CHAPTER 7

Dicamba Spray Droplet Retention on Leaves as Influenced by Nozzle Type, Application Pressure, and Adjuvant Type

Abstract

Off-target movement of growth regulator herbicides can cause severe injury to susceptible plants. Apart from not spraying on windy days or with excessive boom heights, making herbicide applications using nozzles that produce large droplets is the preferred method to reducing herbicide drift. Although large droplets maintain a higher velocity and are more likely to reach the leaf surface in windy conditions, their ability to remain on the leaf surface is not well understood. Upon impaction with the leaf surface, droplets may shatter, bounce, roll off, or be retained on a leaf surface. This study was conducted to evaluate how nozzle types, adjuvants, and pressure impact spray retention on a leaf surface. Common lambsquarters and soybean plants were grown inside a greenhouse located at the Pesticide Application Technology Laboratory, West Central Research and Extension Center, University of Nebraska-Lincoln in North Platte, NE. Three nozzles (XR, AIXR, and TTI) were evaluated at 138, 259, and 379 kPa. Dicamba (0.14 kg ae ha^{-1}) was applied alone and with a non-ionic surfactant (NIS), crop oil (COC), methylated seed oil (MSO), silicone, or drift reduction adjuvant (DRA) and contained 1, 3, 6, 8-pyrene tetra sulfonic acid tetra sodium salt as a tracer. Dicamba spray retention when applied using the XR nozzle, which produced the smallest spray droplets, was 1.75 times greater than when applied with the TTI nozzle which had the largest spray droplets. Applying dicamba with MSO resulted in spray retention on leaf surfaces nearly four times the amount achieved when applying dicamba without an adjuvant. The lowest

application pressure (138 kPa) had more than 10% more dicamba spray retention compared to the higher pressures 259 and 379 kPa. By understanding the impacts of these application parameters on dicamba spray droplet retention, applicators can select application parameters, equipment, and adjuvants that will maximize the amount of dicamba spray retained on the target leaf surface while minimizing dicamba spray drift.

Introduction

Glyphosate-resistant weeds have developed in part due to selection pressure applied to weed populations by the extensive use of glyphosate within corn (*Zea mays* L.), soybean [*Glycine max* (L.) Merr.], and cotton (*Gossypium hirsutum* L.) production systems (Johnson et al. 2009). In response to increasing glyphosate resistance, alternative weed management strategies including herbicide-resistant crop traits are being integrated that use various herbicide modes-of-action that otherwise would not be an option. This includes development of dicamba-resistant, 2,4-D-resistant, and HPPD-inhibitor-resistant soybeans that are being developed by U.S. companies and will soon be available to growers pending regulatory approval. Once approved, the dicamba-, 2,4-D-, and HPPD-resistant technology will enable the use of dicamba, 2,4-D, or HPPD-inhibitors alone and with other herbicides for preplant burndown, at planting, and in-season applications (Davis 2012). This will give growers the ability to control herbicide-resistant weeds growing within a crop with herbicides that otherwise would injure the crop.

Dicamba can be used as preplant burndown or postemergence to selectively control broadleaf weeds in grass crops. Broadleaf crops like soybeans are often grown near grain crops and are vulnerable to off-target movement of dicamba. Previous research has reported dicamba drift injury on cotton, soybean, potato (*Solanum tuberosum*), field bean (*Phaseolus vulgaris*), and tomato (*Lycopersicon esculentum*) (Kruger et al. 2012; Lyon and Wilson 1986; Marple et al. 2008; Wall 1994; Weidenhamer et al. 1989). Dicamba is a phenoxy herbicide with injury symptoms that include cupping and curling of leaves as well as stem epinasty. These injury symptoms are easily recognizable and readily manifest the occurrence of phenoxy herbicide drift. A major concern of herbicide-resistant crops is the incidence of off-target movement of herbicides due to increased reliance on and usage of herbicides for weed control within these systems.

Physical herbicide drift occurs when spray droplets are displaced from their intended flight path due to wind. Application variables that can impact herbicide drift include the use of a hooded sprayer boom (Wolf et al. 1993), the use of drift control agents (Bode et al. 1976), or by lowering the spray boom closer to the ground (Combellack et al. 1996). Apart from not spraying on a windy day, the most influential factor related to herbicide drift is droplet size (Bird et al. 1996; Carlsen et al. 2006; Nuyttens et al. 2007b; Ozkan et al. 1997). Larger droplets maintain their direction and momentum longer and are less prone to be displaced by the wind whereas smaller droplets quickly lose their momentum and become suspended in the air (Nuyttens et al. 2009). Creech et al. (2015a) identified nozzle type as the most important factor determining spray droplet size followed by operating pressure, herbicide spray solution, nozzle orifice size, and carrier volume rate. Increasing the spray pressure decreases droplet size yet herbicide drift may decrease depending on nozzle design due to the dominance of droplet velocity (Miller and Smith 1997).

