Hindawi
International Journal of Agronomy
Volume 2019, Article ID 8159671, 7 pages
https://doi.org/10.1155/2019/8159671

Research Article

Weed Control in Corn and Soybean with Group 15 (VLCFA Inhibitor) Herbicides Applied Preemergence

Nader Soltani, Lynette R. Brown, and Peter H. Sikkema

University of Guelph Ridgetown Campus, Ridgetown, ON N0P 2C0, Canada

Correspondence should be addressed to Nader Soltani; soltanin@uoguelph.ca

Received 13 November 2018; Accepted 28 February 2019; Published 7 April 2019

Academic Editor: Maria Serrano

Limited information exists on the efficacy of pethoxamid for annual grass and broadleaf control in corn and soybean in Ontario. A total of 10 field experiments (5 with corn and 5 with soybean) were conducted during 2015 to 2017 in Ontario, Canada, to compare the weed control efficacy of dimethenamid-*P* at 544 $g{\cdot}ai{\cdot}ha^{-1}$, pethoxamid at 840 $g{\cdot}ai{\cdot}ha^{-1}$, pyroxasulfone at 100 $g{\cdot}ai{\cdot}ha^{-1}$, and *S*-metolachlor at 1050 $g{\cdot}ai{\cdot}ha^{-1}$ applied preemergence (PRE). Reduced weed interference with pyroxasulfone and dimethenamid-*P* resulted in corn yield that was similar to the weed-free control; however, weed interference with pethoxamid and *S*-metolachlor reduced corn yield 28 and 33%, respectively. Reduced weed interference with pyroxasulfone resulted in soybean yield that was similar to the weed-free control; however, weed interference with pethoxamid, dimethenamid-*P*, and *S*-metolachlor reduced soybean yield 27, 27, and 30%, respectively. At 4 and 8 weeks after application (WAA), all VLCFA inhibitor herbicides (Group 15) provided excellent redroot pigweed control (90 to 99%) in corn. There were no differences in common ragweed control, density, and dry weight among the VLCFA inhibitor herbicide evaluated; pyroxasulfone provided highest numeric common ragweed control and lowest numeric density and dry weight. At 4 and 8 WAA, pyroxasulfone provided the best common lambsquarters and wild mustard control and lowest numeric density and dry weight in corn and soybean. At 8 WAA, the VLCFA inhibitor herbicides controlled green foxtail 91 to 96% in corn; dimethenamid-*P* provided better control of green foxtail than pethoxamid in soybean. There were no differences in barnyard grass control among the VLCFA inhibitor herbicides evaluated.

1. Introduction

Soybean and corn are two major agricultural crops produced in Canada [1, 2]. Currently, nearly 50% of soybean and >60% of corn produced in Canada is grown in Ontario [2]. Soybean and corn are ranked as the 1st and 2nd most important field crops grown in Ontario, respectively [1]. In 2016, Ontario soybean and corn growers harvested 1.09 and 0.81 million ha and produced 3.38 and 8.05 million tonnes with a total farm gate value of $1.59 and $1.54 billion, respectively [1]. Effective weed management is critical for profitable soybean and corn production. Weed management has been identified as the single most important aspect of crop production for protecting the full yield potential of the crop [3]. Growers need new weed management options to control problematic weeds in corn and soybean.

Pethoxamid is a new very long chain fatty acid (VLCFA) inhibitor herbicide from the chloroacetamide chemical family that is under consideration for registration in corn and soybean in North America. In sensitive plants, pethoxamid inhibits very long chain fatty acid (VLCFA) elongases, which inhibits fatty acid and subsequent lipid production [4–6]. Pethoxamid controls key grasses such as *Setaria* spp., *Digitaria* spp., *Echinochloa* spp., and broadleaf weeds such as *Amaranthus* spp., *Chenopodium* spp., and *Polygonum* spp. [7]. Pethoxamid also has activity against Group 2, 5, and 9 herbicide-resistant weeds including *Amaranthus palmeri* (S. Watson), *Amaranthus rudis* (L.), and other important annual grass and broadleaf weeds [8]. Pethoxamid primarily interferes with weed seedling development in sensitive plants [8]. In addition to corn and soybean, pethoxamid is currently under consideration for registration in canola, sunflower, cotton, and rice in other regions of North America [8].

Herbicide diversity is crucial for long-term sustainable crop production. Evolution of glyphosate-resistant and multiple-resistant weeds especially weeds resistant to Group 2, 5, 9, 14, and 27 herbicides in recent years is problematic for many growers in North America [9]. These modes-of-action are among the most valuable tools for weed management in corn and soybean [9]. VLCFA inhibitor herbicides provide an alternative mode-of-action to commonly used herbicides and are an effective herbicide option for weed control in corn and soybean. Currently, other VLCFA inhibitor herbicides registered preemergence (PRE) in corn and soybean in Ontario include dimethenamid-*P*, pyroxasulfone, and *S*-metolachlor. However, pethoxamid is not registered for use in corn and soybean in Ontario. Registration of this herbicide may provide corn and soybean growers with a new option to control problematic grass and broadleaf weeds including herbicide-resistant biotypes.

