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Enhancement of Tolpyralate + Bromoxynil Efficacy With Adjuvants in Corn

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Abstract

The most effective adjuvant is often herbicide-specific and dependent on the target weed species. Tolpyralate is a 4-hydroxyphenylpyruvate dioxygenase-inhibiting herbicide that is usually tank-mixed with atrazine for improved weed control in corn (*Zea mays* L.). Previous research has reported that a methylated seed oil (MSO) adjuvant (MSO Concentrate®) enhances the efficacy of tolpyralate + atrazine on several annual broadleaf and grass weed species. The efficacy of tolpyralate can also be improved with the addition of bromoxynil instead of atrazine; however, there is no information in the peer-reviewed literature that tests the efficacy of tolpyralate + bromoxynil with different adjuvants. Therefore, four field trials were conducted in 2020 and 2021 in Ontario, Canada to evaluate the efficacy of tolpyralate + bromoxynil without an added adjuvant and with MSO Concentrate®, Agral® 90, Assist® Oil Concentrate, Carrier®, LI 700®, or Merge® on six annual weed species in corn. The adjuvants did not enhance control of wild mustard (*Sinapis arvensis* L.) or velvetleaf (*Abutilon theophrasti* Medik.) with tolpyralate + bromoxynil. At 8 weeks after application (WAA), common ragweed (*Ambrosia artemisiifolia* L.) control was improved with the addition of MSO Concentrate® or Merge® to tolpyralate + bromoxynil. At 8 WAA, all adjuvants enhanced the control of common lambsquarters (*Chenopodium album* L.) with tolpyralate + bromoxynil similarly except for Assist® Oil Concentrate; Merge® was a better adjuvant than Assist® Oil Concentrate for common lambsquarters control. At 8 WAA, control of barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.] was enhanced with the addition of Assist® Oil Concentrate, Carrier®, MSO Concentrate®, or Merge® to tolpyralate + bromoxynil. Carrier®, MSO Concentrate®, and Merge® enhanced the efficacy of tolpyralate + bromoxynil on *Setaria* spp. at 8 WAA. Control of velvetleaf, wild mustard, common ragweed, *Setaria* spp., and barnyardgrass with tolpyralate + bromoxynil was similar with the six adjuvants evaluated at 8 WAA.

Keywords: barnyardgrass, common lambsquarters, common ragweed, efficacy, grain yield, methylated seed oil, surfactant, velvetleaf, weed control, wild mustard

1. Introduction

Activator adjuvants such as oil adjuvants and surfactants can improve the efficacy of foliar-applied herbicides (Harbour et al., 2003; Langdon et al., 2020). The most effective adjuvant to add to a herbicide depends on the herbicide and target weed species. For example, Nelson et al. (1998) reported that control of common ragweed (*Ambrosia artemisiifolia* L.), common lambsquarters (*Chenopodium album* L.), and velvetleaf (*Abutilon theophrasti* Medik.) with imazethapyr was greater when methylated seed oil (MSO) was used instead of nonionic surfactant; however, with imazamox, only common ragweed control was greater with MSO than with nonionic surfactant. In another study, the control of hemp sesbania [*Sesbania herbacea* (Mill.) McVaugh] was greater with chlorimuron when applied with nonionic surfactant than with crop oil concentrate, while in another study, the control of purple nutsedge (*Cyperus rotundus* L.) with chlorimuron was greater when crop oil concentrate was used instead of nonionic surfactant (Jordan, 1996; Jordan & Burns, 1997). In other work, bromoxynil efficacy on Russian thistle (*Salsola tragus* L.) and kochia [*Bassia scoparia* (L.) A. J. Scott] was not improved with the addition of four different surfactants, while 2,4-D amine efficacy was improved on both weed species with the addition of the same four surfactants (Harbour et al., 2003). In that study, glyphosate efficacy on Russian thistle was enhanced by one surfactant, while control of kochia was improved by two surfactants

(Harbour et al., 2003). Bunting et al. (2005) documented that foramsulfuron + atrazine efficacy was similar on several weed species when applied with either MSO or crop oil concentrate; however, control of giant foxtail (*Setaria faberi* Herrm.), fall panicum (*Panicum dichotomiflorum* Michx.), and waterhemp [*Amaranthus tuberculatus* (Moq.) J. D. Sauer] was greater when MSO was used compared to crop oil concentrate. Identification of the most effective adjuvant to add to a herbicide can improve weed control.

