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Efficacy of dicamba and glyphosate as influenced by carrier water pH and hardness

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Abstract

Herbicide carrier water hardness and pH can be variable depending on the source and geographic location. Herbicide efficacy can be affected by the pH and hardness of water used for spray solution. Field and greenhouse studies were conducted to evaluate the effect of carrier water pH and hardness on premixed dicamba and glyphosate efficacy. Treatments were combinations of water pH at 4, 6.5, or 9; and water hardness at 0 (deionized water), 400, or 800 mg L^{-1} of $CaCO_3$ equivalent. In the field study, dicamba and glyphosate were applied at 0.55 and 1.11 kg ae ha^{-1}, respectively, and half of these rates were applied in the greenhouse study. There was no interaction between carrier water pH and hardness on dicamba and glyphosate efficacy; however, the main effects of carrier water pH and hardness were significant. Herbicide efficacy was reduced with carrier water at pH 9 compared with pH 4. In the field study, common lambsquarters, common ragweed, horseweed, or Palmer amaranth control was improved 6% or more at carrier water at pH 4 compared with pH 9. Similar results were observed with water pH for giant ragweed, Palmer amaranth, or pitted morningglory control in the greenhouse study. Carrier water hardness at 400 or 800 mg L^{-1} reduced common ragweed, giant ragweed, or horseweed control compared with 0 mg L^{-1}. Similarly, common lambsquarters, Palmer amaranth, or pitted morningglory control was reduced at least 10% with carrier water hardness at 800 mg L^{-1} compared with 0 mg L^{-1}. These results indicate carrier water at acidic pH and of no hardness is critical for dicamba and glyphosate application, and spray solution needs to be amended appropriately for an optimum efficacy.

Introduction

Water is the primary carrier solvent for herbicide application. Ground water is commonly used for herbicide application because it is cost effective and easily accessible in most of the farming regions in the United States. However, mineral compositions of the bed rock and aquifer types vary with the geographic location, resulting in variable underground water quality (Durfor and Becker 1964). Water-quality factors such as pH (acidity or alkalinity) and hardness (presence of mineral such as calcium, magnesium, and iron) are highly variable depending on geographic location (Freeze and Cherry 1979). According to Deer and Beard (2001), water pH in the United States can range from 3 to 9. In the midwestern United States, the limestone bedrock contributes to the higher hardness level in the underground water (IDNR 1980). In Indiana, total hardness level of underground water ranges from 50 to 1,250 mg L^{-1} (IDNR 1999).

Variability of spray-water quality can contribute to inconsistent herbicide efficacy (Buhler and Burnside 1983; Devkota and Johnson 2016a; Nalewaja and Matysiak 1991). Carrier water at acidic or alkaline pH is reported to influence efficacy of sulfonylurea herbicides (Green and Cahill 2003; Sarmah and Sabadie 2002). Efficacy of sulfonylurea herbicide was enhanced with carrier water at alkaline pH compared with acidic pH (Sarmah and Sabadie 2002). According to Roskamp et al. (2013b), solubility of saflufenacil was reduced in water at acidic pH, whereas other researchers reported hydrolysis of herbicide molecules at alkaline pH (Deer and Beard 2001; Green and Cahill 2003; Stahlman and Phillips 1979). Green and Hale (2005) reported enhanced efficacy of weak acid herbicide (e.g., glyphosate) with carrier water pH below the acid dissociation constant (pKa).

Presence of hard-water cations in spray water and their negative effect on herbicide efficacy have been reported in various studies (Buhler and Burnside 1983; Devkota et al. 2016a; Mueller et al. 2006; Nalewaja and Matysiak 1991, 1993; Roskamp et al. 2013a; Zollinger et al. 2010). A negative effect of hard-water mineral cations on glyphosate efficacy was reported by Abouziena et al. (2009) and Buhler and Burnside (1983). Glyphosate applied with spray solutions containing calcium cations at 50 mg L^{-1} contributed to reduced activity on wheat (*Triticum aestivum* L.) (Shea and Tupy 1984). Mueller et al. (2006) reported that presence of calcium or magnesium at a concentration greater than 250 mg L^{-1} reduced glyphosate efficacy.