To our knowledge, there is no published research that has collectively compared the weed control efficacy of VLCFA inhibitor herbicides including dimethenamid-*P*, pethoxamid, pyroxasulfone, and *S*-metolachlor in corn and soybean in Ontario. Accordingly, the objective of this research was to compare the efficacy of four VLCFA inhibitor herbicides including dimethenamid-*P* at 544 g·ai·ha^{-1}, pethoxamid at 840 g·ai·ha^{-1}, pyroxasulfone at 100 g·ai·ha^{-1}, and *S*-metolachlor at 1050 g·ai·ha^{-1} applied PRE for the control of problematic weeds in corn and soybean in Ontario.

2. Materials and Methods

Field studies were conducted in 2015, 2016, and 2017 near Exeter (41°68′N, 83°11′W) and Ridgetown (42.7392°N, 81.8871°W), Ontario. There were 5 field experiments with corn (1 in 2015 (Exeter); 2 in 2016 (Ridgetown and Exeter); and 2 in 2017 (Ridgetown and Exeter)) and 5 experiments with soybean (1 in 2015 (Exeter); 2 in 2016 (Ridgetown and Exeter); and 2 in 2017 (Ridgetown and Exeter)). The soil at Exeter was a Brookston clay loam (Orthic Humic Gleysol, mixed, mesic, and poorly drained) with 29–37% sand, 37–44% silt, 26-27% clay, 3.2–3.6% organic matter, and a pH of 7.7. The soil at Ridgetown was a Watford (Gray-Brown Brunisolic, mixed, mesic, sandy, and imperfectly drained)-Brady (Gleyed Brunisolic Gray-Brown Luvisol, mixed, mesic, sandy, and imperfectly drained) with 50-51% sand, 24-25% silt, 25% clay, 3.2–3.9% organic matter, and a pH of 7.1–7.2.

Treatments were arranged in a randomized complete block design. Herbicide treatments (based on manufacturer's recommendation) were dimethenamid-*P* at 544 g·ai·ha^{-1}, pethoxamid at 840 g·ai·ha^{-1}, pyroxasulfone at 100 g·ai·ha^{-1}, and *S*-metolachlor at 1050 g·ai·ha^{-1}. Each experiment included a weedy and a weed-free control. Plots included four rows of corn ("DKC 53–56" or "DKC 42-42 RIB") or soybean ("30–61 RY" or "DKB 27–60 RY") spaced 0.75 m apart in rows that were 10 m long at Exeter and 8 m long at Ridgetown. Corn and soybean were seeded 4 cm deep at a rate of approximately 80,000 and 380,000 seeds·ha^{-1}, respectively. All herbicides were applied 1-2 days after planting using a CO_2 pressurized backpack sprayer calibrated to apply 200 L·ha^{-1} at 240 kPa equipped with a 1.5 m wide boom with four ULD 120-02 nozzles spaced 0.5 m apart. The weed-free control was kept weed-free in corn with *S*-metolachlor/atrazine (2880 g·ai·ha^{-1}) plus mesotrione (140 g·ai·ha^{-1}), applied PRE, and in soybean with imazethapyr (100 g·ai·ha^{-1}) plus metribuzin (400 g·ai·ha^{-1}), applied PRE, followed by hoeing and hand weeding as needed during the growing season.

Weed control was visually estimated at 4 and 8 weeks after herbicide application (WAA) on a scale of 0 to 100, with 0 representing no apparent control and 100 representing complete control. Weed density and the aboveground shoot dry weight (biomass) at 8 WAA were determined from two 0.5 m^{-2} quadrats in each plot. Weeds were separated by weed species and counted before being cut at soil level. Plants were then placed in a paper bag and dried in an oven at 60°C for 2 weeks until constant moisture before recording the dry weights. Weeds selected for analysis needed to be present in at least 2 environments. At corn and soybean maturity, the two middle rows of each plot were harvested with a small plot combine for yield and grain moisture determinations. Seed yields were adjusted to 15.5% seed moisture content for corn and 13% seed moisture content for soybean.

The GLIMMIX procedure in SAS (SAS Institute Inc. 2016 Base SAS® 9.4 Procedures Guide: Statistical Procedures, Fifth Edition, SAS Institute Inc, Cary, NC.) was used with the Laplace estimation method to perform data analysis. Model fixed effect was herbicide treatment, and random effects were environment (location-year combinations), environment by treatment interaction, and replicate within environment. In order to broaden the inference space and for results to be applicable to new location-years, environment and its associated interactions were chosen to be random effects [10, 11]. The significance of fixed and random effects was tested using the *F*-test and likelihood ratio tests, respectively. For each parameter, different distributions were assessed on the model scale and compared using the AICC, Pearson chi-squared/df, examination of the residual plots, and Shapiro–Wilk statistic. Once the best distribution was chosen, the least square means (LSMEANS) were calculated on the data scale using the inverse link function. Tukey's adjustment was applied to pairwise comparisons to determine differences among treatment means at a significance level of 0.05. Percent visible control 4 and 8 WAA for all weed species and common ragweed density and dry weight per square meter were best described using a Gaussian distribution and identity link.

