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Enhancement of tolpyralate efficacy with adjuvants

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Research Article

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Abstract

Tolpyralate is a 4-hydroxyphenylpyruvate dioxygenase–inhibiting herbicide that is applied postemergence for control of annual broadleaf and grass weeds in corn. Current Canadian label recommendations for tolpyralate specify the addition of a methylated seed oil (MSO) adjuvant (MSO Concentrate®) for improved weed control. The efficacy of tolpyralate applied with other proprietary adjuvants has not been widely reported in the peer-reviewed literature. Therefore, four field trials were conducted in corn over 2020 and 2021 in Ontario, Canada, to evaluate MSO Concentrate®, Agral® 90 (nonionic surfactant), Assist® Oil Concentrate (blended surfactant), Carrier® (blended surfactant), LI 700® (nonionic surfactant), and Merge® (blended surfactant) as adjuvants with tolpyralate for the control of annual broadleaf and grass weeds. At 8 wk after application (WAA), tolpyralate applied with MSO Concentrate®, Agral® 90, Assist® Oil Concentrate, Carrier®, or Merge® controlled velvetleaf, wild mustard, barnyardgrass, and foxtail species similarly. These adjuvants also enhanced the efficacy of tolpyralate similarly for the control of common ragweed at 8 WAA with the exception that Agral® 90 was inferior to Merge®. At 8 WAA, tolpyralate controlled common lambsquarters the greatest when applied with MSO Concentrate®, Agral® 90, Carrier®, or Merge®; these adjuvants with the exception of Agral® 90 were superior to Assist® Oil Concentrate. At 8 WAA, tolpyralate applied with LI 700® controlled common ragweed, barnyardgrass, and foxtail species less than when tolpyralate was applied with the other adjuvants tested; control of these weed species with tolpyralate was not improved with LI 700® when compared to tolpyralate applied without an adjuvant. Overall, tolpyralate applied with either MSO Concentrate®, Carrier®, or Merge® controlled all annual broadleaf and grass weed species similarly or greater than tolpyralate applied without an adjuvant or tolpyralate with Agral® 90, Assist® Oil Concentrate, or LI 700® at 8 WAA.

Introduction

Foliar-applied herbicides must be absorbed through shoot tissue and then translocated to the site of action in sufficient quantity to be effective. A significant barrier to foliar-applied herbicide absorption is the leaf cuticle (Hess and Foy 2000; Sharma and Vanden Born 1970). Generally, cuticles with less epicuticular wax are more permeable to herbicides (Hess and Falk 1990; Sharma and Vanden Born 1970; Wyrill and Burnside 1976). The greater permeability with less epicuticular wax content is credited to lower surface tension of the herbicide droplet and decreased contact angle on the leaf surface that increases the wettability of the leaf (Hess and Falk 1990; Taylor et al. 1981; Wyrill and Burnside 1976). When a herbicide spray solution covers a smaller surface area of a leaf, the number of sites for herbicide absorption is reduced (Hess and Falk 1990). Weed species differ in leaf epicuticular wax content (Chachalis et al. 2001). For example, the epicuticular wax content per unit of leaf area in common lambsquarters, velvetleaf, barnyardgrass, and green foxtail [*Setaria viridis* (L.) P. Beauv.] has been reported to be up to 275, 7, 36, and 19 μg cm^{-2}, respectively (Sanyal et al. 2006a, 2006b). Sanyal et al. (2006b) found that the spread of primisulfuron spray solution droplets was greatest on leaves with the least epicuticular wax content. Similarly, Dayan et al. (1996) reported that sulfentrazone foliar absorption was greatest in weed species that had the least epicuticular wax.

Surfactants and oil adjuvants are activator adjuvants that are often added to herbicide formulations or mixtures to improve herbicide efficacy (Dayan et al. 1996; Penner 2000; Young and Hart 1998; Zhang et al. 2013). The use of an appropriate activator adjuvant with an herbicide can decrease the surface tension of a spray droplet and contact angle on a leaf surface for greater leaf wettability (Taylor et al. 1981; Zhang et al. 2013). Foliar absorption of an herbicide can be increased with the use of an activator adjuvant (Dayan et al. 1996; Sharma and Vanden

Born 1970; Young and Hart 1998). The use of methylated seed oil (MSO) with topramezone has been reported to decrease the spray droplet surface tension and leaf contact angle on velvetleaf and giant foxtail (*Setaria faberi* Herrm.) with a concomitant increase in herbicide absorption and weed control efficacy (Zhang et al. 2013).

