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Physical–Chemical Properties, Droplet Size, and Efficacy of Dicamba Plus Glyphosate Tank Mixture Influenced by Adjuvants

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Abstract: Dicamba plus glyphosate tank mixture have been largely adopted for postemergence weed control after the development of dicamba-tolerant crops. Ammonium sulfate is commonly used as water conditioner (WC) to increase glyphosate efficacy, but its use is restricted for dicamba herbicides. The use of non-AMS water conditioner and other adjuvants could be a way to optimize efficacy of this tank mixture while mitigating herbicide off-target movement. The objective of this study was to determine the physical–chemical properties and droplet size distribution of dicamba and glyphosate solutions with and without non-AMS WC alone and tank mixed with other adjuvants and evaluate the response of weed species to these solutions under greenhouse and field conditions. The adjuvants mostly increased density and viscosity and decreased contact angle and surface tension of herbicide solutions. In presence of WC, except for the adjuvants containing drift reducing agent, $Dv_{0.5}$ decreased with the addition of adjuvants. Under greenhouse conditions, biomass reduction increased up to 47 and 33 percentage points for velvetleaf and c. waterhemp when adjuvants were added to solutions without WC, respectively. No increase in control of horseweed and Palmer amaranth was observed with the use of adjuvants under field conditions.

Keywords: physical–chemical properties; herbicide efficacy; adjuvants

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1. Introduction

The introduction of glyphosate-resistant (GR) crops in 1996 has largely contributed to the adoption of glyphosate in the United States. In 1996, the estimated used amount of this herbicide was 11 million kg compared to 136 million kg in 2016 [1]. Currently, glyphosate is the most widely used herbicide in the country [2]. As a consequence of the overuse of this herbicide for a prolonged period of time, high occurrence of GR weed populations has been reported across the country. Currently, there are 17 GR weed species reported in the United States [3]. In 2015, the USDA [4] estimated a reduction in financial returns of 66% and 14% to corn and soybean growers affected by GR weed infestation, respectively.

One of the most effective tactics to prevent, delay, or manage herbicide-resistant weeds is the use of herbicides with different modes of action [5]. In 2017, the release of dicamba-tolerant (DT) crops in the marked which are also tolerant to glyphosate has provided an alternative mode of action to manage GR weeds by allowing postemergence (POST)applications of those two herbicides. In the same year, use of dicamba increased 225% compared with the previous year [6]. Glyphosate is an herbicide that inhibits 5-enolpyruvylshikimate-3-phosphate (EPSP) enzyme leading to depletion of phenylalanine, tyrosine, and tryptophan [7,8] whereas dicamba is a synthetic auxin that mimics the natural plant hormone indole-3-acetic acid causing an epinastic response [9].

Another important tool for managing herbicide-resistant weeds is the use of agricultural spray adjuvants. These adjuvants are commonly added to the spray tank to improve herbicidal activity or application characteristics [10]. Ammonium sulfate (AMS) is a common adjuvant used as a water conditioner (WC) to overcome salt antagonism of weak acids in hard water and to enhance phytotoxicity of several herbicides, such as glyphosate [11]. Pratt et al. (2003) [12] demonstrated that when using tap water (500 ppm of $CaCO_3$), glyphosate solution containing AMS at 2% $v\ v^{-1}$ provided velvetleaf control 53% greater than glyphosate solution alone. Thelen et al. (1995) [11] reported that glyphosate molecule reacts with Ca2+ and other cations present in the water to form a less absorbed glyphosate-Ca salt. Further, in the presence of AMS, sulfate ion from the AMS effectively binds with Ca2+ from solution by forming $CaSO_4$ which prevents the formation of glyphosate-Ca salt and allows NH_{4+} to form the readily absorbed glyphosate-NH_4 salt.

Although dicamba is also a weak acid that has its efficacy increased with addition of AMS in the solution [13], this adjuvant is restricted for dicamba herbicides due to an increase in the formation of volatile dicamba acid [14–16]. Volatility can result in losses up to 90% of an applied herbicide [17,18] and can cause severe injury to sensitive species nearby. Non-AMS WC adjuvants are an alternative to improve dicamba and glyphosate tank mixture (DpG) efficacy without increasing dicamba volatility potential. Zollinger et al. (2016) [19] observed that 10 non-AMS WC adjuvants increased DpG activity in hard water compared with treatment with no WC.

Complementary to non-AMS WC, use of surfactant and humectant could lead to a decrease in dicamba volatility while enhancing herbicide efficacy. Long (2017) [17] suggested that an increase in the amount of dicamba penetrating through the leaf cuticle should reduce the amount of the herbicide available on the leaf surface to volatilize. Surfactants are known for significantly accelerating the penetration of herbicides in plant cuticles [20–22]. Harbors et al. (2003) [23] reported that glyphosate and 2,4-D penetration on kochia (*Bassia scoparia* (L.) A. J. Scott) increased by 14% and 47% when applied with surfactants compared to the herbicides alone, respectively. Surfactants reduce surface tension of spray droplets which increases the contact angle between the droplet and leaf which increases wettability and penetration [24]

Previous research demonstrated that environmental periods with high evaporation rates, such as high temperature and low humidity, increase dicamba volatility potential [25,26]. Even though high temperatures increase foliar absorption of auxin herbicides, that does not necessarily mean a decrease in volatility because the rate of evaporation exceeds the herbicide uptake rate [17,27]. As humectants slow droplet evaporation rates [28], herbicide stays in the liquid form for a longer period of time which may reduce the formation of dicamba vapor. Further, the herbicide uptake by the plant increases since this process just occurs as long as the spray deposit remains moist [29,30], resulting in a reduction of the amount of dicamba available on the leaf to volatilize.

Due to the many complaints received about dicamba symptomology on non-DT crops in the past few years, actions to mitigate off-target movement have become crucial. Besides vapor drift, physical drift is another way of off-target movement. Ferreira et al. (2020) [31] reported that the addition of non-ionic surfactants (NIS) to dicamba plus glyphosate tank mixture (DpG) not only decreased contact angle and surface tension, but also droplet size. Spray droplet size is one of the most important factors affecting physical drift [32] since finer droplets are carried away from the target area by the wind [33]. Drift-reducing agent (DRA) adjuvants alter the viscoelastic properties of the spray solution, increase droplet size, and weight, and minimize the number of easily windborne droplets [34]. The combined action of non-AMS WC with surfactant, humectant, and DRA adjuvants could favor dicamba plus glyphosate tank mixture efficacy as well as mitigate herbicides off-target movement. However, there is a lack of information in the literature about the combination of those adjuvants with dicamba and glyphosate herbicides. Therefore, the objectives of this research were to (1) determine the physical–chemical properties (density, viscosity, dynamic surface tension, static contact angle droplet evaporation rate, and pH) and droplet size distribution of dicamba and glyphosate solutions with and without non-AMS WC alone and tank mixed with surfactant, humectant, and DRA adjuvants and

(2) evaluate the response of weed species to these solutions under greenhouse and field conditions.

2. Materials and Methods

Studies were conducted at the Pesticide Application Technology Laboratory of the University of Nebraska-Lincoln located at the West Central Research, Extension and Education Center (WCREEC) in North Platte, NE, and in Paxton-NE.

Dicamba (Xtendimax® with Vapor Grip®, Monsanto Company, St. Louis, MO, USA) plus glyphosate (Roundup PowerMax®, Monsanto Company, St. Louis, MO, USA) solutions at full dose, 559 and 1541 g ae ha^{-1}, respectively, were arranged in a factorial 2 × 11 treatment design, where 2 consisted of presence or not of a non-AMS WC combined with 10 adjuvants plus an herbicide solution with no adjuvant and an untreated control where no herbicide or adjuvants were applied. Adjuvant types and rates are described in Table 1. All the adjuvants used in this study were experimental. The structural features of these adjuvants are limited and proprietary information of Exacto® Inc. (Sharon, WI, USA). Analyses of the water used in the solutions indicated presence of 188 mg L^{-1} of $CaCO_3$ which categorizes this water as very hard [35]. Spray solutions were prepared simulating a 140 L ha^{-1} carrier volume.

