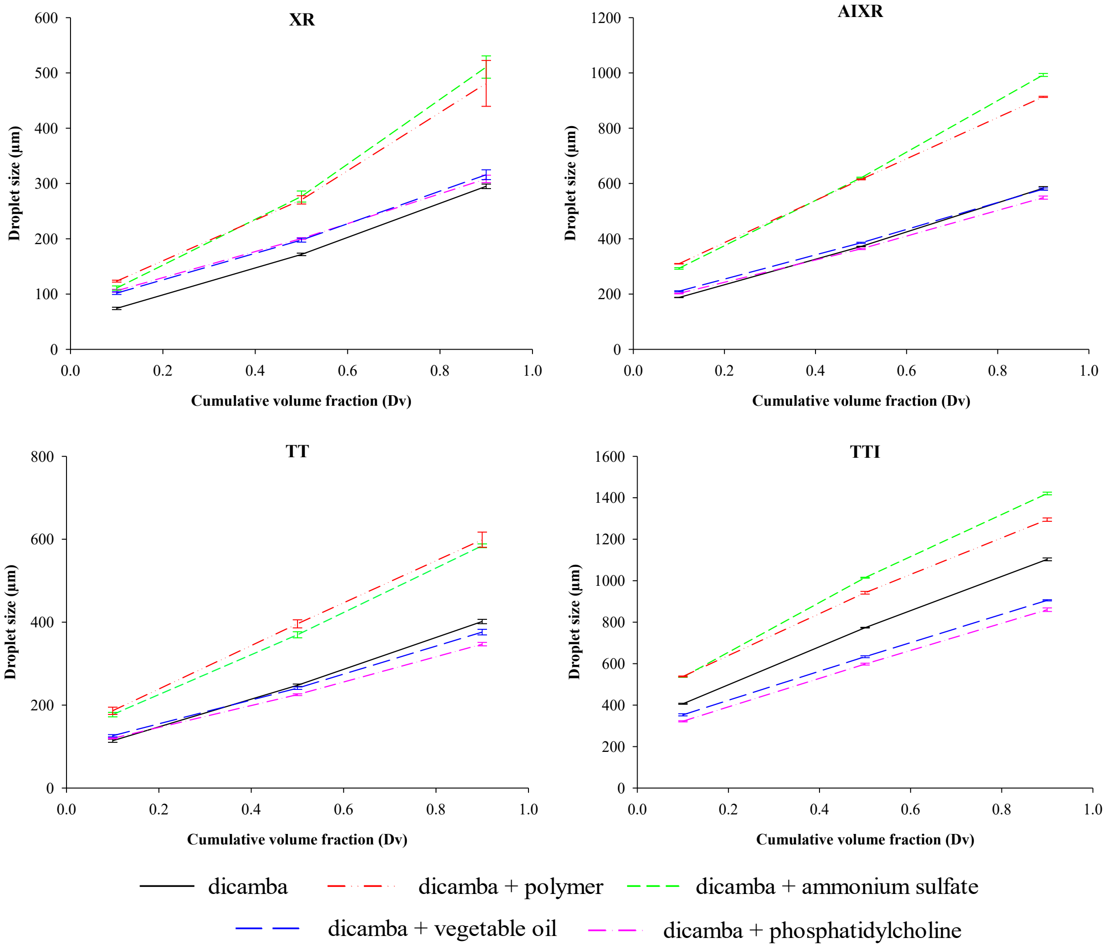

FIGURE 3.1. Droplet diameter below which cumulative volume fraction ($D_{v0.1}$, $D_{v0.5}$, $D_{v0.9}$) produced through different nozzle types in applications of dicamba alone and with adjuvants.

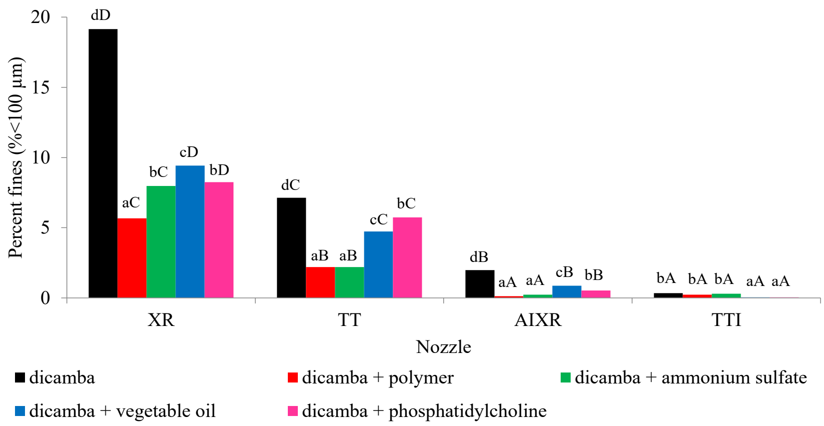

FIGURE 3.2. Volume percentage of droplets smaller than 100 µm produced through different nozzle types in applications of dicamba alone and with adjuvants. Comparisons between solutions, within nozzle type, and between nozzles, within solution, are made by lower and upper cases, respectively. Same letters represent no statistical difference using Tukey's test at $\alpha = 0.05$. $F_{nozzle\ x\ solution} = 72.6^{**}$, significant at $\alpha = 0.01$.

All adjuvants reduced the V_{100} in relation to dicamba alone when sprayed through XR, TT, and AIXR nozzles (Figure 3.2). Although polymer and ammonium sulfate were the two adjuvants that more contributed to reduce the V_{100} using those nozzles, they did not reduce the V_{100} in relation to dicamba alone when sprayed through TTI nozzle. For this nozzle, the lowest V_{100} values were produced using dicamba with vegetable oil (0.03%) and phosphatidylcholine (0.04%), which can be related to their small droplet size, as shown in Figure 3.1. Vegetable oil and phosphatidylcholine had opposite behaviors when non-air induction nozzles were used because vegetable oil produced 1.2% more and 1.0% less droplets prone to drift than phosphatidylcholine when sprayed through XR and TT nozzles, respectively.

The TTI nozzle produced the most uniform droplet spectrum across dicamba solutions; however both air induction nozzles produced similar RS for dicamba with phosphatidylcholine (Figure 3.3). Considering dicamba alone and dicamba with polymer and ammonium sulfate, the XR nozzle produced a greater RS than TT, AIXR, and TTI nozzles. The adjuvants vegetable oil and phosphatidylcholine improved the uniformity of droplet spectrum in comparison with dicamba alone for XR, TT, and AIXR nozzles. The adjuvant ammonium sulfate increased the RS in relation to dicamba alone when sprayed through AIXR nozzle. For TTI nozzle, only the polymer increased the uniformity of droplet spectrum in relation to dicamba alone.

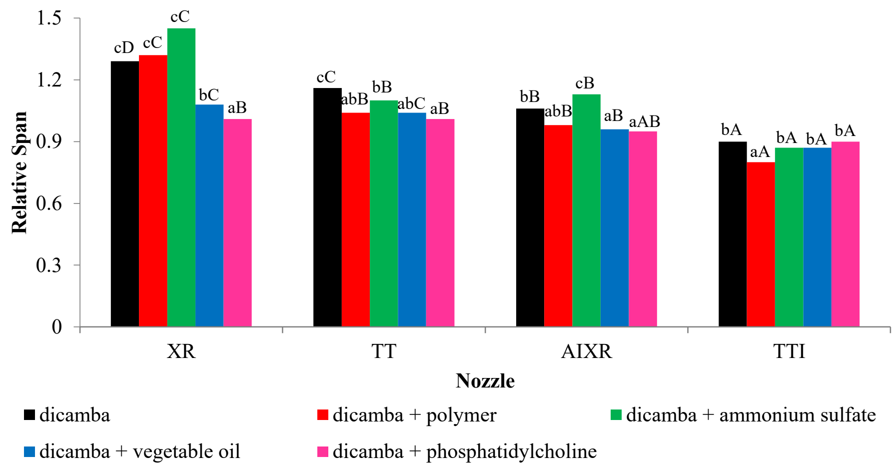

FIGURE 3.3. Relative span of droplet spectrum produced through different nozzle types in applications of dicamba alone and with adjuvants. Comparisons between solutions, within nozzle type, and between nozzles, within solution, are made by lower and upper cases, respectively. Same letters represent no statistical difference using Tukey's test at $\alpha = 0.05$. $F_{nozzle\ x\ solution} = 21.4^{**}$, significant at $\alpha = 0.01$.