In corn, a lognormal distribution (identity link) was used for green pigweed, common lambsquarters, green foxtail density and dry weight, and ragweed and wild mustard density. In soybean, a lognormal distribution was used for common lambsquarters, wild mustard and green foxtail density and dry weight, and barnyardgrass dry weight. The gamma distribution and log link was used for barnyardgrass density. In corn and soybean analysis, for parameters where values of zero were among the values observed (other than for percent control in the weedy control, or density and dry weight in the weed-free control), a value of one was added to all data points. Each density and dry weight data point had a value of one added prior to analysis to accommodate for observed zero values, and the final LSMEANS were adjusted by subtracting one. Treatment means calculated using the lognormal distribution were backtransformed for presentation using a correction for log bias [12].

3. Results and Discussion

Weeds selected for analysis needed to be present in at least 2 environments. For corn experiments, weed species analyzed included redroot pigweed, common ragweed, common lambsquarters, wild mustard, and green foxtail. For soybean experiments, weed species analyzed included common ragweed, common lambsquarters, wild mustard, green foxtail, and barnyardgrass.

3.1. Corn and Soybean Yield. In corn, weeds interference caused a 51% yield reduction (Table 1). Reduced weed interference with pyroxasulfone and dimethenamid-*P* resulted in corn yield that was similar to the weed-free control (Table 1). However, weed interference with pethoxamid and *S*-metolachlor reduced corn yield 28 and 33%, respectively. Stephenson et al. [9] in Louisiana found no yield loss with pyroxasulfone (PRE) at 125 g·ai·ha^{-1} in corn. Knezevic et al. [13] in Nebraska reported that pyroxasulfone has to be applied PRE at approximately 195 g·ai·ha^{-1} to maintain corn yield comparable to 95% of the weed-free control.

In soybean, weeds interference caused 39% yield reduction. Reduced weed interference with the application of pyroxasulfone resulted in soybean yield that was similar to the weed-free control. However, weed interference with dimethenamid-*P*, pethoxamid, and *S*-metolachlor reduced soybean yield 27, 27, and 30%, respectively (Table 1). In other studies, pyroxasulfone applied PRE at 89 g·ai·ha^{-1} decreased soybean yield 18% due to weed interference [14].

Table 1: Yield of corn and soybean treated with various VLCFA inhibitor herbicides, applied preemergence (PRE), near Exeter and Ridgetown in 2015–2017[a].

Treatment	Rate (g·ai·ha^{-1})	Yield (T·ha^{-1})
Corn		
Weed-free control		11.9[a]
Weedy control		5.8[c]
Dimethenamid-*P*	544	9.0[ab]
Pethoxamid	840	8.6[bc]
Pyroxasulfone	100	9.6[ab]
S-metolachlor	1050	8.0[bc]
Soybean		
Weed-free control		3.24[a]
Weedy control		1.99[b]
Dimethenamid-*P*	544	2.37[b]
Pethoxamid	840	2.36[b]
Pyroxasulfone	100	2.68[ab]
S-metolachlor	1050	2.28[b]

[a]Means followed by the same alphabetical letter within a column for each crop are not significantly different according to the Tukey–Kramer multiple range test at $P < 0.05$.

3.2. Redroot Pigweed. There was excellent control of redroot pigweed with all VLCFA inhibitor herbicides in corn. Dimethenamid-*P* at 544 g·ai·ha^{-1}, pethoxamid at 840 g·ai·ha^{-1}, pyroxasulfone at 100 g·ai·ha^{-1}, and *S*-metolachlor at 1050 g·ai·ha^{-1} controlled redroot pigweed as much as 99, 98, 99, and 98%; reduced redroot pigweed density 98, 96, 93, and 92%; and reduced redroot pigweed aboveground dry weight 99, 94, 93, and 91%, respectively (Table 2).

Results are similar to that of Mahoney et al.'s [14], who found 100% control of redroot pigweed with pyroxasulfone (PRE) at 89 g·ai·ha^{-1} in soybean. Li et al. [15] found 99 to 100% of redroot pigweed with dimethenamid-*P* (PRE) at 544 g·ai·ha^{-1} and *S*-metolachlor (PRE) at 1050 g·ai·ha^{-1} in dry bean. Taziar et al. [16] reported 96 to 98% redroot and green pigweed control with dimethenamid-*P* (PRE) at 544 g·ai·ha^{-1}, pyroxasulfone (PRE) at 100 g·ai·ha^{-1}, and *S*-metolachlor (PRE) at 1050 g·ai·ha^{-1} in dry bean. Additionally, pyroxasulfone (PRE) at 150 g·ai·ha^{-1} controlled other *Amaranthus* species such as Palmer amaranth 93 to 96% in corn [9]. Geier et al. [17] reported 82 to 85% control of Palmer amaranth with pyroxasulfone applied PRE at 125 g·ai·ha^{-1} in corn. However, *S*-metolachlor (PRE) at 1070 g·ai·ha^{-1} controlled Palmer amaranth 57 to 87% in the same study [17]. Another study found as much as 97% control of Palmer amaranth with pyroxasulfone (PRE) at 166 g·ai·ha^{-1} in corn [18].