The spray droplet discharged from a nozzle is the vehicle most often used to deliver the herbicide active ingredient to the weed target. The droplet must first travel the distance from the spray boom to the target. Spray droplets leave the nozzle traveling at velocities of 15 to 25 m s^{-1} (Dombrowski and Johns 1963). When a droplet impacts a plant surface, it will either be retained through adhesion, bounce, shatter, or roll off. Droplets that are not retained can continue through the canopy and may be retained on a lower leaf or may impact the ground (Schou et al. 2012). Monocotyledons predominantly have a vertical structure and are more likely to retain smaller droplets than larger droplets (Knoche 1994). Nairn et al. (2014) observed lower adhesion of droplets to hairy leaves due to an increase in the incidence of droplet shatter. Growing conditions can alter the wettability of a plant and decrease droplet retention on the leaf surface (Forster and van Leeuwen 2010). The ability of spray droplets to remain on a plant surface determines the quantity of herbicide potentially available to be taken up by the plant. Herbicide performance increased more frequently on difficult-to-wet species as droplet size decreased in the meta-analysis than easy-to-wet species (Knoche 1994).

Other variables that impact droplet retention include plant morphological characteristics such as leaf angle and pubescence as well as droplet surface tension (Ennis et al. 1952). Retention of spray droplets is more dependent upon dynamic surface tension than equilibrium surface tension (Anderson et al. 1987; De Ruiter et al. 1990). By changing the surface tension of a spray droplet, adjuvants allow spray droplets to spread and remain over a normally repellent leaf surface (Monaco et al. 2002). Thus, adjuvants can increase droplet retention by causing more uniform spreading and wetting of the plant surface and assisting spray droplets to stick to plants (Monaco et al. 2002). For this reason, adjuvants are often added to postemergence spray solutions to enhance spray solution characteristics and/or herbicide activity. Applicators select adjuvants based on many factors namely cost, phytotoxicity risk, compatibility with tank-mix partners, and recommendations from herbicide labels and industry consultants.

In order to mitigate off-target movement of dicamba, herbicide labels recommend applicators use nozzles designed to produce large diameter droplets (Anonymous 2013a). While increasing the spray droplet size of an herbicide application may be effective at mitigating off-target movement (Bode 1987), increasing the spray droplet size of an application can impact herbicide efficacy (Knoche 1994). In addition, the dicamba herbicide label recommends the use of adjuvants and lists many different types that may be used (Anonymous 2013a). While this approach allows an applicator the ability to tailor an application to his/her specific needs, without sufficient knowledge proper selection of the most appropriate adjuvant can be difficult due to the complexity of the system (Zollinger 2009). Although these recommendations are on the dicamba label, researchers have not explored the impact they might have on the retention of spray droplets on their intended targets. The objective of this study was to determine the impact of droplet size, application pressure, and adjuvant type on the spray droplet retention of dicamba. This study will provide applicators with information to allow them to make educated decisions when making dicamba applications.

Materials and Methods

This study was conducted during the fall of 2014 at the Pesticide Application Technology Laboratory (PAT Lab) of the University of Nebraska-Lincoln located at the

West Central Research and Extension Center in North Platte, NE. The study had five replications and two runs separated temporally for each plant species evaluated. A dicamba (0.14 kg ae ha^{-1}) spray solution was applied alone and with a non-ionic surfactant (NIS), crop oil concentrate (COC), methylated seed oil (MSO), silicone based adjuvant, or a drift reduction adjuvant (DRA) (Table 7.1). The AIXR 110025, TTI 110025 and XR 110025 nozzles (Teejet Technologies, Spraying Systems Co., Springfield, IL 62703) were operated at 138, 259, and 379 kPa to deliver 94 L ha^{-1}. A 1, 3, 6, 8-pyrene tetra sulfonic acid tetra sodium salt (PTSA) was added as a tracer dye at 0.6 mg/ml as recommended by Hoffmann et al. (2014) for agricultural sprays. Treatments were applied using a single nozzle track sprayer (Generation III Research Track Sprayer DeVries Manufacturing, Hollandale, MN 56045). Prior to conducting the study, each nozzle and pressure combination was calibrated to ensure equal deposition by mass at the same height and location within the spray pattern that the plant species would be placed. This was completed by using a 15 cm petri dish and making 20 spray passes over the dish. The dish would then be weighed and the speed of the track sprayer would be adjusted until the nozzles each had the same deposition at the target site. This method of calibration was used because it was recognized that simply measuring the output of each nozzle for a period of time would be an insufficient means of calibration for this study because of variations of spray patterns among nozzles at the target site.

Common lambsquarters (*Chenopodium album* L.) and Asgrow® A3253 soybeans were grown in SC10 cone-tainer cells (Stuewe and Sons Inc., Corvallis, OR 97389) that were filled with Professional Growers Mix potting soil (Ball Horticulture Company, West Chicago, IL, 60185). Plants received supplemental nutrition (Scotts Miracle-Gro®

LiquaFeed® All Purpose, The Scotts Company, Marysville, OH, 43041) once per week. Supplemental lighting (NeoSol™ DS 300W, Illumitex, Austin, TX, 78735) was provided to ensure 14 h days. Plants were sprayed with dicamba treatments when the two unifoliate leaves were fully developed on soybean plants and when common lambsquarters had at least four large leaves. For each species, this occurred when plants were 15 to 20 cm tall. Prior to spraying the plants, any foliage above the target leaves was clipped and removed to ensure the spray droplets were not impeded from the target leaves.