Many studies have reported that weed control with 4-hydroxyphenylpyruvate dioxygenase (HPPD)-inhibiting herbicides, such as tolpyralate, are enhanced with the addition of atrazine (Johnson et al., 2002; Kohrt & Sprague, 2017; Whaley et al., 2006; Woodyard et al., 2009). Tolpyralate is registered for POST annual grass and broadleaf weed control in corn (*Zea mays* L.). Metzger et al. (2018) documented that wild mustard (*Sinapis arvensis* L.) and ladysthumb (*Persicaria maculosa* Gray) control with tolpyralate was improved with the addition of atrazine. Therefore, the recommended use of tolpyralate is tank-mixed with atrazine unless atrazine is prohibited in the application region (Anonymous, 2021).

To improve the efficacy of tolpyralate + atrazine, it is recommended to add MSO Concentrate® to the spray solution (Anonymous, 2021). Control of velvetleaf, common lambsquarters, barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.], and green foxtail [*Setaria viridis* (L.) P. Beauv.] was enhanced when MSO Concentrate® was added to tolpyralate + atrazine (Langdon et al., 2020). In contrast, control of common ragweed and wild mustard was not improved at 8 weeks after application (WAA) with the addition of MSO Concentrate® (Langdon et al., 2020). Langdon et al. (2020) also reported that the addition of MSO Concentrate® did not improve weed control when tolpyralate + atrazine was co-applied with glyphosate.

Previous research has reported that bromoxynil can be used in the place of atrazine as a tank-mix partner with HPPD-inhibitors without compromising weed control (Abendroth et al., 2006; Willemse et al., 2021; Woodyard et al., 2009). Studies have found that mesotrione + bromoxynil and mesotrione + atrazine provided similar control of Palmer amaranth (*Amaranthus palmeri* S. Watson), velvetleaf, waterhemp [*Amaranthus tuberculatus* (Moq.) J. D. Sauer], common lambsquarters, and giant ragweed (*Ambrosia trifida* L.) (Abendroth et al., 2006; Woodyard et al., 2009). Willemse et al. (2021) documented that tolpyralate + bromoxynil controlled waterhemp greater than tolpyralate + atrazine at 4 WAA. Weed control efficacy of HPPD-inhibitors can be improved with the addition of bromoxynil to a similar or greater level as the addition of atrazine.

There is little information in the peer-reviewed literature on the efficacy of tolpyralate + bromoxynil with different proprietary adjuvants. Determining the most efficacious adjuvant to add to tolpyralate + bromoxynil could improve weed control with this tank-mix. Therefore, the objective was to identify the most effective adjuvant to add to tolpyralate + bromoxynil for the control of four annual broadleaf and two annual grass weed species.

2. Materials and Methods

In 2020 and 2021, four randomized complete block design field trials, with four blocks each, were conducted at field sites at the University Guelph in Ridgetown, Ontario, Canada [Ridgetown Campus (42.45ºN, 81.88ºW)] and near Exeter, Ontario, Canada [Huron Research Station (43.32ºN, 81.50ºW)] (Table 1). Fields were moldboard plowed in the fall and cultivated in the spring with an s-tine cultivator outfitted with rolling basket harrows before corn planting. Corn was fertilized according to existing recommendations prior to planting. Corn was planted in rows spaced 75 cm apart and 5 cm deep at a population of 85,000 seeds ha^{-1}. Corn hybrids resistant to glyphosate were planted. At the Huron Research Station, DKC42-04RIB® (Bayer CropScience Canada Inc., 160 Quarry Boulevard SE, Calgary, Alberta, Canada, T2C 3G3) was planted in 3 m wide and 10 m long plots. In 2020, DKC42-60RIB® was planted and in 2021 DKC39-97RIB® was planted at Ridgetown Campus in 3 m wide and 8 m long plots. Further trial information is presented in Table 1.

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

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

Note. Abbreviations: OM, organic matter.

[a] Soil cores taken to a depth of 15 cm and subsequent analysis at A&L Canada Laboratories Inc. (2136 Jetstream Road, London, Ontario, Canada, N5V 3P5) were used to determine soil characteristics.

Herbicides were applied at a spray volume of 200 L ha^{-1} through four ULD120-02 spray nozzles (Pentair, 375 5th Avenue NW, New Brighton, Minnesota, USA, 55112) that were at 50 cm spacing attached to a CO_2-powered backpack sprayer set to a pressure of 240 kPa. Each block contained a nontreated and weed-free control. The weed-free control plots were sprayed with an application of bicyclopyrone/mesotrione/*S*-metolachlor/atrazine (Acuron® Herbicide, 7.1/28.5/257/120 g ai L^{-1}, Syngenta Canada Inc., 140 Research Lane, Guelph, Ontario, Canada, N1G 4Z3) applied PRE at a rate of 2,230 g ai ha^{-1}. Glyphosate (Roundup WeatherMAX®, 540 g ae L^{-1}, Bayer CropScience Canada Inc., 160 Quarry Boulevard SE, Calgary, Alberta, Canada, T2C 3G3) at 900 g ae ha^{-1} was applied POST in weed-free control plots if needed followed by hand weeding as required.

