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Research Article

Weed Control in White Bean with Pethoxamid Tank-Mixes Applied Preemergence

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Six field experiments were conducted during 2015 to 2017 in Ontario, Canada, to determine the efficacy of pethoxamid applied alone, and in combination with broadleaf herbicides, for the control of annual grass and broadleaved weeds in white navy bean. Visible injury was generally minimal (0 to 8%) with herbicide treatments evaluated. Weed control was variable depending on the weed species evaluated. Pethoxamid, *S*-metolachlor, halosulfuron, imazethapyr, sulfentrazone, pethoxamid + halosulfuron, pethoxamid + imazethapyr, and pethoxamid + sulfentrazone controlled redroot pigweed 82 to 98%; common ragweed 19 to 93%; common lambsquarters 49 to 84%; and green foxtail 47 to 92% in white bean. Weed biomass and weed density reductions were similar to visible control ratings for herbicides evaluated. Weed interference delayed white bean maturity and reduced yield by 50% in this study. Weed interference in plots sprayed with pethoxamid, *S*-metolachlor, and sulfentrazone reduced white bean yield 36%. White bean yield was similar to the weed-free with other herbicides evaluated. This study concludes that there is potential for the tank-mix of pethoxamid with halosulfuron, imazethapyr, or sulfentrazone for weed control in white bean production.

1. Introduction

White (navy) bean (*Phaseolus vulgaris* L.) is a valuable cash crop grown in various regions of Canada. Ontario and Manitoba farmers grow the majority of white bean produced in Canada. In 2017, Ontario growers produced white bean on 28,000 ha, with an annual production of 6,000,000 tonnes valued at $40 million [1]. Dry bean is extremely sensitive to weed competition. Effective weed management is essential to minimize white bean yield losses from weed interference [2–4]. The average yield losses from uncontrolled weeds in North America was 71%, 52%, and 52% in dry bean, corn, and soybean, respectively, in studies completed by the Weed Science Society of America (WSSA) [5]. In the same WSSA studies, the potential yield loss from uncontrolled weeds in Ontario was 56, 49 and 35% in dry bean, corn, and soybean, respectively [5]. Dry beans have greater sensitivity to herbicides compared to other legumes, such as soybean [6]. There are numerous broadleaf herbicides registered for use in soybean, but most of them cannot be used in beans because of crop injury [6]. Consequently, there are only two registered soil-applied broadleaf herbicides, imazethapyr, and halosulfuron and two postemergence broadleaf herbicides, bentazon and fomesafen for broadleaf weed control in white bean in Ontario, Canada [6]. In contrast, identity preserved (IP) soybean producers in Ontario have at least 12 herbicides for broadleaf weed control—acifluorfen, bentazon, chlorimuron, clomazone, cloransulam, flumetsulam, flumioxazin, fomesafen, imazethapyr, linuron, metribuzin, and thifensulfuron [6]. Despite the wide array of herbicides registered for use in IP soybeans, broadleaf weed control is still considered to be a challenge for soybean growers which highlights the difficulty faced by Ontario white bean growers. New herbicide options that have multiple modes of action are needed to provide effective control of troublesome weeds in white bean production.

Pethoxamid is a new Group 15 herbicide from the chloroacetamide chemical family that can control annual grasses such as foxtail species (*Setaria* spp.), large crabgrass (*Digitaria* spp.), barnyardgrass (*Echinochloa crus-galli* (L.)

P.Beauv.), and broadleaved weeds such as redroot pigweed (*Amaranthus retroflexus* L.), common lambsquarters (*Chenopodium album* L.), and ladysthumb (*Polygonum persicaria* L.) [7–9]. Pethoxamid also has activity against Groups 2, 5, and 9 herbicide-resistant weeds including palmer amaranth (*Amaranthus palmeri* S. Watson), common waterhemp (*Amaranthus Rudis* L.), and other important annual grass and broadleaf weeds [9]. Pethoxamid inhibits very long chain fatty acid (VLCFA) formation in responsive weeds and generally controls weeds prior to emergence [9]. Pethoxamid is generally applied to the soil as a preplant (PP), preplant incorporated (PPI), or preemergence (PRE) herbicide [9].