The ideal adjuvant to use with an herbicide differs among herbicides and weed species (Penner 2000). In previous studies, the use of MSO enhanced weed control more effectively than the use of a nonionic surfactant or crop oil concentrate with isoxaflutole, rimsulfuron, foramsulfuron, and saflufenacil (Bunting et al. 2004; Knezevic et al. 2009; Tonks and Eberlein 2001; Young and Hart 1998). In contrast, Jordan and Burns (1997) reported that chlorimuron efficacy on hemp sesbania [*Sesbania herbacea* (Mill.) McVaugh] was greater with nonionic surfactant than with MSO or crop oil concentrate. The efficacy of chlorimuron applied to purple nutsedge (*Cyperus rotundus* L.) was greater with crop oil concentrate than with nonionic surfactant (Jordan 1996). The efficacy of nicosulfuron applied to wirestem muhly [*Muhlenbergia frondosa* (Poir.) Fernald] has been reported to be greater with the addition of an oil adjuvant than with a nonionic surfactant (Nandula et al. 1995). Strahan et al. (2000) found that a nonionic surfactant improved the efficacy of nicosulfuron to a greater extent than the use of an oil adjuvant for itchgrass [*Rottboellia cochinchinensis* (Lour.) Clayton] control. Bunting et al. (2005) reported that foramsulfuron + atrazine controlled Pennsylvania smartweed [*Persicaria pensylvanica* (L.) M. Gómez], common cocklebur (*Xanthium strumarium* L.), velvetleaf, common lambsquarters, and redroot pigweed (*Amaranthus retroflexus* L.) similarly when applied with either MSO or crop oil concentrate; however, control of giant foxtail, fall panicum (*Panicum dichotomiflorum* Michx.), and waterhemp [*Amaranthus tuberculatus* (Moq.) J.D. Sauer] was greater when MSO was used compared to crop oil concentrate. Harbour et al. (2003) documented four different surfactants that improved the efficacy of 2,4-D amine equally on kochia [*Bassia scoparia* (L.) A.J. Scott] and Russian thistle (*Salsola tragus* L.); however, the same four surfactants did not improve kochia or Russian thistle control with bromoxynil. In contrast, of the four surfactants tested, only two improved kochia control with glyphosate, and only one surfactant enhanced glyphosate efficacy on Russian thistle (Harbour et al. 2003). The most effective adjuvant to enhance the efficacy of an herbicide should not be extrapolated across herbicides, herbicide mixtures, or weed species.

Tolpyralate is a relatively new postemergence 4-hydroxyphenylpyruvate dioxygenase–inhibiting herbicide that controls several annual broadleaf and grass weed species in corn (Metzger et al. 2018a). Tolpyralate is commonly mixed with atrazine to control a broader spectrum of weeds; however, sometimes the addition of atrazine to tolpyralate does not improve weed control (Metzger et al. 2018a). For example, atrazine improved wild mustard and ladysthumb (*Persicaria maculosa* Gray) control when applied with tolpyralate but did not improve the control of common lambsquarters, velvetleaf, common ragweed, *Amaranthus* spp., barnyardgrass, and green foxtail at 8 WAA (Metzger et al. 2018a).

It is recommended to apply tolpyralate with MSO Concentrate® to increase efficacy (Anonymous 2017). It is also advised to apply tolpyralate in a mixture with atrazine; however, some geographic areas are not able to utilize this recommendation where the use of atrazine is restricted or prohibited (Anonymous 2017). The effectiveness of MSO Concentrate® to enhance weed control with tolpyralate + atrazine depends on the weed species and whether glyphosate is included in the mixture (Langdon et al. 2020). Langdon et al. (2020) documented that the addition of MSO Concentrate® to tolpyralate + atrazine improved the control of velvetleaf, *Amaranthus* spp., common lambsquarters, barnyardgrass, and green foxtail at 8 WAA; however, control of common ragweed, wild mustard, and ladysthumb was not improved with the addition of MSO Concentrate®. Additionally, when tolpyralate + atrazine was applied with glyphosate, the addition of MSO Concentrate® did not improve weed control (Langdon et al. 2020).

A comprehensive study comparing the efficacy of tolpyralate when applied with various adjuvants has not been reported in previous research. Therefore, the objective of this study was to evaluate the effect of six proprietary adjuvants on weed control efficacy with tolpyralate on six annual weed species in corn.

Materials and Methods

During 2020 and 2021, four field trials were conducted at University of Guelph–operated field experiment sites in Ridgetown, ON, Canada [Ridgetown Campus (42.45° N, 81.88° W)] and near Exeter, ON, Canada [Huron Research Station (43.32° N, 81.50° W)] (Table 1). The conventionally tilled research sites were fertilized before corn planting to meet corn requirements for Ontario corn production based on prior soil test results (OMAFRA 2017). Corn was seeded to a depth of 5 cm in rows spaced 75 cm apart at approximately 85,000 seeds ha^{-1}. The glyphosate-resistant corn hybrid DKC42-04RIB® (Bayer CropScience Canada Inc., Calgary, AB) was planted at the Huron Research Station in both years. At Ridgetown Campus, DKC42-60RIB® and DKC39-97RIB® glyphosate-resistant corn hybrids (Bayer CropScience Canada Inc., Calgary, AB) were planted in 2020 and 2021, respectively. Plots were 3 m (four corn rows) wide. Plot length was 8 m at Ridgetown Campus and 10 m at the Huron Research Station. The trials were designed as randomized complete blocks with four blocks in each trial. Information pertaining to soil characteristics, corn planting and harvest dates, and treatment application information is presented in Table 1.