Tolpyralate (Shieldex® 400SC Herbicide, 400 g ai L^{-1}, ISK Biosciences Corporation, 740 Auburn Road, Concord, Ohio, USA, 44077) at 30 g ai ha^{-1} and bromoxynil (Pardner® Herbicide, 280 g ai L^{-1}, Bayer CropScience Inc., 160 Quarry Park Boulevard SE, Calgary, Alberta, Canada, T2C 3G3) at 280 g ai ha^{-1} were tank-mixed and applied POST to 10 cm weeds without an added adjuvant or with MSO Concentrate®, Agral® 90, Assist® Oil Concentrate, Carrier®, LI 700®, or Merge® to evaluate corn injury and weed control efficacy. These adjuvants are frequently used with herbicides in Ontario, Canada. Further information relating to each adjuvant is found in Table 2. Depending on the trial location, there were natural infestations of velvetleaf, common ragweed, common lambsquarters, wild mustard, barnyardgrass, and *Setaria* spp. (collectively green and giant foxtail).

Table 2. Adjuvant trade name, adjuvant composition, adjuvant rate, and adjuvant manufacturer for the study of the enhancement of tolpyralate + bromoxynil 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., 3005 Rocky Mountain Avenue, Loveland, Colorado, USA, 80538 https://www.lovelandproducts.com/
Agral® 90	nonylphenoxy polyethoxy ethanol (92%)	0.25% v/v	Syngenta Canada Inc., 140 Research Lane, Guelph, Ontario, Canada, N1G 4Z3 https://www.syngenta.ca/
Assist® Oil Concentrate	paraffin base mineral oil (83%), surfactant blend (17%)	1 L ha^{-1}	BASF Canada Inc., 100 Milverton Drive, Mississauga, Ontario, Canada, L5R 4H1 https://www.basf.com/ca/en.html
Carrier®	mineral oil (50%), surfactant blend (40%)	0.5% v/v	Nufarm Agriculture Inc., 5101, 333-96th Avenue NE, Calgary, Alberta, Canada, T3K 0S3 https://nufarm.com/ca/
LI 700®	phosphatidylcholine, methylacetic acid, and alkyl polyoxyethylene ether (80%)	0.25% v/v	Loveland Products Inc., 3005 Rocky Mountain Avenue, Loveland, Colorado, USA, 80538 https://www.lovelandproducts.com/
Merge®	surfactant blend (50%), petroleum hydrocarbons solvent (50%)	1 L ha^{-1}	BASF Canada Inc., 100 Milverton Drive, Mississauga, Ontario, Canada, L5R 4H1 https://www.basf.com/ca/en.html

Corn injury was estimated with a percentage score (0-100%) at 1, 2, and 4 WAA, with smaller numbers indicating less corn injury. Visible weed control by weed species was assessed at 2, 4, and 8 WAA by visually comparing the aboveground biomass of each plot to the nontreated control within each block and assigning a percentage reduction score (0-100%). At 8 WAA, weeds in two, 0.5 m^2 quadrats in each plot were counted by species, weeds were clipped at the soil surface and placed in paper bags that were subsequently oven dried for dry biomass determination. When corn reached harvest maturity, the center two corn rows of each plot were harvested with a small plot combine. Corn grain yields were adjusted to 15.5% moisture before statistical analysis.

2.1 Statistical Analysis

Analysis of weed control, weed density, weed dry biomass, corn injury, and corn yield was completed with the GLIMMIX procedure in SAS version 9.4 (SAS Institute Inc., 100 SAS Campus Drive, Cary, North Carolina, USA, 27513). A significance level of $\alpha = 0.05$ was used for statistical tests. Treatment was the fixed effect. The random effects were environment (collectively site and year combinations), block nested within environment, and the treatment by environment interaction. Statistical analysis was conducted on pooled data. Suitable transformations were used when required, and distributions used for statistical analysis were those that best met the assumptions that model residuals were random, independent of treatment and design effects, homogeneous, and followed a normal distribution about a mean of zero. Studentized residual plots and the Shapiro-Wilk statistic were visually inspected to confirm the assumptions were met. Velvetleaf and common ragweed control at all assessment timings were arcsine square root transformed prior to analysis, and then back-transformed for means presentation purposes. Common lambsquarters, wild mustard, barnyardgrass, and *Setaria* spp. control data at all assessment timings were not transformed and model residuals were fit to a normal distribution. A lognormal distribution was used for the analysis of the density and dry biomass of each weed species. The omega method of back-transformation (M. Edwards, Ontario Agricultural College Statistics Consultant, University of Guelph, personal communication) was used to back-transform the means for presentation purposes. Normal distribution was used for corn yield and corn injury. The Tukey-Kramer multiple range test was used to compare least-square means, and letter codes were used for the presentation of statistically significant differences of least square means.