Combellack and Miller (2001) reported that oil-based additives, such as vegetable oils, improve the uniformity of droplet spectrum when atomized through air-induction nozzles because a lower amount of air bubbles in droplets is produced. Differently than observed by those authors, the association between vegetable oil and dicamba did not improve the RS in relation to the RS from dicamba alone, whether sprayed through AIXR or TTI nozzle. Probably, these nozzles produced droplets with a high amount of air bubbles; however this characteristic was not measured. It is not possible to predict what happens on droplet spectrum when pesticide solutions are sprayed through an unique nozzle type and vice versa. It depends on the interaction between nozzle type and spray composition. Therefore, the results are in accordance with Butler Ellis and Tuck (1999), who demonstrated that nozzle performance depends upon the interaction between the spray liquid properties and nozzle design. The effect of a particular formulation sprayed through one nozzle may not be the same when sprayed through a different nozzle design. The effects of formulation and spray solution on drift using air induction nozzles are less predictable because the relationships between drift and spray characteristics for these nozzles are less well understood. Additionally, nozzle systems that use air in the spray formation process such as the air induction design are more sensitive to changes in the physical characteristics of the spray liquid than conventional hydraulic pressure nozzles and the changes do not necessarily follow the same trends as with conventional nozzles (MILLER; BUTLER ELLIS, 2000).

Dicamba spray drift depended on the interaction between nozzle type and its association with adjuvants, as well as observed for droplet spectrum. The XR nozzle produced the highest percentage of drift until 6 m downwind across dicamba solutions, except with phosphatidylcholine (Table 3.2). Drift reached values up to 83.1% at 2 m and 27.2% at 6 m. The XR and TT nozzles produced similar drift from 3 to 12 m when phosphatidylcholine was added to dicamba solution. The TTI nozzle produced the lowest percentage of drift from dicamba alone, varying from 10.8% at 2 m to 0.4% at 12 m. In run 2 at 12 m, the air induction nozzles produced similar drift when adjuvants were used, fact observed in run 1 only for polymer.

TABLE 3.2. Percentage of drift from applications of dicamba alone and with adjuvants through flat-fan nozzles in a wind tunnel in two experimental runs

Distance	Nozzle	Solution (Run 1)[a]					Solution (Run 2)				
		dic[b]	dic + pol	dic + am sulf	dic + veg oil	dic + phosp	dic	dic + pol	dic + am sulf	dic + veg oil	dic + phosp
m		%									
2	XR	83.1 dD	42.7 aD	59.4 bD	66.5 cD	61.7 bD	71.4 cD	40.3 aD	43.9 aD	68.4 bcD	64.5 bD
	TT	50.8 cC	18.9 aC	31.4 bC	50.8 cC	56.2 dC	47.3 cC	16.4 aC	27.9 bC	53.7 dC	57.4 dC
	AIXR	35.0 dB	7.5 aB	12.8 bB	25.9 cB	27.1 cB	32.3 cB	4.9 aB	9.4 bB	29.0 cB	31.1 cB
	TTI	10.8 cA	1.9 aA	3.7 bA	13.2 dA	15.9 eA	10.8 bA	1.2 aA	2.8 aA	14.7 bcA	18.5 cA
3	XR	61.1 dD	28.4 aD	42.8 bD	47.4 cD	44.3 bcC	53.7 cD	26.3 aD	29.7 aD	49.9 bcD	46.2 bC
	TT	36.7 cC	12.3 aC	21.0 bC	37.7 cC	41.7 dC	34.8 cC	9.8 aC	17.5 bC	40.4 cdC	43.7 dC
	AIXR	20.5 dB	4.2 aB	6.8 bB	15.2 cB	15.4 cB	18.7 bB	3.9 aB	5.1 aB	17.0 bB	17.3 bB
	TTI	5.2 cA	1.1 aA	1.9 bA	6.6 cA	8.7 dA	5.4 bA	0.9 aA	2.2 aA	7.6 bcA	9.7 cA
4	XR	45.5 dD	19.3 aD	30.9 bD	34.5 cD	31.9 bcC	39.7 cD	18.4 aD	21.9 aD	36.2 bcD	32.6 bC
	TT	25.9 cC	8.1 aC	14.0 bC	26.5 cdC	29.1 dC	25.5 cC	6.3 aC	11.7 bC	28.3 cC	30.4 cC
	AIXR	13.1 dB	2.7 aB	4.4 bB	9.1 cB	9.7 cB	11.5 bB	2.1 aB	3.2 aB	10.5 bB	10.5 bB
	TTI	2.8 bA	0.6 aA	1.0 aA	3.3 bA	4.5 cA	3.0 bA	0.7 aA	0.9 aA	4.1 bA	5.0 bA
5	XR	34.4 cD	13.2 aD	23.1 bD	24.9 bD	23.1 bC	29.9 cD	12.9 aD	15.0 aC	25.9 bcD	23.9 bC
	TT	18.7 cC	5.7 aC	9.9 bC	19.0 cdC	21.5 dC	18.3 cC	4.5 aC	7.8 bB	19.5 cC	21.5 cC
	AIXR	8.5 dB	1.7 aB	2.8 bB	5.8 cB	6.3 cB	7.8 bB	1.4 aB	1.9 aA	6.8 bB	6.6 bB
	TTI	1.6 bA	0.4 aA	0.6 aA	1.8 bcA	2.6 cA	1.9 bcA	0.2 aA	0.9 abA	2.2 bcA	3.0 cA
6	XR	27.2 cD	9.8 aD	18.1 bD	19.5 bD	17.9 bC	23.4 cD	9.5 aD	11.0 aD	19.6 bcD	18.0 bC
	TT	13.9 cC	4.2 aC	7.4 bC	13.9 cC	15.8 cC	13.8 bC	3.3 aC	5.6 aC	14.2 bC	15.8 bC
	AIXR	6.0 cB	1.2 aB	1.9 aB	4.1 bB	4.3 bB	5.4 bB	0.9 aB	1.6 aB	4.7 bB	4.5 bB
	TTI	1.0 bA	0.3 aA	0.3 aA	1.1 bA	1.7 bA	1.1 bcA	0.1 aA	0.4 abA	1.4 bcA	1.9 cA
7	XR	21.5 cD	7.5 aD	14.0 bD	14.9 bD	13.9 bD	18.5 cD	7.2 aC	8.9 aC	15.6 bcD	13.8 bC
	TT	10.6 cC	3.2 aC	5.7 bC	10.4 cC	11.7 cC	10.7 bC	2.5 aB	4.5 aB	10.9 bC	12.0 bC
	AIXR	4.3 cB	0.9 aB	1.4 aB	2.9 bB	3.1 bcB	4.1 bB	0.8 aA	1.3 aA	3.4 bB	3.3 bB
	TTI	0.7 bA	0.2 aA	0.2 aA	0.8 bA	1.1 bA	0.9 abA	0.2 aA	0.6 abA	1.1 abA	1.3 bA
12	XR	8.1 cD	2.6 aC	5.1 bD	5.0 bD	3.9 bC	6.8 cD	2.4 aC	3.2 abB	5.4 bcB	4.8 bcB
	TT	3.7 cC	1.2 aB	1.9 bC	3.4 cC	3.8 cC	3.7 bC	0.9 aB	1.9 abB	3.5 bB	3.8 bB
	AIXR	1.3 cB	0.3 aA	0.4 abB	0.8 bcB	0.9 bcB	1.3 aB	0.4 aAB	0.4 aA	1.1 aA	1.1 aA
	TTI	0.2 aA	0.1 aA	0.1 aA	0.2 aA	0.3 aA	0.4 aA	0.1 aA	0.2 aA	0.4 aA	0.4 aA

[a] Averages followed by the same letter within each distance and run, lower case in the rows and upper case in the columns, do not differ using Tukey's test at α=0.05.
[b] Abbreviations: dic: dicamba; pol: polymer; veg oil: vegetable oil; phop: phosphatidylcholine.