3.3. Common Ragweed. The VLCFA inhibitor herbicides evaluated provided poor control of common ragweed in corn and soybean. At 4 WAA, dimethenamid-*P* at 544 g·ai·ha^{-1}, pethoxamid at 840 g·ai·ha^{-1}, pyroxasulfone at 100 g·ai·ha^{-1}, and *S*-metolachlor at 1050 g·ai·ha^{-1} controlled common ragweed 56, 66, 77, and 42% in corn and 13, 19, 28, and 7% in soybean, respectively (Table 3). However, the results were not always significantly different from the weedy control (Table 3). Generally, there was no decrease in common ragweed density and aboveground dry weight relative to the weedy plots in both crops, except in corn where density of common ragweed was reduced 52, 59, and 63% with dimethenamid-*P*, pethoxamid, and pyroxasulfone, respectively (Table 3).

Results are consistent with other research studies that have shown poor control of common ragweed (7 to 28%) with dimethenamid-*P* (PRE) at 693 g·ai·ha^{-1}, pethoxamid (PRE) at 1200 g·ai·ha^{-1}, pyroxasulfone (PRE) at 150 g·ai·ha^{-1}, and *S*-metolachlor (PRE) at 1600 g·ai·ha^{-1} in corn [19]. Mahoney et al. [14] also reported only 45% common ragweed control with pyroxasulfone (PRE) at 89 g·ai·ha^{-1} in soybean. Belfry et al. [20] also found poor control of common ragweed with pyroxasulfone (PRE) at 100 g·ai·ha^{-1} in soybean. Additionally, Taziar et al. [16] reported poor common ragweed control (5 to 39%) with dimethenamid-*P* (PRE) at 544 g·ai·ha^{-1}, pyroxasulfone (PRE) at 100 g·ai·ha^{-1}, and *S*-metolachlor (PRE) at 1050 g·ai·ha^{-1} in dry bean.

Table 2: Control, density, and dry weight of redroot pigweed in corn treated with VLCFA inhibitor herbicides, applied preemergence (PRE), near Exeter in 2016 and 2017 and Ridgetown in 2017[a].

Treatment	Rate ($g{\cdot}ai{\cdot}ha^{-1}$)	Control (%)		Density (no. m^{-2})	Dry weight ($g{\cdot}m^{-2}$)
		4 WAA	8 WAA		
Corn					
Weed-free control		100	100	0^{a}	0.0^{a}
Weedy control		0^{b}	0^{b}	10.1^{b}	8.9^{b}
Dimethenamid-p	544	99^{a}	99^{a}	0.2^{a}	0.1^{a}
Pethoxamid	840	98^{a}	90^{a}	0.4^{a}	0.5^{a}
Pyroxasulfone	100	99^{a}	99^{a}	0.7^{a}	0.6^{a}
S-metolachlor	1050	98^{a}	96^{a}	0.8^{a}	0.8^{a}

[a]Means followed by the same alphabetical letter within a column for each crop are not significantly different according to the Tukey–Kramer multiple range test at $P < 0.05$.

Table 3: Control, density, and dry weight of common ragweed in corn and soybean treated with VLCFA inhibitor herbicides, applied preemergence (PRE), near Exeter and Ridgetown (2015–2017)[a].

Treatment	Rate ($g{\cdot}ai{\cdot}ha^{-1}$)	Control (%)		Density (no. m^{-2})	Dry weight ($g{\cdot}m^{-2}$)
		4 WAA	8 WAA		
Corn					
Weed-free control		100	100	0.0^{a}	0.0^{a}
Weedy control		0^{b}	0^{a}	51.2^{c}	128.6^{b}
Dimethenamid-*P*	544	56^{a}	13^{a}	24.8^{b}	86.7^{b}
Pethoxamid	840	66^{a}	20^{a}	20.9^{b}	120.0^{b}
Pyroxasulfone	100	77^{a}	30^{a}	18.7^{b}	91.9^{b}
S-metolachlor	1050	42^{a}	12^{a}	36.1^{bc}	141.3^{b}
Soybean					
Weed-free control		100	100	0^{a}	0.0^{a}
Weedy control		0^{b}	0^{b}	26^{b}	29.1^{b}
Dimethenamid-*P*	544	13^{ab}	12^{ab}	26^{b}	37.7^{b}
Pethoxamid	840	17^{a}	19^{a}	23^{b}	31.2^{b}
Pyroxasulfone	100	28^{a}	26^{a}	19^{b}	27.2^{b}
S-metolachlor	1050	7^{ab}	6^{ab}	26^{b}	34.7^{b}

[a]Means followed by the same alphabetical letter within a column for each crop are not significantly different according to the Tukey–Kramer multiple range test at $P < 0.05$.