Table 1. Description of the herbicides and adjuvants evaluated.

Herbicide	Trade Name	Full Rate	Reduced Rate
		g ae ha^{-1}	
Dicamba [a]	Xtendimax® with Vapor Grip®	559	279
Glyphosate [b]	Roundup PowerMax®	1541	385
Adjuvant [c]	Adjuvant type	Rate	Abbreviation
		% $v\ v^{-1}$	
Water conditioner	Non-AMS-water conditioner	0.5	WC
Adjuvant 1	Non-ionic surfactant	0.25	NIS1
Adjuvant 2	Non-ionic surfactant	0.25	NIS2
Adjuvant 3	Non-ionic surfactant-drift reducing agent	0.25	NIS-DRA1
Adjuvant 4	Non-ionic surfactant-drift reducing agent	0.75	NIS-DRA2
Adjuvant 5	Non-ionic surfactant-humectant	0.5	NISH1
Adjuvant 6	Non-ionic surfactant-humectant	0.5	NISH2
Adjuvant 7	Non-ionic surfactant-humectant	0.5	NISH3
Adjuvant 8	Non-ionic surfactant-humectant	0.5	NISH4
Adjuvant 9	Non-ionic surfactant-humectant	0.5	NISH5
Adjuvant 10	Non-ionic surfactant-humectant	0.5	NISH6

[a] Dicamba (Xtendimax® with Vapor Grip®, Monsanto Company, St. Louis, MO, USA). [b] Glyphosate (Roundup PowerMax®, Monsanto Company, St. Louis, MO, USA). [c] Experimental adjuvants provided by Exacto® Inc.

2.1. Physical–Chemical Properties Study

The density and dynamic viscosity of the solutions and water were measured at 20 °C by a density meter (DMATM 4500 M, Anton Paar USA Inc., Ashland, VA, USA) and microviscometer (Lovis 2000 M/ME, Anton Paar USA Inc., Ashland, VA, USA), respectively. A video-based optical contact angle measuring instrument (OCA 15EC, DataPhysics Instruments GmbH, Filderstadt, Germany) was used to measure dynamic surface tension (dST), static contact angle (sCA), and evaporation rate (ER). A liquid circulator (Julabo USA Inc, Allentown, PA, USA) and a humidity generator and controller (HCG, DataPhysics Instruments GmbH, Filderstadt, Germany) were used to maintain the temperature at 25 ± 1 °C and relative humidity (RH) at 20, 40, 60, and 80 ± 1%, respectively. For each treatment solution, physical properties were measured three times for each RH. Moraes et al. (2019) [36] provided detailed information regarding use and operation of the density meter, microviscometer, and OCA 15EC for dST and sCA measurements. Additionally, Fritz et al. (2018) [37] described the ER measurement procedure using the OCA 15EC. In this present study, ER measurements were performed using an initial droplet volume of 0.15 μL and evaporation maximum time interval of 120 s. ER was calculated according to Equation (1):

$$\mathrm{ER} = \left(\frac{\mathrm{Vi} - \mathrm{Vf}}{\mathrm{Tf}} \right) \quad (1)$$

where Vi is the initial volume of the droplet (μL) at 0 s, Vf is the final volume of the droplet at 120 s or in the case of the droplet completely evaporated before the 120 s Vf is equal 0 μL, and Tf is the maximum time interval of 120 s or the time interval (s) in which the droplet completely evaporated before 120 s.

Hidrogenionic potential (pH) measurements were performed using a pH meter (200 Series Benchtop pH/Cond. Meter, Cole-Parmer Instruments, Vernon Hills, IL, USA). Each treatment was measured one time. A plastic cup was filled with the treatment solution and the electrode was placed into the cup until pH reached equilibrium. Between treatments, the electrode was cleaned with distilled water and dried with paper and a plastic cup was discarded and replaced with a new one.

2.2. Droplet Size Distribution Study

Droplet diameters for which 10%, 50%, and 90% of the total spray volume is contained in droplets of lesser diameter ($Dv_{0.1}$, $Dv_{0.5}$, and $Dv_{0.9}$, respectively), volume percentage of droplets smaller than 150 μm (percentage of fines—PF) and the relative span (RS) were measured for each solution using a laser diffraction system (HELOS-VARIO/KR, Sympatec Inc., Clausthal, Germany) with the R7 lens, following methodology described by Butts et al. (2019) and Fritz et al. (2014) [38,39]. PF is an indicator of the potential risk of drift and RS is a dimensionless parameter that indicates uniformity of droplet size distribution, calculated using Equation (2) [40]. Solutions were sprayed through TTI110015 nozzles (Spraying Systems Co., Glendale Heights, IL, USA) operating at 276 kPa with a constant airspeed of 6.7 m s^{-1}. Each solution was replicated three times.

$$\mathrm{RS} = \left(\frac{D_v0.9 - D_v0.1}{D_v0.5} \right) \quad (2)$$

2.3. Efficacy Study in Greenhouse

The study was conducted in a complete randomized block design with four replications, and two experimental runs. Dicamba and glyphosate rates were applied at reduced rates, 279 and 385 g ae ha^{-1}, respectively, to avoid complete weed control. Solutions were sprayed on barnyardgrass (*Echinochloa crus-galli* (L.) P. Beauv.), common lambsquarters (*Chenopodium album* L.), horseweed (*Erigeron canadensis* L.), kochia (Bassia scoparia (L.) A. J. Scott), velvetleaf (*Abutilon theophrasti* Medik.), and common waterhemp (*Amaranthus tuberculatus* (Moq.) J. D. Sauer), grown in 10 cm containers (Stuewe and Sons Inc., Corvallis, OR, USA) using Pro-Mix BX5 (Premier Tech Horticulture Ltd., Riviere-du-Loup, Canada). Greenhouse temperature was maintained between 18 and 28 °C and 60% ± 10% RH. Supplemental LED lighting of 520 μmol s^{-1} (Philips Lighting, Somerset, NJ, USA) was provided to extend daylight period to 16 h. Plants were watered daily using a commercial liquid fertilizer (UNL 5-1-4, Wilbur-Ellis Agribusiness, Aurora, CO, USA) and treated weakly with *Bacillus thuringiniensis* (Gnatrol WDG®, Valent USA, Walnut Creek, CA, USA) to avoid loopers (*Trichoplusia* spp.) and other insects. Once plants were 15 cm tall and horseweed was 10 cm in diameter, they were sprayed using a three-nozzle spray chamber (Generation III Research Track Sprayer DeVries Manufacturing, Hollandale, MN, USA) calibrated to deliver 140 L ha−1 through TTI110015 nozzles (Spraying Systems Co., Glendale Heights, IL, USA) at 1.3 m s^{-1} travel speed and 276 kPa operating pressure. Nozzle spacing and boom height from the top of plants were 51 cm.

At 28 days after application (DAA), visual estimations of injury (VEC) were recorded, and aboveground biomass of surviving plants was harvested and oven-dried at 65 °C until reaching constant dry weight. Dry biomass data was recorded and converted into percentage of biomass reduction as compared with the untreated control according to Equation (3):

$$BR = 100 - \frac{(X * 100)}{Y} \quad (3)$$

where BR is the biomass reduction (%), X is the biomass (g) of an individual experimental unit after being treated and Y is the mean biomass (g) of untreated control.

2.4. Efficacy Study in Field

Two trials on horseweed control were conducted during the growing season of 2019 and 2020 in North Platte-NE and Paxton-NE, respectively, and one trial on Palmer amaranth (Amaranthus palmeri S. Watson) control was conducted during the growing season of 2020 in North Platte-NE. Trials were conducted in a randomized complete block design with four replications. Each plot was 3 m wide by 10 m long. Spray solution combinations and product rates were the same as used in physical properties and droplet size distribution studies. Late-season horseweed (50 cm tall) and Palmer amaranth (40 cm tall) plants were sprayed using a six-nozzle handheld CO_2 pressurized backpack sprayer (Bellspray Inc., Opelousas, LA, USA) calibrated to deliver 140 L ha^{-1} through TTI110015 nozzles (Spraying Systems Co., Glendale Heights, IL, USA) at 1.3 m s^{-1} walking speed and 276 kPa operating pressure. Nozzle spacing and boom height from plants were 51 cm. Plants over recommended application size were used in order to enable treatment comparisons using full herbicides rates. Temperature and relative humidity during applications in 2019 and 2020 are described in Table 2.