All herbicide treatments were applied with a CO_2-powered backpack sprayer that was set to deliver 200 L ha^{-1} at 240 kPa through four ULD120-02 spray nozzles (Pentair, New Brighton, MN) that were spaced 50 cm apart on the spray boom producing a spray width of 2 m. The trials contained a nontreated control plot that received no herbicide applications and a weed-free control in each block. The weed-free control plots were sprayed with bicyclopyrone/mesotrione/*S*-metolachlor/atrazine (Acuron® Herbicide, 7.1/28.5/257/120 g ai L^{-1}; Syngenta Canada Inc., Guelph, ON) applied preemergence at a rate of 2,230 g ai ha^{-1} for season-long annual broadleaf and grass weed control. The weed-free control plots were sprayed with glyphosate (Roundup WeatherMAX®, 540 g ae L^{-1}; Bayer CropScience Canada Inc., Calgary, AB) at 900 g ae ha^{-1} applied postemergence followed by hand weeding as required.

The treatments consisted of tolpyralate (Shieldex® 400SC Herbicide, 400 g ai L^{-1}; ISK Biosciences Corp., Concord, OH) at 30 g ai ha^{-1} applied without adjuvant or with MSO Concentrate®, Agral® 90, Assist® Oil Concentrate, Carrier®, LI 700®, or Merge® to assess crop response and weed control efficacy. These adjuvants were tested with tolpyralate because they are used with many herbicides in Ontario, Canada. Adjuvant composition, manufacturer, and rate information is found in

Table 1. Year, location, soil characteristics, corn planting and harvest dates, herbicide application dates, and corn development stages at application for four field trials at Ridgetown Campus (in Ridgetown, Ontario, Canada) and at the Huron Research Station (near Exeter, Ontario, Canada) in 2020 and 2021.

		Soil characteristics[a]					Treatment application information		
Year	Research site	Texture	OM[b]	pH	Corn planting date	Corn harvest date	Application date	Corn development stage	Corn height
			%						cm
2020	Ridgetown Campus	Sandy clay loam	3.1	7.0	May 26	Nov 5	Jun 16	V3	27
	Huron Research Station	Loam	3.6	7.9	May 6	Oct 26	Jun 8	V4	29
2021	Ridgetown Campus	Sandy clay loam	2.7	6.7	May 14	Oct 1	Jun 12	V5	46
	Huron Research Station	Clay loam	4.4	7.9	Apr 27	Nov 10	Jun 4	V4	32

[a]Soil cores taken to a depth of 15 cm and analyzed at A&L Canada Laboratories Inc. (2136 Jetstream Road, London, Ontario, Canada, N5V 3P5).
[b]Abbreviations: OM, organic matter.

Table 2. Adjuvant trade name, adjuvant composition, adjuvant rate, and adjuvant manufacturer for the study of the enhancement of tolpyralate efficacy for the control of several annual weed species in Ontario, Canada in 2020 and 2021.

Adjuvant trade name	Adjuvant composition	Rate	Manufacturer
MSO Concentrate®	Methylated seed oil of soybean (70%)	0.5% v/v	Loveland Products Inc., Loveland, CO, USA https://www.lovelandproducts.com/
Agral® 90	Nonylphenoxy polyethoxy ethanol (92%)	0.25% v/v	Syngenta Canada Inc., Guelph, ON, Canada https://www.syngenta.ca/
Assist® Oil Concentrate	Paraffin-base mineral oil (83%), surfactant blend (17%)	1 L ha^{-1}	BASF Canada Inc., Mississauga, ON, Canada https://www.basf.com/ca/en.html
Carrier®	Mineral oil (50%), surfactant blend (40%)	0.5% v/v	Nufarm Agriculture Inc. Calgary, AB, Canada https://nufarm.com/ca/
LI 700®	Phosphatidylcholine, methylacetic acid, and alkyl polyoxyethylene ether (80%)	0.25% v/v	Loveland Products Inc. https://www.lovelandproducts.com/
Merge®	Surfactant blend (50%), petroleum hydrocarbons solvent (50%)	1 L ha^{-1}	BASF Canada Inc. https://www.basf.com/ca/en.html

Table 2. The herbicide treatments were applied postemergence when the naturally occurring weed population reached an average canopy height of 10 cm. The weed species present at trial locations were velvetleaf, common ragweed, common lambsquarters, wild mustard, barnyardgrass, and foxtail species (collectively green and giant foxtail).

Corn injury was assessed 1, 2, and 4 WAA on a percentage scale of 0 to 100, with 0% signifying no corn injury and 100% denoting complete corn death. Assessments of visible weed control 2, 4, and 8 WAA for each treatment were taken as percentage estimates of aboveground biomass reduction relative to the nontreated control plot in the respective block on a scale of 0 to 100. After the final weed control assessment at 8 WAA, weed density and aboveground biomass data were determined from each plot by counting the number of each weed species present and clipping the aboveground biomass of each weed at the soil surface within two, 0.5-m^2 quadrats in each plot. The biomass of each weed species was placed in paper bags and dried in a kiln dryer until constant moisture was reached, and then weighed. Corn was harvested by a small-plot combine from the center two rows of each plot after the corn reached harvest maturity. The moisture content and grain weight from plots was obtained so that final corn grain yields could be standardized to 15.5% moisture for statistical analysis.