3.4. Common Lambsquarters. There were less than adequate common lambsquarters control with all VLCFA inhibitor herbicides in corn and soybean. Pyroxasulfone (PRE) at $100\,g{\cdot}ai{\cdot}ha^{-1}$ was the best treatment for the control of common lambsquarters in corn (Table 4). At 4 weeks after herbicide treatment, dimethenamid-*P* (PRE) at $544\,g{\cdot}ai{\cdot}ha^{-1}$, pethoxamid (PRE) at $840\,g{\cdot}ai{\cdot}ha^{-1}$, pyroxasulfone (PRE) at $100\,g{\cdot}ai{\cdot}ha^{-1}$, and *S*-metolachlor (PRE) at $1050\,g{\cdot}ai{\cdot}ha^{-1}$ controlled common lambsquarters 68, 70, 84, and 60% in corn and 43, 33, 56, and 32% in soybean, respectively (Table 4). However, results were not always significantly different from the weedy control (Table 4). Common lambsquarters density was reduced by 74, 78, 92, and 66% in corn with dimethenamid-*P*, pethoxamid, pyroxasulfone, and *S*-metolachlor, respectively (Table 4). Dimethenamid-*P*, pethoxamid, and pyroxasulfone also reduced common lambsquarters density 73, 67, and 82% in soybean, respectively. Common lambsquarters aboveground dry weight was generally comparable to the weedy plots for both crops, except in corn in which dry weight was reduced 87% with pethoxamid and 93% with pyroxasulfone.

In other studies, Jha et al. [21] found that common lambsquarters was controlled 15 to 66% with pyroxasulfone (PRE) at $149\,g{\cdot}ai{\cdot}ha^{-1}$, 33 to 77% with dimethenamid-*P* (PRE) at $840\,g{\cdot}ai{\cdot}ha^{-1}$, and 12 to 65% with acetochlor (PRE) at $1960\,g{\cdot}ai{\cdot}ha^{-1}$ in corn. Mahoney et al. [14] found 76% common lambsquarters control with pyroxasulfone applied PRE at $89\,g{\cdot}ai{\cdot}ha^{-1}$ in soybean. In contrast, Belfry et al. [20] reported minimal control (8 to 9%) of common lambsquarters with $100\,g{\cdot}ai{\cdot}ha^{-1}$ of pyroxasulfone. Other studies have also shown poor common lambsquarters control (8 to 54%) with dimethenamid-*P* (PRE) at $544\,g{\cdot}ai{\cdot}ha^{-1}$, pyroxasulfone (PRE) at $100\,g{\cdot}ai{\cdot}ha^{-1}$, and *S*-metolachlor (PRE) at $1050\,g{\cdot}ai{\cdot}ha^{-1}$ in dry bean [15, 16].

3.5. Wild Mustard. The VLCFA inhibitor herbicides evaluated did not provide adequate wild mustard control in corn and soybean. At 4 WAA, dimethenamid-*P* (PRE) at $544\,g{\cdot}ai{\cdot}ha^{-1}$, pethoxamid (PRE) at $840\,g{\cdot}ai{\cdot}ha^{-1}$, pyroxasulfone (PRE) at $100\,g{\cdot}ai{\cdot}ha^{-1}$, and *S*-metolachlor (PRE) at $1050\,g{\cdot}ai{\cdot}ha^{-1}$ controlled wild mustard 34, 24, 54, and 32% in corn and 62, 48, 70, and 51% in soybean, respectively (Table 5). Wild mustard density and aboveground dry weight were generally similar to the weedy plots for both crops, except in soybean in which density was reduced 83% with pyroxasulfone (Table 5). Results are consistent with other studies that have reported

Table 4: Control, density, and dry weight of common lambsquarters in corn and soybean treated with VLCFA inhibitor herbicides, applied preemergence (PRE), near Exeter in 2015–2017 and Ridgetown in 2017[a].

Treatment	Rate (g·ai·ha^{-1})	Control (%) 4 WAA	Control (%) 8 WAA	Density (no. m^{-2})	Dry weight (g·m^{-2})
Corn					
Weed-free control		100	100	0.0^{a}	0.0^{a}
Weedy control		0^{c}	0^{b}	15.8^{d}	11.9^{c}
Dimethenamid-*P*	544	68^{ab}	63^{a}	4.1^{bc}	4.1^{bc}
Pethoxamid	840	70^{ab}	77^{a}	3.4^{bc}	1.6^{b}
Pyroxasulfone	100	84^{a}	84^{a}	1.3^{b}	0.8^{a}
S-metolachlor	1050	60^{b}	65^{a}	5.4^{c}	7.0^{bc}
Soybean					
Weed-free control		100	100	0^{a}	0.0^{a}
Weedy control		0^{b}	0^{b}	33^{c}	19.4^{b}
Dimethenamid-*P*	544	43^{a}	32^{ab}	9^{b}	8.9^{b}
Pethoxamid	840	33^{a}	30^{ab}	11^{b}	9.9^{b}
Pyroxasulfone	100	56^{a}	43^{a}	6^{b}	7.6^{b}
S-metolachlor	1050	32^{a}	30^{ab}	15^{bc}	15.8^{b}

[a]Means followed by the same alphabetical letter within a column for each crop are not significantly different according to the Tukey–Kramer multiple range test at $P < 0.05$.