Table 2. Temperature and relative humidity (RH) during applications in the field sites of horseweed and Palmer amaranth in 2019 and 2020 growing seasons.

	Horseweed		Palmer Amaranth	
Year	**Temperature (°C)**	**RH (%)**	**Temperature (°C)**	**RH (%)**
2019	17	75	-	-
2020	37	25	33	43

Visual estimations of injury were recorded at 28 DAA. In addition, 10 random plants per plot were marked with orange spray paint before application. At 28 DAA, marked plants were individually evaluated for mortality (dead or alive) and converted into percent of mortality reduction using Equation (4) [41]:

$$M = 100 * \left(\frac{D}{10}\right) \quad (4)$$

where M is mortality (%) and D is the number of dead plants per plot after being treated.

The 10 plants used for mortality evaluation were clipped at the soil surface, harvested, and dried at 65 °C until reaching constant weight. Dry biomass of those 10 plants was recorded and converted into percentage of biomass reduction and compared with the untreated control according to Equation (2).

2.5. Statistical Analyzes

Data were subjected to analysis of variance using the base package in R Statistical Software, version 3.3.1 [42]. Replications were treated as a random effect and year, water conditioner, and other adjuvants as fixed effects. However, for Palmer amaranth, year effect was not included as a fixed effect because of availability of only one-year data. Treatments were compared to each other using Tukey's least significant at $\alpha = 0.05$.

3. Results

3.1. Physical–Chemical Properties Study

The ANOVA table demonstrated a water conditioner versus other adjuvants interaction for density, viscosity, sCA, dST, and ER ($p < 0.001$).

3.1.1. Density

The addition of most adjuvants slightly increased density of DpG solutions regardless of the presence or not of WC (Table 3). For example, in the absence of WC, DpG solutions containing adjuvants NIS1, NIS-DRA2, NISH4, NISH5, and NISH6 presented density of 1.0070 g cm^{-3} compared to 1.0060 g cm^{-3} for DpG alone which corresponds to 0.1%. Furthermore, in the presence of WC, compared to DpG solution with only WC (1.0070 g cm^{-3}), addition of adjuvants, except for NISH1 and NISH2, increased density in a range of 0.0008–0.0018 g cm^{-3} (0.08% to 0.18%).

Table 3. Density and viscosity for dicamba plus glyphosate solutions at 559 and 1541 g ae ha^{-1}, respectively, with and without non-AMS water conditioner alone and tank mixed with 10 adjuvants at 20 °C.

Water Conditioner [a]	Adjuvant [b]	Density		Viscosity	
		g cm^3		mPa s^{-1}	
None	None	1.0060	d	1.0400	j
None	NIS1	1.0070	c	1.0800	e
None	NIS2	1.0060	d	1.0900	d
None	NIS-DRA1	1.0070	c	1.0600	f
None	NIS-DRA2	1.0060	d	1.1250	b
None	NISH1	1.0060	d	1.0500	i
None	NISH2	1.0060	d	1.0500	i
None	NISH3	1.0060	d	1.0500	i
None	NISH4	1.0070	c	1.0500	i
None	NISH5	1.0070	c	1.0500	i
None	NISH6	1.0068	c	1.0550	h
Non-AMS WC	None	1.0070	c	1.0400	j
Non-AMS WC	NIS1	1.0080	b	1.0600	f
Non-AMS WC	NIS2	1.0080	b	1.1000	c
Non-AMS WC	NIS-DRA1	1.0088	a	1.0600	f
Non-AMS WC	NIS-DRA2	1.0078	b	1.1300	a
Non-AMS WC	NISH1	1.0070	c	1.0500	i
Non-AMS WC	NISH2	1.0070	c	1.0575	g
Non-AMS WC	NISH3	1.0080	b	1.0500	i
Non-AMS WC	NISH4	1.0080	b	1.0600	f
Non-AMS WC	NISH5	1.0080	b	1.0600	f
Non-AMS WC	NISH6	1.0078	b	1.0520	i
LSD					
		***		***	

Means followed by the same letter in the column do not differ using Tukey's test at $\alpha = 0.05$. Significance level: *** $p \leq 0.001$. [a], [b] Abbreviations: WC (water conditioner), NIS (non-ionic surfactant), NIS-DRA (non-ionic surfactant-drift reducing agent), NISH (non-ionic surfactant-humectant). WC and NISHs at 0.5 $v\ v^{-1}$; NIS1, NIS2, and NIS-DRA1 at 0.25 $v\ v^{-1}$; NIS-DRA2 at 0.75 $v\ v^{-1}$.

Similar do density, DpG solutions containing adjuvants presented greater viscosity than solutions without adjuvant, regardless of presence or not of WC. In the absence of WC, addition of adjuvant to DpG solutions increased viscosity from 0.01 up to 0.09 mPa s, which is equivalent to 1–9%, compared to DpG solution alone (1.0400 mPa s). Similarly, in the presence of WC, compared to DpG solution with only WC (1.0400 mPa s), addition of adjuvants increased viscosity in a range of 0.01–0.09 mPa s. The highest density was observed with addition of NIS-DRA2, independently of presence or not of WC, but the majority of treatment solutions containing WC presented higher density than solutions without WC.

3.1.2. Dynamic Surface Tension

The influence of adjuvants on the dST of DpG solutions without and with WC was similar at 20%, 40%, and 60% RH (Table 4). For example, in the absence of WC, compared to DpG alone (37 mN m^{-1}), the addition of adjuvants decreased dST in a range of 1–6 mN m^{-1}. Furthermore, in the presence of WC, the addition of all adjuvants, but adjuvant NISH2, decreased dST from 1 to 5 mN m^{-1} compared to DpG with only WC (36 mN m^{-1}). At 80% RH, in the absence of WC, the addition of NIS1, NIS2, NIS-DRA1, NIS-DRA2, NISH3, NISH5, and NISH6 decreased ST from 2 to 5 mN m^{-1} and NISH2 and NISH4 increased dST by 1 mN m^{-1}, compared to DpG with only WC (35 mN m^{-1}). Moreover, in the presence of WC, compared to solution with only WC (32 mN m^{-1}), NIS2 and NISH6 decreased dST in 2 and 1 mN m^{-1}, respectively, and NIS-DRA1, NISH1, NISH2, NISH3, and NISH4 increased dST by 3–6 mN m^{-1}.

Table 4. Dynamic surface tension for dicamba plus glyphosate solutions at 559 and 1541 g ae ha^{-1}, respectively, with and without non-AMS water conditioner alone and tank mixed with 10 adjuvants at 25 °C.

