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Surfactants affect herbicides on kochia (*Kochia scoparia*) and Russian thistle (*Salsola iberica*)

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The effects of surfactants on retention, absorption, and efficacy were determined for bromoxynil, 2,4-D amine, and glyphosate on kochia and Russian thistle. Bromoxynil, 2,4-D amine, and glyphosate retention were similar for both species. Surfactants improved spray retention on kochia and Russian thistle compared with spray mixtures without surfactant. Herbicides mixed with allinol 810-60 surfactant were generally retained better than with MON 0818, oxysorbic 20, or R-11 surfactant. Bromoxynil phytotoxicity was not affected by surfactants, and all surfactants equally enhanced 2,4-D amine phytotoxicity. Glyphosate phytotoxicity to kochia was enhanced only by MON 0818 and oxysorbic 20, and phytotoxicity to Russian thistle was enhanced only by MON 0818. Bromoxynil, with or without surfactants, was absorbed similarly by kochia and Russian thistle. 2,4-D amine and glyphosate absorption were greater with surfactants than without. Kochia and Russian thistle leaves had visibly similar crystalline epicuticular wax structure when plants were grown at $\leq$ 40% or $\geq$ 80% relative humidity, which did influence absorption of these herbicides.

Nomenclature: Bromoxynil; 2,4-D amine; glyphosate; kochia, *Kochia scoparia* (L.) Schrad. KCHSC; Russian thistle, *Salsola iberica* L. SASKA.

Key words: Adjuvant, ^{14}C-herbicides, linear alcohol ethoxylate surfactant, relative humidity.

Kochia (Wicks et al. 1997) and Russian thistle (Blackshaw et al. 1992) commonly affect crops by reducing yields in the Great Plains of the United States and Canada. Kochia and Russian thistle are difficult to control, possibly because of their leaf characteristics. Kochia leaves are generally pubescent, with crystalline epicuticular wax (Nalewaja et al. 1992), which may suspend spray droplets and herbicide above the cuticle (de Ruiter et al. 1990; Wirth et al. 1991), thereby preventing contact with the epicuticular surface for absorption. Russian thistle leaves are slender and round, and herbicide spray droplets having high surface tension may roll off the leaf surface.

Physical factors that affect herbicide retention include spray volume, droplet size, and droplet surface tension (Matysiak 1995). Herbicide formulation also influenced spray droplet dispersal patterns on the leaf (Hess et al. 1981; Hess and Falk 1990). Leaf traits that influence herbicide retention include surface topography (Boize et al. 1976), roughness (Antonious and Snyder 1993), and crystalline or amorphous epicuticular waxes (de Ruiter et al. 1990; Wirth et al. 1991).

Spray droplet dynamic surface tension is thought to be the most important characteristic related to spray droplet retention by difficult-to-wet plants (Green and Green 1991). However, dynamic surface tension was not nearly as important as the ethoxylate chain length of the surfactant for rimsulfuron phytotoxicity (Green and Green 1993) or methylglucose absorption (Stock et al. 1993). These findings indicate that surfactants also function in ways other than facilitating spray retention.

The objective of this research was to determine the effect of surfactants on bromoxynil, 2,4-D amine, and glyphosate spray retention, efficacy, and absorption by kochia and Russian thistle.

Materials and Methods

General Procedure

Kochia and Russian thistle were seeded in containers containing 100% peat potting material[1] and were thinned to one plant per container. Plants were watered and fertilized for healthy growth. Plants were grown in the greenhouse with 30 and 25 C day and night temperatures and a 16-h photoperiod supplemented with metal halide lights at 300 μmol m^{-2} s^{-1} photosynthetic photon flux. Relative humidity ranged from 30 to 50%.

Bromoxynil octanoate ester[2] at 280 g ai ha^{-1}, 2,4-D dimethylamine[3] at 280 g ae ha^{-1}, or glyphosate isopropylamine[4] at 70 g ae ha^{-1} was applied to 2- to 3-cm-tall kochia and 4- to 6-cm-tall Russian thistle. Spray mixtures were delivered in 160 L ha^{-1} spray volume with 280 kPa air using a moving-nozzle sprayer equipped with a TeeJet® XR8001[5] nozzle tip. Surfactants were added to spray mixtures at 0.25% (v/v) and included oxysorbic 20[6] (polyethylated sorbitol fatty acid esters and 20 moles polyoxyethylene), MON 0818[7] (tallow amine polyethoxylate, 20% ethylene oxide), allinol 810-60[8] (linear alcohol ethoxylate, 60% ethylene oxide), and R-11[9] (octyl phenoxy polyethoxy ethanol, isopropanol, and compounded silicone). Herbicide treatments without surfactant were also included.