Protonation or deprotonation of the herbicide molecule in a solution is based on the pKa value. When spray solution pH is below the pKa, the herbicide molecule is protonated in the solution. The protonation of the herbicide molecule may prevent salt complex formation while cations are present in the spray solution (Nalewaja et al. 1994). However, when pH is above the pKa, deprotonation of the herbicide molecule occurs, and presence of mineral cations can form an herbicide-salt complex. Besides hydrolysis of weak acid herbicides, alkaline water can increase binding of herbicide molecules with salt cations and enhance herbicide-cation complex formation (Altland 2010; Green and Cahill 2003). Sethoxydim efficacy on oat (*Avena sativa* L.) was reduced when spray solution was at alkaline pH and calcium or sodium were present in the solution (Nalewaja et al. 1994). Buhler and Burnside (1983) also reported a similar result: glyphosate efficacy was increased by 30% with the addition of an acidifying agent in well water compared with efficacy without an acidifying agent. The authors reported that increased herbicide effectiveness by addition of an acidic agent with underground water was due to the reduction of glyphosate-salt cation complex formation at lower water pH.

Water-quality factors such as pH or hardness could be variable depending on geographic locations. Depending on the nature of herbicide chemistry, carrier water pH and hardness might have a considerable negative impact on its efficacy. Researchers have shown the phytotoxicity of glyphosate is affected not only by spray-solution pH but also by anions or cations present in the spray solution. However, there is a lack of information on the potential interaction of carrier water pH and hardness on weed control efficacy of a dicamba-and-glyphosate mixture. This study was conducted to evaluate the effect of carrier water pH and hardness on efficacy of a premix of low-volatility dicamba and glyphosate for weed control.

Materials and Methods

Field Studies

Field experiments were conducted in the summer of 2013 and 2014 in the absence of a crop. Four weed species were evaluated at different sites. The common ragweed trial was conducted at Southeast Purdue Agricultural Center, IN (39°01N, 85°31W), where the soil type was a Clermont silt loam with 1.5% organic matter and pH of 6.3. In 2013, the horseweed site was at Thockmorton-Purdue Agricultural Center, IN (40°17Nm 86°54W), where the soil type was a Toronto-Milbrook silt loam with 2.9% organic matter and pH 6.2. In 2014, horseweed was evaluated at the Purdue University Meigs farm near Romney, IN (40°16N, 86°52W), where the soil type was a Crosby-Miami silt loam with 2.9% organic matter and pH 6.9. A grower's field near Twelve Mile, IN (41°N, 86°41W) was the site for common lambsquarters and Palmer amaranth for both years. Soil type at this site was a Bloomfield loamy sand with 1.9% organic matter and pH 6.5.

The experimental design was a randomized complete block design with a factorial arrangement of treatments and four replications. The factors evaluated were carrier water pH and hardness. Carrier water pH was maintained at 4, 6.5, or 9 using organic pH buffer salts at 0.1 M concentration in deionized water. Potassium hydrogen phthalate salt (Acros Organics, Geel, Belgium), potassium phosphate monobasic salt (potassium phosphate monobasic crystals, Avantor Performance Materials Inc., Phillipsburg, NJ), or Tris salt [Tris (hydroxymethyl)aminomethane, Acros Organics, Geel, Belgium] was dissolved in deionized water to create water pH at 4, 6.5, or 9, respectively. In addition, each carrier water pH level was adjusted at 0 (i.e., deionized water), 400, or 800 mg L^{-1} hardness level (only 0 or 800 mg L^{-1} was used for evaluation of common lambsquarters and Palmer amaranth). Calcium (calcium chloride dihydrate, granular; Macron Fine Chemicals, Avantor Performance Materials, Inc., Center Valley, PA) and magnesium (magnesium sulfate anhydrous; Fisher Scientific, Pittsburgh, PA) was used in a 3:1 ratio to adjust water hardness.