Table 5: Control, density, and dry weight of wild mustard in corn and soybean treated with VLCFA inhibitor herbicides, applied preemergence (PRE), near Exeter in 2015 and 2017[a].

Treatment	Rate (g·ai·ha^{-1})	Control (%) 4 WAA	Control (%) 8 WAA	Density (no. m^{-2})	Dry weight (g·m^{-2})
Corn					
Weed-free control		100	100	0.0^{a}	0.0^{a}
Weedy control		0^{b}	0^{b}	118.2^{b}	195.4^{b}
Dimethenamid-*P*	544	34^{ab}	25^{a}	56.3^{b}	109.7^{b}
Pethoxamid	840	24^{ab}	31^{a}	53.7^{b}	143.3^{b}
Pyroxasulfone	100	54^{a}	57^{a}	9.5^{b}	37.0^{ab}
S-metolachlor	1050	32^{ab}	19^{ab}	71.0^{b}	160.3^{b}
Soybean					
Weed-free control		100	100	0^{a}	0.0^{a}
Weedy control		0^{b}	0^{c}	23^{c}	76.9^{b}
Dimethenamid-*P*	544	62^{a}	35^{ab}	9^{abc}	20.2^{b}
Pethoxamid	840	48^{a}	23^{bc}	20^{c}	58.2^{b}
Pyroxasulfone	100	70^{a}	51^{a}	4^{ab}	8.1^{ab}
S-metolachlor	1050	51^{a}	16^{bc}	14^{bc}	35.6^{b}

[a]Means followed by the same alphabetical letter within a column for each crop are not significantly different according to the Tukey–Kramer multiple range test at $P < 0.05$.

14 to 48, 2 to 33, and 63 to 95% control of wild mustard with dimethenamid-*P* at 544 g·ai·ha^{-1}, pyroxasulfone at 100 g·ai·ha^{-1}, and *S*-metolachlor at 1050 g·ai·ha^{-1} applied PRE in dry bean, respectively [16].

3.6. Green Foxtail. The VLCFA inhibitor herbicides controlled green foxtail 55–96% in corn and soybean (Table 6). At 8 WAA, dimethenamid-*P* at 544 g·ai·ha^{-1}, pethoxamid at 840 g·ai·ha^{-1}, pyroxasulfone at 100 g·ai·ha^{-1}, and *S*-metolachlor at 1050 g·ai·ha^{-1} controlled green foxtail 96, 91, 96, and 96% in corn and 89, 60, 74, and 78% in soybean, respectively (Table 6). Dimethenamid-*P*, pethoxamid, pyroxasulfone, and *S*-metolachlor reduced green foxtail density 99, 88, 95, and 95% in corn and 92, 62, 90, and 88% in soybean, respectively (Table 6). Similarly, dimethenamid-*P*, pethoxamid, pyroxasulfone, and *S*-metolachlor reduced green foxtail aboveground dry weight 99, 91, 93, and 97% in corn and 93, 63, 93, and 93% in soybean, respectively.

In other studies, Geier et al. [17] reported 95% green foxtail control with pyroxasulfone applied PRE at 125 g·ai·ha^{-1} in corn. However, *S*-metolachlor (PRE) at 1070 g·ai·ha^{-1} controlled green foxtail 88% in the same study [17]. Mahoney et al. [14] reported 86% control of green foxtail with pyroxasulfone (PRE) at 89 g·ai·ha^{-1} in soybean. Belfry et al. [20] found as much as 61% control of green foxtail with pyroxasulfone (PRE) at 100 g·ai·ha^{-1} in soybean. Taziar et al. [16] also found 99, 99, and 98% green foxtail control with dimethenamid-*P* (PRE) at 544 g·ai·ha^{-1}, pyroxasulfone (PRE) at 100 g·ai·ha^{-1}, and *S*-metolachlor (PRE) at 1050 g·ai·ha^{-1} in dry bean, respectively. Additionally, Li et al. [15] found 92 to 99% control of green foxtail with dimethenamid-*P* (PRE) at 544 g·ai·ha^{-1} and *S*-metolachlor (PRE) at 1050 g·ai·ha^{-1} in dry bean.

Table 6: Control, density, and dry weight of green foxtail in corn and soybean treated with VLCFA inhibitor herbicides, applied preemergence (PRE), near Exeter in 2015–2017 and Ridgetown in 2017[a].