3. Results and Discussion

3.1 Velvetleaf

Velvetleaf data were pooled across both sites from Ridgetown Campus in 2020 and 2021. At 2, 4, and 8 WAA, the adjuvant treatments with tolpyralate + bromoxynil did not improve velvetleaf control (Table 3). We speculate that the aggressive adjuvant system in bromoxynil [product formulation: bromoxynil octanoate, heptanoate mixed ester; naphthalene; 2-methylpropan-1-ol; solvent naphtha (petroleum), heavy aromatic] negated the need of an additional adjuvant for velvetleaf control with the tank-mix of tolpyralate + bromoxynil. Similarly, Harbour et al. (2003) found that four different surfactants did not improve kochia or Russian thistle control with bromoxynil. In contrast, Langdon et al. (2020) reported that velvetleaf control with tolpyralate + atrazine was enhanced with the addition of MSO Concentrate®; however, when glyphosate was co-applied with tolpyralate + atrazine, MSO Concentrate® did not improve velvetleaf control. Previous research has reported >90% velvetleaf control with bromoxynil applied without the addition of an adjuvant, which may have contributed to the inability to detect a benefit of adjuvant addition to tolpyralate + bromoxynil (Corbett et al., 2004). In the current study, velvetleaf control was 89-100% at 2, 4, and 8 WAA when tolpyralate + bromoxynil was applied with and without the addition of adjuvants. This is comparable to previous studies that reported velvetleaf control of 86-99% with tolpyralate + MSO Concentrate®, tolpyralate + atrazine + MSO Concentrate®, tolpyralate + atrazine + glyphosate, and tolpyralate + atrazine + glyphosate + MSO Concentrate® (Langdon et al., 2020; Metzger et al., 2018). In agreement with the control data, the density and dry biomass reduction of velvetleaf with tolpyralate + bromoxynil was similar among the different adjuvant treatments. Tolpyralate + bromoxynil applied with Agral® 90, Assist® Oil Concentrate, Carrier®, or Merge® reduced the density of velvetleaf by 98-100% and the dry biomass by > 99%.

Table 3. Influence of adjuvants with tolpyralate + bromoxynil on velvetleaf (*Abutilon theophrasti*) control (2, 4, and 8 weeks after application), 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		
	--------------------- % ---------------------			plants m^{-2}	plants m^{-2}
Weed-free control	100	100	100	0.0 a	0.0 a
Nontreated control	0 b	0 b	0 b	8.6 c	31.8 b
Tolpyralate + bromoxynil	90 a	89 a	89 a	2.1 bc	3.9 ab
+ LI 700®	93 a	93 a	93 a	0.5 abc	4.7 ab
+ Agral® 90	98 a	99 a	99 a	0.2 ab	0.0 a
+ Assist® Oil Concentrate	98 a	98 a	99 a	0.2 ab	0.1 a
+ Carrier®	100 a	98 a	98 a	0.0 ab	0.0 a
+ MSO Concentrate®	97 a	98 a	98 a	0.4 abc	1.9 ab
+ Merge®	99 a	100 a	100 a	0.1 ab	0.0 a

Note. Abbreviations: WAA, weeks after application.

[a] All treatments listed except the weed-free and nontreated control included tolpyralate at a rate of 30 g ai ha^{-1} and bromoxynil at a rate of 280 g ai ha^{-1}.

[b] Means within the same column followed by the same lowercase letter do not statistically differ according to the Tukey-Kramer multiple range test at $\alpha = 0.05$.