In run 1, the addition of adjuvants in dicamba solutions reduced the drift across distances using the XR nozzle, and until 6 m using the AIXR nozzle. At distances up to 5 m, dicamba with polymer reduced the drift in relation to the others solutions sprayed through XR, TT, and AIXR nozzles. Using non-air induction nozzles, polymer reduced the drift from 2 to 12 m. Beyond 6 m, dicamba with polymer and ammonium sulfate produced similar drift when sprayed through air induction nozzles. At 12 m, the adjuvants vegetable oil and phosphatidylcholine did not reduce drift in comparison with dicamba alone using the AIXR nozzle. For TT and TTI nozzles, the adjuvant phosphatidylcholine increased the drift in relation to dicamba alone at distances up to 5 m. At 5 m, this adjuvant increased the drift by 15% and 62% in comparison with dicamba alone when sprayed through TT and TTI nozzle, respectively. At further distances, there was no difference between dicamba alone and solutions of dicamba with phosphatidylcholine and vegetable oil. These two adjuvants reduced the size of droplets produced through TT and TTI nozzles, which consequently increased the drift in relation to dicamba alone, even though producing lower V_{100}.

In general, the results obtained in run 1 were sustained in run 2. The highest and lowest percentages of drift from dicamba alone solution were generated through XR and TTI nozzles, respectively. The air induction nozzles produced lower drift than non-air induction nozzles across distances and dicamba solutions; however, the TT and AIXR nozzles produced similar drift at 12 m spraying dicamba with polymer. Spraying dicamba with phosphatidylcholine, the XR and TT nozzles produced similar drift from 3 to 12 m. At 12 m, the AIXR and TTI nozzles produced percentages of drift from 0.1 to 1.1% for dicamba with adjuvants solutions. Dicamba with polymer and ammonium sulfate reduced the drift in relation to dicamba alone sprayed through XR, TT, and AIXR nozzle until 7 m. Dicamba with vegetable oil and phosphatidylcholine, and dicamba alone sprayed through TT, AIXR, and TTI nozzles, produced similar drift at 4, 5, 6, 7, and 12 m. Drift from dicamba with phosphatidylcholine was 1.7 and 1.8 times greater than drift from dicamba alone using the TTI nozzle at 2 and 3 m, respectively. Dicamba solutions, associated or not with drift-reducing adjuvants, produced similar results at 12 m using air induction nozzles.

Johnson et al. (2006) evaluated glyphosate spray drift with drift-reducing nozzles and adjuvants on grain sorghum crop, and also observed that air induction (AI) nozzles reduced the drift considerably in comparison with XR nozzle, but not significantly in relation to TT nozzles. The authors found that the polymer reduced the drift when sprayed through AI nozzle, but not for XR nozzles. Their results are not in accordance with results from this study because dicamba drift was reduced when polymer was added to the solution sprayed through non-air induction nozzles. Oliveira et al. (2013) measured drift from 30 solutions with adjuvants sprayed through XR 8003 nozzle in a wind tunnel. Similarly than observed in run 1 of this study, the authors observed that vegetable oil reduced the drift in relation to the solution with no adjuvants. Hilz and Vermeer (2013) reported that nozzle type has a more expressive influence on drift reduction than formulated product or a spray additive. Drift-reducing adjuvants should be used when their effects are known to avoid undesirable results, such as those observed for the combination between phosphatidylcholine and TTI nozzle.

In both runs, percentage of drift from dicamba applications through XR, TT, and AIXR nozzles, as well as from dicamba alone and dicamba with vegetable oil and phosphatidylcholine sprayed through TTI nozzle, decreased exponentially as distance from the nozzles increased (Figure 3.4). All significant regression models were adjusted by two-parameter exponential functions ($\hat{y} = ae^{-bx}$), with coefficient of determination values over 99% (Table 3.3). There was no model that fit drift data generated in dicamba applications through TTI nozzle using polymer in both runs and ammonium sulfate in run 2. The coefficient "a" of functions reduced as droplet size increased, which indicates that there was a tendency that drift models were closer to linear models as droplet size increased, although this model was non-significant in any situation.

As previously described, polymer and ammonium sulfate were the adjuvants with better capacity of drift reduction; however, there is lack of information about their effect on efficacy when associated with dicamba. Therefore, in addition to the results demonstrated in this study, efficacy assays are needed to achieve a complete recommendation about the use of drift-reducing adjuvants, mainly using air induction nozzles, which are expected to be recommended in new dicamba labels and its applications.