Spray Retention

Kochia and Russian thistle were sprayed with herbicide–surfactant mixtures plus Chicago Sky Blue dye[10] at 2.5 g L^{-1}. Immediately after treatment, each plant was cut approximately 1 cm above the soil surface, placed in a test tube with 5 ml of water plus 0.0625% (v/v) oxysorbic 20 surfactant, and vigorously shaken for 15 s to wash the dye from the plant. The plants were rinsed with water as they were removed from the tube, and the solution in each tube was brought to a final volume of 15 ml. Dye absorbance was measured at 625 nm with a spectrophotometer. Standard curves for dye absorbance with bromoxynil, 2,4-D amine, and glyphosate were similar, so a single standard curve was used to determine micrograms of dye retained. The equation of the line from the standard curve was linear ($R^2 \geq 0.98$). Each plant was placed in a coin envelope and dried in a forced-air oven at 60 C for 24 h to determine plant dry weight. Data were expressed as microliters of spray retained per gram of plant dry weight.

Herbicide Efficacy

Herbicides were applied to kochia and Russian thistle in the greenhouse as described previously in the general procedure. Visual estimates of biomass reduction were determined 14 d after treatment by comparing treated with untreated plants. Kochia and Russian thistle were cut approximately 1 cm above the soil surface and fresh weights determined. Biomass reduction was calculated as percent fresh weight reduction of treated plants compared with untreated ones.

Herbicide Absorption

Kochia and Russian thistle were grown in a greenhouse for 1 to 2 wk as described above and transferred to growth chambers. Two growth chambers were maintained at 30 and 25 C day and night temperatures and a 16-h photoperiod by fluorescent and incandescent light bulbs giving 700 μmol m^{-2} s^{-1} photosynthetic photon flux. One growth chamber was maintained at $\leq$ 40% relative humidity (RH) and the other chamber at $\geq$ 80% RH. Kochia and Russian thistle plants were left in the two humidity environments for 7 to 10 d before herbicides were applied.

Herbicide absorption was determined by ^{14}C-herbicides (> 98% chemical purity) mixed with different surfactants. ^{14}C-bromoxynil (300 Bq $mmol^{-1}$), ^{14}C-2,4-D (500 kBq $mmol^{-1}$), or ^{14}C-glyphosate (1.9 MBq $mmol^{-1}$) were added to the same nonradioactive herbicides to obtain concentrations of 1,750 mg L^{-1} bromoxynil, 1,750 mg L^{-1} 2,4-D, and 440 mg L^{-1} glyphosate, which were equivalent to the herbicide concentrations in the retention and efficacy experiments. Herbicide plus surfactant treatments were applied to a kochia or Russian thistle leaf as three 1-μl droplets using a Wiretrol-microdispenser pipette.[11] The three droplets were dispensed within a 1-cm^2 area on each respective kochia or Russian thistle leaf. Herbicide treatments without surfactant would not dispense as 1-μl droplets and therefore, were applied as one 3-μl droplet using a microliter syringe.[12] Leaves selected for treatment were young, fully expanded, and located in the upper two-thirds to three-fourths of the plant.

Leaves were removed 48 h after treatment, and unabsorbed ^{14}C-herbicide was removed from the leaf surface by rapidly dipping the leaf 10 times in 15-ml scintillation counting solution, composed of 1:1 (v/v) toluene:ethanol with 1.5 g L^{-1} POPOP {1,4-bis-[4-methyl-5-phenyl-oxazolyl]-benzene} and 5 g L^{-1} PPO (2,5-diphenyloxazole). Scintillation solutions were assayed for radioactivity using a liquid scintillation spectrometer. Herbicide absorbed was calculated as the percentage of that applied that was not removed in the leaf wash. Data were expressed as percent absorbed of the total amount of ^{14}C-herbicide applied.