3.2 Common Ragweed

Common ragweed results are pooled results from all four field trials. At 2, 4, and 8 WAA, tolpyralate + bromoxynil controlled common ragweed similarly when applied with LI 700®, Agral® 90, Assist® Oil Concentrate, Carrier®, MSO Concentrate®, or Merge®; control was > 90% at all assessment timings (Table 4). Similarly, tolpyralate + MSO Concentrate®, tolpyralate + atrazine + MSO Concentrate®, tolpyralate + atrazine + glyphosate, and tolpyralate + atrazine + glyphosate + MSO Concentrate® have been documented to control common ragweed > 90% (Langdon et al., 2020; Metzger et al., 2018). At 2 WAA, tolpyralate + bromoxynil applied with Merge® or Carrier® controlled common ragweed greater than tolpyralate + bromoxynil applied without an added adjuvant while the other adjuvants did not improve control. At 4 and 8 WAA, control of common ragweed was greater when tolpyralate + bromoxynil was applied with Merge® or MSO Concentrate® than when no added adjuvant was used. Similarly, Langdon et al. (2020) reported that the addition of MSO Concentrate® to tolpyralate + atrazine improved common ragweed control at 4 WAA. At 4 and 8 WAA, control of common ragweed was not enhanced with the addition of LI 700®, Agral® 90, Assist® Oil Concentrate, or Carrier® to tolpyralate + bromoxynil. Corbett et al. (2004) reported that bromoxynil applied without an added adjuvant controlled common ragweed at least 90%, which could contribute to the lack of enhancement of tolpyralate + bromoxynil efficacy with an additional adjuvant. The density reduction of common ragweed was 76-94% with tolpyralate + bromoxynil applied without and with added adjuvants. In agreement with common ragweed density reduction, the dry biomass reduction of common ragweed with tolpyralate + bromoxynil applied with and without added adjuvants was 79-99%.

Table 4. Influence of adjuvants with tolpyralate + bromoxynil on common ragweed (*Ambrosia artemisiifolia*) control (2, 4, and 8 weeks after application), 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		
	---------------------- % ----------------------			plants m^{-2}	g m^{-2}
Weed-free control	100	100	100	0 a	0.0 a
Nontreated control	0 c	0 c	0 c	17 c	201.3 c
Tolpyralate + bromoxynil	86 b	85 b	82 b	4 b	42.4 b
+ LI 700®	93 ab	91 ab	92 ab	3 ab	33.8 ab
+ Agral® 90	95 ab	96 ab	95 ab	1 ab	11.5 ab
+ Assist® Oil Concentrate	96 ab	95 ab	95 ab	2 ab	15.5 ab
+ Carrier®	96 a	95 ab	96 ab	2 ab	18.1 ab
+ MSO Concentrate®	96 ab	97 a	97 a	2 ab	11.1 ab
+ Merge®	98 a	99 a	99 a	1 ab	2.5 ab

Note. Abbreviations: WAA, weeks after application.

[a] All treatments listed except the weed-free and nontreated control included tolpyralate at a rate of 30 g ai ha^{-1} and bromoxynil at a rate of 280 g ai ha^{-1}.

[b] Means within the same column followed by the same lowercase letter do not statistically differ according to the Tukey-Kramer multiple range test at $\alpha = 0.05$.

3.3 Common Lambsquarters

Common lambsquarters results are from the pooled results of all four trials. At 2, 4, and 8 WAA, all adjuvants evaluated with tolpyralate + bromoxynil improved the control of common lambsquarters except for Assist® Oil Concentrate (Table 5). Similarly, Langdon et al. (2020) found that MSO Concentrate® improved common lambsquarters control with tolpyralate + atrazine. Merge® was a better adjuvant than Assist® Oil Concentrate with tolpyralate + bromoxynil for the control of common lambsquarters. LI 700®, Agral® 90, Carrier®, and MSO Concentrate® improved the control of common lambsquarters similar to Merge® with tolpyralate + bromoxynil. Blackshaw (1998) reported that Agral® 90 and MSO were similarly effective with imazamox for control of common lambsquarters. Bromoxynil applied without an added adjuvant has been documented to control common lambsquarters > 90% in a previous study, which may have contributed to the inability to detect differences between some of the adjuvant treatments (Corbett et al., 2004). Similar to the common lambsquarters control with tolpyralate + bromoxynil with adjuvants in this study, other research has reported > 90% control of common lambsquarters with mesotrione + bromoxynil, tolpyralate + MSO Concentrate®, and tolpyralate + atrazine + MSO Concentrate® (Langdon et al., 2020; Metzger et al., 2018; Woodyard et al., 2009). The density and dry biomass reduction of common lambsquarters was similar when tolpyralate + bromoxynil was applied with and without an added adjuvant; the density reduction was 87-97% and the dry biomass reduction was 95-99%.