A premix of dicamba (0.55 kg ae ha^{-1}) and glyphosate formulation (1.11 kg ae ha^{-1}) (MON 76757; diglycolamine salt of dicamba [18.82%], monoethanolamine salt of glyphosate [37.94%], surfactant [≤3%], and formulating ingredients [≤40.24%]; Monsanto Company, St. Louis, MO) was used. Treatments were applied with a CO_2-pressurized backpack sprayer with a TeeJet XR11002 nozzle (Spraying Systems Co., Springfield, IL) at a volume of 140 L ha^{-1} with a pressure of 172 kPa, and a speed of 4.8 km hr^{-1}. An untreated check was also included for treatment evaluation. Weed densities at treatment applications were 20 to 300 plants m^{-2} for common ragweed; 80 to 200 plants m^{-2} for horseweed; 2 to 10 plants m^{-2} for common lambsquarters; and 20 to 150 plants m^{-2} for Palmer amaranth. Weed species were 5- to 20-cm tall at treatment application timings.

Greenhouse Studies

Greenhouse studies were conducted during fall 2013 and spring 2014. Bioassay plants were established using potting medium (Redi-Mix, Sun-Gro Redi-Earth Plug and Seedling Mix, Sun-Gro Horticulture, Bellevue, WA). Giant ragweed, Palmer amaranth, and pitted morningglory seeds were germinated on 26 by 26 by 6 cm^3 polyflats using potting medium. The 164-cm^3 cone-containers (Ray Leach SC-10 Super Cell Conetainers; Stuewe & Sons, Tangent, OR) were filled with potting medium and seedlings at the one to two true-leaf stage were transplanted. Transplants were watered daily and fertilized weekly [Miracle-Gro® Water-Soluble All-Purpose Plant Food (24-8-16); Scotts Miracle-Gro Products Inc., Marysville, OH]. The greenhouse was maintained at minimum and maximum temperatures of 25 and 28°C, respectively, and supplemental lighting was used to provide a 16-h photoperiod.

The experimental design was a randomized complete block design with a factorial arrangement of treatments and four replications. The factors evaluated were carrier water pH and hardness. Water pH was adjusted at 4, 6.5, or 9, and hardness levels were adjusted at 0, 400, or 800 mg L^{-1}, as for the field study. A premix of dicamba and glyphosate was applied at reduced rate, 0.275 and 0.55 kg ae ha^{-1}, respectively. In addition, an untreated check was included for treatment evaluation. Treatments were applied on giant ragweed, 10- to 15-cm tall; Palmer amaranth, 8- to 12-cm tall; and pitted morningglory at the five to six-leaf stage. Treatments were sprayed using a compressed air-track sprayer at 140 L ha^{-1}, with a TeeJet 8002EVS nozzle (Spraying Systems Co.), at a spraying speed of 4.8 km h^{-1}.

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Table 1. Control, plant density, and biomass reduction of common ragweed and horseweed with dicamba and glyphosate applied at 0.55 plus 1.11 kg ae ha^{-1}, respectively, as affected by carrier water pH and hardness at 4 wk after treatment in the field experiment.[a]

		Common ragweed						Horseweed					
		Control[b]		Plant density reduction[c]		Biomass reduction[d]		Control		Plant density reduction		Biomass reduction	
Factor	Unit	2013	2014	2013	2014	2013	2014	2013	2014	2013	2014	2013	2014
		%											
Water pH	4	83 a	88 a	96 a	88 a	93 a	85 a	89 a	78 a	70 a	63 a	78 a	53 a
	6.5	82 ab	81 b	93 a	87 a	92 a	84 a	85 ab	71 ab	67 ab	44 ab	76 a	48 ab
	9	77 b	79 b	91 a	80 b	90 a	82 a	78 b	62 b	64 b	34 b	74 a	38 b
Water hardness[e]	0	88 a	94 a	97 a	94 a	94 a	88 a	89 a	78 a	74 a	52 a	79 a	50 a
	400	81 b	81 b	94 a	83 b	92 a	87 a	85 a	68 b	64 ab	50 a	76 ab	49 a
	800	70 c	72 c	90 a	75 c	90 a	76 b	77 b	64 b	62 b	37 b	70 b	39 b