Statistical Analyses

Herbicide retention and efficacy experiments were designed as a randomized complete block with four replicates and a factorial arrangement of weed species, herbicides, and surfactants, and were repeated. The ^{14}C-herbicide absorption experiment was also designed as a randomized complete block with three replicates of each weed species per treatment and a factorial arrangement of relative humidity, weed species, herbicides, and surfactants. Each combination of treatments was repeated twice more for a total of three experiment repetitions. Mean square error terms were homogeneous, as determined by F-tests at $P \leq 0.001$, so experiment repetitions were combined. Treatment differences were tested with the appropriate experiment repetition-by-treatment error term at $P \leq 0.05$ instead of the error mean square term. Linear correlation analysis determined the relationship among herbicide retention, absorption, and efficacy.

Results and Discussion

Spray Retention

Weed-by-surfactant and weed-by-herbicide interactions were not significant, indicating that spray retention on kochia and Russian thistle was similar regardless of surfactant or herbicide formulation. Leaf morphology differences, such as epicuticular wax structure, are known to influence spray retention (Holloway 1970). Our data suggest that despite significant morphological differences, spray retention was similar between kochia and Russian thistle. However, spray retention data are presented separately for kochia and Russian thistle because of their unique morphological characteristics.

Spray retention by kochia and Russian thistle was similar irrespective of whether the spray contained 2,4-D amine, bromoxynil, or glyphosate, averaged across surfactant treatments (Table 1). Glyphosate and 2,4-D amine are in water-soluble formulations, while bromoxynil is an ester in an emulsifiable formulation. Despite these formulation differences, spray retention by kochia and Russian thistle was similar with these three herbicides.

Additionally, the herbicide-by-surfactant interaction was not significant (data not shown), suggesting that the influence of surfactants on spray retention was similar for each herbicide formulation. Previously, spray retention by wheat (*Triticum aestivum* L.) of the water-soluble formulation of glyphosate was influenced more by surfactants than by the emulsifiable concentrate formulation of fluazifop-P (Nalewaja et al. 1996). Our data for kochia and Russian thistle suggest otherwise because similar increases in spray retention occurred when surfactants were added to 2,4-D amine, bromoxynil, and glyphosate formulations.

Spray retention on kochia was greatest for mixtures containing allinol 810-60 surfactant, averaged across herbicides (Table 1). Additionally, spray mixtures containing MON 0818, oxysorbic 20, or R-11 surfactants were retained on

TABLE 1. Surfactant and herbicide effects on spray retention by kochia (*Kochia scoparia* L. Schrad) and Russian thistle (*Salsola iberica* L.).[a]

Treatment	Kochia	Russian thistle
	μl spray g^{-1} plant dry wt	
Herbicide[b]		
Bromoxynil	11.9	8.1
2,4-D amine	12.8	9.0
Glyphosate	11.7	8.9
LSD (0.05)	NS[c]	NS
Surfactant[d]		
None	8.2	5.5
Allinol 810-60	16.2	10.0
MON 0818	11.1	9.2
Oxysorbic 20	12.7	8.9
R-11	12.4	9.9
LSD (0.05)	2.9	2.4

[a] Weed-by-herbicide and weed-by-surfactant interactions were not significant, but weed species are morphologically different, so data are presented for kochia and Russian thistle separately.
[b] Herbicides averaged across all surfactant treatments.
[c] Abbreviation: NS, not significant.

TABLE 2. Kochia (*Kochia scoparia* L. Schrad) and Russian thistle (*Salsola iberica* L.) fresh wt reduction from herbicides as influenced by surfactants.

Surfactant	Kochia			Russian thistle		
	Bromoxynil	2,4-D-amine	Glyphosate	Bromoxynil	2,4-D-amine	Glyphosate
	(% fresh wt reduction[a])					
None	95	27	21	96	41	8
Allinol 810-60	97	40	9	96	61	2
MON 0818	95	44	82	95	61	68
Oxysorbic 20	92	43	71	95	60	18
R-11	94	40	26	96	60	2
LSD (0.05)	8			18		

[a] Weed-by-herbicide-by-surfactant interaction was not significant but weed species are morphologically different, so data are presented for kochia and Russian thistle separately.

kochia more than spray mixtures without surfactant, averaged across herbicides. Spray retention on Russian thistle was similar with all surfactants, but surfactants increased spray retention compared with no surfactant.