Water Conditioner [a]	Adjuvant [b]	20% RH		40% RH		60% RH		80% RH	
				mN m^{-1}					
None	None	37	a	37	a	37	a	35	b
None	NIS1	32	f	32	f	32	f	31	g
None	NIS2	31	g	31	g	31	g	30	h
None	NIS-DRA1	35	c	35	c	35	c	34	d
None	NIS-DRA2	33	e	33	e	33	e	32	f
None	NISH1	35	c	35	c	35	c	35	b
None	NISH2	36	b	36	b	36	b	36	a
None	NISH3	34	d	34	d	34	d	33	e
None	NISH4	36	b	36	b	36	b	36	a
None	NISH5	35	c	35	c	35	c	32	f
None	NISH6	31	g	31	g	31	g	30	h
Non-AMS WC	None	36	b	36	b	36	b	32	f
Non-AMS WC	NIS1	33	e	33	e	33	e	32	f
Non-AMS WC	NIS2	31	g	31	g	31	g	30	h
Non-AMS WC	NIS-DRA1	34	d	34	d	34	d	33	e
Non-AMS WC	NIS-DRA2	33	e	33	e	33	e	32	f
Non-AMS WC	NISH1	35	c	35	c	35	c	35	c
Non-AMS WC	NISH2	36	b	36	b	36	b	36	a
Non-AMS WC	NISH3	34	d	34	d	34	d	34	d
Non-AMS WC	NISH4	35	c	35	c	35	c	35	b
Non-AMS WC	NISH5	35	c	35	c	35	c	32	f
Non-AMS WC	NISH6	32	f	32	f	32	f	31	g
LSD									
		***		***		***		***	

Means followed by the same letter in the column do not differ using Tukey's test at α = 0.05. Significance level: *** $p \leq 0.001$. [a], [b] Abbreviations: WC (water conditioner), NIS (non-ionic surfactant), NIS-DRA (non-ionic surfactant-drift reducing agent), NISH (non-ionic surfactant-humectant). WC and NISHs at 0.5 $v\,v^{-1}$; NIS1, NIS2, and NIS-DRA1 at 0.25 $v\,v^{-1}$; NIS-DRA2 at 0.75 $v\,v^{-1}$.

3.1.3. Static Contact Angle

At 20% RH, the addition of NIS1, NIS2, NIS-DRA 1, NISH3, NISH5, and NISH 6 to DpG solutions without WC decreased CA by 2–11° compared to DpG alone (38°) (Table 5). Additionally, compared to DpG with only WC (39°), the addition of adjuvants, except for NISH2 and NISH 5, to DpG solution with WC decreased sCA by 2–9°. Similarly, at 40% and 60% RH, sCA decreased when the majority of adjuvants were added to DpG solutions. However, at 40% RH, NISH2 and NISH4 increased sCA when added to DpG solution without and with WC, respectively. At 80% RH, in the absence of WC, the addition of NIS1 and NIS2 decreased CA in 4° and NISH2, NISH3, NISH4, NISH5 and NISH6 increased sCA in a range of 3–6°, compared to DpG alone (36°). Additionally, compared to DpG only with WC, in the presence of WC, NIS1, NIS2, NIS-DRA1, NIS-DRA2, NISH1, NISH5, and NISH6 decreased sCA by 4–6° and NISH2 and NISH4 increased by 3° and 10°.

Table 5. Static contact angle for dicamba plus glyphosate solutions at 559 and 1541 g ae ha^{-1}, respectively, with and without non-AMS water conditioner alone and tank mixed with 10 adjuvants at 25 °C.

Water Conditioner [a]	Adjuvant [b]	20% RH		40% RH		60% RH		80% RH	
		Degrees							
None	None	38	bcd	40	c	42	a	36	fg
None	NIS1	32	hi	33	gh	31	ij	32	j
None	NIS2	28	k	32	gh	32	hi	32	j
None	NIS-DRA1	37	cde	37	de	36	de	35	fg
None	NIS-DRA2	33	ghi	34	fg	35	ef	35	g
None	NISH1	36	ef	33	fg	36	def	35	fg
None	NISH2	40	a	45	a	40	ab	41	bc
None	NISH3	33	ghi	34	fg	34	efg	39	cde
None	NISH4	41	a	40	c	41	ab	42	bc
None	NISH5	35	fg	39	c	39	bc	41	bc
None	NISH6	27	k	27	j	26	k	28	k
Non-AMS WC	None	39	abc	40	c	38	cd	38	de
Non-AMS WC	NIS1	34	fgh	34	fg	33	ghi	34	gh
Non-AMS WC	NIS2	30	j	31	hi	30	j	32	hij
Non-AMS WC	NIS-DRA1	33	ghi	34	fg	31	ij	32	ij
Non-AMS WC	NIS-DRA2	35	fg	35	ef	31	ij	32	hij
Non-AMS WC	NISH1	37	de	37	de	33	ghi	34	ghi
Non-AMS WC	NISH2	39	ab	40	c	40	ab	41	bc
Non-AMS WC	NISH3	32	hi	34	fg	34	fgh	40	bcd
Non-AMS WC	NISH4	37	de	43	b	40	bc	48	a
Non-AMS WC	NISH5	40	ab	39	cd	38	cd	37	ef
Non-AMS WC	NISH6	32	i	30	i	32	ij	32	hij
		***		***		***		***	

Means followed by the same letter in the column do not differ using Tukey's test at α = 0.05. Significance level: *** $p \leq 0.001$. [a], [b] Abbreviations: WC (water conditioner), NIS (non-ionic surfactant), NIS-DRA (non-ionic surfactant-drift reducing agent), NISH (non-ionic surfactant-humectant). WC and NISHs at 0.5 $v\ v^{-1}$; NIS1, NIS2, and NIS-DRA1 at 0.25 $v\ v^{-1}$; NIS-DRA2 at 0.75 $v\ v^{-1}$.

3.1.4. Evaporation Time

At 20% RH, in the absence of WC, the use of NIS2, NIS-DRA2, NISH1, NISH2, NISH4, NISH5, and NISH6 increased ER from 0.6 to 3 $\times$ 10^{-3} µL s^{-1} (75% to 375%) compared to DpG alone (0.8 $\times$ 10^{-3} µL s^{-1}) (Table 6). However, in the presence of WC, DpG solutions with adjuvants presented lower ER in a range of 0.9–3.3 $\times$ 10^{-3} µL s^{-1} (25% to 96%) than DpG with only WC (3.6 $\times$ 10^{-3} µL s^{-1}). At 40% RH, the influence of adjuvants on DpG solutions without and with WC was opposite. In the absence of WC the use of adjuvants, except for NIS-DRA2 and NISH6, decreased ER in a range of 0.3–1.0 $\times$ 10^{-3} µL s^{-1} (21% to 77%) compared to DpG alone (1.4 $\times$ 10^{-3} µL s^{-1}). Contrarily, in the presence of WC, the use of all adjuvants increased ER in a range of 0.2–1.4 µL s^{-1} (66% to 467%), compared to DpG with only WC (0.3 $\times$ 10^{-3} µL s^{-1}). At 60% RH, DpG solutions with adjuvants presented greater ER than solutions without adjuvant, independently of the presence or not of WC. In the absence of WC, compared to DpG alone (0.4 $\times$ 10^{-3} µL s^{-1}), ER increased in a range of 0.3–1.2 $\times$ 10^{-3} µL s^{-1} (75–300%) when adjuvants were added. Additionally, in the presence of WC, with the addition of adjuvants ER increased from 0.2 to 0.5 $\times$ 10^{-3} µL s^{-1} (25–250%) compared to DpG with only WC (0.8 $\times$ 10^{-3} µL s^{-1}). At 80% RH, the addition of most adjuvants to DpG solutions without WC did not change ER, compared to DpG alone (0.9 $\times$ 10^{-3} µL s^{-1}). However, in the presence of WC, the addition of NIS2, NIS-DRA2, NISH2, and NISH6 decreased ER decreased from 0.7 up to 0.8 $\times$ 10^{-3} µL s^{-1} (50% up to 57%) and adjuvants NISH3 and NISH5 increased by 1.1 $\times$ 10^{-3} µL s^{-1} (79%) and 0.3 $\times$ 10^{-3} µL s^{-1} (21%), respectively, compared to DpG with only WC (1.4 $\times$ 10^{-3} µL s^{-1}).

Table 6. Evaporation rate for dicamba plus glyphosate solutions at 559 and 1541 g ae ha^{-1}, respectively, with and without non-AMS water conditioner alone and tank mixed with 10 adjuvants at 25 °C.