Table 5. Influence of adjuvants with tolpyralate + bromoxynil on common lambsquarters (*Chenopodium album*) control (2, 4, and 8 weeks after application), 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		
	--------------------- % ---------------------			plants m^{-2}	g m^{-2}
Weed-free control	100	100	100	0 a	0.0 a
Nontreated control	0 d	0 d	0	31 c	150.4 c
Tolpyralate + bromoxynil	85 c	85 c	86 c	4 b	6.9 b
+ LI 700®	93 ab	93 ab	96 ab	1 ab	1.4 ab
+ Agral® 90	93 ab	93 ab	96 ab	2 ab	2.7 ab
+ Assist® Oil Concentrate	90 bc	89 bc	91 bc	2 b	3.9 ab
+ Carrier®	94 ab	94 ab	95 ab	2 ab	2.4 ab
+ MSO Concentrate®	95 ab	95 ab	97 ab	3 b	3.4 ab
+ Merge®	98 a	98 a	99 a	2 ab	1.0 ab

Note. Abbreviations: WAA, weeks after application.

[a] All treatments listed except the weed-free and nontreated control included tolpyralate at a rate of 30 g ai ha^{-1} and bromoxynil at a rate of 280 g ai ha^{-1}.

[b] Means within the same column followed by the same lowercase letter do not statistically differ according to the Tukey-Kramer multiple range test at $\alpha = 0.05$.

3.4 Wild Mustard

Wild mustard results are the pooled results from the Huron Research Station in 2020 and 2021. Tolpyralate + bromoxynil without and with an added adjuvant controlled wild mustard similarly at 2, 4, and 8 WAA (Table 6). Similarly, the addition of MSO Concentrate® did not improve wild mustard control with tolpyralate + atrazine (Langdon et al., 2020). Bromoxynil applied alone without added adjuvants has been documented to control wild mustard > 90% (Nalewaja & Skrzypczak, 1986). Therefore, the bromoxynil component of the tank-mix likely contributed to the excellent wild mustard control with tolpyralate + bromoxynil as tolpyralate + MSO Concentrate® controlled wild mustard < 60% in a previous study (Metzger et al., 2018). At 2, 4, and 8 WAA, wild mustard control was 93-97, 96-99, and 98-100%, respectively. Similarly, tolpyralate + atrazine + MSO Concentrate®, tolpyralate + atrazine + glyphosate, and tolpyralate + atrazine + glyphosate + MSO Concentrate® controlled wild mustard > 90% in previous studies (Langdon et al., 2020; Metzger et al., 2018). In support of the control data, the density and dry biomass reduction of wild mustard was similar among the different adjuvant treatments. The density and dry biomass reductions of wild mustard were > 99% when tolpyralate + bromoxynil was applied with and without added adjuvants.

Table 6. Influence of adjuvants with tolpyralate + bromoxynil on wild mustard (*Sinapis arvensis*) control (2, 4, and 8 weeks after application), 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		
	---------------------- % ---------------------			plants m^{-2}	g m^{-2}
Weed-free control	100	100	100	0 a	0.0 a
Nontreated control	0 b	0 b	0 b	70.2 c	119.5 b
Tolpyralate + bromoxynil	93 a	96 a	98 a	0.5 ab	0.3 a
+ LI 700®	95 a	97 a	98 a	0.3 ab	0.0 a
+ Agral® 90	94 a	97 a	99 a	0.6 ab	0.4 a
+ Assist® Oil Concentrate	97 a	99 a	99 a	0.1 ab	0.0 a
+ Carrier®	95 a	97 a	99 a	0.9 b	0.5 a
+ MSO Concentrate®	96 a	98 a	99 a	0.8 ab	0.2 a
+ Merge®	97 a	99 a	100 a	0.2 ab	0.1 a

Note. Abbreviations: WAA, weeks after application.

[a] All treatments listed except the weed-free and nontreated control included tolpyralate at a rate of 30 g ai ha^{-1} and bromoxynil at a rate of 280 g ai ha^{-1}.

[b] Means within the same column followed by the same lowercase letter do not statistically differ according to the Tukey-Kramer multiple range test at $\alpha = 0.05$.