[a]Data were arcsine square-root transformed and separated by experimental year for the analysis.
[b]Means within a column and among each factor levels followed by the same letter are not different based on adjusted Tukey at $\alpha = 0.05$.
[c]Plant density reduction was calculated by subtracting the final density count of each treatment from the initial density count and converting the result to a percentage of the initial density count.
[d]Biomass reduction was calculated by subtracting the dry weight of each treatment from that of the untreated control and converting the result to a percentage of the untreated control.
[e]Unit for water hardness level is mg L^{-1} of $CaCO_3$ equivalent.

Data Collection and Statistical Analysis

In the field study, a 1-m^{-2} area was marked within each plot, and common ragweed, horseweed, common lambsquarters, and Palmer amaranth were counted prior to treatment application to establish initial density. After the treatments were applied, plots were visually rated for percent control on a 0% to 100% scale (where 0 is no injury or similar to untreated check, and 100 is complete death of plant). Control ratings were collected at 4 and 3 wk after treatment (WAT) from the field and greenhouse experiments, respectively. At 4 WAT, the number of live plants were counted from the marked 1-m^{-2} area to establish final density, and aboveground weed biomass was harvested. For the greenhouse study, plants were harvested at 3 WAT. Harvested plant samples were placed in the forced-air drier at 60°C for 1 wk and dry weight was recorded. Plant density was converted to percent density reduction of initial count and dry weight was converted to percent biomass reduction compared with the untreated check.

Data were analyzed separately for each weed species using PROC GLMMIX in SAS, version 9.3 (SAS Institute Inc., Cary, NC). Data were checked for constant variance and normality using PROC UNIVARIATE in SAS, and data were transformed as needed. In the field experiment, control, density reduction, and biomass reduction data for all weed species were arcsine square-root transformed. For the greenhouse experiment, control and biomass reduction data were arcsine square-root transformed. Data were subjected to ANOVA. For the field study, the effect of experiment year was significant; therefore, data were separated by year for additional analysis. For the greenhouse study, a significant run effect was not observed; therefore, data were combined over experimental runs for additional analysis. There was no interaction of carrier water pH and hardness on dicamba and glyphosate efficacy in the field or greenhouse experiments. Therefore, treatment means were separated by carrier water pH or hardness levels using adjusted Tukey at $\alpha \leq 0.05$. After mean separation, data were back-transformed for reporting results in percentage units.

Results and Discussion

Field Studies

Effect of carrier water pH or hardness was significant on dicamba and glyphosate efficacy for common ragweed control (Table 1). In 2013, common ragweed control was greater at acidic (pH 4) than alkaline (pH 9) water pH. Common ragweed control was also greater at pH 4 compared with pH 6.5 or 9 in 2014. A difference in common ragweed density reduction was observed between pH 4 or 6.5 compared with pH 9 in 2014. Plant density reduction was at least7% more with water at acidic pH compared with alkaline pH in 2014. For both years, common ragweed control with dicamba and glyphosate was improved at least 7% with 0 versus 400 versus 800 mg L^{-1} hardness levels. Similar results were observed with water hardness levels on common ragweed density reduction in 2014. A difference in biomass reduction was also observed between 0 and 800 mg L^{-1} hardness levels in 2014.

The effect of carrier water pH was significant for dicamba and glyphosate efficacy on horseweed control, where control was improved at least 11% at pH 4 compared with pH 9 for both years (Table 1). Similar results were observed for horseweed density reduction, which was at least 6% more with acidic pH compared with alkaline pH. No differences were observed among water pH levels for horseweed biomass reduction in 2013. However, acidic pH was associated with greater horseweed biomass reduction (≥15% more) compared with alkaline pH in 2014. Carrier water hardness levels affected herbicide efficacy: horseweed control was greater at 0 or 400 mg L^{-1} compared with 800 mg L^{-1} in 2013, whereas a difference existed between 0 compared with 400 or 800 mg L^{-1} in 2014. Horseweed density or biomass reduction was at least 9% more with water hardness at 0 compared to 800 mg L^{-1} in both years. In addition, differences were observed between water hardness at 400 compared to 800 mg L^{-1} for horseweed density and biomass reduction in 2014.