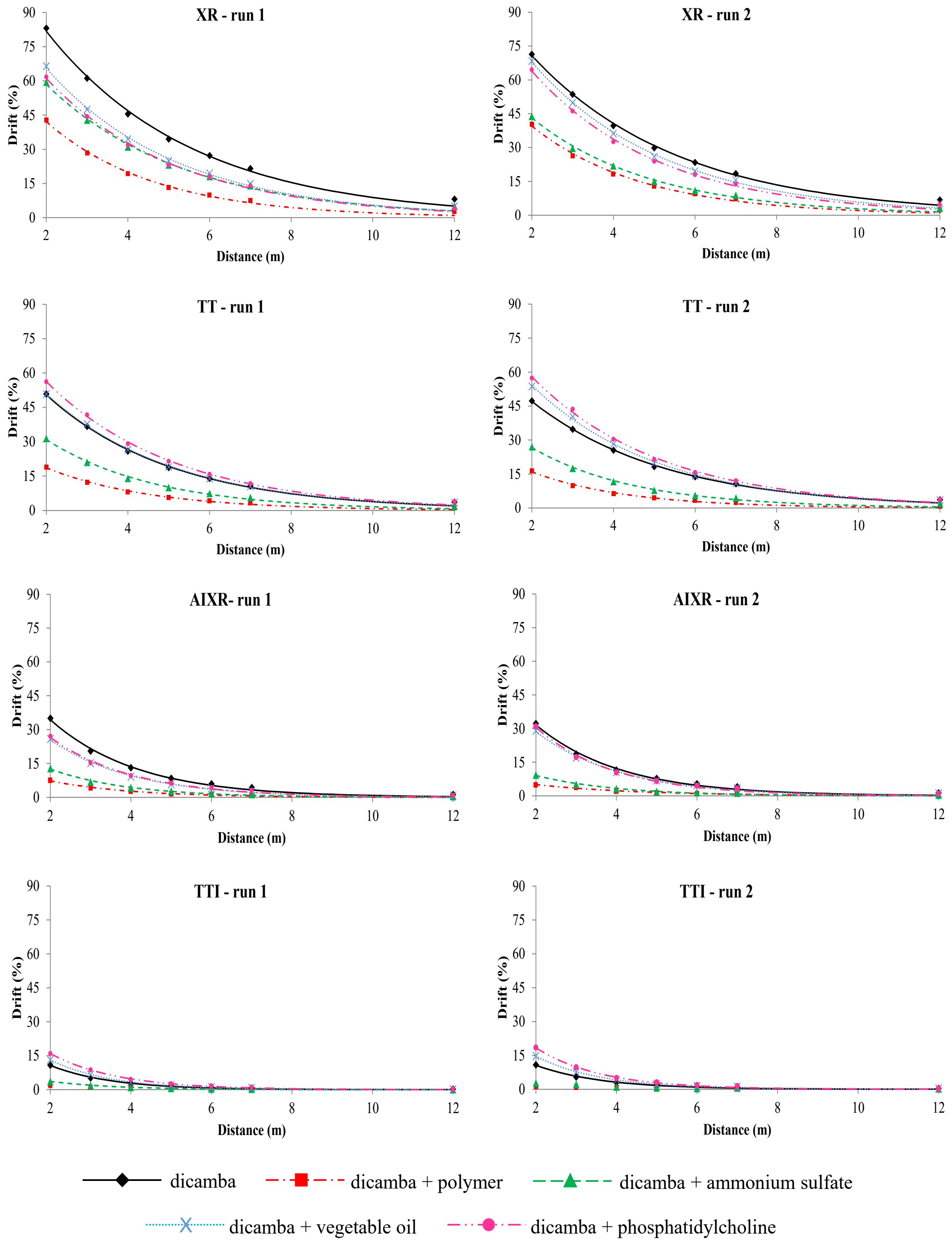

FIGURE 3.4. Drift curves from applications of dicamba alone and with adjuvants through different nozzle types in a wind tunnel in two experimental runs.

TABLE 3.3. Functions and R^2 generated by regression analysis using five dicamba solutions sprayed through different nozzle types in two experimental runs

Run	Solution[a]	Nozzle							
		XR		AIXR		TT		TTI	
		function ($\hat{y}$ =)	R^2	function ($\hat{y}$ =)	R^2	function ($\hat{y}$ =)	R^2	function ($\hat{y}$ =)[b]	R^2
			%		%		%		%
1	Dic	$142.4e^{-0.2775x}$	99.6	$87.6e^{-0.4666x}$	99.5	$96.1e^{-0.3219x}$	99.8	$40.4e^{-0.6645x}$	99.5
	Dic + pol	$88.9e^{-0.3735x}$	99.5	$19.7e^{-0.4913x}$	99.2	$40.6e^{-0.3888x}$	99.4	ns	-
	Dic + am sulf	$106.4e^{-0.2991x}$	99.6	$35.4e^{-0.5184x}$	99.1	$64.9e^{-0.3698x}$	99.5	$12.4e^{-0.6154x}$	99.7
	Dic + veg oil	$121.9e^{-0.3098x}$	99.7	$68.2e^{-0.4907x}$	99.6	$96.6e^{-0.3200x}$	99.8	$50.5e^{-0.6730x}$	99.9
	Dic + phosp	$113.8e^{-0.3113x}$	99.8	$70.4e^{-0.4874x}$	99.4	$105.8e^{-0.3159x}$	99.8	$53.2e^{-0.6025x}$	99.8
2	Dic	$123.0e^{-0.2766x}$	99.7	$82.1e^{-0.4765x}$	99.3	$86.4e^{-0.3037x}$	99.8	$35.8e^{-0.6067x}$	99.3
	Dic + pol	$82.4e^{-0.3674x}$	99.5	$11.0e^{-0.3900x}$	97.5	$37.6e^{-0.4285x}$	98.9	ns	-
	Dic + am sulf	$84.9e^{-0.3388x}$	99.5	$24.7e^{-0.4994x}$	98.6	$58.9e^{-0.3957x}$	99.2	ns	-
	Dic + veg oil	$125.6e^{-0.3076x}$	99.7	$74.6e^{-0.4972x}$	99.6	$103.7e^{-0.3246x}$	99.7	$51.3e^{-0.6268x}$	99.8
	Dic + phosp	$121.0e^{-0.3192x}$	99.7	$85.8e^{-0.5162x}$	99.5	$109.3e^{-0.3174x}$	99.7	$62.9e^{-0.6165x}$	99.7

[a] Abbreviations: dic: dicamba; pol: polymer; veg oil: vegetable oil; phop: phosphatidylcholine.
[b] Abbreviation: ns: non-significant at $\alpha = 0.05$.

4 CONCLUSIONS

Droplet spectrum and dicamba drift depended on the interaction between spray composition and nozzle type. As the air induction nozzles produced less droplets prone to drift and lower percentage of drift from 2 to 12 m than non-air induction, they should be used to spray dicamba. Using TT and TTI nozzles, the adjuvant phosphatidylcholine increased the drift until 5 m when compared with dicamba alone. At 12 m downwind from TTI nozzle, dicamba solutions with or without any adjuvant produced similar drift. Drift decreased exponentially in applications through XR, TT, and AIXR as distance from the nozzles increased.

The adjuvants had better results on drift potential reduction at closer distances than at further distances. Vegetable oil and phosphatidylcholine once associated with dicamba reduced the droplet size in relation to dicamba alone when sprayed through TTI nozzle. The polymer and ammonium sulfate increased the droplet size for all nozzle types, which might reduce damages caused by drift into nearby non-dicamba-tolerant crops.

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CHAPTER IV

SPRAY DRIFT AND DROPLET SPECTRUM FROM DICAMBA AND GLYPHOSATE APPLICATIONS IN A WIND TUNNEL[7]

[7] Paper published in Weed Technology, v. 31, n. 3, p. 387-395, 2017.

SPRAY DRIFT AND DROPLET SPECTRUM FROM DICAMBA AND GLYPHOSATE APPLICATIONS IN A WIND TUNNEL

ABSTRACT

With the recent introductions of glyphosate and dicamba-tolerant crops, such as soybean and cotton, there will be an increase in post-applied tank-mixtures of these two herbicides. However, few studies have been conducted to evaluate drift from dicamba applications. This study aimed to evaluate the effects of dicamba with and without glyphosate sprayed through standard and air induction flat-fan nozzles on droplet spectrum and drift in a wind tunnel. Two standard (XR and TT) and two air induction (AIXR and TTI) 110015 nozzles were used. The applications were made at 276 kPa pressure in a 2.2 m s^{-1} wind speed. The spray solutions were prepared using 0.6% v v^{-1} of dicamba and 1.2% v v^{-1} of glyphosate, composed of dicamba alone 561 g ae ha^{-1} and dicamba + glyphosate at 561 + 1,262 g ae ha^{-1}). The droplet spectrum was measured using a laser diffraction system. Artificial targets were used as drift collectors, positioned in a wind tunnel from 2 to 12 m downwind from the nozzle. The drift was determined using a fluorescent tracer added to solutions, quantified by fluorimetry. Dicamba droplet spectrum and drift depend on the association between herbicide solution and nozzle type. Dicamba alone produced coarser droplets than dicamba + glyphosate when sprayed through air induction nozzles. Drift decreased exponentially as downwind distance increased, and it was reduced using air induction nozzles for both herbicide solutions.

Keywords: herbicide, tank-mixture, environmental contamination.

DERIVA E ESPECTRO DE GOTAS EM APLICAÇÕES DE DICAMBA E GLIFOSATO EM TÚNEL DE VENTO

RESUMO

Com os recentes desenvolvimentos de culturas tolerantes aos herbicidas glifosato e dicamba, como a soja e o algodão, haverá um aumento do uso desses herbicidas em mistura em tanque. Entretanto, poucos estudos tem sido realizados para avaliar a deriva em aplicações de dicamba. Este trabalho objetivou avaliar a deriva em túnel de vento e o espectro de gotas em aplicações de dicamba, associado ou não ao glifosato, utilizando-se pontas de jato plano com e sem indução de ar. As aplicações foram realizadas em túnel de vento, com velocidade do vento de 2,2 m s^{-1}, pressão de 276 kPa, utilizando-se as pontas jato plano padrão (XR e TT) e com indução de ar (AIXR e TTI). As soluções herbicidas foram preparadas usando-se 0,6% v v^{-1} de dicamba e 1,2% v v^{-1} de glifosato, compostas por dicamba a 561 g ea ha^{-1} e dicamba + glifosato a 561 + 1.262 g ea ha^{-1}). O espectro de gotas foi medido por sistema de difração a laser. A deriva foi quantificada por fluorimetria após a extração de um corante fluorescente de alvos artificiais posicionados de 2 a 12 m da ponta de pulverização. A deriva e o espectro de gotas dependem da associação entre a solução herbicida e o tipo de ponta. A solução dicamba sem glifosato produziu gotas mais grossas do que a solução contendo os dois herbicidas quando aplicadas por pontas com indução de ar. A deriva reduziu exponencialmente à medida em que a distância em relação à ponta aumentou, sendo que as maiores reduções foram provocadas por pontas com indução de ar para ambas as soluções herbicidas.