Plants were placed individually in the center of the track sprayer 50 cm below the tip of the nozzle. In addition, a 15 cm petri dish was placed at the height of the plant canopy to collect spray deposition. This was used to further verify that equal amounts of deposition were applied across all treatment combinations. If any differences were observed, data was corrected to ensure equal comparison across treatment factors and that no bias was present. After a plant was sprayed, it was removed from the track sprayer and treated leaves were clipped into pre-labeled plastic recloseable bags. The leaves were then rinsed immediately with 40 ml of a 9:1 distilled water to isopropyl alcohol solution added using a bottle top dispenser (Model 60000-BTR, LabSciences, Inc., Reno, NV, 89510). This solution provided the maximum recovery of PTSA deposits in a study conducted by Hoffmann et al. (2014). After the PTSA dye was successfully suspended in the liquid, a two ml sample was drawn with a pipette to fill a glass cuvette. The cuvette was placed in a PTSA module inside a fluorometer (Trilogy Laboratory Fluorometer, Turner Designs, Sunnyvale, CA, 94085) and fluorescence data were collected.

Data were corrected to account for differences in leaf area and recovery as follows. After the leaves were rinsed, they were removed from the bags and dried using paper towels. The total leaf area for all leaves used for each plant was determined using an LI-3100 leaf area meter (LI-COR, Lincoln, NE, 68504). To evaluate recovery of the PTSA dye from leaf surfaces, 20 µl of each spray solution was pipetted directly onto leaves of each species and into plastic bags. The leaves were then clipped into plastic bags and rinsed and processed in the same manner as regular leaf samples with 40 ml of distilled water and isopropyl alcohol solution. Bags without leaves were also processed in the same manner. The recovery of PTSA dye from the plant surface was a percentage of the amount observed from bags with no leaves.

The spray droplet spectrum for each treatment combination was evaluated in 2014 using the low speed wind tunnel at the PAT Lab. The system and process used to collect the spray droplet data has been described extensively in a previous manuscript (Creech et al. 2015b). The laser is able to classify the spray droplet spectrum in a number of different categories to compare the spray droplet spectra of different treatments. The treatments in this study were compared using the $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ parameters which represent the droplet size such that 10, 50, and 90% of the spray volume is contained in droplets of equal or smaller values, respectively. The amount of spray volume contained in droplets smaller than 200 µm was also used for comparison. The spray classifications used in this manuscript were derived from reference curves created from reference nozzle data at the PAT Lab as described by ASAE S572.1 (ASABE 2009) (Table 7.1). The use of reference nozzles and curves allow for comparison of data obtained from other laboratories or methods (Fritz et al. 2014).

Statistical Analysis. Results from common lambsquarters and soybean spray droplet retention on leaf surfaces were analyzed separately because the treatments were applied at different times.

Spray droplet retention rates were calculated as a percent of the applied rate as determined from the amount of spray collected in the adjacent petri dish. Spray droplet retention data from each species were compared using a generalized linear mixed model analysis of variance in the GLIMMIX procedure of SAS v9.3 (SAS Institute, Cary, NC 27513). Data from the runs of each species were combined within each experiment because they did not differ significantly. Replication was nested within run and considered a random effect in the model. LS means were compared for significant fixed effects at an alpha level of 0.05.

Results and Discussion

Spray Droplet Size. The droplet size spectra of each treatment are presented in Table 7.1. In general, the addition of a silicone adjuvant to dicamba produced the smallest spray droplets, followed by MSO, DRA, COC, NIS, and dicamba without an adjuvant. These spray solutions had $D_{v0.5}$ values of 482, 489, 507, 524, 546, and 559 µm, respectively, when averaged over nozzle type and pressure (Table 7.1). The different nozzle types had the greatest variability among $D_{v0.5}$ values when averaged over adjuvant and pressure. The AIXR, TTI, and XR nozzles had average $D_{v0.5}$ values of 505, 812, and 237, respectively (Table 7.1). The difference in spray droplet size among nozzles is also apparent when comparing the amount of spray volume contained in droplets less than 200 µm. The TTI nozzle typically had less than one percent while the XR nozzle had nearly

50% of its spray volume contained in droplets less than 200 µm when applications were made at 379 kPa (Table 7.1). Increasing the application pressure decreased spray droplet size as determined by $D_{v0.5}$ values from 629 µm to 495 and 430 µm averaged across nozzle type and spray solution for 138, 259, and 924 kPa, respectively (Table 7.1). The different combination of variables in the study resulted in spray classifications ranging from Very Fine to Ultra Coarse (Table 7.1). Spray droplets are the means of transportation frequently used in herbicide applications to deliver a lethal dose of chemical to the target plant species. Furthermore, the spray droplet size is highly correlated to the velocity of the droplets (Nuyttens et al. 2009) and the rate of change of size with distance from spray release. Smaller droplets may initially have a high velocity when emitted through the nozzle but their low mass allows them to rapidly decelerate. At the plant location, these small droplets, with their relatively slower velocities, are more readily retained on a leaf surface (Ramsdale and Messersmith 2001). Understanding these principles and the spray droplet characteristics of the treatment variables described in Table 7.1 will give further clarity and reasoning to the results presented hereafter.