Treatment	Rate ($g{\cdot}ai{\cdot}ha^{-1}$)	Control (%)		Density (no. m^{-2})	Dry weight ($g{\cdot}m^{-2}$)
		4 WAA	8 WAA		
Corn					
Weed-free control		100	100	0.0^{a}	0.0^{a}
Weedy control		0^{b}	0^{b}	29.9^{d}	11.3^{b}
Dimethenamid-*P*	544	84^{a}	96^{a}	0.4^{ab}	0.1^{a}
Pethoxamid	840	71^{a}	91^{a}	3.6^{c}	1.0^{a}
Pyroxasulfone	100	81^{a}	96^{a}	1.6^{bc}	0.8^{a}
S-metolachlor	1050	94^{a}	96^{a}	1.5^{bc}	0.3^{a}
Soybean					
Weed-free control		100	100	0^{a}	0.0^{a}
Weedy control		0^{c}	0^{c}	50^{c}	22.8^{d}
Dimethenamid-*P*	544	88^{a}	89^{a}	4^{b}	1.5^{b}
Pethoxamid	840	55^{b}	60^{b}	19^{c}	8.4^{c}
Pyroxasulfone	100	70^{ab}	74^{ab}	5^{b}	1.7^{b}
S-metolachlor	1050	78^{a}	78^{ab}	6^{b}	1.5^{b}

[a]Means followed by the same alphabetical letter within a column for each crop are not significantly different according to the Tukey–Kramer multiple range test at $P < 0.05$.

Table 7: Control, density, and dry weight of barnyardgrass treated with VLCFA inhibitor herbicides, applied preemergence (PRE), in soybean near Exeter (2017) and Ridgetown (2017)[a].

Treatment	Rate ($g{\cdot}ai{\cdot}ha^{-1}$)	Control (%)		Density (no. m^{-2})	Dry weight ($g{\cdot}m^{-2}$)
		4 WAA	8 WAA		
Soybean					
Weed-free control		100	100	0^{a}	0.0^{a}
Weedy control		0^{b}	0^{b}	36^{c}	39.8^{c}
Dimethenamid-*P*	544	80^{a}	80^{a}	11^{bc}	3.5^{abc}
Pethoxamid	840	48^{ab}	35^{ab}	14^{bc}	12.9^{bc}
Pyroxasulfone	100	56^{ab}	53^{ab}	13^{bc}	4.0^{abc}
S-metolachlor	1050	60^{a}	61^{ab}	5^{ab}	1.2^{ab}

[a]Means followed by the same alphabetical letter within a column for each crop are not significantly different according to the Tukey–Kramer multiple range test at $P < 0.05$.

3.7. Barnyardgrass. VLCFA inhibitor herbicides evaluated did not consistently control barnyardgrass in soybean. At 4 and 8 WAA, dimethenamid-*P* at 544 $g{\cdot}ai{\cdot}ha^{-1}$, pethoxamid at 840 $g{\cdot}ai{\cdot}ha^{-1}$, pyroxasulfone at 100 $g{\cdot}ai{\cdot}ha^{-1}$, and *S*-metolachlor at 1050 $g{\cdot}ai{\cdot}ha^{-1}$ controlled barnyardgrass up to 80, 48, 56, and 61% in soybean, respectively (Table 7). However, results were not always significantly different from the weedy control (Table 7). Density and aboveground dry weight of barnyardgrass were comparable to the weedy plots for all VLCFA inhibitor herbicides except for *S*-metolachlor which reduced which decreased density 86% and aboveground dry weight 97% (Table 7). In other studies, pyroxasulfone (PRE) at 150 $g{\cdot}ai{\cdot}ha^{-1}$ controlled barnyardgrass 93 to 96% in corn [9]. Yamaji et al. [22] also found 100% barnyardgrass control with pyroxasulfone (PRE) at 125 to 250 $g{\cdot}ai{\cdot}ha^{-1}$ in corn.

4. Conclusions

Corn grain yield was similar to weed-free control with pyroxasulfone and dimethenamid-*P*. There was excellent redroot pigweed control with all VLCFA inhibitor herbicides in corn. There were no differences in common ragweed control, but pyroxasulfone provided the highest numeric control with the lowest density and aboveground dry weight among the VLCFA inhibitor herbicides evaluated in corn. Pyroxasulfone provided the best control of common lambsquarters and wild mustard among the VLCFA inhibitor herbicides evaluated in corn.

Soybean yield was similar to weed-free with pyroxasulfone. There were no differences in common ragweed and common lambsquarters control, but pyroxasulfone provided the highest numeric control with the lowest weed density and aboveground dry weight among the VLCFA inhibitor herbicides in soybean. Pyroxasulfone provided the best control of wild mustard in soybean. Pethoxamid provided the poorest control of green foxtail and barnyardgrass among the VLCFA inhibitor herbicides evaluated in soybean.

Based on this study, pethoxamid at the rate evaluated in this study does not provide improved annual grass and broadleaf weed control compared to currently registered VLCFA inhibitor herbicides in corn and soybean. Further research is needed to evaluate the impact of higher rates of pethoxamid and possible tankmix combinations to determine if it has a fit for weed management in corn and soybean in Ontario, Canada.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This project was funded in part by Grain Farmers of Canada (GFO) and the Growing Forward II Program of the Agricultural Adaptation Council.

References

[1] S. Mailvaganam, "Area, yield, production and farm value of specified field crops," in *2012–2017 (Imperial and Metric Units)*, Ontario Ministry of Agriculture and Food, Ontario, Canada, 2018, http://www.omafra.gov.on.ca/english/stats/crops/estimate_new.htm#metric.