Herbicide Efficacy

Bromoxynil provided 92 to 97% fresh weight reductions of kochia and Russian thistle, regardless of surfactant, which minimized differences between surfactant types (Table 2). 2,4-D amine plus allinol 810-60, MON 0818, oxysorbic 20, or R-11 surfactants was more phytotoxic to kochia (40 to 44% fresh weight reduction) than 2,4-D amine without a surfactant (27% fresh weight reduction). Kochia fresh weight reduction by 2,4-D amine was similar among all surfactants. Likewise, allinol 810-60, MON 0818, oxysorbic 20, and R-11 surfactants enhanced 2,4-D amine phytotoxicity to Russian thistle compared with 2,4-D amine alone.

Kochia and Russian thistle visible control data were greater in magnitude than fresh weight reduction data. However, the interpretation of surfactant effects on 2,4-D amine phytotoxicity to kochia and Russian thistle was similar based on these two evaluation techniques. Visual estimates indicated greater kochia control by 2,4-D amine plus surfactants (81 to 85%) than 2,4-D alone (40%) (data not shown). Control of Russian thistle with 2,4-D amine was similar, whether applied with or without surfactants (81 to 89%). Auxin herbicides alter some plants by affecting growth regulation pathways (Fedtke 1982). Additionally, 2,4-D amine-treated plants exhibit epinasty, particularly bending and twisting of stems and leaf blades, plus stem elongation, and tissue swelling (WSSA 2002). Therefore, fresh weight reduction measurements likely underestimated 2,4-D amine phytotoxicity to kochia and Russian thistle, which continued to grow in biomass after treatment even though the growth was abnormal.

Glyphosate at 70 g ha^{-1} generally provided less and more varied kochia and Russian thistle control compared to bromoxynil or 2,4-D amine (Table 2). Glyphosate was applied at a reduced rate to maximize treatment differences, which may have contributed to the variable control compared to bromoxynil and 2,4-D amine. Glyphosate phytotoxicity to kochia was substantially greater with MON 0818 or oxysorbic 20 surfactants than glyphosate alone or glyphosate plus allinol 810-60 or R-11 surfactants. Russian thistle fresh weight was also reduced more by glyphosate plus MON 0818 than glyphosate plus allinol 810-60, oxysorbic 20, or R-11 surfactants or glyphosate alone.

Previously, glyphosate injury to velvetleaf (*Abutilon theophrasti* Medic.), soybean [*Glycine max* (L.) Merr.], and common lambsquarters (*Chenopodium album* L.) was greater when applied with a cationic surfactant than with allinol nonionic surfactants (Riechers et al. 1995). Results from our research agree that phytotoxicity to kochia and Russian thistle was greater with glyphosate plus the cationic surfactant MON 0818 than glyphosate plus allinol 810-60 nonionic surfactant (Table 2).

Glyphosate phytotoxicity to kochia was also slightly greater with MON 0818 cationic surfactant than with oxysorbic 20 nonionic surfactant (Table 2). Glyphosate was most phytotoxic when applied with secondary alcohol ethoxylate surfactants having high hydrophilic–lipophilic balance (HLB) values from 17 to 18 (Manthey et al. 1996). The HLB value of oxysorbic 20 is 16.7 compared to 12 for allinol 810-60, which likely contributed to greater kochia control by glyphosate with oxysorbic 20 than allinol 810-60 nonionic surfactants.

A spray droplet of glyphosate mixed with allinol 810-60 spread rapidly and formed a thin deposit (Nalewaja and Matysiak 1995). When glyphosate was mixed with surfactants having longer chain lengths or increased ethoxylate components, little droplet spread occurred resulting in a more spherically shaped deposit or pile. The pile deposit evaporated slower than the thin deposit, which spread over a greater area. Consequently, glyphosate absorption and efficacy were greater when applied with surfactants that produced a pile deposit compared to surfactants that produced a thin deposit. A pile-type deposit was also formed with MON 0818 because this surfactant did not enhance droplet spread nearly as much as allinol 810-60 (Woznica and Messersmith 1994). Droplet spread on adaxial leaf surfaces generally increased as surfactant HLB value decreased from 15 to 12 (Manthey et al. 1996). The rapid spread of droplets

Table 3. ^{14}C-herbicide absorbed by weeds as affected by surfactants and herbicides.