Common lambsquarters. Common lambsquarters was used for this experiment because it has a leaf surface composed of crystalline epicuticular wax which makes it difficult to wet (Harr et al. 1991). A significant three-way interaction ($P = 0.0025$) was observed among nozzle type, pressure, and spray solution as they relate to dicamba spray droplet retention on common lambsquarters leaves. Due to the large number of treatment interactions, the many differences will not be covered individually, rather trends will be discussed. The use of adjuvants significantly increased the amount of spray retained on the surface of common lambsquarters (Table 7.3). Of the top ranked 15 treatments for dicamba retention, MSO accounted for six instances, followed by COC, NIS, and silicone with four, three, and two instances, respectively. These 15 highest ranked treatments had an average spray retention of 24% of the applied rate (Table 7.3). Dicamba applied without an adjuvant, ranked near the bottom in comparison to other treatments with adjuvants with less than 10% spray retention on common lambsquarters leaf surfaces (Table 7.3). The addition of DRA to the dicamba solution only moderately increased retention compared to dicamba alone. These two treatments had less than half the dicamba spray retention that the top ranked 15 treatments had. For the most part, the use of NIS and silicone with dicamba was most often ranked near the middle of all the treatments for spray retention.

In most instances, the spray droplet classifications for the dicamba alone and with DRA treatments that were ranked in the last 15 were Coarse, Extremely Coarse, and Ultra Coarse (Table 7.3). The majority of these treatments were applied with TTI and AIXR nozzles. The few exceptions were the treatments applied with the XR nozzle that produced Fine and Medium spray classifications. Although these XR nozzle treatments had smaller spray droplets, it was not enough to overcome the poor retention observed when only using dicamba or dicamba with DRA. Conversely, 10 of the 15 highest ranked treatments for spray retention were applied with XR nozzles that had spray classifications of Very Fine to Medium (Table 7.3). Of the remaining five highest ranked treatments, three were attributed to the AIXR nozzle with Coarse to Extremely Coarse spray classifications and two were applied with the TTI nozzle with Extremely Coarse and Ultra Coarse spray classifications. It would be expected that larger spray droplets would not remain on the leaf surface as easily as smaller droplets.

The treatments with the greatest amount of spray retention were each applied at the lowest pressure evaluated, 138 kPa, although dicamba treatments with NIS applied with the XR nozzle and MSO applied with the AIXR nozzle were not different than some lesser treatments (Table 7.3). Treatments applied at 138 kPa had on average 25% more spray retention on common lambsquarters leaves. Differences between 259 and 379 kPa were more subtle and no general trend was obvious other than they were ranked toward the middle to last in most instances. At 50 cm below the nozzle, Nuyttens et al. (2009) observed an increase in droplet velocity only for droplets greater than 200 µm in diameter. Thus, any reduction in spray droplet retention caused by increasing the application pressure would impact the TTI and AIXR nozzle more which had less than 10% of their spray volume contained in droplets less than 200 µm (Table 7.2). In comparison, the XR nozzle had as much as 59% of its spray volume contained in droplets less than 200 µm and droplet velocity would not have been as important as a variable.

Soybeans. The dicamba spray retention on soybean leaves as influenced by adjuvant, nozzle type, and application pressure was similar to that observed with common lambsquarters. A significant three-way interaction ($P = 0.0003$) was observed among the three variables as they relate to dicamba spray droplet retention on soybean leaves. The use of adjuvants significantly increased the amount of spray retained on the surface of soybean (Table 7.4). Of the top ranked 15 treatments for dicamba retention in soybean, MSO accounted for eight instances, followed by NIS and silicone with three and COC with one. These 15 highest ranked treatments had an average spray retention of 37% (Table 7.4). Similar to common lambsquarters, dicamba applied without an adjuvant or with DRA occupied the 15 lowest rankings with less than 15% spray retention on average

(Table 7.4). The addition of DRA to the dicamba solution only moderately increased retention compared to dicamba alone. In comparing the spray retention of adjuvants applied with dicamba to soybean and common lambsquarters the biggest difference was that NIS and silicone had greater retention on average than COC on soybean. The opposite is true for common lambsquarters which had greater dicamba droplet retention when using COC.

Of the ten treatments ranked the highest for spray droplet retention, eight were applied using the XR nozzle that produced spray classifications from Very Fine to Medium (Table 7.4). The remaining two positions of the top ten ranked treatments were the AIXR nozzle when applying dicamba with MSO. The TTI nozzle when applying a dicamba and MSO spray solution ranked 11th, 12th, and 13th with spray classifications of Extremely Coarse and Ultra Coarse (Table 7.4). Although the TTI nozzle produces relatively large droplets compared to the other nozzle evaluated, the use of MSO was able to overcome the antagonistic properties of large droplets relating to retention on a leaf surface. The next time the TTI nozzle appears in the table is when applications were made with silicone at 259 kPa. Where the MSO was able to compensate somewhat for the large droplet size of the TTI nozzle, the same is true for the XR nozzle when used with dicamba alone or with DRA. As previously reported, dicamba alone or with DRA performed had very low spray droplet retention on soybean leaves. The highest ranked treatments when using either dicamba alone or with DRA were all achieved when using the XR nozzle producing Fine to Medium spray droplets. Soybean leaves, especially on young plants, are observed to be fairly pubescent. Reduced spray retention has been observed on hairy leaves due to an increase in the incidence of droplet shatter (Nairn et al. 2014). Thus, smaller droplets, with less velocity and momentum, are less likely to shatter and therefore may be more disposed to remain on the leaf surface similar to what was observed with the XR nozzle.