The effect of carrier water pH was significant for dicamba and glyphosate efficacy on common lambsquarters control. In 2013, common lambsquarters control was greater at pH 4 compared

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Table 2. Control, plant density, and biomass reduction of common lambsquarters and Palmer amaranth with dicamba and glyphosate applied at 0.55 plus 1.11 kg ae ha^{-1}, respectively, as affected by carrier water pH and hardness at 4 wk after treatment in the field experiment.[a]

		Common lambsquarters						Palmer amaranth					
		Control[b]		Plant density reduction[c]		Biomass reduction[d]		Control		Plant density reduction		Biomass reduction	
Factor	Unit	2013	2014	2013	2014	2013	2014	2013	2014	2013	2014	2013	2014
		%											
Water pH	4	97 a	97 a	100 a	89 a	98 a	78 a	84 a	74 a	63 a	45 a	86 a	52 a
	6.5	93 ab	95 a	98 a	88 a	97 a	75 a	77 ab	67 b	50 ab	33 ab	82 ab	45 ab
	9	86 b	88 b	90 b	85 a	97 a	73 a	72 b	63 b	33 b	22 b	75 b	40 b
Water hardness[e]	0	97 a	96 a	100 a	89 a	98 a	80 a	83 a	74 a	61 a	42 a	86 a	49 a
	800	87 b	88 b	90 b	87 a	96 a	71 b	72 b	62 b	31 b	28 b	76 b	40 b

[a]Data were arcsine square-root transformed and separated by experimental year for the analysis.
[b]Means within a column and among each factor levels followed by the same letter are not different based on adjusted Tukey at $\alpha = 0.05$.
[c]Plant density reduction was calculated by subtracting the final density count of each treatment from the initial density count and converting the result to a percentage of the initial density count.
[d]Biomass reduction was calculated by subtracting the dry weight of each treatment from that of the untreated control and converting the result to a percentage of the untreated control.
[e]Unit for water hardness level is mg L^{-1} of $CaCO_3$ equivalent.

with pH 9. Control was greater at pH 4 and 6.5 compared with pH 9 in 2014 (Table 2). Overall, the common lambsquarters control at acidic pH was improved at least 9% compared with alkaline pH. Density was reduced at least 8% at pH 4 or 6.5 compared with pH 9 in 2013. Otherwise, few significant differences were observed with water pH for common lambsquarters density and biomass reduction. Carrier water hardness also affected herbicide efficacy of common lambsquarters control: 0 mg L^{-1} water hardness had 8% or better control compared with 800 mg L^{-1}. A difference between 0 mg L^{-1} and 800 mg L^{-1} water hardness was observed for common lambsquarters density reduction in 2013, whereas the difference existed between deionized water and 800 mg L^{-1} for biomass reduction in 2014.

The effect of carrier water pH was significant for dicamba and glyphosate efficacy on Palmer amaranth control. Water at pH 4 had greater control of Palmer amaranth compared with pH 9 in 2013 (Table 2). Palmer amaranth control was greater at pH 4 or 6.5 compared with pH 9 in 2014. Overall, Palmer amaranth control was improved 7% or better at acidic water pH compared with alkaline pH. The difference between acidic and alkaline pH was also observed for Palmer amaranth density (≥23%) and biomass reduction (≥9%) in both years. Water hardness at 800 mg L^{-1} resulted in reduced Palmer amaranth control by 11% compared with deionized water. Palmer amaranth density and biomass reduction was at least 14% and 9% less, respectively, with water hardness at 800 mg L^{-1} compared with deionized water.