Surfactant	^{14}C-bromoxynil		^{14}C-2,4-D		^{14}C-glyphosate	
	Kochia[a]	Russian thistle[b]	Kochia	Russian thistle	Kochia	Russian thistle
	(% absorption[c])					
None	93	96	44	50	82	80
Allinol 810-60	96	88	85	96	93	92
MON 0818	95	95	91	90	97	99
Oxysorbic 20	85	86	94	95	97	96
R-11	93	89	95	96	98	98
LSD (0.05)	5					

[a] Kochia (*Kochia scoparia* L. Schrad).
[b] Russian thistle (*Salsola iberica* L.).
[c] Weed-by-surfactant-by-herbicide interaction was significant, and data are averaged across relative humidity, which was not significant.

containing allinol 810-60 surfactant was likely due to its low HLB value of 12.

Even though a herbicide and surfactant spray is retained well by the plant, retention may not directly reflect the efficacy potential of the herbicide (Nalewaja and Matysiak 1995). Spray retention by Russian thistle was similar for glyphosate plus allinol 810-60, MON 0818, oxysorbic 20, or R-11 surfactants, but glyphosate phytotoxicity to Russian thistle was much greater with MON 0818 than the other surfactants (Tables 1 and 2). Similarly, spray retention on kochia was greatest for herbicides applied with allinol 810-60 surfactant, but glyphosate plus allinol 810-60 was less phytotoxic to kochia than glyphosate alone. These results suggest that spray deposit characteristics that influence herbicide absorption are more important for determining glyphosate phytotoxicity than spray retention.

Herbicide Absorption

^{14}C-bromoxynil, ^{14}C-2,4-D amine, and ^{14}C-glyphosate absorption by kochia and Russian thistle were similar for $\leq$ 40% or $\geq$ 80% RH (data not shown). Evidently, the cuticles of kochia and Russian thistle were not changed enough by differences in relative humidity for 7 to 10 d to affect herbicide absorption. Kochia leaves from plants grown at either $\leq$ 40% or $\geq$ 80% RH had visibly similar crystalline leaf wax structures prior to treatment when viewed by scanning electron microscopy. Russian thistle grown at either relative humidity also had similar crystalline wax structures. Comparing kochia and Russian thistle, the leaf waxes appeared structurally similar based on the vertically oriented epicuticular wax platelets. These wax plate similarities potentially accounted for the similar herbicide absorption between species.

^{14}C-bromoxynil applied alone or with allinol 810-60, MON 0818, or R-11 surfactants was absorbed similarly by kochia (Table 3). ^{14}C-bromoxynil plus oxysorbic 20 was absorbed less by kochia than ^{14}C-bromoxynil alone or ^{14}C-bromoxynil plus other surfactants. However, Russian thistle absorbed less ^{14}C-bromoxynil plus allinol 810-60, oxysorbic 20, or R-11 surfactants than ^{14}C-bromoxynil plus MON 0818 or ^{14}C-bromoxynil alone.

^{14}C-bromoxynil applied with allinol 810-60 was absorbed more by kochia (96%) than by Russian thistle (88%) (Table 3). The opposite occurred with ^{14}C-2,4-D amine applied with allinol 810-60, where absorption was less by kochia (85%) than by Russian thistle (96%). However, ^{14}C-herbicides applied with MON 0818, oxysorbic 20, or R-11 surfactants were absorbed similarly by kochia and Russian thistle. Leaf surface characteristics, physicochemical properties of the cuticle, and adjuvant properties can all interact to influence the biological efficacy of herbicides (Hess and Falk 1990; Kirkwood 1999). The surfactants examined herein likely interacted differently with kochia and Russian thistle leaves, thus affecting ^{14}C-herbicide absorption.

^{14}C-2,4-D amine or ^{14}C-glyphosate absorption by kochia and Russian thistle increased when applied with a surfactant compared to the herbicides alone (Table 3). The one 3-µl droplet of ^{14}C-2,4-D amine or ^{14}C-glyphosate applied without a surfactant remained intact as a sphere on both kochia and Russian thistle leaves, resulting in only 44 to 82% absorption. The one 3-µl droplet rather than the three 1-µl droplets was used for ^{14}C-2,4-D amine or ^{14}C-glyphosate, when applied without a surfactant, because the 1-µl droplet would not transfer from the pipette to the plants. The 3-µl droplet was large and visibly similar in contact with the leaf as a water droplet, suggesting the surface tension was similar to water and that the droplet contact angle was high for both species. The droplet appeared to have poor contact with the cuticle, which probably accounted for the reduced absorption compared to herbicide solutions with a surfactant.