Similar to the results observed with common lambsquarters, spray droplet retention increased on soybean leaves when applied at 138 kPa in most instances (Table 7.4). Smaller spray droplets slow down more quickly compared to larger droplets due to the effect of air drag (Goering et al. 1972). At 50 cm below the nozzle tip, spray droplets 120 µm and smaller have velocities at or less than 2 m s^{-1} (Nuyttens et al. 2009) Spray droplets larger than 400 µm in diameter have a relatively constant velocity as pressure increases (Nuyttens et al. 2009). The TTI nozzle had less than 10% of its spray volume contained in droplets less than 400 µm when averaged across treatments (Table 7.2). Because of this, the impact of increasing application pressure when using the TTI nozzle had no significant effect and in most cases the adjuvant treatments when using the TTI nozzle were ranked almost identically (Table 7.4). Nuyttens et al. (2009) reported that the velocity droplets with diameters between 200 and 400 µm were most responsive to increasing spray pressure 50 cm below the nozzle tip. Because the spray droplet spectrums ranged from Very Fine to Ultra Coarse depending on the treatment, the influence of increasing application pressure varied.

As environmental concerns instigated by the risk of herbicide spray drift shift the pendulum to larger spray droplet sizes, the proper selection and use of adjuvants and operating pressure can aid in ensuring herbicide efficacy is not marginalized. This research will serve as a basis for future studies as researchers attempt to define the ideal nozzle-adjuvant-pressure combination that will maximize herbicide performance by increasing spray droplet retention and transfer of lethal dose to the plant while minimizing off-target movement due to spray drift.

The addition of adjuvants to the dicamba spray solution had the greatest impact on spray droplet retention. Retention increased on average 4.5 and 3.7 times by adding MSO to the dicamba spray solution for common lambsquarters and soybean, respectively. The use of a DRA purportedly reduces the number of fine droplets and increases spray droplet deposition (Anonymous 2013d). While spray droplet deposition is a necessary requirement for herbicide activity on targeted plants, of equal or greater importance is the amount retained on the leaf surface. In this study, the use of the DRA with dicamba increased the amount of spray retained on the leaf surface by 34 and 40% for common lambsquarters and soybean, respectively, when averaged over other treatment variables. Compared to dicamba alone this is a significant increase but compared to other adjuvants the increase was minimal. Whether this increase is due to increased spray deposition, retention, or both is unknown. When applying the spray solutions to leaf surfaces manually to calculate recovery, it was evident that silicone has high spreading capabilities. This would permit the spreading of spray droplets applied to the upper surface of leaves to cover a wide area and spread around the leaf margin to the underside of the leaves. Although this level of spreading was not observed by the other spray solutions, silicone was consistently ranked near the middle of the spray solutions evaluated. Spreading may deflect some of the spray droplet momentum from rebounding or shattering when impacting the leaf surface, however, it may lead to excessive runoff. The adjuvants evaluated were applied at a single rate and were not combined with other adjuvants. Further research is needed to know if other rates or adjuvant combinations can be used to achieve a greater amount of droplet retention.

The interaction between spray solution and nozzle type can change the risk of drift and may impact spray droplet retention and herbicide efficacy in some circumstances (Miller and Butler Ellis 2000). Nozzles are the most influential component of a spray application process in the determination of spray droplet size (Creech et al. 2015a). Retention with the XR nozzle that produces Very Fine to Medium spray droplets was nearly 2 times greater than the TTI nozzle that produced Extremely Coarse to Ultra Coarse spray droplets. This demonstrated the impact droplet size can have on droplet retention. However, it is important to recognize this study was conducted under ideal conditions in a spray chamber with no apprehension for herbicide drift. Under normal field conditions, applicators must weigh the risks of herbicide drift from the application while maintaining high spray droplet deposition, retention, and herbicide efficacy. Bode (1987) reported the significance of the diameter of a spray droplet related to particle drift as a 100 µm diameter droplet can travel 7.5 times further off-target than a 500 µm droplet in 5 kph wind speed. For this reason, the use of an XR nozzle is not justifiable in many scenarios. The same is especially true when applying a product similar to dicamba with a nozzle that produces fine droplets that can cause severe damage to sensitive plants. On the other hand, droplets too large are difficult to retain on a leaf surface or to achieve high number densities of droplets because as one increases droplet diameter by a factor of 2, there is a reduction of 8 x the number of droplets.

