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MHR waterhemp control

Control of multiple herbicide-resistant waterhemp (*Amaranthus tuberculatus*) with acetochlor-based herbicide mixtures in corn

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Nomenclature: waterhemp, *Amaranthus tuberculatus* (Moq.) J.D. Sauer.

Abstract

Waterhemp is a summer annual, broadleaf weed with high fecundity, short seed longevity in the soil, and wide genetic diversity. Populations have evolved resistance to five herbicide modes of action (Groups 2, 5, 9, 14, and 27), which are present across southern Ontario; this has increased the challenge of controlling this competitive weed species in corn, the most important grain crop produced worldwide, and the highest value agronomic crop in Ontario. Acetochlor is a Group 15 soil-applied residual herbicide that has activity on many grass and broadleaf weeds but has yet to be registered in Canada. The objective of this study was to ascertain whether mixtures of acetochlor with flumetsulam, dicamba, atrazine, isoxaflutole/diflufenican, or mesotrione + atrazine applied preemergence would increase the control of multiple herbicide-resistant (MHR) waterhemp in corn. Five field trials were conducted between 2022 and 2023. No corn injury was observed. Acetochlor applied alone controlled MHR waterhemp 97% 12 weeks after application (WAA). All herbicide mixtures controlled MHR waterhemp similarly at ≥98% 12 WAA; there were no differences among herbicide mixtures. Flumetsulam, dicamba, and atrazine provided lower MHR waterhemp control than all other herbicide treatments and did not reduce density or biomass. Acetochlor reduced waterhemp density 98%, while the acetochlor mixtures reduced density similarly at 99 to 100%. This study concludes that the acetochlor mixtures evaluated provide excellent waterhemp control; however, control was not greater than acetochlor alone. Herbicides herbicide mixtures should be used as a best management practice to mitigate the evolution of herbicide resistance.

Keywords: Corn injury, waterhemp control, waterhemp biomass, waterhemp density, waterhemp emergence, residual herbicides, yield

Introduction

Corn is a very important crop for the Canadian economy and for Ontario specifically. In 2021, nearly 13 million tonnes of corn were produced in Canada, 62% of which was produced in Ontario (StatsCan 2015; USDA 2022). Corn is the highest-value crop grown in the province of Ontario accounting for $1.8 billion (CAD) in 2021 (OMAFRA 2021). The majority of the remainder of Canadian corn is produced from Ontario's neighboring provinces to the east and west, Quebec and Manitoba, respectively (StatsCan 2015). The average corn yield in Canada is slightly less than US yields at 9.1 tonnes ha^{-1} (USDA 2022) but is susceptible to yield loss from weeds.

Since 2002, Ontario growers have been dealing with herbicide-resistant waterhemp, which is a summer annual, broadleaf weed (Costea et al. 2005; Heap 2022; Nordby et al. 2007) and a member of the Amaranthus family. Waterhemp is difficult to distinguish from other species in the same family. Similar to Palmer amaranth, waterhemp is a dioecious species; male and female reproductive organs are found on separate plants that cross-pollinate, and the female plant produces small reddish to black seeds (Costea et al. 2005; Sarangi et al. 2017). Copious amounts of tiny, round seeds are produced from all Amaranthus species, including waterhemp; in one study, a single redroot pigweed plant produced 291,000 seeds, while waterhemp produced 289,000 seeds (Sellers et al. 2003). Hartzler et al. (2004) reported that a single waterhemp plant produced 4.8 million seeds, demonstrating its high fecundity.