There is limited information on the effect of spray-solution pH on growth regulator herbicides; however, to our knowledge, no information exists regarding effect of carrier water pH on efficacy of newer low-volatility dicamba and glyphosate formulations. Woznica et al. (2003) reported that quinclorac efficacy was unaffected with solution at alkaline pH. However, they reported that presence of mineral cations in solution with alkaline pH reduced quinclorac efficacy. The efficacy of a premix of 2,4-D choline and glyphosate was greater with water at an acidic pH compared with an alkaline pH (Devkota and Johnson 2019). Researchers evaluating effect of carrier water pH on glyphosate have concluded that efficacy is greater at acidic pH than at alkaline pH (Shea and Tupy 1984; Stahlman and Phillips 1979).

The results of this study showed that efficacy of a premix of dicamba and glyphosate was reduced with hard water. These results correspond with the results of previous studies evaluating effect of water hardness or hard-water cations on 2,4-D, dicamba, or glyphosate (Mueller et al. 2006; Nalewaja et al. 1991; Nalewaja and Matysiak 1993; Patton et al. 2016; Roskamp et al. 2013a). Nalewaja et al. (1991) illustrated that 2,4-D amine efficacy on kochia [*Kochia scoparia* (L.) Schrad.] was negatively affected by the presence of calcium, magnesium, or iron in the carrier water. The presence of calcium or magnesium in carrier water also resulted in reduced common lambsquarters control with 2,4-D amine (Roskamp et al. 2013a). Water hardness at 800 mg L^{-1} reduced dimethylamine dicamba efficacy at least 50% and sodium salt of dicamba efficacy at least 25% for kochia control (Nalewaja and Matysiak 1993). Glyphosate efficacy was reduced by 10% for broadleaf signalgrass [*Urochloa platyphylla* (Munro ex C. Wright) R.D. Webster], Palmer amaranth, pitted morningglory, and yellow nutsedge (*Cyperus esculentus* L.) control when spray solution consisted of a calcium or magnesium concentration of greater than 250 mg L^{-1} (Mueller et al. 2006). Similarly, the negative effect of calcium and magnesium mineral cations has been reported on premixed 2,4-D choline plus glyphosate efficacy (Devkota and Johnson 2016b).

Greenhouse Studies

Similar to the field study, there was no interaction of water pH and hardness on dicamba and glyphosate efficacy in the greenhouse experiments. Water pH affected giant ragweed, Palmer amaranth, and pitted morningglory control (Table 3). Giant ragweed and Palmer amaranth control at pH 4 was increased by 7% or better compared with pH 9. Pitted morningglory control was improved at least 7% with pH 4 or 6.5 compared with pH 9. Water pH had no effect on biomass reduction of any of the weed species evaluated in this study. Water hardness had a significant effect on dicamba and glyphosate efficacy for giant ragweed, Palmer amaranth, and pitted morningglory control. Giant ragweed control was reduced 11% or more with water hardness at 0 versus 400 versus 800 mg L^{-1}. Palmer amaranth control and pitted morningglory control were reduced 15% and 9%, respectively, with 0 mg L^{-1} compared with 800 mg L^{-1} water hardness. Despite the differences in weed control ratings with dicamba and glyphosate at various water hardness levels, no significant differences were

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Table 3. Control and biomass reduction of giant ragweed Palmer amaranth, and horseweed with dicamba and glyphosate applied at 0.275 plus 0.55 kg ae ha^{-1}, respectively, as affected by carrier water pH and hardness at 3 wk after treatment in the greenhouse experiment.[a]

		Giant ragweed		Palmer amaranth		Pitted morningglory	
Factor	Unit	Control[b]	Biomass reduction[c]	Control	Biomass reduction	Control	Biomass reduction
		%					
Water pH	4	83 a	64 a	89 a	76 a	64 a	34 a
	6.5	80 ab	61 a	83 ab	74 a	65 a	30 a
	9	76 b	59 a	78 b	72 a	57 b	26 a
Water hardness[d]	0	91 a	62 a	90 a	74 a	66 a	31 a
	400	79 b	64 a	84 ab	75 a	61 ab	32 a
	800	68 c	59 a	75 b	74 a	57 b	27 a

[a]Data were arcsine square-root transformed and separated by experimental year for the analysis.
[b]Means within a column and among each factor levels followed by the same letter are not different based on adjusted Tukey at $\alpha = 0.05$.
[c]Biomass reduction was calculated by subtracting the dry weight of each treatment from that of the untreated control and converting the result to a percentage of the untreated control.
[d]Unit for water hardness level is mg L^{-1} of $CaCO_3$ equivalent.

observed on giant ragweed, Palmer amaranth, and pitted morningglory biomass reduction.