Water Conditioner [a]	Adjuvant [b]	20% RH		40% RH		60% RH		80% RH	
					μL s^{-1}				
None	None	0.8×10^{-3}	i–m	1.4×10^{-3}	b	0.4×10^{-3}	j	0.9×10^{-3}	gh
None	NIS1	0.6×10^{-3}	klm	1.0×10^{-3}	def	1.4×10^{-3}	ab	0.9×10^{-3}	fgh
None	NIS2	1.4×10^{-3}	f–j	0.6×10^{-3}	ij	0.7×10^{-3}	i	1.1×10^{-3}	efg
None	NIS-DRA1	0.7×10^{-3}	j–m	0.7×10^{-3}	hi	1.1×10^{-3}	def	1.1×10^{-3}	efg
None	NIS-DRA2	2.6×10^{-3}	cde	1.7×10^{-3}	a	0.8×10^{-3}	hi	1.3×10^{-3}	de
None	NISH1	1.6×10^{-3}	fgh	1.1×10^{-3}	de	1.4×10^{-3}	abc	0.7×10^{-3}	h
None	NISH2	2.0×10^{-3}	def	0.5×10^{-3}	jk	0.8×10^{-3}	hi	1.1×10^{-3}	efg
None	NISH3	1.1×10^{-3}	h–l	1.1×10^{-3}	d	1.5×10^{-3}	ab	0.6×10^{-3}	h
None	NISH4	3.8×10^{-3}	a	0.4×10^{-3}	kl	0.8×10^{-3}	hi	2.0×10^{-3}	b
None	NISH5	1.9×10^{-3}	efg	0.9×10^{-3}	fg	1.5×10^{-3}	a	1.1×10^{-3}	efg
None	NISH6	3.0×10^{-3}	bc	1.4×10^{-3}	b	0.9×10^{-3}	gh	1.1×10^{-3}	efg
Non-AMS WC	None	3.6×10^{-3}	ab	0.3×10^{-3}	l	0.8×10^{-3}	hi	1.4×10^{-3}	de
Non-AMS WC	NIS1	4.0×10^{-4}	lm	0.9×10^{-3}	fg	1.2×10^{-3}	cde	1.3×10^{-3}	de
Non-AMS WC	NIS2	1.3×10^{-3}	g–k	0.5×10^{-3}	jk	1.1×10^{-3}	def	0.7×10^{-3}	h
Non-AMS WC	NIS-DRA1	0.3×10^{-3}	m	1.3×10^{-3}	bc	1.3×10^{-3}	bcd	1.6×10^{-3}	cd
Non-AMS WC	NIS-DRA2	2.7×10^{-3}	cd	1.3×10^{-3}	b	1.0×10^{-3}	fgh	0.6×10^{-3}	h
Non-AMS WC	NISH1	1.4×10^{-3}	f–j	0.9×10^{-3}	fg	1.1×10^{-3}	efg	1.4×10^{-3}	cde
Non-AMS WC	NISH2	1.6×10^{-3}	f–i	1.7×10^{-3}	a	1.1×10^{-3}	efg	0.7×10^{-3}	h
Non-AMS WC	NISH3	0.8×10^{-3}	j–m	0.9×10^{-3}	efg	1.2×10^{-3}	cde	2.5×10^{-3}	a
Non-AMS WC	NISH4	2.7×10^{-3}	cd	1.7×10^{-3}	a	1.1×10^{-3}	efg	1.3×10^{-3}	def
Non-AMS WC	NISH5	1.0×10^{-3}	h–m	0.8×10^{-3}	gh	1.1×10^{-3}	efg	1.7×10^{-3}	bc
Non-AMS WC	NISH6	1.6×10^{-3}	fgh	1.1×10^{-3}	cd	1.4×10^{-3}	ab	0.6×10^{-3}	h
		***		***		***		***	

Means followed by the same letter in the column do not differ using Tukey's test at α = 0.05. Significance level: *** $p \leq 0.001$. [a], [b] Abbreviations: WC (water conditioner), NIS (non-ionic surfactant), NIS-DRA (non-ionic surfactant-drift reducing agent), NISH (non-ionic surfactant-humectant). WC and NISHs at 0.5 $v\ v^{-1}$; NIS1, NIS2, and NIS-DRA1 at 0.25 $v\ v^{-1}$; NIS-DRA2 at 0.75 $v\ v^{-1}$.

3.1.5. pH

In the absence of WC, the addition of most adjuvants did not change pH for DpG solutions compared to DpG alone, but there were some exceptions (Table 7). Compared to DpG alone (4.9), the use of adjuvants NIS1 and NISH6 decreased pH to 4.5 and 4.7, respectively, and adjuvant NISH4 increased to 5.0. Similarly, in the presence of WC, most adjuvants did not change pH compared to DpG solution with only WC (5.1). However, adjuvants NIS1 and NISH6 decreased pH to 4.9 and 5.0, respectively, and adjuvants NIS2, NIS-DRA1, NISH2, and NISH5 increased pH to 5.2. Overall pH for solutions without WC was 4.9 and for solution with WC was 5.1.

Table 7. pH for dicamba plus glyphosate solutions at 559 and 1541 g ae ha^{-1}, respectively, with and without non-AMS water conditioner alone and tank mixed with 10 adjuvants.

Solution [a]	Water Conditioner [b]	Adjuvant [c]	pH
Water	None	None	7.5
DpG	None	None	4.9
DpG	None	NIS1	4.5
DpG	None	NIS2	4.9
DpG	None	NIS-DRA1	4.9
DpG	None	NIS-DRA2	4.9
DpG	None	NISH1	4.9
DpG	None	NISH2	4.9
DpG	None	NISH3	4.9
DpG	None	NISH4	5.0

Table 7. *Cont.*

Solution [a]	Water Conditioner [b]	Adjuvant [c]	pH
DpG	None	NISH5	4.9
DpG	None	NISH6	4.7
DpG	Non-AMS WC	None	5.1
DpG	Non-AMS WC	NIS1	4.9
DpG	Non-AMS WC	NIS2	5.2
DpG	Non-AMS WC	NIS-DRA1	5.2
DpG	Non-AMS WC	NIS-DRA2	5.1
DpG	Non-AMS WC	NISH1	5.1
DpG	Non-AMS WC	NISH2	5.2
DpG	Non-AMS WC	NISH3	5.1
DpG	Non-AMS WC	NISH4	5.1
DpG	Non-AMS WC	NISH5	5.2
DpG	Non-AMS WC	NISH6	5.0

[a] Abbreviation: DpG, dicamba (Xtendimax® with Vapor Grip®, Monsanto Company, St. Louis, MO, USA) plus glyphosate (Roundup PowerMax®, Monsanto Company, St. Louis, MO, USA). [b, c] Abbreviations: WC (water conditioner), NIS (non-ionic surfactant), NIS-DRA (non-ionic surfactant-drift reducing agent), NISH (non-ionic surfactant-humectant). WC and NISHs at 0.5 $v\ v^{-1}$; NIS1, NIS2, and NIS-DRA1 at 0.25 $v\ v^{-1}$; NIS-DRA2 at 0.75 $v\ v^{-1}$.

3.2. Droplet Size Study

The ANOVA table demonstrated a water conditioner versus other adjuvants interaction for $Dv_{0.1}$, $Dv_{0.5}$, $Dv_{0.9}$, PF, and RS ($p < 0.001$). Addition of adjuvants to DpG solutions without and with non-AMS WC resulted in variable response on volumetric diameters, and consequently, on PF (Table 8). Compared to DpG alone, in the absence of WC, the addition of NIS1, NIS2, NISH3, and NISH6 presented finer Dv0.5 and NIS-DRA1, NIS-DRA2, NISH2, NISH4, and NISH5 coarser $Dv_{0.5}$. However, in the presence of WC, DpG solutions containing adjuvants, except for NIS-DRA2, presented finer $Dv_{0.5}$ than DpG with only WC. As expected, in the absence of WC, with the addition of NIS2, NISH3, and NISH6 PF was 3–28% lower than DpG alone (0.46%). However, when NIS-DRA2 and NISH6 were added to the solution PF was 5–17% greater than DpG alone. Moreover, in the presence of WC, compared to DpG solution with only WC (0.41%), PF was 3–22% higher when adjuvants, except NIS-DRA2 and NISH5, were added to solution. The addition of NIS-DRA2 decreased PF to 0.18%. Regarding RS, the addition of NIS1, NIS2, NIS-DRA1, NIS-DRA2, NISH2, NISH4, and NISH5 to DpG solution without WC decreased RS compared to DpG alone. In the presence of WC, compared to DpG with only WC, while NIS2, NIS-DRA1, NIS-DRA2 increased, RS, NIS1, NISH3, and NISH6 decreased.