Growers in Ontario and the USA are plagued by MHR waterhemp populations. The first record of herbicide-resistant waterhemp in Ontario dates back to 2002 when resistance to WSSA Group 2 acetolactate synthase (ALS) inhibitors and WSSA Group 5 photosystem II (PSII) inhibitors was confirmed (Heap 2022). Since then, 5-way resistant waterhemp populations have been confirmed in seven Ontario counties; another eleven counties have 2, 3, or 4-way resistance (Symington et al. 2022). 5-way resistant waterhemp populations are resistant to the Group 2, 5, 5-enolpyruvateshikimate-3-phosohate synthase (EPSPS) inhibitors (WSSA Group 9), protoporphyrinogen oxidase (PPO) inhibitors (WSSA Group 14), and 4-hydroxyphenylpyruvate dioxygenase (HPPD) inhibitors (WSSA Group 27) (Symington 2022). Waterhemp is a widespread problem in the USA; it has been confirmed in all but nine states (GROW, n.d.; USDA 2014). In the USA, waterhemp has evolved resistance to Groups 2, 4, 5, 9, 14, 15, and 27 herbicides (Heap 2022; Shergill et al. 2018; Strom et al. 2020). Multiple resistance drastically reduces the number of effective herbicides that can be used to control waterhemp in corn; this is very problematic due to potential corn yield loss from waterhemp interference. High waterhemp densities cause greater crop yield losses; yet, even low waterhemp densities can reduce corn yield (Cordes et al. 2004). Corn yield losses were <10% when waterhemp was present at <82 plants m^{-2} ; in contrast, yield losses as high as 74% have been reported in corn (Cordes et al. 2004; Steckel and Sprague 2004).

Corn yield can be greatly impacted by weed interference. A meta-analysis conducted by Soltani et al. (2016) concluded that there would be an average corn yield loss of 50% in North America if producers did not implement weed management tactics. Ontario growers are encouraged to keep their corn fields free of weeds from corn emergence to the V6 to minimize yield losses from weed interference (OMAFRA 2009). This timing correlates with much of the research conducted on the critical period for weed control in corn which varies from emergence to V14 (Hall et al. 1992; Page et al. 2012) and depends on factors such as relative time of weed and crop emergence, weed species composition, weed density, soil characteristics, tillage practices, nutrient availability, environmental conditions, and planting date (Hall et al. 1992; Knezevic et al. 2002; Van Acker et al. 1993). With effective weed management programs corn yield losses due to weed interference can be minimized (Soltani et al. 2022).

The use of effective waterhemp herbicides, such as the WSSA Group 15 herbicides, can result in reduced weed interference, higher corn yields, and fewer weed seeds returned to the soil weed seedbank (Gressel and Segel 1990; Gianessi and Reigner 2007). Acetochlor is a chloroacetanilide herbicide that can be applied preplant (PP), preplant incorporated (PPI), preemergence (PRE), or early postemergence (ePOST) relative to the corn crop to control non-emerged small-seeded annual grass and some small-seeded annual broadleaf weeds (Anonymous 2012; Anonymous 2018; Shaner 2014). Approved for use in the USA in 1994 (de Guzman et al. 2005) it is now widely used for weed management in corn, cotton, and soybean (Armel et al. 2003; Cahoon et al. 2015; Jhala et al. 2015). Acetochlor inhibits very long-chain fatty acid elongase enzyme and is absorbed by the roots and shoots of emerging weed seedlings (Shaner 2014). Research has concluded that there is a sufficient margin of crop safety for the use of acetochlor in corn. Janak and Grichar (2016) found that even when acetochlor was applied at the

2X rate, corn injury did not exceed 3%. Additionally, acetochlor is an effective waterhemp herbicide. Jhala et al. (2015) reported that acetochlor (1,680 g ai ha^{-1}) applied PRE controlled MHR waterhemp 80% 60 days after planting. Though acetochlor can be applied ePOST relative to the crop, it has little activity on emerged weeds which need to be controlled with another weed management tactic (Armel et al. 2003). The tolerance of corn to acetochlor POST allows for later applications that provide residual control of waterhemp that can emerge throughout the growing season.

To the best of our knowledge, no research has been conducted on the efficacy of acetochlor herbicide mixtures PRE for MHR waterhemp control in corn in Ontario. The objective of this study was to evaluate MHR waterhemp control with acetochlor-based herbicide mixtures applied PRE in corn.