Palavras-chave: herbicida, mistura em tanque, contaminação ambiental.

1 INTRODUCTION

Herbicide application is an important activity in crop protection systems. It provides effective and economical weed control and is the primary method of weed control in agronomic crops (HEAP, 2014). The value of the worldwide herbicide market grew by 39% between 2002 and 2011 (GIANESSI, 2013), and in the USA alone the use of herbicides increased 130% between 2002 and 2010 (OSTEEN; FERNANDEZ-CORNEJO, 2013).

Glyphosate is the most commonly used row-crop herbicide worldwide. Perhaps the most important aspect of its success has been the introduction of glyphosate-tolerant crops in 1996 (DUKE; POWLES, 2008). Because glyphosate is a non-selective herbicide with broad-spectrum control, there is a risk of injury to neighboring crops through unintended crop exposure from spray drift. It is assumed that up to 10% of the applied herbicide can reach non-target crop plants in the form of spray drift (AL-KHATIB et al., 2003), but the proportion could be higher (FELIX et al., 2011).

Besides glyphosate-tolerant crops, recent introductions of soybean and cotton cultivars genetically modified with tolerance to the synthetic auxin herbicide dicamba will allow this compound to be used with greater flexibility. However, it may expose susceptible soybean and cotton cultivars to non-target herbicide drift. Previous research has determine soybean and cotton to be highly sensitive to low-dose of dicamba (EGAN et al., 2014).

Spray drift is defined as the quantity of plant protection product carried out of the sprayed (treated) area by air currents during an application. It persists as one of the major problems in modern row-crop production agriculture (NUYTTENS et al., 2011; TSAI et al., 2005). One way of reducing drift has been the use of air induction nozzles. During the past ten years, this type of nozzle has been recommended by many nozzle manufacturers and researchers to reduce spray drift by producing larger droplets with a smaller portion of drift-prone droplets than standard hydraulic nozzles (GULER et al., 2007).

Different techniques have been used to study spray drift. Since weather conditions cannot be controlled, it is very difficult to repeat spray drift measurements in the field with a high degree of repeatability (MILLER; BUTLER ELLIS, 2000). Controlled conditions found in wind tunnels make them suited for studies where relative drift values are required (DERKSEN et al., 1999; HISLOP et al., 1993; SIDAHMED et al., 2004).

This information has been used to classify equipment provided to the end user, so that appropriate spray equipment could be selected to minimize the risk of spray drift (PARKIN et al., 1994).

Much research has been conducted to evaluate glyphosate drift (DEEDS et al., 2006; ELLIS; GRIFFIN, 2002; KOGER et al., 2005; SCHRÜBBERS et al., 2014), but few studies have been developed to evaluate dicamba drift, especially co-applied with glyphosate. There is a great potential for use due to the development of tolerant crops to both herbicides.

The objectives of this study were to evaluate the drift and droplet spectrum from dicamba with and without glyphosate sprayed through standard and air induction flat-fan nozzles in a wind tunnel.

2 MATERIALS AND METHODS

Experiment was conducted at the Pesticide Application Technology Laboratory (PAT Lab) at the West Central Research and Extension Center of the University of Nebraska-Lincoln in North Platte, NE, USA, in 2015. The experimental design was a 2 x 4 x 7 split-plot arranged in a completely random design with four replications. Main plot, sub-plot, and sub-sub-plot consisted of two herbicide treatments, four nozzle types, and seven downwind distances from the nozzle (2, 3, 4, 5, 6, 7, 12 m), respectively, which were points where data were collected.

The two herbicide treatments evaluated were dicamba (Clarity®, BASF Corporation, Research Triangle Park, NC, USA) alone and dicamba + glyphosate (Roundup PowerMax®, Monsanto Company, St. Louis, MO, USA) at 561 g ae ha^{-1} and 561 + 1,262 g ae ha^{-1}, respectively, applied at 200 L ha^{-1}. In addition, a PTSA fluorescent tracer (1,3,6,8-pyrenetetrasulfonic acid tetrasodium salt) (Spectra Colors Corp., Kearny, NJ, USA) was added to the solutions at 1 g L^{-1} to be detected by fluorimetry afterwards (HOFFMANN et al., 2014). Nozzle types included Extended Range (XR), Turbo TeeJet (TT), Air-Induction Extended Range (AIXR), and Turbo TeeJet Induction (TTI) (Spraying Systems Co., Wheaton, IL, USA). All nozzles were 110015 flat-fan nozzles and were evaluated at a pressure of 276 kPa. A digital manometer was fixed next to each nozzle to ensure that the pressure was the same for all nozzles. Each replication consisted of a continuous 10-second application, controlled by a digital auto shut-off timer switch

(Intermatic Inc., EI 400C, Spring Grove, IL, USA). All distances were sprayed at the same time and each set was considered one replication.

2.1 Determination of drift

All treatments were applied in a wind tunnel with a working section of 1.2 m wide, 1.2 m high, and 15 m long was used. This wind tunnel uses an axial fan (Hartzell Inc., Piqua, OH, USA) to generate and move air flow from the fan into an expansion chamber located in front of the tunnel. The wind speed was fixed at 2.2 m s^{-1} (8 km h^{-1}). Environmental conditions during applications were kept at 20ºC (± 2ºC) and 60 to 70% relative humidity.

This study was conducted twice, separated temporally to represent two experimental runs. All conditions such as treatments, wind tunnel set up, and procedures were the same for both runs. Drift was determined according to the ISO/DIS 22856-1 Standard (ISO 22856, 2008) with a few modifications. Prior to each application, artificial collectors composed of colorless round strings 2 mm diameter (Blount Inc., Magnum Gatorline™, Portland, OR, USA) and 1.0 m length were positioned at each distance, parallel and perpendicular to the tunnel floor and its length, respectively.

Collectors and nozzle were placed at 0.1 m and 0.6 m above the tunnel floor and in the longitudinal center of the wind tunnel, respectively. A 1.2 m x 0.5 m rug with polyethylene blades 1 cm tall (GrassWorx LLC., St. Louis, MO, USA) was positioned on the sprayed area to absorb droplets, simulating a leaf surface (Figure 2.1, Chapter II). Once the application was performed, strings were collected and placed individually into pre-labeled plastic bags and then placed into a dark container to prevent photodegradation of the tracer. Samples were kept in the dark until fluorimetric analysis could be conducted.

In the laboratory, 50 mL of 1:9 isopropyl alcohol:destilled water solution was added to each plastic bag using a bottle top dispenser (LabSciences Inc., 60000-BTR, Reno, NV, USA). Samples were then swirled and shaken to release fluorescent material. After tracer was suspended in solution, a 1.5 mL aliquot from each sample bag was drawn to fill a glass cuvette. The cuvette was placed in a PTSA module inside a fluorimeter (Turner Designs, Trilogy 7200.000, Sunnyvale, CA, USA) using ultra-violet light to collect fluorescence data. The fluorimeter was initially calibrated to Relative Fluorescence Unit (RFU), which was converted into mg L^{-1} using a calibration curve for the tracer (Figure 2.2, Chapter II). The percentage of drift for each distance was calculated using the Equations 1 and 2 shown in Chapter II.