The nonradioactive glyphosate and 2,4-D amine were water-soluble formulations that likely did not affect the surface tension of the mixture. In contrast, nonradioactive bromoxynil was an emulsifiable formulation that reduced the surface tension of the mixture. The 3-µl droplet of bromoxynil alone was in good contact with kochia and Russian thistle leaves and spread in a manner similar to the three 1-µl droplets of bromoxynil plus surfactants. Thus, absorption of ^{14}C-bromoxynil was not enhanced by the addition of surfactants.

de Ruiter and Meinen (1995) listed several reasons that created difficulties for comparing the outcome of efficacy experiments with absorption and translocation of ^{14}C-herbicides, such as differences of droplet size, application sites on the plant, duration of the herbicide experiment, or herbicide concentration. Subsequently, absorption of ^{14}C-glyphosate was poorly correlated with efficacy data. All herbicides in our research had a low linear correlation between absorption and spray retention ($R^2 = 0.002$; $P \leq 0.05$) or absorption and phytotoxicity (percent fresh weight reduction) ($R^2 = 0.04$; $P \leq 0.05$) to weed species. The linear correlation function explained only 29% ($P \leq 0.05$) of the variation in herbicide retained and phytotoxicity to weed species.

The present research demonstrated that certain surfactants, e.g., allinol 810-60, enhanced spray retention properties of water-soluble herbicides. However, surfactant and herbicide combinations with similar retention may have opposite effects on weed control, such as glyphosate plus allinol 810-60 compared with glyphosate plus MON 0818 (Tables 1 and 2). Thin droplet deposits may hinder herbicide absorption and efficacy because of rapid drying. Conversely, pile deposits may enhance herbicide absorption and efficacy because the pile dries slowly and provides a high concentration gradient for absorption (Nalewaja and Matysiak 1995).

The results of our research indicate the complexity and importance of giving consideration to species, herbicides, and environment in selection of adjuvants to maximize postemergence herbicide efficacy.

Sources of Materials

Mention of trade names or products does not constitute endorsement or recommendation for use.

[1] Sunshine® Mix No. 1, Sun Gro Horticulture Inc., 15831 N.E. 8th Street, Bellevue, WA 98004.

[2] Buctril® formulation of bromoxynil, Aventis CropScience, 2 T. W. Alexander Drive, Research Triangle Park, NC 27709.

[3] Weedar® formulation of 2,4-D, Aventis CropScience, 2 T. W. Alexander Drive, Research Triangle Park, NC 27709.

[4] Rodeo® formulation of glyphosate, Monsanto Co., 800 N. Lindbergh Boulevard, St. Louis, MO 63167.

[5] Spraying Systems Co., North Avenue at Schmale Road, Wheaton, IL 60189-7900.

[6] Tween 20® surfactant containing sorbitan monolaurate and 20 mol polyoxyethylene from Uniqema, 3411 Silverside Road, Wilmington, DE 19850-5391.

[7] MON 0818 cationic surfactant containing tallow amine polyethoxylate, 20% ethylene oxide, Monsanto Co., 800 N. Lindberg Boulevard, St. Louis, MO 63167.

[8] Alfonic 810-60® surfactant containing linear alcohol ethoxylate, 60% ethylene oxide, Condea Vista Chemical Co., 900 Threadneedle, Houston, TX 77079.

[9] R-11® surfactant containing 90% octyl phenoxy polyethoxy ethanol, isopropanol, and compounded silicone, WILFARM, LLC, 1952 W. Market Street, Nappanee, IN 46550.

[10] Sigma Chemical, P.O. Box 14508, St. Louis, MO 63178-9916.

[11] Drummond Scientific Co., 500 Parkway, Broomall, PA 19008.

[12] Hamilton Co., 4970 Energy Way, Reno, NV 89502.

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Literature Cited

Antonious, G. F. and J. C. Snyder. 1993. Trichome density and pesticide retention and half-life. J. Environ. Sci. Health B 28:205–219.

Blackshaw, R. E., R. J. Morrison, H.-H. Muendel, and B. T. Roth. 1992. Weed control in safflower (*Carthamus tinctorius*) with flurtamone. Weed Sci. 40:110–114.