Materials and Methods

Experimental Methods

Three field trials were conducted in 2022 near Cottam, ON (42.149046°N, -82.683986°W), Newbury, ON (42.727962°N, -81.822588°W), and on Walpole Island, ON (42.561915°N, -82.502111°W) and two field trials were conducted in 2023 near Newbury, ON (42.690165°N, -81.822698°W) and on Walpole Island, ON (42.562696°N, -82.503749°W). At each site, there were naturally occurring populations of waterhemp that were 5-way resistant to the WSSA Groups 2, 5, 9, 14, and 27 herbicides (Symington et al. 2022). Soil characteristics for each site are presented in Table 1.

The previous crop at each site was soybean. Seedbed preparation consisted of vertical tillage in the fall followed by cultivation in the spring. Corn hybrids were seeded at a rate of approximately 83,000 seeds ha^{-1} to a depth of 4.0-5.0 cm in rows spaced 75 cm apart. Plot measurements were 2.25 m wide (3 corn rows) by 8 m long. Glyphosate (Roundup WeatherMAX®, Bayer Crop Science Inc., Suite 100 3131 114th Avenue S.E., Calgary, Alberta, Canada, T2Z 3X2) (450 g ai ha^{-1}) was applied POST to the entire experimental area to control glyphosate-susceptible waterhemp and all other weed species. The trials were established as a randomized complete block design (RCBD) with four blocks. Each trial included 15 herbicide treatments plus a nontreated (weedy) and a weed-free control. Herbicide active ingredient, rate, trade name, and manufacturer are presented in Table 2. The weed-free control was maintained weed-free with *S*-metolachlor/atrazine/mesotrione/bicyclopyrone (Acuron®, Syngenta Canada, 140 Research Ln, Guelph, Ontario, Canada, N1G 4Z3) (2,026 g ai ha^{-1}) applied PRE followed by glufosinate (Liberty® 200 SN, BASF Canada, 5025 Creekbank Rd, Mississauga, Ontario, Canada, L4W 5R2) (500 g ai ha^{-1}) applied POST; hand weeding was completed when required. The weed-free control was the only treatment to receive a POST application. Herbicide treatments were applied PRE with a CO_2-pressurized backpack sprayer calibrated to deliver 200 L ha^{-1} at 240 kPa. A spray width of 2 m was produced from a 1.5 m boom equipped with four ultra-low drift nozzles (ULD 120-02, Hypro, Pentair Ltd., London, UK) spaced 50 cm apart. Due to miscommunication with the grower for Walpole Island 2023, the PRE application was made after corn and soybean emergence; therefore, glufosinate (500 g ai ha^{-1}) was applied to control all emerged waterhemp. Corn hybrid, corn planting, herbicide application, corn emergence, and corn harvest dates are presented in Table 3.

Visible corn injury assessments were completed at two and four weeks after emergence (WAE) on a percent scale; 0 represented no corn injury and 100 designated complete corn death. Visible MHR waterhemp control as an estimation of the biomass reduction relative to the nontreated control was assessed at 4, 8, and 12 weeks after application (WAA) on a percent scale; 0 indicated no control and 100 indicated complete waterhemp control. At 8 WAA, waterhemp density was determined by counting and hand-harvesting plants from two arbitrarily placed 0.25 m^2 quadrats within each plot. Waterhemp plants were clipped at the soil surface, placed into paper bags, and kiln-dried to consistent moisture. Samples were weighed using an analytical balance and the dry shoot biomass was recorded. In 2022, at harvest maturity, two corn rows were combined with a small plot combine; seed moisture content (%) and weight were recorded. Corn was not combined in 2023. Corn grain yield was adjusted to 15.5% moisture prior to statistical analysis.