Increasing the application pressure had the smallest effect on droplet retention. This may be explained by first understanding that the trend with the nozzle types in this study is that as pressure increases spray droplet size decreases, both of which are counteractive. Secondly, velocities for droplets with diameters between 200 and 400 μm are highly responsive to increasing spray pressure when those velocities are measured at a distance close to that of the ground, i.e. ~50 cm below the nozzle tip (Nuyttens et al. 2009). Thus, changes in application pressure to droplets with diameters below and above that range of droplet sizes would have minimal effect on changing the droplet velocity near the target leaves. Applications made at 138 kPa had greater spray droplet retention than the other pressures. This could be attributed to the fact that herbicide solutions applied at lower pressures have spray droplets beginning at a slower velocity and reach their sedimentation velocity quicker than when sprayed at higher pressures (Nuyttens et al. 2009). In the scenario of making applications at 138 kPa, droplets would impact the leaf surface with relatively low velocity and momentum thus reducing droplet bounce and shatter.

Current and future research at the PAT Lab will identify application parameters and adjuvants that maximize both spray droplet retention on leaf surfaces and herbicide efficacy against a range of weed types including narrow leaf grasses and broad leaf species. The treatments identified will then be evaluated for their propensity to move off-target via particle drift. The objective of this study was to determine the impact of droplet size, application pressure, and adjuvant type on the spray droplet retention of dicamba. This study found that applying dicamba with no additional adjuvant significantly reduced the amount of spray droplets retained on leaf surfaces. The addition of adjuvants, particularly MSO, increased spray retention. This research also found that coarser sprays are poorly retained on leaf surfaces, as compared to finer sprays. Additionally, lower pressure applications increase retention compared to those at higher pressures. Although the use of the XR nozzle should not be used for a dicamba application in the field, it helped to illustrate that smaller droplets are better retained than larger droplets. Based on the results from this research, if applicators use the nozzle and adjuvant types and scenarios in this study, they should consider using Coarse to Extremely Coarse droplets at lower pressures to reduce drift potential while using an MSO or COC to achieve maximum droplet retention on the leaves. By understanding the impacts of these application parameters on dicamba spray droplet retention, applicators can select application parameters, equipment, and adjuvants that will maximize the amount of dicamba spray retained on the target leaf surface while minimizing dicamba spray drift potential.

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Table 7.1. Source of materials used in spray droplet retention study.

Common name	Trade name	Treatment rate	Manufacturer
Crop oil concentrate	R.O.C. ®	1.0% v/v	Wilbur-Ellis Company, Fresno, CA, 94596
Dicamba	Clarity®	0.14 kg ae ha^{-1}	BASF Corporation, Research Triangle Park, NC, 27709
Drift agent	In-Place®	0.3 L ha^{-1}	Wilbur-Ellis Company, Fresno, CA, 94596
Methylated seed oil	Super Spread MSO®	1.0% v/v	Wilbur-Ellis Company, Fresno, CA, 94596
Non-ionic surfactant	R-11®	0.25% v/v	Wilbur-Ellis Company, Fresno, CA, 94596
Silicone adjuvant	Syl-Coat®	0.95 L ha^{-1}	Wilbur-Ellis Company, Fresno, CA, 94596

Table 7.2. Volume diameters below which droplets of equal or smaller size constitute 10, 50, and 90% ($D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$) of the total spray volume and percent spray volume less than 200 µm for each adjuvant, nozzle, and pressure combination used. The relative span is a dimensionless parameter indicative of the uniformity of the distribution of the droplet sizes of the spray. Spray classification determined in accordance with ASAE S572.1 standards from reference curves generated using the same methods to determine spray quality of the treatments.

			Droplet size				Relative span	Spray classification[c]
Adjuvant[a]	Nozzle[b]	Pressure	$D_{v0.1}$	$D_{v0.5}$	$D_{v0.9}$	V<200		
		kPa	µm			%		
COC	AIXR	138	339	632	924	1.68	0.93	XC
COC	AIXR	259	259	488	715	4.42	0.93	VC
COC	AIXR	379	217	416	616	7.89	0.96	C
COC	TTI	138	584	1010	1366	0.35	0.78	UC
COC	TTI	259	420	770	1099	0.98	0.88	UC
COC	TTI	379	345	670	984	1.79	0.95	UC
COC	XR	138	148	295	483	22.70	1.13	M
COC	XR	259	116	232	382	38.17	1.14	F
COC	XR	379	103	206	343	47.44	1.17	F
DRA	AIXR	138	333	613	882	1.79	0.89	XC
DRA	AIXR	259	261	481	702	4.27	0.92	VC
DRA	AIXR	379	225	423	656	6.99	1.02	C
DRA	TTI	138	537	924	1240	0.32	0.76	UC
DRA	TTI	259	403	735	1046	0.99	0.88	UC
DRA	TTI	379	332	632	944	1.94	0.97	XC
DRA	XR	138	158	308	489	19.41	1.08	M
DRA	XR	259	121	236	394	36.66	1.16	F
DRA	XR	379	104	210	350	46.13	1.18	F
MSO	AIXR	138	277	537	761	4.90	0.90	XC
MSO	AIXR	259	240	450	652	5.67	0.91	VC
MSO	AIXR	379	208	403	622	8.98	1.03	C
MSO	TTI	138	532	927	1309	0.22	0.84	UC
MSO	TTI	259	382	713	1018	1.18	0.89	UC
MSO	TTI	379	315	621	946	2.49	1.01	XC
MSO	XR	138	160	304	465	19.00	1.00	M
MSO	XR	259	124	235	367	35.66	1.03	F
MSO	XR	379	108	209	338	45.99	1.10	F
NIS	AIXR	138	332	661	972	2.39	0.97	XC