Water pH and hardness affected glyphosate plus dicamba efficacy on giant ragweed, Palmer amaranth, and pitted morningglory control. However, similar results were not observed for weed biomass reduction, and this was attributed to the callus tissue growth on treated plants. Researchers have observed a similar phenomenon where sublethal rates of growth regulator herbicide induced growth of callus tissue on treated plants, resulting in increased biomass production (Devkota et al. 2016b; Dowler 1969; Enloe et al. 1999; Roskamp et al. 2013a). Other researchers who evaluated lower rates of growth-regulator herbicides have reported callus growth and its influence on weed biomass data (Dowler 1969; Roskamp et al. 2013a). Application of reduced rates of quinclorac and 2,4-D on field bindweed (*Convolvulus arvensis* L.) resulted in a negative correlation between control rating and biomass data (Enloe et al. 1999). In these studies, authors primarily focused on control rating data.

In the current study, we showed that water at an alkaline pH or that the presence of hard water cations can negatively affect weed control efficacy of dicamba and glyphosate. The current product labels on newer dicamba formulations do not allow spray solution to be at acidic pH, because of increased risk for dicamba volatility (US EPA 2018). However, we showed that dicamba efficacy could be maximized at acidic water pH. We extensively reviewed databases for underground water quality in Indiana and found that water pH ranges from 4 to 9. The information from these databases were the rationale for adjusting the water pH range from 4 to 9 in this study, although water sources in this pH range are not common throughout the United States. Because of the volatility characteristics associated with dicamba at low pH solutions, additional research should evaluate spray-solution pH adjustment for optimizing dicamba and glyphosate efficacy while preserving the low-volatility technology of newer dicamba formulations. For water hardness, the important considerations for applying these herbicide mixtures could be using spray water without hardness levels, or at low hardness levels, and using effective water-conditioning agents. Water-quality factors should be critically evaluated when developing recommendations for optimizing efficacy of a premix of low-volatility dicamba and glyphosate. Evaluation of water-conditioning agents is warranted for improving herbicide efficacy against spray-water hardness.

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References

Abouziena HF, Elmergawi RA, Sharma S, Omar AA, Singh M (2009) Zinc antagonizes glyphosate efficacy on yellow nutsedge (*Cyperus esculentus*). Weed Sci 57:16–20

Altland J (2010) Water quality affects herbicide efficacy. Available at http://oregonstate.edu/dept/nursery-weeds/feature_articles/spray_tank/spray_tank.htm. Accessed: July 10, 2019

Buhler DD, Burnside OC (1983) Effect of water quality, carrier volume, and acid on glyphosate phytotoxicity. Weed Sci 31:163–169

Deer HM, Beard R (2001) Effect of water pH on the chemical stability of pesticides. https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=1074&context=extension_histall. Accessed: November 14, 2019

Devkota P, Johnson WG (2016a) Glufosinate efficacy as influenced by carrier water pH, hardness, foliar fertilizer, and ammonium sulfate. Weed Technol 30:848–859

Devkota P, Johnson WG (2016b) Effect of carrier water hardness and ammonium sulfate on efficacy of 2,4-D choline and premixed 2,4-D choline plus glyphosate. Weed Technol 30:878–887

Devkota P, Johnson WG (2019) Influence of carrier water pH, foliar fertilizer, and ammonium sulfate on 2,4-D and 2,4-D plus glyphosate efficacy. Weed Technol 33:562–568

Devkota P, Spaunhorst DJ, Johnson WG (2016a) Influence of carrier water pH, hardness, foliar fertilizer, and ammonium sulfate on mesotrione efficacy. Weed Technol 30:617–628