Table 8. Dv0.1, Dv0.5, and Dv0.9 (droplet diameters for which 10, 50, and 90% of the total spray volume is contained in droplets of lesser diameter, respectively), percentage of fines (PF) and relative span (RS) for dicamba plus glyphosate solutions at 559 and 1541 g ae ha−1, respectively, with and without non-AMS water conditioner alone and tank mixed with 10 adjuvants at 246 kPa using TTI110015 nozzle.

Water Conditioner [a]	Adjuvant [b]	Parameters									
		Dv0.1		Dv0.5		Dv0.9		PF		RS	
		µm									
None	None	371	c	717	e	1069	e	0.46	c	0.97	d
None	NIS1	369	c	710	d	1057	d	0.47	c	0.96	c
None	NIS2	349	a	653	a	964	a	0.51	d	0.94	b
None	NIS-DRA1	375	d	724	a	1073	e	0.47	c	0.96	c
None	NIS-DRA2	502	e	941	g	1350	f	0.18	a	0.9	a
None	NISH1	372	c	718	e	1068	e	0.48	c	0.97	d
None	NISH2	377	d	729	f	1078	e	0.43	b	0.96	c
None	NISH3	360	b	702	c	1046	c	0.58	e	0.97	d
None	NISH4	375	d	727	f	1075	e	0.46	c	0.96	c

Table 8. *Cont.*

Water Conditioner [a]	Adjuvant [b]	Parameters									
		Dv0.1		Dv0.5		Dv0.9		PF		RS	
		µm									
None	NISH5	375	d	727	f	1075	e	0.47	c	0.96	c
None	NISH6	349	a	684	b	1026	b	0.63	f	0.98	d
Non-AMS WC	None	383	e	736	f	1083	e	0.41	b	0.95	c
Non-AMS WC	NIS1	363	c	709	c	1060	d	0.52	e	0.98	d
Non-AMS WC	NIS2	343	a	645	a	941	a	0.53	e	0.92	b
Non-AMS WC	NIS-DRA1	377	d	727	d	1074	e	0.45	c	0.96	c
Non-AMS WC	NIS-DRA2	509	f	949	g	1362	f	0.14	a	0.90	a
Non-AMS WC	NISH1	373	d	721	d	1069	d	0.48	d	0.96	c
Non-AMS WC	NISH2	381	e	731	e	1078	e	0.42	b	0.95	c
Non-AMS WC	NISH3	362	c	705	c	1053	c	0.56	f	0.98	d
Non-AMS WC	NISH4	377	d	729	e	1076	e	0.44	c	0.96	c
Non-AMS WC	NISH5	375	d	726	d	1073	e	0.47	d	0.96	c
Non-AMS WC	NISH6	350	b	685	b	1029	b	0.63	g	0.99	d
		***		***		***		***		***	

Means followed by the same letter in the column do not differ using Tukey's test at $\alpha = 0.05$. Significance level: *** $p \leq 0.001$. [a], [b] Abbreviations: WC (water conditioner), NIS (non-ionic surfactant), NIS-DRA (non-ionic surfactant-drift reducing agent), NISH (non-ionic surfactant-humectant). WC and NISHs at 0.5 $v\ v^{-1}$; NIS1, NIS2, and NIS-DRA1 at 0.25 $v\ v^{-1}$; NIS-DRA2 at 0.75 $v\ v^{-1}$.

3.3. Greenhouse Study

A significant interaction for water conditioner versus other adjuvants was demonstrated by the ANOVA table for VEC and BR for barnyardgrass, kochia, velvetleaf, and c. waterhemp ($p < 0.001$). For common lambsquarters, its high control by reduced doses of DpG meant, comparisons between treatments were not possible. Therefore, no significant interaction WC versus other adjuvants and main effects were detected for any of the above-mentioned parameters. Overall, VEC and BR for this weed species were above 99% and 95%, respectively (data not shown).

3.3.1. Barnyardgrass

In general, the addition of adjuvants did not change VEC for DpG solutions, independently of the presence or not of WC (Table 9). However, there were a few exceptions. Compared to DpG alone (61%), in the absence of WC, adjuvant NIS2 decreased VEC by 25% and adjuvant NISH6 increased VEC by 28%. Furthermore, in the presence of WC, addition of adjuvant NIS2 and NISH6 decreased VEC by 16% and 14%, respectively, compared to DpG with only WC (69%).

Similar to VEC, BR did not change with the use of most adjuvants. However, in the absence of WC, the use of adjuvant NIS2 decreased BR by 22%, compared to DpG alone (78%). Moreover, when adjuvant NISH1 was added to solution with WC, BR decreased by 18%, compared do DpG with WC only (80%).

3.3.2. Horseweed

VEC of horseweed by DpG solutions without and with WC was 97% and 98%, respectively. No differences were observed with the addition of adjuvants to DpG solutions, independently of presence or not of WC. However, the addition of adjuvants NIS-DRA1 and NISH5 decreased BR by 4% and 5% and by 3% and 4% for treatment solutions without and with WC, compared to DpG alone (93%) and DpG with only WC (91%), respectively.

Table 9. Biomass reduction (BR) and visual estimation of control (VEC) of barnyardgrass, horseweed, kochia, velvetleaf, and c. waterhemp at 28 days after application (28 DAA) for dicamba plus glyphosate solutions at 279 and 385 g ae ha^{-1}, respectively, with no water conditioner and with non-AMS water conditioner alone or tank mixed with 10 adjuvants in greenhouse experiments.

Water Conditioner [a]	Adjuvant [b]	Barnyardgrass		Horseweed		Kochia		Velvetleaf		C. Waterhemp	
		VEC	BR	VEC	BR	VEC	BR	VEC	BR	VEC	BR
		%									
None	none	61 efg	78 a–e	98 a	93 a	79 h	76 def	41 d	28 e	52 g	58 e
None	NIS1	59 fg	76 b–e	99 a	93 a	88 c–f	79 b–e	74 abc	69 a–d	86 a–f	85 a–d
None	NIS2	36 h	56 fg	98 a	92 abc	85 d–h	80 bcd	75 abc	69 a–d	90 a–e	80 a–d
None	NIS–DRA1	54 g	77 a–e	94 a	89 b–f	81 gh	66 g	74 abc	65 a–d	96 ab	91 ab
None	NIS–DRA2	72 cde	84 abc	97 a	90 a–f	83 e–h	71 efg	73 abc	70 a–d	79 ef	73 cd
None	NISH1	61 efg	82 abc	98 a	90 a–f	81 f–h	73 d–g	73 abc	65 a–d	89 a–e	84 a–d
None	NISH2	52 g	64 ef	97 a	91 a–e	88 b–e	85 abc	73 abc	73 ab	95 ab	90 ab
None	NISH3	70 def	83 abc	98 a	92 abc	86 c–g	78 cde	73 abc	70 a–d	96 ab	90 ab
None	NISH4	52 g	66 de	98 a	90 a–f	85 d–h	75 def	76 abc	66 a–d	91 a–e	87 abc
None	NISH5	51 g	73 cde	97 a	88 ef	89 a–d	81 a–d	74 abc	57 d	92 a–d	88 abc
None	NISH6	89 a	94 a	97 a	89 b–f	95 a	88 a	81 a	75 ab	94 abc	89 ab
Non-AMS WC	none	69 def	80 a–d	93 a	91 a–d	85 d–h	77 cde	73 abc	71 abc	96 ab	93 a
Non-AMS WC	NIS1	71 def	86 abc	100 a	92 ab	85 d–h	74 d–g	73 abc	67 a–d	93 a–d	89 ab
Non-AMS WC	NIS2	53 g	73 cde	98 a	92 abc	79 f–h	68 fg	71 abc	69 a–d	81 def	82 a–d
Non-AMS WC	NIS–DRA1	74 bcd	86 abc	98 a	88 c–f	81 fgh	74 d–g	73 abc	69 a–d	86 a–f	86 a–d
Non-AMS WC	NIS–DRA2	83 abc	91 ab	98 a	91 a–e	84 d–h	77 cde	76 abc	68 a–d	93 abc	87 abc
Non-AMS WC	NISH1	55 g	62 g	99 a	92 ab	89 a–d	87 ab	68 c	58 cd	94 abc	92 ab
Non-AMS WC	NISH2	71 de	82 abc	99 a	92 abc	92 abc	85 abc	71 c	63 bcd	77 f	71 de
Non-AMS WC	NISH3	77 bcd	87 abc	98 a	92 ab	89 a–e	86 abc	75 abc	71 abc	85 b–f	82 a–d
Non-AMS WC	NISH4	76 bcd	86 abc	97 a	88 def	92 abc	80 a–d	82 a	78 a	88 a–f	85 a–d
Non-AMS WC	NISH5	71 de	85 abc	99 a	87 f	89 a–e	78 b–e	74 abc	67 a–d	83 c–f	77 bcd
Non-AMS WC	NISH6	84 abc	92 ab	98 a	90 a–f	94 ab	88 a	77 abc	75 ab	97 a	93 a
		**	***	-	***	***	**	***	***	***	***