3.5 Barnyardgrass

Barnyardgrass results are the pooled results from all four field trials. At 2 WAA, Merge® was a more effective adjuvant to add to tolpyralate + bromoxynil than LI 700®, Agral® 90, Assist® Oil Concentrate, and Carrier® for the control of barnyardgrass (Table 7). At 2 WAA, MSO Concentrate® was more effective than LI 700®, but was similar to Agral® 90, Assist® Oil Concentrate, Carrier®, and Merge® when applied with tolpyralate + bromoxynil for the control of barnyardgrass. Similarly, clethodim controlled barnyardgrass greater when applied with MSO than with LI 700® (Jordan et al., 1996). At 2 WAA, the use of LI 700® did not improve barnyardgrass control compared to when no added adjuvant was used with tolpyralate + bromoxynil. At 4 WAA, tolpyralate + bromoxynil plus the six adjuvants evaluated controlled barnyardgrass similarly; however, LI 700®, Agral® 90, and Assist® Oil Concentrate did not improve the control of barnyardgrass compared to when no added adjuvant was used. Barnyardgrass control at 8 WAA was comparable to the results at 4 WAA as the six adjuvants were similarly effective for the control of barnyardgrass with tolpyralate + bromoxynil; however, the use of LI 700® or Agral® 90 did not improve the control of barnyardgrass when added to tolpyralate + bromoxynil. Similarly, Langdon et al. (2020) reported that MSO Concentrate® improved barnyardgrass control with tolpyralate + atrazine and control was less than 90% at 8 WAA which is similar to this study. Tolpyralate + bromoxynil applied without or with an added adjuvant did not reduce barnyardgrass density or dry biomass. The lack of differences between the different treatments for barnyardgrass density and dry biomass reduction may be attributed to the variable density among plots within trials and because barnyardgrass tillered more in plots where control of other weed species was achieved due to reduced competition between weeds. Additionally, the placement of the quadrats where the density and biomass were obtained from may have contributed to the variability of barnyardgrass density and dry biomass data. Therefore, the efficacy of each treatment is likely better represented with the visible control data because this data considered an overview of the entire plot area.

Table 7. Influence of adjuvants with tolpyralate + bromoxynil on barnyardgrass (*Echinochloa crus-galli*) control (2, 4, and 8 weeks after application), 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		
	--------------------- % ---------------------			plants m^{-2}	g m^{-2}
Weed-free control	100	100	100	0 a	0.0 a
Nontreated control	0 e	0 c	0 c	18 b	18.9 b
Tolpyralate + bromoxynil	63 d	56 b	53 b	18 b	12.5 ab
+ LI 700®	71 cd	70 ab	71 ab	4 b	3.4 ab
+ Agral® 90	73 bc	71 ab	70 ab	20 b	12.6 ab
+ Assist® Oil Concentrate	73 bc	71 ab	72 a	20 b	9.0 ab
+ Carrier®	75 bc	74 a	74 a	16 b	7.7 ab
+ MSO Concentrate®	82 ab	80 a	79 a	15 b	8.1 ab
+ Merge®	85 a	86 a	85 a	10 b	10.0 ab

Note. Abbreviations: WAA, weeks after application.

[a] All treatments listed except the weed-free and nontreated control included tolpyralate at a rate of 30 g ai ha^{-1} and bromoxynil at a rate of 280 g ai ha^{-1}.

[b] Means within the same column followed by the same lowercase letter do not statistically differ according to the Tukey-Kramer multiple range test at $\alpha = 0.05$.

3.6 Setaria spp.

Setaria spp. results are the pooled results from all four field trials. At 2 WAA, the control of *Setaria* spp. with tolpyralate + bromoxynil was greater when Merge® was used instead of LI 700®, Agral® 90, or Assist® Oil Concentrate (Table 8). Carrier® and MSO Concentrate® were as effective as Merge® with tolpyralate + bromoxynil for the control of *Setaria* spp. at 2 WAA. LI 700® did not improve the control of *Setaria* spp. at 2 WAA with tolpyralate + bromoxynil. *Setaria* spp. control was similar with tolpyralate + bromoxynil plus the six adjuvants evaluated at 4 and 8 WAA; however, Carrier®, MSO Concentrate®, and Merge® were the only adjuvants to improve control of *Setaria* spp. with tolpyralate + bromoxynil compared to when no added adjuvant was used. Tolpyralate + atrazine efficacy on green foxtail has also been enhanced with the addition of MSO Concentrate® in a previous study that also reported less than 90% control of green foxtail at 8 WAA (Langdon et al., 2020). The density and dry biomass reduction of *Setaria* spp. was similar when LI 700®, Agral® 90, Assist® Oil Concentrate, Carrier®, MSO Concentrate®, Merge®, or no added adjuvant was used with tolpyralate + bromoxynil. Tolpyralate + bromoxynil + Merge® reduced the dry biomass of *Setaria* spp. 90%. Similar to barnyardgrass, the lack of differences between the different treatments for *Setaria* spp. density and dry biomass reduction may have been due to variable density of *Setaria* spp. within trials, tillering of *Setaria* spp., and quadrat placement. Therefore, it is likely that visible control data is more reflective of the relative efficacy of each treatment.