Boize, L., C. Gudin, and G. Purdue. 1976. The influence of leaf surface roughness on the spreading of oil spray drops. Ann. Appl. Biol. 84: 205–211.

de Ruiter, H. and E. Meinen. 1995. Influence of surfactant and water stress on the efficacy, absorption and translocation of glyphosate. Pages 211–216 *in* R. E. Gaskin, ed. Fourth International Symposium on Adjuvants for Agrochemicals. Rotorua, New Zealand: New Zealand Forest Research Institute Bulletin No. 193.

de Ruiter, H., A.J.M. Uffing, E. Meinen, and A. Prins. 1990. Influence of surfactants and plant species on leaf retention of spray solutions. Weed Sci. 38:567–572.

Fedtke, C. 1982. Herbicides with auxin activity. Pages 159–176 *in* Biochemistry and Physiology of Herbicide Action. New York: Springer-Verlag.

Green, J. H. and J. M. Green. 1991. Dynamic surface tension as a predictor of herbicide enhancement by surface active agents. Brighton Crop Prot. Conf. 4:357–365.

Green, J. H. and J. M. Green. 1993. Surfactant structure and concentration strongly affect rimsulfuron activity. Weed Technol. 7:633–640.

Hess, F. D., D. E. Bayer, and R. H. Falk. 1981. Herbicide dispersal patterns: III. As a function of formulation. Weed Sci. 29:224–229.

Hess, F. D. and R. H. Falk. 1990. Herbicide deposition on leaf surfaces. Weed Sci. 38:280–288.

Holloway, P. 1970. Surface factors affecting the wetting of leaves. Pestic. Sci. 1:156–163.

Kirkwood, R. C. 1999. Recent developments in our understanding of the plant cuticle as a barrier to the foliar uptake of pesticides. Pestic. Sci. 55:69–77.

Manthey, F. A., E. F. Szelezniak, and J. D. Nalewaja. 1996. Relationship between droplet spread and herbicide phytotoxicity. Pages 182–191 *in* M. J. Hopkinson, H. M. Collins, and G. R. Gross, eds. Pesticide Formulations and Application Systems. Philadelphia, PA: American Society for Testing and Materials.

Matysiak, R. 1995. Role of adjuvants in product retention and form of deposit on targets. Pages 112–119 *in* R. E. Gaskin, ed. Fourth International Symposium on Adjuvants for Agrochemicals. Rotorua, New Zealand: New Zealand Forest Research Institute Bulletin No. 193.

Nalewaja, J. D. and R. Matysiak. 1995. Ethoxylated linear alcohol surfactants affect glyphosate and fluazifop absorption and efficacy. Pages 291–296 *in* R. E. Gaskin, ed. Fourth International Symposium on Adjuvants for Agrochemicals. Rotorua, New Zealand: New Zealand Forest Research Institute Bulletin No. 193.

Nalewaja, J. D., R. Matysiak, and T. P. Freeman. 1992. Spray droplet residual of glyphosate in various carriers. Weed Sci. 40:576–589.

Nalewaja, J. D., R. Matysiak, and S. Panigrahi. 1996. Ethoxylated linear alcohols affect glyphosate and fluazifop-P spray delivery, retention, and efficacy. Pages 192–200 *in* M. J. Hopkinson, H. M. Collins, and G. R. Gross, eds. Pesticide Formulations and Application Systems. Philadelphia, PA: American Society for Testing and Materials.

Riechers, D. E., L. M. Wax, R. A. Liebl, and D. G. Bullock. 1995. Surfactant effects on glyphosate efficacy. Weed Technol. 9:281–285.

Stock, D., P. J. Holloway, B. T. Grayson, and P. Whitehouse. 1993. Development of a predictive uptake model to rationalise selection of polyoxyethylene surfactant adjuvants for foliage-applied agrochemicals. Pestic. Sci. 37:233–245.

Wicks, G. A., A. R. Martin, and G. E. Hanson. 1997. Controlling kochia (*Kochia scoparia*) in soybean (*Glycine max*) with postemergence herbicides. Weed Technol. 11:567–572.

Wirth, W., S. Strop, and W. Jacobsen. 1991. Mechanisms controlling leaf retention of agricultural spray solutions. Pestic. Sci. 33:411–420.

Woznica, Z. and C. G. Messersmith. 1994. Glyphosate retention and absorption by cattail (*Typha xglauca* Godr.) as influenced by nonionic surfactants. Rocz. Nauk. Rol., Ser. E 24(1/2):87–91.

[WSSA] Weed Science Society of America. 2002. 2,4-D. Pages 111–115 *in* W. K. Vencill, ed. Herbicide handbook. 8th ed. Lawrence, KS: Weed Science Society of America.

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