Statistical Analysis

Visible weed control, weed density, weed dry biomass, corn injury, and corn yield were analyzed in a generalized linear mixed model in SAS version 9.4 (SAS Institute Inc., Cary, NC) using the GLIMMIX procedure. A significance level of $\alpha = 0.05$ was used for all statistical tests. Treatment was the only fixed effect within the statistical tests. The random effects included environment (collective term for site and year combinations), block nested within the environment, and the treatment-by-environment interaction. There were no significant treatment-by-environment interactions, so data were pooled across environments for all response parameters; however, weed species were not always present at all trials. When a weed species was absent from an environment, then that environment was excluded from data analysis for that weed species. Transformations and distributions used for each response parameter were those that best met the assumptions that residuals were random, independent of treatment and design effects, homogeneous, and followed a normal distribution about a mean of zero. To confirm that these assumptions were met, studentized residual plots and the Shapiro-Wilk test were examined. Velvetleaf, common ragweed, common lambsquarters, and wild mustard control at all assessment timings were arcsine square root–transformed and were later back-transformed for the presentation of results. Barnyardgrass and foxtail species control data at all assessment timings were not transformed, as the model residuals were normally distributed. Velvetleaf, common ragweed, common lambsquarters, barnyardgrass, and foxtail species density and dry biomass data were analyzed with a log-normal distribution. Wild mustard density data were analyzed with a log-normal distribution, whereas dry biomass data were analyzed with a normal distribution. When a log-normal distribution was used, the data were back-transformed with a correction for log bias using the omega method of back-transformation (M Edwards, Ontario Agricultural College Statistics Consultant, University of Guelph, personal communication) for the presentation of results (Rothery 1988). Corn yield was analyzed with a normal distribution. The least square means for each response parameter were compared across treatments using the Tukey-Kramer multiple-comparison test. Letter codes were used to demonstrate statistically significant differences among treatments.

Results and Discussion

Velvetleaf

Velvetleaf was present at Ridgetown Campus; data were pooled for 2020 and 2021. Tolpyralate applied without an adjuvant controlled velvetleaf 31% at 2 WAA (Table 3). Tolpyralate applied with LI 700® did not control velvetleaf any better than tolpyralate applied without an adjuvant at 2, 4, and 8 WAA. At 2 WAA, tolpyralate applied with Carrier® or Agral® 90 controlled velvetleaf similarly to tolpyralate applied with LI 700®, but better than tolpyralate applied without an adjuvant. At 2 WAA, tolpyralate applied with Merge® controlled velvetleaf better than when tolpyralate was applied with LI 700®, Agral® 90, or Carrier® (78% compared to 39% to 58%). Tolpyralate applied with Assist® Oil Concentrate or MSO Concentrate® controlled velvetleaf similarly to tolpyralate applied with Merge®, but control was not greater than tolpyralate plus Agral® 90 or Carrier® at 2 WAA. Similarly, previous studies have documented the addition of MSO to tolpyralate + atrazine or topramezone improved control of velvetleaf (Langdon et al. 2020; Zhang et al. 2013). At 4 and 8 WAA, Merge® was the only adjuvant to enhance the control of velvetleaf with tolpyralate greater than LI 700® (86% to 90% compared to 39% to 43%); however, tolpyralate applied with MSO Concentrate®, Agral® 90, Assist® Oil Concentrate, or Carrier® controlled velvetleaf similarly to tolpyralate with Merge®. No adjuvant used with tolpyralate reduced the density or dry biomass of velvetleaf relative to the nontreated control. Opportunistic growth of velvetleaf may have occurred in plots with control of common ragweed, common lambsquarters, and foxtail species, which were at higher densities than velvetleaf. Additionally, velvetleaf density was variable within environments, which would contribute to variability in the collection of density and biomass data from the randomly placed quadrats. This may have contributed to the inability to detect differences in velvetleaf density and dry biomass between the various adjuvants with tolpyralate. Flagging a specific number of velvetleaf plants in each plot before herbicide application and collecting density and biomass from only those plants may have provided more representative density and dry biomass data. Additionally, in agreement with an observation by Metzger et al. (2018b), velvetleaf was injured in plots treated with tolpyralate as evidenced by necrosis of the leaves, but these plants still contributed to velvetleaf density and dry biomass. Therefore, the density and dry biomass of velvetleaf may not be truly reflective of the relative velvetleaf control. The visible weed control may be a more reliable measure of the efficacy of each treatment, as it is an overview of the entire plot area and not restricted to two, 0.5-m^2 quadrats.