Means followed by the same letter in the column do not differ using Tukey's test at α = 0.05. Significance levels: -, nonsignificant at α = 0.05; ** $p \leq 0.01$; *** $p \leq 0.001$. [a], [b] Abbreviations: WC (water conditioner), NIS (non-ionic surfactant), NIS-DRA (non-ionic surfactant-drift reducing agent), NISH (non-ionic surfactant-humectant). WC and NISHs at 0.5 $v\ v^{-1}$; NIS1, NIS2, and NIS-DRA1 at 0.25 $v\ v^{-1}$; NIS-DRA2 at 0.75 $v\ v^{-1}$.

3.3.3. Kochia

In the absence of WC, the use of adjuvants NIS1, NISH2, NISH3, NISH5, and NISH6 increased VEC in a range of 7–16% compared to DpG alone (79%). DpG plus adjuvant NISH6 presented a VEC of 95%. Further, for DpG solutions in the presence of WC, adjuvants NISH5, NISH4, NISH6 increased VEC in a range of 7–9% compared to DpG only with WC (85%).

When WC was not added to the solution, BR was also greater for DpG solutions containing adjuvants NISH2 (85%) and NISH6 (88%) than DpG alone (76%). However, with addition of adjuvant NIS-DRA1, BR was 13% lower than DpG alone. For DpG solutions with WC, addition of adjuvant NISH1 and NISH6 increased BR by 10% and 11%, respectively, and adjuvant NIS2 reduced by 9%, both compared to DpG with only WC (77%).

3.3.4. Velvetleaf

The addition of adjuvants to DpG solutions without WC increased VEC in a range of 32 to 40% compared to DpG alone (41%). The highest VEC (81%) was observed with addition of adjuvant NISH6. In the presence of WC, solution with adjuvant NISH4 was the only that presented greater VEC (82%) than DpG with only WC (77%).

The influence of adjuvants on BR for solution without and with WC was similar to VEC. In absence of WC, solutions containing adjuvants presented greater BR in a range of 29–47% compared to DpG alone (41%). Additionally, DpG plus adjuvant NISH6 presented the highest BR (75%). Furthermore, in the presence of WC, DpG plus adjuvant NISH4 was again the only solution that had greater BR (78%) than DpG with only WC (71%).

3.3.5. Common Waterhemp

The influence of adjuvants on DpG solutions VEC was very similar as for velvetleaf in the absence of WC. The use of adjuvants increased VEC from 27% to 44% compared to DpG alone (52%). The highest VEC was achieved with addition of adjuvant NIS-DRA1 and NISH3. However, in the presence of WC, the addition of adjuvants NIS2, NISH2, and NISH5 reduced VEC in 15%, 19%, and 13%, respectively, compared to DpG solution with only WC (96%).

The BR increased from 15% to 32% with addition of adjuvants to DpG solutions without WC, compared to DpG alone (58%). DpG plus adjuvant NIS-DRA1 provided the highest BR (91%). However, in the presence of WC, adjuvant NISH2 and NISH5 decreased BR by 22% and 16%, compared to solution with only WC (93%).

3.4. Field Study

The ANOVA table demonstrated no significant interaction FOR WC versus other adjuvants for VEC, BR and M for horseweed. However, main effect adjuvant was significant for VEC ($p < 0.01$). For Palmer amaranth, no WC versus other adjuvants and main effects were detected for any of the parameters aforementioned.

3.4.1. Horseweed

The average VEC by DpG solutions without WC was 91% and with WC was 90% (Table 10). Among adjuvants treatments, VEC by DpG plus adjuvant NIS-DRA1 and by DpG plus adjuvant NISH4 were 3% lower than DpG plus NIS-DRA2 (92%). The overall biomass reduction and mortality were 65% and 59% for DpG solutions without WC and 64% and 60% for DpG solutions with WC. Further, the average biomass reduction and mortality among adjuvants treatments were 64% and 59%, respectively.

Table 10. Biomass reduction (BR), visual estimation of control (VEC), and mortality (M) of horseweed across years (2019 and 2020) and Palmer amaranth single year (2020) at 28 DAA (days after application) for dicamba plus glyphosate solutions at 559 and 1541 g ae ha^{-1}, respectively, with and without non-AMS water conditioner alone and tank mixed with 10 adjuvants in field experiments.

	Horseweed			Palmer Amaranth		
	Parameter					
Water Conditioner [a]	**VEC**	**BR**	**M**	**VEC**	**BR**	**M**
			%			
None	91 A	65 A	59 A	59 A	49 A	18 A
Non-AMS WC	90 A	64 A	59 A	60 A	46 A	16 A
	-	-	-	-	-	-
Adjuvant [b]						
None	91 ab	62 a	55 a	57 a	38 a	22 a
NIS1	91 ab	63 a	66 a	59 a	51 a	17 a
NIS2	90 ab	65 a	59 a	61 a	50 a	17 a
NIS-DRA1	89 b	65 a	54 a	58 a	51 a	21 a
NIS-DRA2	92 a	64 a	63 a	59 a	33 a	15 a
NISH1	90 ab	64 a	60 a	59 a	60 a	19 a
NISH2	91 ab	62 a	55 a	59 a	52 a	25 a
NISH3	90 ab	69 a	57 a	62 a	48 a	12 a
NISH4	89 b	64 a	60 a	61 a	53 a	16 a
NISH5	91 ab	67 a	62 a	62 a	43 a	20 a
NISH6	91 ab	61 a	60 a	53 a	46 a	5 a
	**	-	-	-	-	-

Means followed by the same letter in the column do not differ using Tukey's test at α = 0.05. Significance levels: -, nonsignificant at α = 0.05; ** $p \leq 0.01$. [a, b] Abbreviations: WC (water conditioner), NIS (non-ionic surfactant), NIS-DRA (non-ionic surfactant-drift reducing agent), NISH (non-ionic surfactant-humectant). WC and NISHs at 0.5 $v\ v^{-1}$; NIS1, NIS2, and NIS-DRA1 at 0.25 $v\ v^{-1}$; NIS-DRA2 at 0.75 $v\ v^{-1}$.

3.4.2. Palmer Amaranth

Overall VEC was 59% and 60% by DpG solutions without WC and with WC, respectively. Additionally, the average VEC among adjuvants treatments was 60%. DpG solutions without WC provided a biomass reduction and mortality of 49% and 18% compared to 46% and 17% for DpG solutions with WC. Moreover, the average biomass reduction and mortality was 49% and 17% among adjuvants treatments, respectively.