Statistical Analysis

Statistical analysis was performed as a RCBD using PROC GLIMMIX in SAS 9.4 (SAS Institute Inc., Cary, NC). Herbicide treatment was the fixed effect; random effects included the environment (site by year), replicate within environment, and the treatment by environment. All environments were pooled together for analysis. Variances were verified to be normal and homogenous with the use of the PROC UNIVARIATE procedure. The Shapiro-Wilk test statistic and linear studentized residuals were analyzed to ensure the assumptions of normality that residuals are random, independent, normally distributed, have a mean of zero, and homogenous, were met. The nontreated control and weed-free control were omitted from the dataset for analysis of waterhemp control and corn injury; the weed-free control was not included for analysis of waterhemp density and biomass. Corn injury and visible waterhemp control utilized an arcsine square root transformation and normal distribution while density and biomass fit a lognormal distribution. Corn yield used a normal distribution. All data that were transformed or analyzed with non-Gaussian distributions were back transformed for presentation of results.

In order to determine the expected level of corn injury, and the expected level of MHR waterhemp control, Colby's equation (Equation 1) was used. Expected values were computed by replicate for the treatments involving a mixture with acetochlor from the observed corn injury and waterhemp values for each herbicide applied alone.

$$\text{Expected} = (A + B) - [(A * B) / 100] \quad [1]$$

Where:

A = value of first herbicide in herbicide mixture applied alone

B = value of second herbicide in herbicide mixture applied alone

A modification to the above Colby's equation was made (Equation 2) to calculate the expected values for waterhemp density and biomass by replicate. This was completed for the mixtures containing acetochlor by using the observed density and biomass values for herbicides applied alone and the density and biomass from the nontreated control.

$$\text{Expected} = (A*B)/W \quad [2]$$

Where:

A = value of first herbicide in mixture applied alone

B = value of second herbicide in mixture applied alone

W = value of nontreated control

After expected values were calculated, a two-tailed t-test was run in SAS to compare the expected values to the observed values for the acetochlor-based mixtures. A significance level of $\alpha=0.05$ was used to determine the nature of the relationship. The relationship was antagonistic when the observed value was less than the expected value, additive when the two values were similar, and synergistic if the observed value was greater than the expected value.

Results and Discussion

Rainfall at all sites varied from 0.2 to 30.7 mm 7 days after treatment application. Control is low rainfall environments though, showed the same trends as those in high moisture areas.

Corn Injury

The herbicide treatments evaluated caused <1% corn injury at 2 and 4 WAE (data not presented). These results are similar to a study conducted by Janak and Grichar (2016) who reported that acetochlor (5,165 g ai ha^{-1}) caused <3% corn injury.

Multiple-Herbicide-Resistant Waterhemp Visible Control

Acetochlor (2,950 g ai ha^{-1}) controlled MHR waterhemp 99% at 4 WAA (Table 4). Strom et al. (2019) reported only 75% control of waterhemp at 4 WAA with acetochlor applied at 2,700 g ai ha^{-1}. In the study by Strom et al. (2019) the encapsulated formulation of acetochlor was used; in contrast, the emulsifiable concentrate was used in the current study. Hausman et al. (2013) found that the emulsifiable concentrate formulation of acetochlor at 1,680 and 3,360 g ai ha^{-1} provided 85 and 94% control of waterhemp, respectively at 4 WAA. Similarly, flumetsulam (50 g ai ha^{-1}), dicamba (600 g ai ha^{-1}), and atrazine (1,490 g ai ha^{-1}) controlled waterhemp 79, 79, and 81%, respectively. This low level of control with flumetsulam and atrazine is expected since there were Group 2 and 5-resistant biotypes at all trial locations. Meyer et al. (2016) reported that dicamba PRE provided poor waterhemp control and suggested that this was due to rainfall which reduced the length of residual waterhemp control with dicamba. Isoxaflutole/diflufenican (191 g ai ha^{-1}), mesotrione + atrazine (140 + 1,490 g ai ha^{-1}), all acetochlor mixtures, isoxaflutole/thiencarbazone-methyl + atrazine (104 + 800 g ai ha^{-1}), isoxaflutole/diflufenican + atrazine (191 + 800 g ai ha^{-1}), dimethenamid-p/saflufenacil (735 g ai ha^{-1}), and *S*-metolachlor/atrazine/mesotrione/bicyclopyrone (2,026 g ai ha^{-1}) controlled waterhemp 99-100%; control was similar to acetochlor applied alone but greater than flumetsulam, dicamba, or atrazine applied alone. All acetochlor mixture interactions were additive. Willemse et al. (2021a) similarly reported 99% control of waterhemp 4 WAA with mesotrione + atrazine and *S*-metolachlor/atrazine/mesotrione/bicyclopyrone PRE which are similar to the control in the current study.