Common Ragweed

Common ragweed was naturally occurring at all environments, so the data were pooled across four environments. Control of common ragweed with tolpyralate without an adjuvant was 24% to 31% at 2, 4, and 8 WAA (Table 4). At 2 WAA, control of common ragweed was enhanced with the addition of LI 700® to tolpyralate; however, at 4 and 8 WAA, there was no increase in common ragweed control when LI 700® was added to tolpyralate. At 2, 4, and 8 WAA, the addition of Agral® 90 to tolpyralate resulted in greater control of common ragweed than when LI 700® was added to tolpyralate (69% to 80% compared to 40% to 46%). Merge® improved the control of common ragweed with tolpyralate greater than Agral® 90 at 2, 4, and 8 WAA (87% to 95% compared to 69% to 80%). Carrier®, Assist® Oil Concentrate, and MSO Concentrate® enhanced the efficacy of tolpyralate similar to Merge®, but not greater than Agral® 90 at 2, 4, and 8 WAA. Metzger et al. (2018a) reported >90% control of common ragweed with tolpyralate applied with MSO Concentrate® at 8 WAA, which is comparable to the control in this study. Tolpyralate applied without an adjuvant or with LI 700® did not reduce the density of common ragweed. Tolpyralate applied with Merge®, Carrier®, Assist® Oil Concentrate, Agral® 90, or MSO Concentrate® reduced common ragweed density 82%, 71%, 71%, 65%, and 56%, respectively. Similarly, tolpyralate applied with Merge®, Carrier®, Assist® Oil Concentrate, Agral® 90, or MSO Concentrate® reduced common ragweed dry biomass more than tolpyralate applied without an adjuvant (92% to 97% compared to 73%). Tolpyralate applied with Merge® or Assist® Oil Concentrate reduced the dry biomass of common ragweed greater than when LI 700® was used with tolpyralate (95% to 97% compared to 83%).

Common Lambsquarters

Common lambsquarters was present in all four trials, so the data presented were pooled across the four trials. Control of common lambsquarters with tolpyralate in the absence of an adjuvant was 14% to 17% at 2, 4, and 8 WAA (Table 5). The addition of LI 700® or Assist® Oil Concentrate to tolpyralate improved common lambsquarters control to 43% to 44% and 63% to 64%, respectively, at 2, 4, and 8 WAA. At 2, 4, and 8 WAA, the addition of Agral® 90 to tolpyralate controlled common lambsquarters better than tolpyralate applied with LI 700® but not better than tolpyralate with Assist® Oil Concentrate. Applying tolpyralate with Carrier® or Assist® Oil Concentrate resulted in similar common lambsquarters control at 2 WAA, but at 4 and 8 WAA Carrier® was a better adjuvant to use with tolpyralate for common lambsquarters control. Tolpyralate applied with Merge® or MSO Concentrate® controlled common lambsquarters better than tolpyralate applied with Assist® Oil Concentrate or LI 700® at 2, 4, and 8 WAA (86% to 94% compared to 43% to 64%). Similarly, Langdon et al. (2020) reported that the addition of MSO Concentrate® to tolpyralate + atrazine improved common lambsquarters control. No differences in common lambsquarters control with tolpyralate were detected between the use of Merge®, MSO Concentrate®, Agral® 90, or Carrier® at 2, 4, and 8 WAA. Blackshaw (1998) also did not detect differences in common lambsquarters control when imazamox was applied with Agral® 90 or MSO. Similar to this study, Metzger et al. (2018a) reported >90% control of common lambsquarters with tolpyralate applied with MSO Concentrate®.

Table 3. Influence of adjuvants with tolpyralate on velvetleaf control at 2, 4, and 8 wk after application (WAA), density, and dry biomass in corn from two field trials in Ontario, Canada in 2020 and 2021.

Treatment[a]	Control			Density	Dry biomass
	2 WAA[b]	4 WAA	8 WAA		
	%			No. plants m^{-2}	g m^{-2}
Weed-free control	100	100	100	0 a	0.0 a
Nontreated control	0 e	0 d	0 d	6 b	12.6 b
Tolpyralate	31 d	26 c	28 cd	2 ab	1.4 ab
+ LI 700®	39 cd	39 bc	43 bc	3 b	2.3 ab
+ Agral® 90	58 bc	61 abc	62 abc	5 b	14.7 ab
+ Assist® Oil Concentrate	66 ab	72 ab	77 ab	1 ab	4.1 ab
+ Carrier®	56 bc	65 ab	72 ab	1 ab	3.2 ab
+ MSO Concentrate®	69 ab	74 ab	79 ab	3 b	4.5 ab
+ Merge®	78 a	86 a	90 a	1 ab	1.6 ab

[a]All treatments listed except the weed-free and nontreated control included tolpyralate at a rate of 30 g ai ha^{-1}.
[b]Means within column followed by the same lowercase letter do not statistically differ according to the Tukey-Kramer multiple-range test at $\alpha = 0.05$.

Table 4. Influence of adjuvants with tolpyralate on common ragweed control at 2, 4, and 8 wk after application (WAA), density, and dry biomass in corn from four field trials in Ontario, Canada in 2020 and 2021.