Halosulfuron (Group 2, ALS inhibitor), imazethapyr (Group 2, ALS inhibitor), sulfentrazone (Group 14, PPO inhibitor), and *S*-metolachlor (Group 15, VLCFA inhibitor) have potential to control problematic weeds in Ontario including redroot pigweed, common lambsquarters, common ragweed, wild mustard (*Sinapis arvensis* L.), nutsedge species (*Cyperus* spp.), ladysthumb (*Polygonum persicaria* L.), velvetleaf (*Abutilon theophrasti* Medic.), and cocklebur (*Xanthium strumarium* L.), including glyphosate and triazine-resistant biotypes [10]. Halosulfuron, imazethapyr, and sulfentrazone provide variable control of annual grasses such as *Setaria*, *Digitaria*, *Echinochloa*, and *Panicum* species [4]. The spectrum of weeds controlled with pethoxamid can be increased if tank-mixed with other herbicides such as halosulfuron, imazethapyr, or sulfentrazone.

The purpose of this study was to determine the efficacy of pethoxamid compared to *S*-metolachlor applied PRE and to determine if broadleaf weed control can be improved with the addition of halosulfuron, imazethapyr, or sulfentrazone to pethoxamid applied PRE.

2. Materials and Methods

A total of six field experiments were conducted over a three-year period (2015, 2016, and 2017) at the Huron Research Station (41°68′N, 83°11′W), Exeter, Ontario, and the University of Guelph Ridgetown Campus (42.7392° N, 81.8871° W), Ridgetown, Ontario (one site at each research station per year). The soil at Exeter was a Brookston clay loam (Orthic Humic Gleysol, mixed, mesic, and poorly drained) with 35% sand, 43% silt, 22% clay, 3.6% organic matter, and a pH of 7.6 in 2015; 41% sand, 35% silt, 24% clay, 2.9% organic matter, and a pH of 7.7 in 2016; and 32% sand, 42% silt, 26% clay, 3.2% organic matter, and a pH of 7.7 in 2017. 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 52% sand, 24% silt, 24% clay, 4.3% organic matter, and a pH of 7.3 in 2015; 59% sand, 20% silt, 21% clay, 3.4% organic matter, and a pH of 6.7 in 2016; and 49% sand, 26% silt, 25% clay, 4.3% organic matter, and a pH of 6.4 in 2017. Seedbed preparation at all sites consisted of fall moldboard plowing, followed by two passes with a field cultivator in spring.

Herbicide treatments arranged in a randomized complete block (with four replicates) included pethoxamid at 840 g ai ha^{-1}, *S*-metolachlor at 1050 g ai ha^{-1}, halosulfuron at 35 g ai ha^{-1}, imazethapyr at 75 g ai ha^{-1}, sulfentrazone at 140 g ai ha^{-1}, pethoxamid + halosulfuron at 840 + 35 g ai ha^{-1}, pethoxamid + imazethapyr at 840 + 75 g ai ha^{-1}, and pethoxamid + sulfentrazone at 840 + 140 g ai ha^{-1}. Each replicate included a weedy and a weed-free control. Each plot consisted of four rows of white bean ("T9905") spaced 0.75 m apart in rows that were 10 m long at Exeter and 8 m long at Ridgetown. Beans were planted approximately 4 cm deep at a rate of approximately 250,000 seeds ha^{-1}.

Herbicide treatments were applied to the soil surface (not incorporated) 1-2 days after planting using a CO_2-pressurized backpack sprayer calibrated to deliver 200 L·ha^{-1} at 240 kPa. The boom was 1.5 m long with four ultralow drift ULD120-02 nozzles spaced 0.5 m apart providing a spray width of 2 m.

White bean injury was estimated on a scale of 0 (no visible injury) to 100% (complete plant death) 2 and 4 weeks after crop emergence (WAE). Percent control of dominant weed species which included redroot pigweed, common ragweed, common lambsquarters, and green foxtail was estimated visually at 4 and 8 weeks after treatment application (WAT), and weed density (plants·m^{-2}) and weed dry weight (g·m^{-2}) were determined at 8 WAT 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 to a constant moisture and then weighed. Yields were determined by harvesting the two middle rows of white bean in each plot using a small plot combined at crop maturity. Seed yield was adjusted to 18% seed moisture content.