Table 8. Influence of adjuvants with tolpyralate + bromoxynil on *Setaria* spp. control (2, 4, and 8 weeks after application), 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		
	---------------------- % ---------------------			plants m^{-2}	g m^{-2}
Weed-free control	100	100	100	0 a	0.0 a
Nontreated control	0 e	0 c	0 c	42 b	68.1 c
Tolpyralate + bromoxynil	62 d	56 b	52 b	28 b	31.7 bc
+ LI 700®	72 cd	70 ab	68 ab	12 b	13.4 bc
+ Agral® 90	74 bc	73 ab	70 ab	24 b	21.7 bc
+ Assist® Oil Concentrate	74 bc	75 ab	73 ab	31 b	17.9 bc
+ Carrier®	77 abc	77 a	77 a	22 b	18.1 bc
+ MSO Concentrate®	84 ab	83 a	81 a	23 b	15.0 bc
+ Merge®	87 a	87 a	86 a	16 b	6.9 ab

Note. Abbreviations: WAA, weeks after application.

[a] All treatments listed except the weed-free and nontreated control included tolpyralate at a rate of 30 g ai ha^{-1} and bromoxynil at a rate of 280 g ai ha^{-1}.

[b] Means within the same column followed by the same lowercase letter do not statistically differ according to the Tukey-Kramer multiple range test at $\alpha = 0.05$.

3.7 Corn Injury and Grain Yield

Corn injury did not exceed 7% at any assessment timing (Table 9). At 1 WAA, the use of no added adjuvant or LI 700® with tolpyralate + bromoxynil caused less corn injury than when Assist® Oil Concentrate, Carrier®, MSO Concentrate®, or Merge® was used with tolpyralate + bromoxynil. At 1 WAA, corn injury from tolpyralate + bromoxynil + Agral® 90 was similar to when no added adjuvant, LI 700®, or Merge® was used with tolpyralate + bromoxynil. At 2 WAA, the co-application of tolpyralate + bromoxynil with Assist® Oil Concentrate, Carrier®, MSO Concentrate®, or Merge® caused more corn injury than when no added adjuvant was used with tolpyralate + bromoxynil. LI 700® and Agral® 90 did not increase corn injury with tolpyralate + bromoxynil at 2 WAA. No corn injury was observed at 4 WAA.

Weed interference caused 67% corn yield loss (Table 9). Reduced weed interference with tolpyralate + bromoxynil with or without an added adjuvant resulted in corn yields that were similar to corn kept weed-free for the entire season. Similarly, Carey and Kells (1995) documented that a single herbicide application when weeds were 10 cm in height prevented corn yield reduction.

Table 9. Influence of adjuvants with tolpyralate + bromoxynil on corn injury (1 and 2 weeks after application) and corn grain yield from four field trials in Ontario, Canada in 2020 and 2021

Treatment[a]	Corn injury		Corn yield
	1 WAA[b]	2 WAA	
	------------------- % -------------------		kg ha^{-1}
Weed-free control	0 a	0 a	12,700 a
Nontreated control	0 a	0 a	4,200 b
Tolpyralate + bromoxynil	2 b	2 ab	10,900 a
+ LI 700®	3 b	2 bc	10,600 a
+ Agral® 90	4 bc	3 bcd	10,700 a
+ Assist® Oil Concentrate	7 d	4 d	11,300 a
+ Carrier®	7 d	4 d	11,600 a
+ MSO Concentrate®	6 d	3 cd	11,700 a
+ Merge®	6 cd	4 d	11,400 a

Note. Abbreviations: WAA, weeks after application.

[a] All treatments listed except the weed-free and nontreated control included tolpyralate at a rate of 30 g ai ha^{-1} and bromoxynil at a rate of 280 g ai ha^{-1}.

[b] Means within the same column followed by the same lowercase letter do not statistically differ according to the Tukey-Kramer multiple range test at $\alpha = 0.05$.

In summary, there were few differences in weed control efficacy with tolpyralate + bromoxynil applied with or without an added adjuvant for the six weed species evaluated at 8 WAA. Velvetleaf and wild mustard control was not enhanced with the addition of an adjuvant to tolpyralate + bromoxynil. At 8 WAA, Merge® and MSO Concentrate® enhanced control of common ragweed, common lambsquarters, barnyardgrass, and *Setaria* spp. with tolpyralate + bromoxynil. At 8 WAA, the adjuvants performed similarly with tolpyralate + bromoxynil for the control of all six weed species with the exception that Assist® Oil Concentrate was inferior to Merge® for common lambsquarters control. This study suggests that adjuvant selection with tolpyralate + bromoxynil may not be as important as with other herbicides; however, an adjuvant is still required for the control of several weed species. Future research should investigate the control of other weed species with tolpyralate + bromoxynil with the adjuvants tested in this study in a variety of environments.

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