Devkota P, Whitford F, Johnson WG (2016b) Influence of spray-solution temperature and holding duration on weed control with premixed glyphosate and dicamba formulation. Weed Technol 30:116–122

Dowler CC (1969) A cucumber bioassay test for the soil residues of certain herbicides. Weed Sci 17:309–310

Durfor CN, Becker E (1964) Public water supplies of the 100 largest cities in the United States; 1962. U.S. Geological Survey Water Supply Paper 1812. Washington, DC: US Government Printing Office. 364 p

Enloe SF, Westra P, Nissen SJ, Miller SD, Stahlman PW (1999) Use of quinclorac plus 2,4-D for controlling field bindweed (*Convolvulus arvensis*) in fallow. Weed Technol 13:731–736

Freeze RA, Cherry JA (1979) Groundwater. Englewood Cliffs, NJ: Prentice-Hall. 604 p

Green JM, Cahill WR (2003) Enhancing the biological activity of nicosulfuron with pH adjusters. Weed Technol 17:338–345

Green JM, Hale T (2005) Increasing the biological activity of weak acid herbicides by increasing and decreasing the pH of the spray mixture. Journal of ASTM International 2:62–71

[IDNR] Indiana Department of Natural Resources (1980) Water quality. http://www.in.gov/dnr/water/files/804_Water_Quality.pdf. Accessed: July 15, 2019

[IDNR] Indiana Department of Natural Resources (1999) Ambient ground water chemistry. https://www.in.gov/dnr/water/5246.htm. Accessed: July 10, 2019

Mueller TC, Main CL, Thompson MA, Steckel LE (2006) Comparison of glyphosate salts (isopropylamine, diammonium, and potassium) and calcium and magnesium concentrations on the control of various weeds. Weed Technol 20:164–171

Nalewaja JD, Matysiak R (1991) Salt antagonism of glyphosate. Weed Sci 39:622–628

Nalewaja, JD, Matysiak R (1993) Spray carrier salts affect herbicide toxicity to kochia (*Kochia scoparia*). Weed Technol. 7:154–158

Nalewaja, JD, Matysiak R, Szeleniak E (1994) Sethoxydim response to spray carrier chemical properties and environment. Weed Technol 8:591–597

Nalewaja JD, Woznica Z, Matysiak R (1991) 2,4-D amine antagonism by salts. Weed Technol 5:873–880

Patton AJ, Weisenberger DV, Johnson WG (2016) Divalent cations in spray water influence 2,4-D efficacy on dandelion (*Taraxacum officinale*) and broadleaf plantain (*Plantago major*). Weed Technol 30:431–440

Roskamp JM, Chahal GS, Johnson WG (2013a) The effect of cations and ammonium sulfate on the efficacy of dicamba and 2,4-D. Weed Technol 27:72–77

Roskamp J, Turco R, Bischoff M, Johnson WG (2013b) The influence of carrier water pH and hardness on saflufenacil efficacy and solubility. Weed Technol 27:527–533

Sarmah AK, Sabadie J (2002) Hydrolysis of sulfonylurea herbicides in soils and aqueous solutions: a review. J Agric Food Chem 50:6253–6265

Shea PJ, Tupy DR (1984) Reversal of cation-induced reduction in glyphosate activity with EDTA. Weed Sci 32:802–806

Stahlman PW, Phillips WM (1979) Effects of water quality and spray volume on glyphosate phytotoxicity. Weed Sci 27:38–41

US EPA (2018) [Letter to Thomas Marvin, Bayer CropScience re: Notification per PRN 98-10 – Minor revisions and correction of typos]. https://www3.epa.gov/pesticides/chem_search/ppls/000524-00617-20181105.pdf. Accessed: July 26, 2019

Woznica Z, Nalewaja JD, Messersmith CG, Milkowski P (2003) Quinclorac efficacy as affected by adjuvants and spray carrier water. Weed Technol 17:582–588

Zollinger RK, Nalewaja JD, Peterson DE, Young BG (2010) Effect of hard water and ammonium sulfate on weak acid herbicide activity. ASTM Journal 7(6):1–10