Data analysis was carried out using the GLIMMIX procedure in SAS (Ver. 9.4, SAS Institute Inc., Cary, NC), and the Laplace method was used for estimation. Herbicide treatments were considered fixed effects while environment (year and location), replication within the environment, and the environment by treatment interaction were considered random effects. Random effects were chosen in order to be able to apply conclusions to a broader range of environments than those studied [11, 12]. The significance of fixed effects was tested using the *F*-test, and likelihood ratio tests were used to determine the significance of random effects. Different distributions were assessed using the AICC and Pearson chi-squared test/df (for overdispersion), as well as the examination of studentized residual plots and the Shapiro–Wilk statistic. Once the best distribution was confirmed, least square means (LSMEANS) were calculated and Tukey's adjustment was applied to pairwise comparisons to determine differences among treatment means ($p < 0.05$). Final yield and percent control of redroot pigweed, common ragweed, common lambsquarters, and green foxtail at 4 and 8 WAA were analyzed using a Gaussian distribution and identity link. Percent injury was analyzed using the poisson distribution (2 WAT) and the negative binomial distribution (4 WAT); the log link was used in both cases. Percent white bean moisture at harvest was analyzed using a gamma distribution and log link. Redroot pigweed, common ragweed, common lambsquarters, and green foxtail density and dry weight data were best described using a lognormal distribution and identity link. Injury evaluations, density, and dry weight data had a value of one added prior to analysis to accommodate for observed zero values, and the final LSMEANS were adjusted by subtracting one. Data were combined over environments. Treatment means calculated using the lognormal distribution were back-transformed for presentation due to the fact that there is no link function to display values on the mean scale. The backtransformation included a correction for log bias [13]. In all cases where a treatment was assigned a value of 0 (weedy check for percent control and weed-free check for density and dry weight) or 100 (weed-free check for percent control), it was excluded from the analysis because the data for these treatments had zero variance. However, the LSMEANS output provides information on whether each treatment least square mean differs from zero. This information was used to identify differences between the treatments included in the analysis, and the excluded check treatments, which were assigned a value of zero.

3. Results and Discussion

3.1. Crop Response. White bean injury was <9% with herbicide treatments evaluated at 2 and 4 WAE (Table 1). At 2 or 4 WAE, herbicides evaluated caused 1 to 8% white bean injury (Table 1). Weed interference delayed white bean maturity and reduced yield by 50% in this study (Table 1). Weed interference in plots sprayed with pethoxamid, *S*-metolachlor, and sulfentrazone reduced white bean yield 36%. However, other herbicide treatments evaluated provided similar seed yield as the weed-free control (Table 1). Results are similar to other studies that have shown 0 to 9% injury with pethoxamid, *S*-metolachlor, halosulfuron, imazethapyr, and sulfentrazone applied PRE alone or in combination with other herbicides in dry bean [4, 14–17]. In another study, preemergence application of pethoxamid also caused 6% injury when applied at 1200 g·ai·ha^{-1} and 10% injury when applied at 2400 g·ai·ha^{-1} in white bean [16]. In another study, *S*-metolachlor plus imazethapyr caused as much as 20% crop injury in dry bean under some environmental conditions [14].

Table 1: Percent visible injury 2 and 4 weeks after crop emergence (WAE), moisture and yield of white bean treated with various PRE herbicides in 2015, 2016, and 2017.

Treatment	Rate (g·ai/ha)	Injury (%) 2 WAE	Injury (%) 4 WAE	Moisture (%)	Yield (t/ha)
Weedy check		0^{a}	0^{a}	18.6^{b}	1.1^{c}
Weed-free check		0^{a}	0^{a}	17.5^{a}	2.2^{a}
Pethoxamid	840	2.5^{bcd}	1.0^{ab}	18.2^{ab}	1.4^{bc}
S-metolachlor	1050	1.0^{abc}	0.4^{ab}	18.1^{ab}	1.4^{bc}
Halosulfuron	35	0.2^{ab}	0.7^{ab}	18.0^{ab}	1.8^{ab}
Imazethapyr	75	0.6^{abc}	2.2^{bcd}	18.0^{ab}	1.7^{abc}
Sulfentrazone	140	2.3^{bc}	1.9^{bcd}	18.1^{ab}	1.4^{bc}
Pethoxamid + halosulfuron	840 + 35	2.9^{cd}	1.4^{abc}	18.0^{ab}	2.1^{a}
Pethoxamid + imazethapyr	840 + 75	3.1^{cd}	6.1^{cd}	18.2^{ab}	1.9^{ab}
Pethoxamid + sulfentrazone	840 + 140	8.3^{d}	7.9^{d}	18.1^{ab}	1.7^{abc}

Data were combined over environments and years. Means followed by the same letter within a column are not significantly different according to the Tukey–Kramer multiple range test at $p < 0.05$.