Acetochlor controlled MHR waterhemp 98% which was similar to all herbicide treatments except flumetsulam, dicamba, and atrazine which provided between 57 to 66% control 8 WAA (Table 4). At 60 days after treatment, or 8.5 weeks, Hausman et al. (2013) reported that acetochlor (3,360 g ai ha^{-1}) controlled waterhemp 87% which is slightly lower than the findings from this study. All acetochlor based mixtures were additive and controlled waterhemp 99% which was similar to acetochlor, isoxaflutole/diflufenican, mesotrione + atrazine, isoxaflutole/thiencarbazone-methyl + atrazine, isoxaflutole/diflufenican + atrazine, dimethenamid-p/saflufenacil, and *S*-metolachlor/atrazine/mesotrione/bicyclopyrone. Armel et al. (2003) reported that acetochlor + mesotrione (1,800 + 160 g ai ha^{-1}) PRE controlled smooth pigweed, a relative of waterhemp, 95 to 99% at 8 WAA which is similar to the control with mesotrione + atrazine or acetochlor + mesotrione + atrazine in the current study. Steckel et al. (2002) published that acetochlor/atrazine provided 91% waterhemp control at 8 WAA which is similar to the control (99%) with acetochlor + atrazine in this study. Acetochlor, all acetochlor-based mixtures, isoxaflutole/thiencarbazone-methyl + atrazine, isoxaflutole/diflufenican + atrazine, dimethenamid-p/saflufenacil, and *S*-metolachlor/atrazine/mesotrione/bicyclopyrone provided greater waterhemp control than dicamba, atrazine, and flumetsulam applied alone.

Dicamba, atrazine, and flumetsulam controlled waterhemp 53, 55, and 64%, respectively at 12 WAA (Table 4). Acetochlor controlled MHR waterhemp 97% and all acetochlor mixtures provided 98 to 99% control; all acetochlor mixtures were additive. Isoxaflutole/thiencarbazone-methyl + atrazine (104 + 800 g ai ha^{-1}), isoxaflutole/diflufenican + atrazine (191 + 800 g ai ha^{-1}), dimethenamid-p/saflufenacil (735 g ai ha^{-1}), and *S*-metolachlor/atrazine/mesotrione/bicyclopyrone (2,026 g ai ha^{-1}) controlled waterhemp 95 to 99%.

Multiple-Herbicide-Resistant Waterhemp Density and Biomass

At 8 WAA there was 482 plants m^{-2} in the nontreated control (Table 5). All locations contained naturally high seedbank infestation levels that varied from 54 plants m^{-2} to 6741 plants m^{-2}. Acetochlor reduced MHR waterhemp density 98% relative to the nontreated control. Similarly, Hausman et al. (2013) reported that acetochlor (3,360 g ai ha^{-1}) reduced resistant waterhemp density 96%. Flumetsulam, dicamba, and atrazine did not reduce waterhemp density relative to the nontreated control. Similarly, Meyer et al. (2016) reported that dicamba (560 g ae ha^{-1}) reduced waterhemp density by only 19%. Isoxaflutole/diflufenican and mesotrione + atrazine reduced waterhemp density by 96 and 90%, respectively. All acetochlor mixtures reduced MHR waterhemp density 99 to 100%. The mixtures of acetochlor with flumetsulam, dicamba, atrazine, or isoxaflutole/diflufenican were additive. Based on Colby’s equation, one waterhemp plant was expected in the mixture of acetochlor + mesotrione + atrazine, however, 5 plants were observed, demonstrating an antagonistic interaction. Isoxaflutole/thiencarbazone-methyl + atrazine, isoxaflutole/diflufenican + atrazine, dimethenamid-p/saflufenacil and *S*-metolachlor/atrazine/mesotrione/bicyclopyrone reduced waterhemp density 95 to 99%. Willemse et al. (2021a) reported that *S*-metolachlor/atrazine/mesotrione/bicyclopyrone reduced waterhemp density 100% similar to the 99% reduction in the current study.