NIS	AIXR	259	246	506	810	5.77	1.11	VC
NIS	AIXR	379	207	432	679	9.16	1.09	C
NIS	TTI	138	589	1044	1410	0.21	0.79	UC
NIS	TTI	259	458	860	1244	0.72	0.92	UC
NIS	TTI	379	374	728	1069	1.47	0.96	UC
NIS	XR	138	127	274	468	28.71	1.24	M
NIS	XR	259	101	218	379	43.61	1.27	F
NIS	XR	379	89	194	337	52.44	1.28	F
None	AIXR	138	350	663	964	1.84	0.93	XC
None	AIXR	259	259	513	800	4.73	1.05	VC
None	AIXR	379	215	442	697	8.22	1.09	C
None	TTI	138	618	1094	1480	0.16	0.79	UC
None	TTI	259	465	887	1286	0.65	0.92	UC
None	TTI	379	379	746	1091	1.40	0.95	UC
None	XR	138	136	282	470	25.77	1.18	M
None	XR	259	100	219	380	43.30	1.28	F
None	XR	379	85	188	332	54.78	1.31	F
Silicone	AIXR	138	309	587	862	2.26	0.94	XC
Silicone	AIXR	259	233	449	679	6.23	0.99	VC
Silicone	AIXR	379	201	401	641	9.86	1.10	C
Silicone	TTI	138	511	896	1268	0.33	0.85	UC
Silicone	TTI	259	385	716	1021	1.15	0.89	UC
Silicone	TTI	379	328	637	953	2.09	0.98	XC
Silicone	XR	138	141	267	413	26.81	1.02	F
Silicone	XR	259	114	209	336	46.03	1.06	VF
Silicone	XR	379	98	183	292	58.71	1.06	VF

[a] Abbreviations: COC, crop oil concentrate; DRA, drift reduction agent; MSO, methylated seed oil; NIS, non-ionic surfactant.

[b] Nozzles used were 110025, Teejet Technologies, Spraying Systems Co., Springfield, IL 62703.

[c] Spray classification categories were derived from reference curves generated at the Pesticide Application Technology Laboratory per ASAE S572.1 where VF = Very Fine, F = Fine, M = Medium, C = Coarse, VC = Very Coarse, XC = Extremely Coarse, and UC = Ultra Coarse.

Table 7.3. Spray droplet retention on common lambsquarters leaves as a percent of the total spray volume applied. Spray classification determined in accordance with ASAE S572.1 standards from reference curves generated using the same methods to determine spray quality of the treatments.

Adjuvant[a]	Nozzle[b]	Pressure	Spray classification[c]	Retention[d]
		kPa		%
COC	XR	138	M	29.2 a
MSO	XR	138	M	29.1 a
NIS	XR	138	M	27.5 ab
MSO	AIXR	138	XC	26.6 ab
MSO	TTI	379	XC	25.4 bc
COC	AIXR	138	XC	25.3 bc
Silicone	XR	379	VF	24.7 b-d
NIS	XR	259	F	22.0 c-e
COC	XR	259	F	21.7 d-f
COC	XR	379	F	21.3 d-f
MSO	AIXR	379	C	21.3 d-f
MSO	TTI	138	UC	21.0 ef
MSO	XR	379	F	20.6 e-g
NIS	XR	379	F	20.6 e-g
Silicone	XR	138	F	20.5 e-g
MSO	AIXR	259	VC	20.2 e-g
Silicone	XR	259	VF	20.0 e-g
COC	AIXR	379	C	19.8 e-g
MSO	XR	259	F	19.3 e-h
COC	TTI	138	UC	19.2 e-h
Silicone	AIXR	138	XC	19.0 e-i
NIS	AIXR	138	XC	18.9 e-i
COC	AIXR	259	VC	18.5 f-j
MSO	TTI	259	UC	17.4 g-k
COC	TTI	379	UC	16.0 h-l
NIS	AIXR	259	VC	15.7 j-m
Silicone	TTI	379	XC	15.1 j-n
COC	TTI	259	UC	14.5 k-o
Silicone	AIXR	379	C	14.1 k-p
DRA	XR	138	M	14.0 k-p
Silicone	AIXR	259	VC	13.3 l-q
NONE	XR	259	F	13.1 l-q