4. Discussion

Previous studies reported that density, viscosity, surface tension, contact angle, droplet size, and droplet evaporation of the spray solution can change with the addition of adjuvants to the spray solution [43–46]. Results confirmed that density and viscosity of solutions containing NIS, NIS-DRA, and NIS-surfactant were greater than herbicide alone, independently of the presence of water conditioner. Similar results were found by Assuncao et al. (2019) [47] in which glyphosate solution containing a synthetic adjuvant presented density 2.2% higher than glyphosate alone. Furthermore, Moraes et al. (2019) [36] demonstrated that lactofen containing COC (crop oil concentrate), NIS, MSO (methylated soybean oil) and COC-DRA increased viscosity by 4.3%, 2.6%, 3.6%, and 5.7%, respectively, compared to lactofen alone. As expected, the highest viscosity observed in this present study was also by solutions containing DRA, since these types of adjuvants work by changing the viscoelastic properties of the spray solution, yielding a coarser spray with greater mean droplet sizes and weights, and minimizing the number of small, easily windborne droplets [34].

Furthermore, results showed that the majority of solutions containing adjuvants presented lower sCA and dST. All adjuvants used in this study contained NIS and the primary purpose of a surfactant is to reduce the surface tension and contact angle between the spray droplet and the plant surface which increases wettability and herbicide penetration into the leaf [48]. However, surfactant nature and concentration, presence of other adjuvants herbicide formulation and surrounding vapor can also affect surface tension and contact angle [49–53] which may explain that some of the adjuvants did not work as expected by maintaining or increasing dST and sCA. Those uncommon results were observed mainly at 80% RH which indicates that adjuvants effects are less likely to occur at high humidities. Besides penetration and wettability, sCA and dST directly impact evaporation rate of the droplet. According to Li et al. (2019) [54], surfactant could shorten the evaporation duration of the droplet, since in some cases the adjuvant reduces the spray solution surface tension that would accelerate the spreading and evaporation. Additionally, surfactants that reduce contact angle can result in a 10-fold increase in surface area available for evaporation [55]. Although some of the adjuvants in this study contained a humectant in their formulation, it was not enough to decrease evaporation rate in all scenarios, especially at high humidities, 60% and 80% RH, where droplet evaporation is naturally slower. Another factor affecting evaporation rate is the droplet size [44]. Larger droplets will take a longer time to evaporate which may explain the fact that solutions containing NIS-DRA2 presented greater $Dv_{0.5}$ among adjuvants and also consistently decreased evaporation rate in the absence of WC. However, in the presence of WC, the decrease was not consistent throughout all the RHs which indicates that droplet evaporation rate is dependent on multiple factors.

The droplet spectrum has been recognized as the most important variable to reduce spray drift [56]. The Spray Drift Task Force defined physical properties as one of the primary factors affecting droplet size spectrum. Cunha and Alves (2019) [43] concluded that viscosity and surface tension were the most affected physical properties by the addition of adjuvants. While a decrease in surface tension causes a decrease in droplet size, an increase in density results in formation of larger droplets [57,58] which explain the variable influence of adjuvant on droplet spectra in this study. However, solutions containing NIS-DRA2 presented the highest Dv0.5 and lowest PF which indicates that density was more important to determine droplet spectrum in this case.

One of the most important factors to consider when applying tank mixture of dicamba and glyphosate is the pH of the spray solution. At pH below 5.0, dicamba will convert to the acid form that has very high vapor potential [16]. Results obtained from this study showed that in the absence of WC only NISH4 would be adequate since all the other treatments solutions including DpG alone presented pH lower than 5. However, except for DpG plus NIS1, all treatment solutions presented pH above 5 in the presence of WC, which indicates that WC has in its compositions elements that increase pH. Moreover, considering the initial pH of the water was 7.5, all DpG solutions acidified the water which agrees with results found by Mueller and Steckel (2019) [14].

Greenhouse studies demonstrated that the influence of adjuvants on herbicide effectiveness in the absence of WC was species specific. Although for barnyardgrass, horseweed, and kochia most adjuvant treatments performed similarly to DpG alone, for velvetleaf and c. waterhemp, all adjuvants tested improved herbicide effectiveness. Weed species have different foliar surface characteristics (e.g., cuticle, number of stomata and trichomes, leaf position and angle and leaf age) that impose barriers to herbicide deposition [29,51,59,60]. However, in the presence of WC most adjuvant treatments were comparable to DpG solution with only WC, independently of weed species. Those results indicate that water hardness is one of the main factors decreasing DpG efficacy which agrees with research published by Devkota and Johnson, (2019) [61]. Furthermore, except for velvetleaf, reduced herbicide efficacy was noticed with the addition of some adjuvants to DpG solutions with and without WC.

Under field conditions, no significant differences in VEC, BR, and M were observed across years for horseweed trials, even though weather conditions at the application time varied in 2019 and 2020 (Table 1). Applications were performed under mild temperature and high RH in 2019 and under high temperature and low RH in 2020 (Table 1). The activity of POST herbicides is usually favored under warm and humid conditions [62]. Thus, the conditions were not ideal in any of the years this study was conducted which may explain the similarity in results across years despite the differences in temperature and RH. Additionally, there are other factors that can influence DpG efficacy under field conditions (e.g., UV light, weed density) that were not analyzed in this study. Furthermore, the addition of adjuvants did not increase DpG solutions efficacy for both horseweed and Palmer amaranth, regardless the presence or not of WC. In research published by Eubank et al. (2013) [63], VEC of horseweed by saflufenacil plus NIS at 0.25 and 0.5 $v\ v^{-1}$ was similar to saflufenacil alone at 28 DAA under field conditions. Additionally, Petersen et al. (1985) [64] reported that the use of a surfactant (Nacotrol) did not increase K-salt of 14 C-dicamba absorption into soybean leaves. One possible explanation for the null or antagonistic effects of the adjuvants observed in this present study is that NIS contained in all adjuvants decreased the dST and sCA, but adjuvants also increased Dv0.5, especially NIS-DRAs. Thus, as each type of application requires a specific droplet size for optimum biological activity [65], the improvement in wettability and herbicide penetration may not be enough to overcome the unsatisfactory herbicide coverage by the coarser droplets. Additionally, these larger spray droplets are less likely to adhere to a leaf surface which may result in roll or fall-off of those spray droplets, and consequently in a reduction of herbicide efficacy [24]. Regarding the humectants, the humidity under greenhouse conditions may be enough to prevent rapid droplet drying regardless of surfactant humectancy, but the control of horseweed and Palmer amaranth fields trials sprayed under hot and dry weather conditions did not increase with the addition of NISH which indicates the humectant formulation or concentration may be not adequate for DpG solutions.

5. Conclusions

Overall, results demonstrated that even though the adjuvants promote changes in the physical properties of spray solutions that would increase herbicide penetration, wettability, and droplet drying time, it will not necessarily result in higher weed control under greenhouse and field conditions. Regarding the use of WC with DpG, the majority of the solutions in presence of WC presented pH $\geq$ 5.0. Contrarily, in the absence of WC, except DpG + NISH4, solutions presented pH $\leq$ 5. Furthermore, DpG solutions containing only

WC demonstrated similar velvetleaf and c. waterhemp biomass reduction to DpG solutions plus adjuvants without WC. Those results indicate that the use of a WC decreases potential of dicamba vapor while being as effective as NIS, NIS-DRA, and NISH in improving velvetleaf and c. waterhemp control in hard water. When spraying dicamba it is essential to take actions to mitigate vapor and particle drift. The adjuvants containing DRA increased $Dv_{0.5}$ and decreased the percentage of driftable fines. However, the of majority of NIS and NISH adjuvants decreased $Dv_{0.5}$ and increased PF which increases risk of particle drift. Some adjuvants can have an antagonistic effect on herbicide efficacy by decreasing weed control and/or increasing drift potential. The main goal of adding adjuvants to tank mixture is to optimize herbicide effectiveness and/or spray application characteristics. Therefore, an adjuvant is only recommended when attending its purpose without causing any negative effects.

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