There was 93.1 g m^{-2} of waterhemp biomass in the nontreated control at 8 WAA (Table 5). Acetochlor reduced waterhemp biomass by 95%, which was similar to all other herbicide treatments evaluated except flumetsulam, dicamba, or atrazine which reduced waterhemp biomass by 45, 49, and 55%, respectively. All acetochlor mixtures reduced waterhemp biomass by 97 to 100%; all interactions were additive. Isoxaflutole/thiencarbazone-methyl + atrazine, isoxaflutole/diflufenican + atrazine, dimethenamid-p/saflufenacil and *S*-metolachlor/atrazine/mesotrione/bicyclopyrone reduced waterhemp biomass 90 to 98%.

Corn Yield

There was no difference in corn yield in this study. Despite large densities of MHR waterhemp in the nontreated control, the various herbicide treatments evaluated were able to delay waterhemp emergence long enough that when they did emerge the corn crop was successfully able to outcompete them. The majority of emerged waterhemp likely remained small due to a lack of light as explained by the red: far red light ratio (Markham and Stoltenberg 2009).

In summary, acetochlor mixtures with flumetsulam, dicamba, atrazine, isoxaflutole/diflufenican, or mesotrione + atrazine controlled MHR waterhemp ≥98% at 4, 8, and 12 WAA and reduced density and biomass ≥99 and ≥97%, respectively; however, these values were similar to acetochlor applied alone. At 8 WAA, flumetsulam, dicamba, and atrazine controlled waterhemp 57 to 66%, reduced density by 21 to 46%, and reduced biomass by 45 to 55%. At 8 WAA, isoxaflutole/thiencarbazone-methyl + atrazine, isoxaflutole/diflufenican + atrazine, dimethenamid-p/saflufenacil and S-metolachlor/atrazine/mesotrione/bicyclopyrone controlled waterhemp 96 to 99%, reduced density 95 to 99%, and reduced biomass 90 to 98%. No corn yield differences were present at harvest. Although acetochlor-based herbicide mixtures did not improve waterhemp control and did not reduce waterhemp density and biomass relative to acetochlor, these herbicide mixtures might reduce the selection intensity for the evolution of further herbicide-resistant waterhemp biotypes in Ontario fields. Delaying herbicide resistance should be an important consideration when developing best management practices for waterhemp control programs in Ontario corn production.

Practical Implications

Waterhemp continues to develop resistance to new herbicide modes of action and has become a challenging weed to control in many parts of North America. Waterhemp populations have evolved resistance to five herbicide modes of action (Groups 2, 5, 9, 14, and 27) which are present across southern Ontario; this has increased the challenge of controlling this competitive weed species in corn, the most important grain crop produced worldwide, and the highest value agronomic crop in Ontario. Acetochlor is a Group 15 soil-applied residual herbicide that has activity on many small-seeded annual grass and some small-seeded annual broadleaf weeds. The mixtures of acetochlor with flumetsulam, dicamba, atrazine, isoxaflutole/diflufenican, or mesotrione + atrazine applied preemergence caused minimal injury or yield reduction in corn. Acetochlor applied alone provided excellent control of MHR waterhemp. Similarly, the mixtures of acetochlor with flumetsulam, dicamba, atrazine, isoxaflutole/diflufenican, or mesotrione + atrazine applied preemergence provided ≥98% control of MHR waterhemp at 12 WAA. There were no differences among herbicide mixtures for control or yield. This study shows that acetochlor herbicide mixtures evaluated provide excellent waterhemp control; however, control was not greater than acetochlor alone. Combining acetochlor with broadleaf herbicides evaluated can potentially help reduce selection intensity for the evolution of herbicide-resistant biotypes.