2.2 Droplet spectrum

Droplet spectrum for each spray and nozzle combination was evaluated at 276 kPa pressure and analyzed using a Sympatec HELOS-VARIO K/R laser diffraction droplet sizing system (Sympatec Inc., Clausthal, Germany) set up with R7 lens with a dynamic size range of 9 to 3700 µm. The distance from the nozzle tip to the laser was 0.3 m. This system is integrated into the wind tunnel and the wind speed was maintained at 6.7 m s^{-1} during data acquisition, following methodology proposed by Fritz et al. (2014). A minimum of three replicated measurements were made for each treatment, with each replication consisted of a complete vertical traverse of the spray plume. Spray parameters of interest were $D_{v0.1}$, $D_{v0.5}$ and $D_{v0.9}$, which are the droplet diameter (µm) for 10%, 50%, and 90%, respectively, of the total spray volume contained in droplets of equal or lesser size. Relative span (RS) and volume percentage of droplets smaller than 100 µm (V_{100}) were also recorded. Relative span is a dimensionless parameter indicative of uniformity of droplet size distribution, while V_{100} is an indicator of the potential risk of drift.

2.3 Statistical analysis

For analysis of percentage of drift data, Kolmogorov-Smirnov (K-S) and Levene's tests were applied to analyze normality of residuals and homogeneity of variance, respectively, using SPSS Statistical Software, version 17.0 (SPSS Inc., Chicago, IL, USA). In cases that the assumptions were significant at $\alpha = 0.01$, the data were transformed by arc sine $[(x/100)^{0.5}]$ and subjected to a new analysis.

Data (original and transformed) were subjected to analysis of variance (ANOVA) using Sisvar Statistical Software, version 5.6 (FERREIRA, 2011). When significant differences were observed, herbicide solutions and nozzles were compared to each other for each distance using Tukey's multiple comparison test, whereas regression analysis was performed for distances both at $\alpha = 0.05$. All adjustments of the regressions were made using SigmaPlot Software, version 11.0 (Systat Software Inc., Chicago, IL, USA).

Normality of residuals and homogeneity of variance of droplet spectrum data were also analyzed using Shapiro Wilk and Levene's tests, respectively. If necessary, $D_{v0.1}$,

$D_{v0.5}$, $D_{v0.9}$ and RS data were transformed by $(x + 0.5)^{0.5}$ and V_{100} data were transformed by arc sine $[(x/100)^{0.5}]$. Volume percentage of droplets smaller than 100 µm (V_{100}) and RS data were subjected to analysis of variance using Sisvar Statistical Software, version 5.6 (FERREIRA, 2011) and averages were compared using Tukey's test at $\alpha = 0.05$. Confidence interval of 95% were used for $D_{v0.1}$, $D_{v0.5}$ and $D_{v0.9}$ comparisons using SigmaPlot, version 11.0. Differently than represented for RS and V_{100}, this analysis was performed to produce a graphical representation of cumulative volume fraction.

3 RESULTS AND DISCUSSION

Assumptions from the original V_{100} and drift data were not reached at $\alpha = 0.01$; therefore, data were transformed proceeding all comparisons between treatments to improve the analysis. It was applicable to both runs. For the other variables, ANOVA was conducted using the original data.

Droplet spectrum was significantly affected by spray composition for AIXR and TTI nozzles (Figure 4.1), producing smaller droplets when dicamba was combined with glyphosate. For this solution, there was a reduction in $D_{v0.5}$ values (also known as volumetric median diameter) of approximately 8.9% and 6.8% for TTI (704 µm) and AIXR (347 µm), respectively.

Meyer et al. (2015) evaluated the droplet spectrum of dicamba, glyphosate and glufosinate sprayed through three nozzles at 141 L ha^{-1} carrier volume and 276 kPa pressure. They did not observed differences on $D_{v0.5}$ between dicamba and dicamba + glyphosate for TT, AIXR and TTI nozzles. However, it is important to recognize that the authors used a different dicamba formulation and lower carrier volume which may explain differences in results.

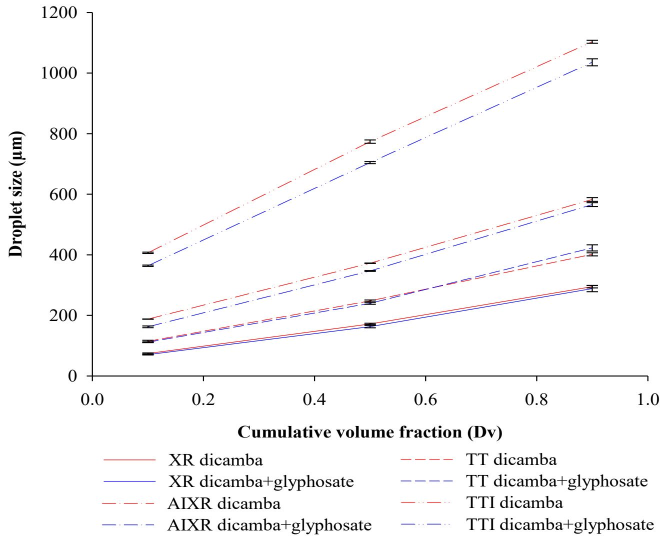

FIGURE 4.1. Droplet diameter for the cumulative volume fraction ($D_{v0.1}$, $D_{v0.5}$, $D_{v0.9}$) of four different nozzle types and two herbicide solutions.

Droplet spectrum produced through extended range nozzles (XR and AIXR) resulted in lower V_{100} when dicamba alone was sprayed (Figure 4.2). In contrast, when sprayed through TTI nozzle, dicamba alone produced higher V_{100} (0.33%) compared to dicamba + glyphosate (0.02%). The highest and lowest potential risks of drift were observed for XR and TTI nozzles, respectively, for both herbicide solutions. The XR nozzle produced much smaller droplets than the TTI nozzle whose droplets were on average 4-fold larger than those produced by XR, which means that the V_{100} increased as the droplet size decreased.

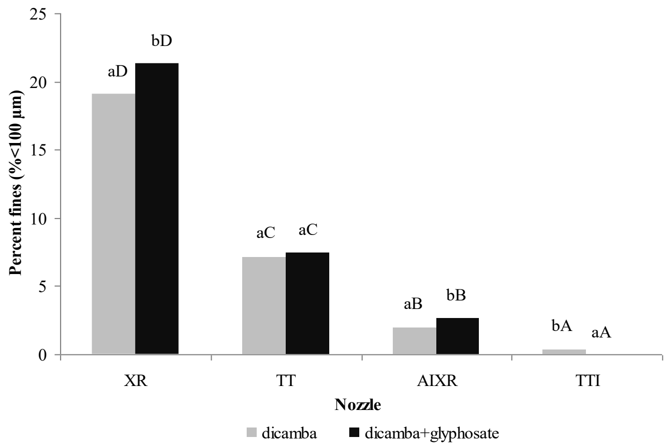

FIGURE 4.2. Volume percentage of droplets smaller than 100 µm produced through four different nozzle types using two herbicide solutions. Comparisons between solutions for each nozzle type and between nozzles for each solution are made by lower and upper cases, respectively. Same letters represent no statistical difference using Tukey's test at $\alpha = 0.05$. $F_{nozzle\ x\ solution} = 27.7^{**}$, significant at $\alpha = 0.01$.

Comparing nozzles within dicamba + glyphosate solution, TTI and TT nozzles had a difference in potential risk of drift by 99%, whereas AIXR and XR had a difference of 88%. Combellack et al. (1996) studied drift potential of flat-fan nozzles in a wind tunnel and observed that the low-drift standard nozzle reduced drift by 62% compared to the same nozzle without air induction.