[2] Statistics Canada, *Table 001-0017-Estimated Areas, Yield, Production and Average Farm Price of Principal Field Crops, in Metric Units, Annual*, Statistics Canada, Ottawa, Canada, 2018, http://soycanada.ca/statistics/production/.

[3] R. S. Baucom and J. S. Holt, "Weeds of agricultural importance: bridging the gap between evolutionary ecology and crop and weed science," *New Phytologist*, vol. 184, no. 4, pp. 741–743, 2009.

[4] D. Post-Beittenmiller, "Biochemistry and molecular biology of wax production in plants," *Annual Review of Plant Physiology and Plant Molecular Biology*, vol. 47, no. 1, pp. 405–430, 1996.

[5] P. Böger, B. Matthes, and J. Schmalfuss, "Towards the primary target of chloroacetamides-new findings pave the way," *Pest Management Science*, vol. 56, no. 6, pp. 497–508, 2000.

[6] S. Trenkamp, W. Martin, and K. Tietjen, "Specific and differential inhibition of very-long-chain fatty acid elongases from *Arabidopsis thaliana* by different herbicides," *Proceedings of the National Academy of Sciences*, vol. 101, no. 32, pp. 11903–11908, 2004.

[7] U. Mazarura, "Effect of pethoxamid (TKC-94) rate and application time on weed control and phytotoxicity in flue-cured tobacco," *Greener Journal of Plant breeding and Crop Science*, vol. 1, no. 1, pp. 1–7, 2013.

[8] B. Hunt, J. Barrentine, T. Hayden et al., "Pethoxamid— a new herbicide for use in agronomic and horticultural crops," in *Proceedings of the 55th Annual Meeting of the Weed Science Society of America*, pp. 9–12, Lexington, KY, USA, February 2015.

[9] D. O. Stephenson, J. A. Bond, J. L. Griffin et al., "Weed management programs with pyroxasulfone in field Corn (*Zea mays*)," *Weed Technology*, vol. 31, no. 4, pp. 496–502, 2017.

[10] R.-C. Yang, "Towards understanding and use of mixed-model analysis of agricultural experiments," *Canadian Journal of Plant Science*, vol. 90, no. 5, pp. 605–627, 2010.

[11] W. W. Stroup, *Generalized Linear Mixed Models: Modern Concepts, Methods and Applications*, CRC Press, Taylor & Francis Group, Boca Raton, FL, USA, 2012.

[12] P. Rothery, "A cautionary note on data transformation: bias in back-transformed means," *Bird Study*, vol. 35, no. 3, pp. 219–221, 1988.

[13] S. Z. Knezevic, A. Datta, J. Scott, and P. J. Porpiglia, "Dose-response curves of KIH-485 for preemergence weed control in corn," *Weed Technology*, vol. 23, no. 1, pp. 34–39, 2009.

[14] K. J. Mahoney, C. Shropshire, and P. H. Sikkema, "Weed management in conventional- and No-till soybean using flumioxazin/pyroxasulfone," *Weed Technology*, vol. 28, no. 2, pp. 298–306, 2014.

[15] Z. Li, R. Van Acker, D. E. Robinson, N. Soltani, and P. H. Sikkema, "Managing weeds with herbicides in white bean in Canada: a review," *Canadian Journal of Plant Science*, vol. 97, pp. 755–766, 2017.

[16] A. N. Taziar, N. Soltani, C. Shropshire et al., "Sulfentrazone tank mix partners for weed control in white bean (*Phaseolus vulgaris* L.)," *Canadian Journal of Plant Science*, vol. 96, pp. 1037–1044, 2016.

[17] P. W. Geier, P. W. Stahlman, and J. C. Frihauf, "KIH-485 and S-metolachlor efficacy comparisons in conventional and no-tillage corn," *Weed Technology*, vol. 20, no. 3, pp. 622–626, 2006.

[18] G. L. Steele, P. J. Porpiglia, and J. M. Chandler, "Efficacy of KIH-485 on Texas panicum (*Panicum texanum*) and selected broadleaf weeds in corn," *Weed Technology*, vol. 19, no. 4, pp. 866–869, 2005.

[19] N. Soltani, L. Brown, and P. H. Sikkema, "Control of glyphosate-resistant common ragweed in corn with pre-emergence herbicides," *Canadian Journal of Plant Science*, vol. 98, no. 4, pp. 959–962, 2018.

[20] K. D. Belfry, K. E. McNaughton, and P. H. Sikkema, "Weed control in soybean using pyroxasulfone and sulfentrazone," *Canadian Journal of Plant Science*, vol. 95, no. 6, pp. 1199–1204, 2015.

[21] P. Jha, V. Kumar, J. Garcia, and N. Reichard, "Tank mixing pendimethalin with pyroxasulfone and chloroacetamide herbicides enhances in-season residual weed control in corn," *Weed Technology*, vol. 29, no. 2, pp. 198–206, 2015.

[22] Y. Yamaji, H. Honda, M. Kobayashi, R. Hanai, and J. Inoue, "Weed control efficacy of a novel herbicide, pyroxasulfone," *Journal of Pesticide Science*, vol. 39, no. 3, pp. 165–169, 2014.