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Table 1. Year, location, and soil characteristics from three field trials (2022) and two field trials (2023) conducted in southwestern Ontario, Canada.

Year	Location	Soil texture	Sand	Silt	Clay	OM	pH	CEC
			--------------------------%----------------------------					
2022	Cottam	Sandy loam	55	27	17	2.2	5.7	9.1
2022	Newbury	Loamy sand	84	11	4	2.5	6.7	11.6
2022	Walpole Island	Sandy loam	69	21	10	1.8	6.4	16.8
2023	Newbury	Loamy sand	84	11	4	2.5	6.7	11.6
2023	Walpole Island	Sandy loam	69	21	9	1.8	6.4	16.8

Abbreviations: OM, organic matter; CEC, cation exchange capacity.

[a] Soil analysis performed by A&L Canada Laboratories Inc. (2136 Jetstream Road, London, Ontario, Canada, N5V 3P5) from soil cores taken from 0-15 cm.

Table 2. Herbicide active ingredient, rate, trade name, and manufacturer of products used to investigate acetochlor-based herbicide mixtures in corn for multiple-herbicide-resistant waterhemp control from three field trials (2022) and two field trials (2023) conducted in southwestern Ontario, Canada.

Herbicides	Rate	Trade name	Manufacturer
	g ai ha^{-1}		
Acetochlor	2,950	Harness®	Bayer Crop Science
Flumetsulam	50	Broadstrike™ RC	Corteva Agriscience
Dicamba	600	Xtendimax®	Bayer Crop Science
Atrazine[a]	1,490 or 800	Aatrex®	Syngenta Canada
Isoxaflutole/diflufenican	191	Brodal®	Bayer Crop Science
Mesotrione	140	Callisto®	Syngenta Canada
Isoxaflutole/thiencarbazone-methyl	74/30	Corvus™	Bayer Crop Science
Dimethenamid-p/saflufenacil	660/75	Integrity®	BASF
S-metolachlor/atrazine/mesotrione/bicyclopyrone	1,259/588/140/35	Acuron®	Syngenta Canada

Bayer Crop Science Inc., Suite 100, 3131 114th Avenue S.E., Calgary, Alberta, Canada, T2Z 3X2; Corteva Agriscience, Suite 2450, 215-2nd Street SW, Calgary, Alberta, Canada, T2P 1M4; Syngenta Canada Inc., 140 Research Lane, Guelph, Ontario, Canada, N1G 4Z3; BASF, 5025 Creekbank Road, Mississauga, Ontario, Canada, L4W 5R2

[a] Atrazine was applied at 1,490 g ai ha^{-1} for all treatments besides the co-application of isoxaflutole/thiencarbazone-methyl + atrazine and isoxaflutole/diflufenican + atrazine

Table 3. Year, location, corn hybrid, and corn planting, herbicide application, corn emergence, and corn harvest dates from five field trials (2022) and two field trials (2023) conducted in southwestern Ontario, Canada.

Year	Location	Corn hybrid	Planting date	Application date	Emergence date	Harvest date
2022	Cottam	DKC46-82RIB	May 17	May 18	May 25	October 20
2022	Newbury	DKC46-82RIB	May 12	May 13	May 20	October 24
2022	Walpole Island	DKC46-82RIB	June 21	June 23	June 26	November 9
2023	Newbury	P0075YHR	May 26	May 29	June 2	_
2023	Walpole Island	Pride 7197G8	May 27	June 15	June 5	_

Table 4. Multiple herbicide-resistant waterhemp control at 4, 8, and 12 weeks after acetochlor-based herbicide mixtures applied preemergence from five field trials conducted in 2022 and 2023 in southwestern Ontario, Canada.