Dicamba + glyphosate generated more heterogeneous droplet spectrum compared to dicamba alone for all nozzles tested. This is explained by higher relative span (Figure 4.3), indicating that this combination widened the droplet spectrum. Similarly, V_{100} from XR and AIXR nozzles were higher for dicamba + glyphosate compared to dicamba alone. A more heterogeneous droplet spectrum tends to produce higher percentage of fine droplets. However, it can vary with nozzle type as was observed for the TTI nozzle, which produced lower V_{100} and higher relative span using dicamba + glyphosate. It is well known that different nozzle types respond differently to changes in fluid physical properties (BUTLER ELLIS et al., 2001), and flat-fan and air induction nozzles all produce a wide spectrum of droplet sizes (MATTHEWS, 2000).

When comparing nozzles within each solution, greater relative spans were associated with smaller droplet sizes. Therefore, TTI produced more homogeneous droplets, followed by AIXR, TT and XR nozzles. Similar results were observed for V_{100}, meaning this variable may be correlated with relative span as well.

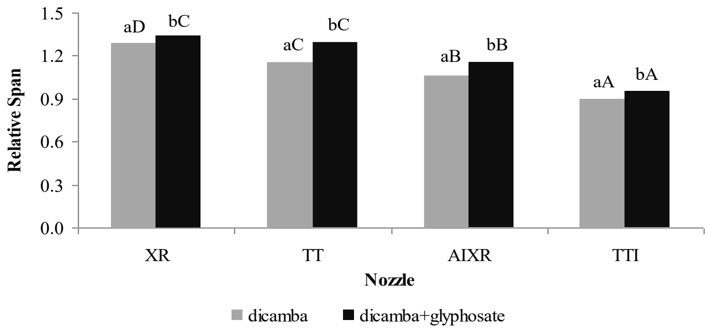

FIGURE 4.3. Relative span of droplets produced through four different nozzle types using two herbicide solutions. Comparisons between solutions for each nozzle type and between nozzles for each solution are made by lower and upper cases, respectively. Same letters represent no statistical difference using Tukey's test at $\alpha = 0.05$. $F_{nozzle\ x\ solution} = 7.3^{**}$, significant at $\alpha = 0.01$.

In run 1, the highest percentage of drift was observed for the XR nozzle at all distances for both solutions, except at 12 m for dicamba alone, where drift from this nozzle was similar to drift produced by TT (Table 4.1). The highest and lowest percentage of drift were 65.9% at 2 m and 0.1% at 12 m produced by XR and TTI nozzles, respectively, which were expected due to the differences in droplet size between the two nozzles. Butler Ellis et al. (2002) evaluated spray characteristics and drift performance of air induction nozzles and concluded that spray drift was largely influenced by droplet size with larger $D_{v0.5}$ resulting in less drift.

Dicamba + glyphosate resulted in less drift than dicamba alone sprayed through XR and AIXR nozzles whereas the opposite was observed for TTI nozzle. It has been clearly reported that the final result depends on the combination between the solution and nozzle. Miller and Butler Ellis (2000) reported that physicochemical properties of solution, including adjuvants, produce inconsistent results between nozzles, especially for air induction nozzles. In many cases, such as observed in this study, there are interactions between nozzle type and spray solution.

It is expected to observe greater drift in cases with higher V_{100} and where the droplet spectrum is more heterogeneous. However, it was not observed in this study. Although dicamba alone sprayed through XR nozzle produced lower V_{100} and more homogeneous droplet spectrum compared to dicamba + glyphosate, greater drift was observed.

Several studies have shown that droplets smaller than 100 µm are more prone to drift (ANTUNIASSI et al., 2014; MURPHY et al., 2000; NUYTTENS et al., 2007; WOLF, 2000). However, greater drift is not necessarily observed in cases with higher volume percentage of fine droplets. In order to accurately predict drift based on droplet size, it is important to have the full droplet spectrum. Even though the TTI nozzle produced higher V_{100} with dicamba alone, larger droplets were produced, and in turn, lower percentage of drift compared to dicamba + glyphosate.

Differently from run 1, in run 2, dicamba alone and dicamba + glyphosate sprayed through the TT, AIXR and TTI nozzles produced similar percentage of drift (Table 4.1). At 12 m, TT and AIXR nozzles generated similar drift for dicamba alone. However, AIXR produced less drift than TT for dicamba + glyphosate. The AIXR produced less drift than TT and no differences were observed between the two standard nozzles, similarly noticed between the two air induction nozzles. Drift produced by TTI nozzle was approximately 95% lower than drift produced by XR nozzle.

This shows that air induction nozzles are an excellent alternative to reduce the environmental contamination. Stainier et al. (2006) evaluated potential drift of two phenmediphan formulations associated with different adjuvants using standard and air induction flat-fan nozzles and found that the air induction nozzles reduced by 83% the potential drift compared to standard nozzles. Taylor et al. (1999) also reported reductions in fallout deposits using air induction nozzles, which varied from 89 to 91% depending on orifice size of nozzle. However, their use cannot be broadly recommended for all pesticide applications due to herbicide efficacy. Some herbicides have shown increased efficacy when sprayed using an air induction nozzle while for others the efficacy is reduced. According to Meyer et al. (2015), nozzle selection does not solely affect the efficacy of the application. When spraying dicamba, nozzle selection requirements will primarily be based on their ability to minimize drift (have a high $D_{v0.5}$ and low V_{100}).

TABLE 4.1. Percentage of drift from herbicide applications in a wind tunnel, measured from 2 to 12 m downwind from different nozzle types in two experimental runs

Distance	Herbicide solution	Nozzle (Run 1)[a]				Nozzle (Run 2)			
		XR	TT	AIXR	TTI	XR	TT	AIXR	TTI
m		%							
2	dicamba	65.9 dB	40.1 cA	15.6 bB	4.5 aA	56.1 dB	35.8 cA	14.7 bA	3.3 aA
	dicamba + glyphosate	56.3 dA	40.9 cA	14.2 bA	6.9 aB	49.5 dA	37.6 cA	13.2 bA	5.4 aB
3	dicamba	40.8 dB	23.3 cA	8.1 bB	1.8 aA	31.7 dB	18.8 cA	6.7 bA	1.2 aA
	dicamba + glyphosate	33.5 dA	23.5 cA	6.9 bA	2.9 aB	28.0 dA	20.4 cA	5.8 bA	2.2 aA
4	dicamba	25.3 dB	14.0 cA	4.8 bB	0.8 aA	19.3 dB	10.7 cA	3.7 bA	0.8 aA
	dicamba + glyphosate	20.5 dA	13.4 cA	3.7 bA	1.7 aB	17.1 dA	11.7 cA	3.1 bA	1.2 aA
5	dicamba	16.6 dB	9.6 cB	3.6 bB	0.5 aA	13.0 dB	6.6 cA	2.4 bA	0.5 aA
	dicamba + glyphosate	13.1 dA	7.8 cA	2.3 bA	1.1 aB	10.9 dA	7.3 cA	1.9 bA	0.8 aA
6	dicamba	12.1 dB	6.9 cB	2.9 bB	0.3 aA	9.3 dB	4.3 cA	1.5 bA	0.4 aA
	dicamba + glyphosate	8.6 dA	5.3 cA	1.7 bA	0.9 aB	7.6 dA	4.9 cA	1.3 bA	0.4 aA
7	dicamba	8.9 dB	5.3 cB	2.6 bB	0.2 aA	6.5 dB	3.3 cA	1.2 bA	0.4 aA
	dicamba + glyphosate	6.2 dA	3.5 cA	1.4 bA	0.8 aB	5.0 cA	3.4 bA	1.0 aA	0.6 aA
12	dicamba	3.0 cB	2.7 cB	1.9 bB	0.1 aA	2.0 cA	0.9 bA	0.4 bA	0.1 aA
	dicamba + glyphosate	1.9 cA	1.1 bA	0.8 abA	0.6 aB	1.7 bA	0.9 bA	0.3 aA	0.1 aA
[b]Original data		$F_{Levene} = 3.860^{**}$; K-S = 0.191**				$F_{Levene} = 5.735^{**}$; K-S = 0.243**			
Transformed data		$F_{Levene} = 2.851^{**}$; K-S = 0.108**				$F_{Levene} = 3.829^{**}$; K-S = 0.156**			
[c]$F_{sol\ x\ noz\ x\ dist}$		9.8**				2.9**			

[a] Averages followed by the same letter within each distance and run, lower case in the rows and upper case in the columns, do not differ using Tukey's test at $\alpha = 0.05$.
[b] F_{Levene} and K-S values of the F statistic for the Levene's test and K-S for the Kolmogorov-Smirnov's test, respectively. Data transformed by arc sine $[(x/100)^{0.5}]$.
[c] $F_{sol\ x\ noz\ x\ dist}$: Calculated F-value for the interaction between herbicide solution, nozzle and distance. **Significant at $\alpha = 0.01$.