Table 2: Percent control, density, and dry weight of redroot pigweed pigweed 2 and 4 weeks after herbicide treatment (WAT) in white bean treated with pethoxamid applied PRE in 2015, 2016, and 2017.

Treatment	Rate (g·ai/ha)	Control (%) 2 WAT	Control (%) 4 WAT	Density (#/m^2)	Dry weight (g/m^2)
Weedy check		0^{b}	0^{b}	13.6^{d}	18.4^{d}
Weed-free check		100^{a}	100^{a}	0.0^{a}	0.0^{a}
Pethoxamid	840	84^{a}	70^{a}	2.6^{bc}	2.5^{bc}
S-metolachlor	1050	82^{a}	71^{a}	2.1^{bc}	2.5^{bc}
Halosulfuron	35	89^{a}	76^{a}	1.8^{bc}	2.1^{abc}
Imazethapyr	75	88^{a}	72^{a}	2.9^{c}	6.3^{cd}
Sulfentrazone	140	93^{a}	87^{a}	0.8^{abc}	1.0^{abc}
Pethoxamid + halosulfuron	840 + 35	97^{a}	94^{a}	0.6^{abc}	1.0^{abc}
Pethoxamid + imazethapyr	840 + 75	91^{a}	82^{a}	1.4^{abc}	2.2^{abc}
Pethoxamid + sulfentrazone	840 + 140	98^{a}	98^{a}	0.3^{ab}	0.3^{ab}

Data were combined over environments and years. Means followed by the same letter within a column are not significantly different according to the Tukey–Kramer multiple range test at $p < 0.05$.

3.2. Weed Control. Weed control was variable depending on the weed species evaluated. Herbicides evaluated controlled redroot pigweed 82 to 98% at 2 WAT and 70 to 98% at 4 WAT (Table 2). Redroot pigweed density and biomass reduction were similar to the control ratings. Herbicides evaluated reduced redroot pigweed density 79 to 98% and biomass 66 to 98%, although biomass reduction was not statistically significant than the weedy check for the imazethapyr treatment (Table 2). In other studies, *S*-metolachlor and pyroxasulfone applied PRE-controlled redroot pigweed 98% [18]. Sulfentrazone applied alone or tank-mixed with *S*-metolachlor or pyroxasulfone provided >90% control of redroot pigweed in white bean [17].

Common ragweed control was weak (except for halosulfuron treatments) with most of the herbicide treatments evaluated (Table 3). Halosulfuron and pethoxamid + halosulfuron controlled common ragweed from 89% to 93% at 2 WAT and from 88% to 92% at 4 WAT (Table 3). Halosulfuron alone and in combination with pethoxamid reduced common ragweed density 87 to 90% and biomass 91 to 95% in white bean (Table 3). However, common ragweed density and biomass were not significantly different than the weedy check with other herbicides evaluated in white bean (Table 3). In other studies, preemergence application of halosulfuron provided >90% control of common ragweed in white bean [4]. Results with other herbicides are similar to other research that has shown *S*-metolachlor and pyroxasulfone provide only 28 to 39% control of common ragweed

Table 3: Percent control, density, and dry weight of common ragweed 2 and 4 weeks after herbicide treatment (WAT) in white bean treated with pethoxamid applied PRE in 2015, 2016, and 2017.

Treatment	Rate (g·ai/ha)	Control (%) 2 WAT	Control (%) 4 WAT	Density (#/m^2)	Dry weight (g/m^2)
Weedy check		0^{d}	0^{e}	14.8^{b}	22.0^{cd}
Weed-free check		100	100	0.0^{a}	0.0^{a}
Pethoxamid	840	19^{cd}	25^{cd}	10.2^{b}	19.6^{cd}
S-metolachlor	1050	7^{cd}	19^{d}	18.2^{b}	35.5^{d}
Halosulfuron	35	89^{a}	88^{a}	1.5^{a}	1.9^{b}
Imazethapyr	75	57^{ab}	63^{ab}	7.7^{b}	9.6^{c}
Sulfentrazone	140	4^{cd}	25^{cd}	11.2^{b}	24.6^{cd}
Pethoxamid + halosulfuron	840 + 35	93^{a}	92^{a}	1.9^{a}	1.0^{ab}
Pethoxamid + imazethapyr	840 + 75	77^{a}	79^{ab}	6.9^{b}	9.7^{c}
Pethoxamid + sulfentrazone	840 + 140	38^{bc}	54^{bc}	10.4^{b}	21.4^{cd}

Data were combined over environments and years. Means followed by the same letter within a column are not significantly different according to the Tukey–Kramer multiple range test at $p < 0.05$.