NIS	AIXR	379	C	13.0 l-q
Silicone	TTI	138	UC	12.8 l-q
DRA	XR	379	F	12.7 l-r
NIS	TTI	259	UC	12.6 l-r
NIS	TTI	138	UC	12.4 m-r
Silicone	TTI	259	UC	11.9 n-r
DRA	XR	259	F	11.8 n-s
NONE	XR	138	M	11.6 n-s
NIS	TTI	379	UC	11.4 o-t
NONE	XR	379	F	10.9 p-u
DRA	AIXR	379	C	10.3 q-u
DRA	AIXR	259	VC	10.0 u-w
DRA	TTI	259	UC	9.3 r-w
DRA	AIXR	138	XC	8.4 s-w
NONE	AIXR	259	VC	8.1 t-w
DRA	TTI	138	UC	7.8 u-w
NONE	AIXR	379	C	7.8 u-w
NONE	AIXR	138	XC	7.8 u-w
NONE	TTI	379	UC	7.7 u-w
DRA	TTI	379	XC	7.5 u-w
NONE	TTI	138	UC	6.8 vw
NONE	TTI	259	UC	6.1 w

[a] Abbreviations: COC, crop oil concentrate; DRA, drift reduction agent; MSO, methylated seed oil; NIS, non-ionic surfactant.

[b] Nozzles used were 110025, Teejet Technologies, Spraying Systems Co., Springfield, IL 62703.

[c] Spray classification categories were derived from reference curves generated at the Pesticide Application Technology Laboratory per ASAE S572.1 where VF = Very Fine, F = Fine, M = Medium, C = Coarse, VC = Very Coarse, XC = Extremely Coarse, and UC = Ultra Coarse.

[d] Means followed by the same letter are not significantly different at $\alpha = 0.05$.

Table 7.4. Spray droplet retention on soybean leaves as a percent of the total spray volume applied. Spray classification determined in accordance with ASAE S572.1 standards from reference curves generated using the same methods to determine spray quality of the treatments.

Adjuvant[a]	Nozzle[b]	Pressure	Spray classification[c]	Retention[d]
		kPa		%
NIS	XR	138	M	44.1 a
MSO	XR	138	M	43.5 a
Silicone	XR	379	VF	39.9 ab
MSO	AIXR	138	XC	37.8 bc
COC	XR	138	M	37.5 b-d
NIS	XR	379	F	36.9 b-d
MSO	AIXR	379	C	36.7 b-d
Silicone	XR	138	F	36.2 b-e
MSO	XR	379	F	35.9 b-e
Silicone	XR	259	VF	35.8 b-f
MSO	TTI	379	XC	34.7 c-g
MSO	TTI	138	UC	33.3 c-h
MSO	TTI	259	UC	33.2 d-h
NIS	XR	259	F	31.9 e-i
MSO	AIXR	259	VC	31.9 e-i
MSO	XR	259	F	31.3 f-j
Silicone	AIXR	138	XC	30.9 g-k
COC	XR	379	F	29.3 h-l
DRA	XR	138	M	29.2 h-l
NIS	AIXR	138	XC	28.1 i-m
COC	XR	259	F	27.8 i-m
NIS	AIXR	379	C	27.2 j-m
Silicone	AIXR	379	C	26.6 k-n
COC	AIXR	259	VC	25.9 l-o
NIS	AIXR	259	VC	25.4 l-p
COC	AIXR	138	XC	24.3 m-q
Silicone	TTI	259	UC	23.6 m-r
NIS	TTI	138	UC	23.4 m-r
Silicone	TTI	138	UC	22.9 n-s
NIS	TTI	259	UC	22.6 n-t
Silicone	TTI	379	XC	22.1 n-t
DRA	XR	379	F	21.8 o-t

COC	TTI	259	UC	21.7 o-t
COC	AIXR	379	C	21.6 o-u
Silicone	AIXR	259	VC	20.8 p-v
COC	TTI	138	UC	20.3 q-v
NIS	TTI	379	UC	19.9 r-w
COC	TTI	379	UC	19.6 r-w
None	XR	379	F	18.6 s-w
DRA	XR	259	F	18.5 t-w
None	XR	259	F	17.3 u-x
None	XR	138	M	17.1 v-x
DRA	TTI	138	UC	15.5 w-y
DRA	TTI	379	XC	13.1 x-z
DRA	AIXR	259	VC	13.0 x-z
DRA	AIXR	138	XC	12.6 yz
None	AIXR	379	C	12.6 yz
DRA	TTI	259	UC	12.4 yz
DRA	AIXR	379	C	12.4 yz
None	AIXR	259	VC	11.6 yz
None	AIXR	138	XC	11.3 yz
None	TTI	138	UC	11.2 yz
None	TTI	379	UC	9.9 z
None	TTI	259	UC	9.1 z

[a] Abbreviations: COC, crop oil concentrate; DRA, drift reduction agent; MSO, methylated seed oil; NIS, non-ionic surfactant.

[b] Nozzles used were 110025, Teejet Technologies, Spraying Systems Co., Springfield, IL 62703.

[c] Spray classification categories were derived from reference curves generated at the Pesticide Application Technology Laboratory per ASAE S572.1 where VF = Very Fine, F = Fine, M = Medium, C = Coarse, VC = Very Coarse, XC = Extremely Coarse, and UC = Ultra Coarse.

[d] Means followed by the same letter are not significantly different at $\alpha = 0.05$.