Figure 4.4 and Table 4.2 represent regressions for each combination of herbicide solution and nozzle. All functions were adjusted by two-parameter exponential equations, with R-squares over 94% in run 1 and 96% in run 2. Thus, for all studied conditions, drift decreased exponentially as the downwind distance from nozzle increased. Drift distributions have been based on potential function by Alves and Cunha (2014), Ganzelmeier et al. (1995), and Meli et al. (2003), on four-parameter exponential decay function by Bueno et al. (2016) and Holterman and van de Zande (2003), and logistic function by Koger et al. (2005). Therefore, just one type of function cannot be generalized for all conditions, as seen in drift data which are variable and dependent on the physicochemical properties of the spray solution, nozzle type and orifice size, wind speed and location of the study (wind tunnel, bench or field).

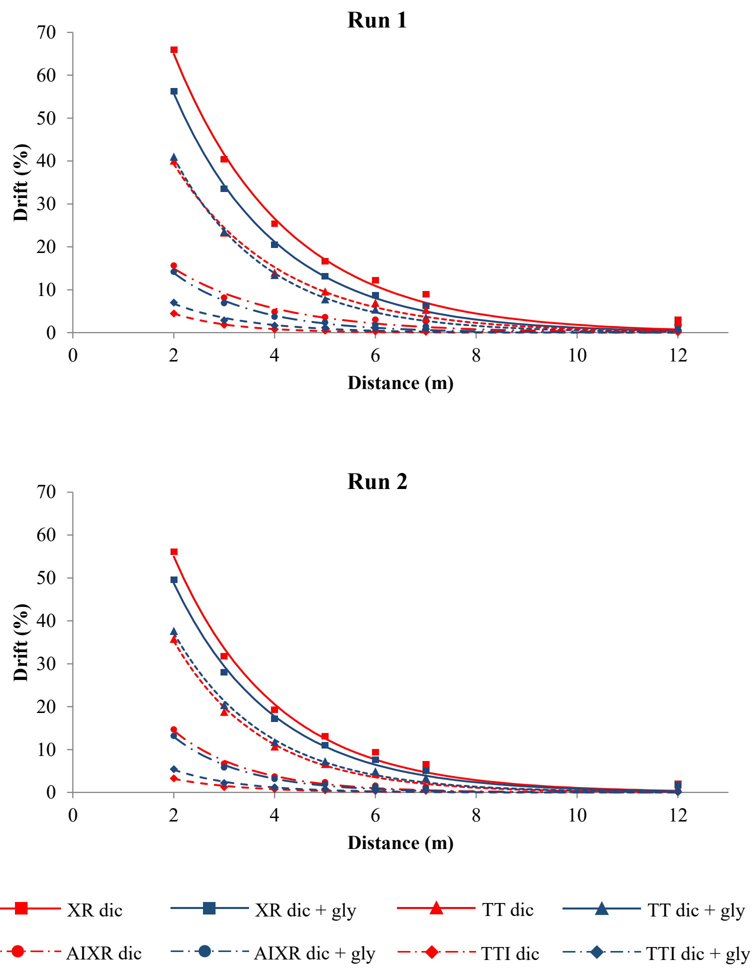

FIGURE 4.4. Percentage of drift from dicamba (dic) and glyphosate (gly) applications using four different nozzle types in two experimental runs.

TABLE 4.2. Functions, R^2 and F_c generated by regression analysis using two different herbicide solutions sprayed through four nozzle types in two experimental runs

Solution[a]	Nozzle	Run 1			Run 2		
		Function ($\hat{y}$ =)	R^2	[b]F_c**	Function ($\hat{y}$ =)	R^2	F_c
			%			%	
Dic	XR	$158.48e^{-0.4461x}$	99.50	5116.2	$146.96e^{-0.4918x}$	99.28	1716.5**
	TT	$101.19e^{-0.4732x}$	98.76	1827.8	$111.14e^{-0.5741x}$	99.49	733.1**
	AIXR	$39.48e^{-0.4856x}$	94.49	238.0	$53.89e^{-0.6609x}$	98.82	121.0**
	TTI	$23.63e^{-0.8369x}$	99.60	26.3	$13.37e^{-0.7188x}$	96.40	5.7**
Dic + gly	XR	$146.67e^{-0.4838x}$	99.74	3899.7	$133.96e^{-0.5051x}$	99.56	1374.8**
	TT	$119.95e^{-0.5394x}$	99.81	2148.6	$112.42e^{-0.5539x}$	99.59	812.0**
	AIXR	$48.20e^{-0.6226x}$	98.39	236.2	$52.50e^{-0.7002x}$	98.96	99.2**
	TTI	$25.62e^{-0.6673x}$	95.32	51.9	$23.54e^{-0.7463x}$	98.17	16.4**

[a] Abbreviations: dic: dicamba; gly: glyphosate.
[b] F_c: Calculated F-value. **Significant at $\alpha = 0.01$.

It is important to mention that a lower percentage of drift was obtained at second run experiment, where the highest and lowest results were 56.1% at 2 m and 0.1% at 12 m whereas in the first run they were 65.9% and 0.1%, respectively. Different results from first and second runs can be explained by having only a few replications. Four replications are considered an acceptable and consistent number to be used when there are many treatments involved. However, as drift studies produce variable results, they should involve a larger number of replications whenever possible.

Although Fritz et al. (2012) comment that wind tunnel evaluations offer a quick and inexpensive method for evaluating a large numbers of treatments, without issues of variability seen under field conditions, indeed field studies should be conducted to ensure that the results from this study may be applied in the field. As mentioned by Gil and Sinfort (2005), drift models cannot substitute field determination, but rather as a powerful complement that aids understanding of the phenomenon. In addition, Combellack et al. (1996) and Nuyttens et al. (2009) have described that the potential drift is reduced by increasing the liquid flow rate. Therefore, because this study involved only 110015 nozzles, additional studies should be conducted with greater flow rates to evaluate if similar results are observed.

4 CONCLUSIONS

Dicamba droplet spectrum and drift depended on the association between herbicide solution and nozzle type. These factors should be considered to reduce product losses and minimize environmental contamination. Dicamba alone produced coarser droplets than dicamba + glyphosate when sprayed through air induction nozzles. In addition, dicamba + glyphosate sprayed through extended range nozzles generated higher volume percentage of droplets smaller than 100 μm. Lastly, more homogeneous droplet spectrum was observed for dicamba alone solution and as droplet size increased.

Drift decreased exponentially as downwind distance increased and was reduced using air induction nozzles for both herbicide solutions. Dicamba alone produced greater drift than dicamba + glyphosate when sprayed through AIXR whereas the opposite was observed for TTI nozzles in run 1. However, in run 2, both herbicide solutions produced similar drift when sprayed through these same nozzles.

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APPENDIX A

FIGURE 1A. Wind tunnel facility: structure of the tunnel (a), spraying controller (b), spray zone (c), and positions of drift collectors (d and e).

FIGURE 2A. Nozzles used in dicamba applications. From the left to the right: XR, TT, AIXR, TTI, and 100 mesh filter. (Photos: Sousa Alves, 2015)