Treatment[a]	Control			Density	Dry biomass
	2 WAA[b]	4 WAA	8 WAA		
	%			No. plants m^{-2}	g m^{-2}
Weed-free control	100	100	100	0 a	0.0 a
Nontreated control	0 e	0 d	0 d	34 e	376.6 d
Tolpyralate	24 d	31 c	31 c	25 de	100.8 c
+ LI 700®	40 c	45 c	46 c	17 cde	65.5 bc
+ Agral® 90	69 b	79 b	80 b	12 bcd	29.2 ab
+ Assist® Oil Concentrate	79 ab	90 ab	92 ab	10 b	17.4 a
+ Carrier®	76 ab	85 ab	89 ab	10 bc	25.2 ab
+ MSO Concentrate®	79 ab	91 ab	91 ab	15 bcd	28.9 ab
+ Merge®	87 a	94 a	95 a	6 ab	9.8 a

[a]All treatments listed except the weed-free and nontreated control included tolpyralate at a rate of 30 g ai ha^{-1}.
[b]Means within column followed by the same lowercase letter do not statistically differ according to the Tukey-Kramer multiple-range test at $\alpha = 0.05$.

Table 5. Influence of adjuvants with tolpyralate on common lambsquarters control at 2, 4, and 8 wk after application (WAA), density, and dry biomass in corn from four field trials in Ontario, Canada in 2020 and 2021.

Treatment[a]	Control			Density	Dry biomass
	2 WAA[b]	4 WAA	8 WAA		
	%			No. plants m^{-2}	g m^{-2}
Weed-free control	100	100	100	0 a	0.0 a
Nontreated control	0 e	0 e	0 e	28 cd	98.5 c
Tolpyralate	14 d	17 d	16 d	32 d	111.7 c
+ LI 700®	44 c	43 c	43 c	17 bcd	57.7 bc
+ Agral® 90	80 ab	84 ab	86 ab	10 bcd	7.6 bc
+ Assist® Oil Concentrate	63 bc	64 bc	64 bc	16 cd	29.8 bc
+ Carrier®	86 ab	88 a	89 a	7 bc	10.4 bc
+ MSO Concentrate®	86 a	91 a	91 a	9 bcd	6.3 abc
+ Merge®	90 a	93 a	94 a	4 b	3.7 ab

[a]All treatments listed except the weed-free and nontreated control included tolpyralate at a rate of 30 g ai ha^{-1}.
[b]Means within column followed by the same lowercase letter do not statistically differ according to the Tukey-Kramer multiple-range test at $\alpha = 0.05$.

In agreement with common lambsquarters control data, Merge® was a better adjuvant than Assist® Oil Concentrate with tolpyralate in the reduction of common lambsquarters density (86% compared to 43%); however, tolpyralate plus Merge®, MSO Concentrate®, Agral® 90, Carrier®, or LI 700® reduced common lambsquarters density similarly. Tolpyralate applied without an adjuvant did not reduce the dry biomass of common lambsquarters, whereas tolpyralate applied with Merge® reduced the dry biomass of common lambsquarters by 96%.

Wild Mustard

Wild mustard was only present at the Huron Research Station, so the data presented were pooled from 2020 and 2021. The addition of LI 700® to tolpyralate did not improve wild mustard control at 2, 4, and 8 WAA (Table 6). Tolpyralate applied with Agral® 90 did not control wild mustard any better than tolpyralate applied with LI 700® at 2, 4, and 8 WAA. Tolpyralate plus Carrier®, Assist® Oil Concentrate, MSO Concentrate®, or Merge® increased wild

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Table 6. Influence of adjuvants with tolpyralate on wild mustard control at 2, 4, and 8 wk after application (WAA), density, and dry biomass in corn from four field trials in Ontario, Canada in 2020 and 2021.

Treatment[a]	Control			Density	Dry biomass
	2 WAA[b]	4 WAA	8 WAA		
	—— % ——			No. plants m^{-2}	g m^{-2}
Weed-free control	100	100	100	0 a	0.0 a
Nontreated control	0 e	0 d	0 d	38 c	81.0 c
Tolpyralate	10 d	14 c	14 c	33 bc	68.9 bc
+ LI 700®	20 cd	21 bc	21 bc	39 bc	90.1 c
+ Agral® 90	32 bc	35 bc	38 abc	40 c	63.3 bc
+ Assist® Oil Concentrate	48 ab	53 ab	56 ab	48 c	46.0 bc
+ Carrier®	46 b	49 ab	52 ab	47 c	52.5 bc
+ MSO Concentrate®	51 ab	51 ab	56 ab	38 bc	55.2 bc
+ Merge®	72 a	72 a	72 a	19 b	22.7 ab

[a]All treatments listed except the weed-free and nontreated control included tolpyralate at a rate of 30 g ai ha^{-1}.
[b]Means within column followed by the same lowercase letter do not statistically differ according to the Tukey-Kramer multiple-range test at $\alpha = 0.05$.

Table 7. Influence of adjuvants with tolpyralate on barnyardgrass control at 2, 4, and 8 wk after application (WAA), density, and dry biomass in corn from four field trials in Ontario, Canada in 2020 and 2021.