Treatment	Rate	Visible waterhemp control					
		4 WA		8 WAA		12 WAA	
	g ai ha^{-1}	------------------------ % ----------------------					
Weed-free control		100		100		100	
Nontreated control		0		0		0	
Acetochlor	2,950	99	a	98	a	97	a
Flumetsulam	50	79	b	60	b	53	b
Dicamba	600	79	b	57	b	55	b
Atrazine	1,490	81	b	66	b	64	b
Isoxaflutole/diflufenican	191	99	a	97	a	97	a
Mesotrione + atrazine	140 + 1,490	99	a	95	a	94	a
Acetochlor + flumetsulam	2,950 + 50	100 (100)	a	99 (97)	a	98 (96)	a
Acetochlor + dicamba	2,950 + 600	100 (100)	a	99 (98)	a	99 (97)	a
Acetochlor + atrazine	2,950 + 1,490	100 (99)	a	99 (97)	a	99 (96)	a
Acetochlor + isoxaflutole/diflufenican	2,950 + 191	100 (100)	a	99 (99)	a	99 (99)	a
Acetochlor + mesotrione + atrazine	2,950 + 140 + 1,490	100 (100)	a	99 (99)	a	99 (98)	a
Isoxaflutole/thiencarbazone-methyl + atrazine	104 + 800	99	a	96	a	95	a
Isoxaflutole/diflufenican + atrazine	191 + 800	100	a	99	a	99	a
Dimethenamid-p/saflufenacil	735	99	a	97	a	95	a
S-metolachlor/atrazine/mesotrione/bicyclopyrone	2,026	99	a	98	a	97	a

Abbreviations: WAA, weeks after application

[a] Means followed by the same letter (a-b) within a column are not significantly different according to Tukey-Kramer at $p<0.05$.

[b] Values in parentheses represent expected values from Colby's Equation.

Table 5. Multiple herbicide-resistant waterhemp density and biomass at 8 weeks after acetochlor-based herbicide mixtures applied preemergence and corn yield from five field trials conducted in 2022 and 2023 in southwestern Ontario, Canada.

Treatment	Rate	Density	Biomass	Yield			
	g ai ha^{-1}	plants m^{-2}		g m^{-2}		T ha^{-1}	
Weed-free control		0		0		9.91	a
Nontreated control		482	d	93.1	c	8.56	a
Acetochlor	2,950	9	abc	4.2	a	9.99	a
Flumetsulam	50	258	d	51.4	bc	8.68	a
Dicamba	600	279	d	47.4	c	8.69	a
Atrazine	1,490	382	d	41.9	bc	8.92	a
Isoxaflutole/diflufenican	191	18	abc	5.2	a	9.44	a
Mesotrione + atrazine	140 + 1,490	48	c	8.1	ab	9.84	a
Acetochlor + flumetsulam	2,950 + 50	6 (3)	abc	2.5 (5.4)	a	9.56	a
Acetochlor + dicamba	2,950 + 600	3 (2)	ab	0.7 (3.9)	a	8.80	a
Acetochlor + atrazine	2,950 + 1,490	6 (4)	abc	2.8 (1.8)	a	9.93	a
Acetochlor + isoxaflutole/diflufenican	2,950 + 191	2 (1)	a	0.1 (0.3)	a	9.47	a
Acetochlor + mesotrione + atrazine	2,950 + 140 + 1,490	5 (1)*	abc	1.0 (1.8)	a	9.82	a
Isoxaflutole/thiencarbazone-methyl + atrazine	104 + 800	25	bc	3.5	a	9.43	a
Isoxaflutole/diflufenican + atrazine	191 + 800	6	abc	1.8	a	9.44	a
Dimethenamid-p/saflufenacil	735	9	abc	9.7	a	9.46	a
S-metolachlor/atrazine/mesotrione/bicyclopyrone	2,026	7	abc	5.1	a	9.38	a

[a] Means followed by the same letter (a-d) within a column are not significantly different according to Tukey-Kramer at $p<0.05$.

[b] Values in parentheses represent expected values from Colby's Equation.

[c] * denotes significance at $p<0.05$ between observed and expected values based on a two-tailed t-test.