Treatment[a]	Control			Density	Dry biomass
	2 WAA[b]	4 WAA	8 WAA		
	—— % ——			No. plants m^{-2}	g m^{-2}
Weed-free control	100	100	100	0 a	0.0 a
Nontreated control	0 e	0 d	0 b	6 b	3.0 ab
Tolpyralate	8 e	6 cd	4 b	12 b	17.2 b
+ LI 700®	23 d	20 c	18 b	14 b	17.4 b
+ Agral® 90	60 bc	53 b	52 a	11 b	6.8 b
+ Assist® Oil Concentrate	58 bc	51 b	51 a	13 b	11.5 b
+ Carrier®	57 c	54 ab	55 a	12 b	8.9 b
+ MSO Concentrate®	70 ab	65 ab	64 a	8 b	7.6 b
+ Merge®	75 a	72 a	71 a	10 b	6.5 ab

[a]All treatments listed except the weed-free and nontreated control included tolpyralate at a rate of 30 g ai ha^{-1}.
[b]Means within column followed by the same lowercase letter do not statistically differ according to the Tukey-Kramer multiple-range test at $\alpha = 0.05$.

mustard control more than LI 700® at 2 WAA (46% to 72% compared to 20%). The addition of Merge® to tolpyralate resulted in greater wild mustard control than when Carrier®, Agral® 90, or LI 700® were added to tolpyralate at 2 WAA (72% compared to 20% to 46%); tolpyralate plus Assist® Oil Concentrate, MSO Concentrate®, or Merge® provided similar control of wild mustard at 2 WAA. Merge® was the only adjuvant used with tolpyralate that controlled wild mustard better than the use of LI 700® at 4 and 8 WAA (72% compared to 21%). At 8 WAA, the use of Merge® with tolpyralate was similar to MSO Concentrate®, Assist® Oil Concentrate, Carrier®, and Agral® 90 for wild mustard control. Previous research reported <60% control of wild mustard with tolpyralate + MSO Concentrate®, which is similar to this study (Metzger et al. 2018a). Tolpyralate applied with Merge® reduced the density and dry biomass of wild mustard by 50% and 72%, respectively. The dry biomass of wild mustard was less when tolpyralate was applied with Merge® instead of LI 700®.

Barnyardgrass

Barnyardgrass was present and pooled from all four trials. Tolpyralate did not control barnyardgrass when applied without an adjuvant at 2, 4, and 8 WAA (Table 7). Tolpyralate plus Merge®, Carrier®, Assist® Oil Concentrate, Agral® 90, or MSO Concentrate® controlled barnyardgrass better than tolpyralate applied with LI 700® at 2, 4, and 8 WAA (51% to 75% compared to 18% to 23%). Similarly, Jordan et al. (1996) found that MSO was a better adjuvant than LI 700® with clethodim for barnyardgrass control. At 2 WAA, tolpyralate applied with Merge® controlled barnyardgrass better than tolpyralate applied with Agral® 90, Assist® Oil Concentrate, or Carrier® but similar to MSO Concentrate®. At 4 WAA, tolpyralate applied with MSO Concentrate® controlled barnyardgrass similarly to tolpyralate applied with Merge®, Agral® 90, Assist® Oil Concentrate, or Carrier®. Langdon et al. (2020) documented that the addition of MSO Concentrate® to tolpyralate + atrazine improved barnyardgrass control. At 8 WAA, Merge®, Carrier®, Assist® Oil Concentrate, Agral® 90, and MSO Concentrate® enhanced the efficacy of tolpyralate similarly. The use of LI 700® did not improve the efficacy of tolpyralate on barnyardgrass at 8 WAA. No differences among the different tolpyralate-plus-adjuvant treatments existed for the density and dry biomass of barnyardgrass. The density and dry biomass data for barnyardgrass may not reflect visible control data because the barnyardgrass density was variable within trials, so the visible control evaluation of the entire plot area may not be represented in the two, 0.5-m^2 quadrats randomly placed in each plot. Opportunistic growth of barnyardgrass by greater tillering also occurred in plots with greater broadleaf control, which would contribute to some variation in the barnyardgrass dry biomass data. Despite the limitations in barnyardgrass density and dry biomass data, the visible control data were reflective of the relative efficacy of each treatment on barnyardgrass.

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Table 8. Influence of adjuvants with tolpyralate on foxtail species control at 2, 4, and 8 wk after application (WAA), density, and dry biomass in corn from four field trials in Ontario, Canada in 2020 and 2021.

Treatment[a]	Control			Density	Dry biomass
	2 WAA[b]	4 WAA	8 WAA		
	%	%	%	No. plants m^{-2}	g m^{-2}
Weed-free control	100	100	100	0 a	0.0 a
Nontreated control	0 e	0 d	0 c	67 b	96.0 b
Tolpyralate	14 d	8 cd	7 bc	61 b	81.5 b
+ LI 700®	29 c	25 c	24 b	50 b	35.9 b
+ Agral® 90	63 b	60 ab	55 a	37 b	13.3 b
+ Assist® Oil Concentrate	61 b	56 b	54 a	42 b	21.6 b
+ Carrier®	62 b	57 b	58 a	28 b	11.7 b
+ MSO Concentrate®	76 a	72 ab	72 a	36 b	13.0 b
+ Merge®	79 a	77 a	78 a	23 b	7.6 b

[a]All treatments listed except the weed-free and nontreated control included tolpyralate at a rate of 30 g ai ha^{-1}.
[b]Means within column followed by the same lowercase letter do not statistically differ according to the Tukey-Kramer multiple-range test at $\alpha = 0.05$.

Foxtail Species

Foxtail species data were pooled across all four trials. At 2 WAA, tolpyralate applied with Merge® or MSO Concentrate® controlled foxtail species better than tolpyralate applied with Agral® 90, Assist® Oil Concentrate, Carrier®, or LI 700® (76% to 79% compared to 29% to 63%) (Table 8). Previous research with sethoxydim reported that Merge® improved green foxtail control greater than Agral® 90 and LI 700® (Harker 1992). Tolpyralate applied with MSO Concentrate® controlled foxtail species 76% at 2 WAA, which is consistent with previous research (Metzger et al. 2018a). LI 700® enhanced the control of foxtail species with tolpyralate the least of the adjuvants tested at 2 WAA. At 4 WAA, tolpyralate applied with Merge®, MSO Concentrate®, or Agral® 90 controlled foxtail species similarly; however, tolpyralate with MSO Concentrate® or Agral® 90 did not control foxtail species better than tolpyralate with Assist® Oil Concentrate or Carrier®. LI 700® did not improve control of foxtail species with tolpyralate at 4 and 8 WAA, whereas the other five adjuvants enhanced the control of foxtail species with tolpyralate similarly at 8 WAA. In previous studies, control of foxtail species with tolpyralate + atrazine, topramezone, and isoxaflutole was improved with the addition of MSO (Langdon et al. 2020; Young and Hart 1998; Zhang et al. 2013). No differences were detected for foxtail species density or dry biomass reduction with tolpyralate plus the adjuvants evaluated. Similar to barnyardgrass, variation in the density of foxtail species occurred within trials, which would contribute to the inability to observe differences in the density and dry biomass of foxtail species among the treatments. Additionally, foxtail species tillered more in plots where control of broadleaf weed species was achieved as a result of a reduction in interspecific competition. This would contribute to greater biomass per plant. There were numeric differences in the density and dry biomass reduction of foxtail species, which may hold biological significance despite the lack of statistical significance. Generally, these numeric differences reflected the visible control data.

Corn Injury and Corn Yield

Corn injury with all treatments was ≤2%, ≤1%, and 0% at 1, 2, and 4 WAA, respectively (data not presented). Metzger et al. (2018b) also reported excellent tolerance of corn to tolpyralate.

Corn yield was reduced 73% from season-long weed interference in this study (Table 9). The use of Merge® with tolpyralate resulted in corn yield similar to the season-long weed-free control. The use of no adjuvant or LI 700® with tolpyralate did not increase corn yield compared to the nontreated control. The poor weed control associated with these treatments is likely the reason for no difference in corn yield between the nontreated control and application of tolpyralate alone and with LI 700®. The six adjuvants tested with tolpyralate resulted in corn yields that were similar to each other; however, only Carrier®, MSO Concentrate®, and Merge® increased corn yield compared to the use of no adjuvant.

Table 9. Influence of adjuvants with tolpyralate on corn grain yield from four field trials in Ontario, Canada in 2020 and 2021.

Treatment[a]	Corn yield[b]
	kg ha^{-1}
Weed-free control	12,400 a
Nontreated control	3,400 d
Tolpyralate	5,100 cd
+ LI 700®	6,700 bcd
+ Agral® 90	7,800 bc
+ Assist® Oil Concentrate	8,400 bc
+ Carrier®	8,900 b
+ MSO Concentrate®	8,900 b
+ Merge®	9,700 ab

[a]All treatments listed except the weed-free and nontreated control included tolpyralate at a rate of 30 g ai ha^{-1}.
[b]Means within column followed by the same lowercase letter do not statistically differ according to the Tukey-Kramer multiple-range test at $\alpha = 0.05$.

This is the first research that demonstrates the enhancement of tolpyralate efficacy with various adjuvants when tolpyralate is not mixed with atrazine. Although tolpyralate is usually mixed with atrazine, some geographic areas are restricted or prohibited from the application of atrazine. Therefore, this study provides valuable information on adjuvant selection for use with tolpyralate when atrazine is not used. This study identified that Merge® and MSO Concentrate® enhanced the efficacy of tolpyralate to a similar as or greater level than the other adjuvants tested at 2, 4, and 8 WAA. Tolpyralate applied with Carrier® controlled all weed species similarly to tolpyralate plus Merge® or MSO Concentrate® at 8 WAA. LI 700® was the only adjuvant tested with tolpyralate that was consistently inferior to at least one adjuvant for control at 8 WAA of all the weed species evaluated. Future research should test these adjuvants with tolpyralate on other weed species and in geographical areas outside of Ontario, Canada.

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