Table 4: Percent control, density, and dry weight of lambsquarters 2 and 4 weeks after herbicide treatment (WAT) in white bean treated with pethoxamid applied PRE in 2015, 2016, and 2017.

Treatment	Rate (g·ai/ha)	Control (%) 2 WAT	Control (%) 4 WAT	Density (#/m^2)	Dry weight (g/m^2)
Weedy check		0^{d}	0^{c}	12.4^{d}	9.6^{c}
Weed-free check		100	100	0.0^{a}	0.0^{a}
Pethoxamid	840	53^{bc}	42^{b}	4.3^{c}	4.5^{c}
S-metolachlor	1050	49^{c}	31^{b}	5.8^{cd}	4.5^{c}
Halosulfuron	35	81^{ab}	78^{a}	1.2^{b}	0.7^{b}
Imazethapyr	75	83^{a}	83^{a}	0.7^{ab}	0.1^{ab}
Sulfentrazone	140	84^{a}	81^{a}	0.2^{ab}	0.1^{ab}
Pethoxamid + halosulfuron	840 + 35	82^{ab}	79^{a}	0.7^{b}	0.5^{ab}
Pethoxamid + imazethapyr	840 + 75	83^{a}	83^{a}	0.2^{ab}	0.1^{ab}
Pethoxamid + sulfentrazone	840 + 140	82^{a}	81^{a}	0.4^{ab}	0.2^{ab}

Data were combined over environments and years. Means followed by the same letter within a column are not significantly different according to the Tukey–Kramer multiple range test at $p < 0.05$.

[18]. Lack of common ragweed control with sulfentrazone alone or tank-mixed with imazethapyr is similar to Taziar et al. [18] who observed 35% common ragweed control with these herbicides in white bean.

Common lambsquarters was controlled the least (31 to 53%) with pethoxamid and *S*-metolachlor among the herbicide treatments evaluated (Table 4). Other herbicides evaluated controlled common lambsquarters from 81% to 84% at 2 WAT and from 78% to 83% at 4 WAT (Table 4). Pethoxamid and *S*-metolachlor provided inadequate reduction in biomass and density of common lambsquarters (Table 4). Halosulfuron, imazethapyr, sulfentrazone, pethoxamid + halosulfuron, pethoxamid + imazethapyr, and pethoxamid + sulfentrazone reduced common lambsquarters density from 90% to 98% and biomass from 93% to 99% in white bean (Table 4). Results are similar to other studies that have shown >95% control of common lambsquarters with halosulfuron or its tank-mix with trifluralin, dimethenamid-*P*, and *S*-metolachlor [4]. Sulfentrazone in combination with *S*-metolachlor or pyroxasulfone has been shown to control common lambsquarters greater than 90% in white bean [17].

Green foxtail was controlled the least with halosulfuron and sulfentrazone among the herbicide treatments evaluated (Table 5). *S*-metolachlor, imazethapyr, pethoxamid + imazethapyr, and pethoxamid + sulfentrazone provided the best control of green foxtail (88% to 92% at 2 WAT and 76% to 89% at 4 WAT) in white bean (Table 5). Halosufuron and sulfentrazone applied alone provided no significant reduction in green foxtail density and biomass except for sulfentrazone which provided 78% reduction in green foxtail biomass (Table 5). However, pethoxamid, *S*-metolachlor, imazethapyr, pethoxamid + halosulfuron, pethoxamid + imazethapyr, and pethoxamid + sulfentrazone reduced green foxtail density 81% to 93% and green foxtail biomass 86% to 97% in white bean (Table 5). In other studies, *S*-metolachlor applied PRE-controlled green foxtail 98% in dry bean [18]. Halosulfuron tank-mixed with *S*-metolachlor has been shown to provide greater than 90% control of grasses including green foxtail [4]. Additionally, sulfentrazone applied alone or tank-mixed with *S*-metolachlor or pyroxasulfone has been shown to provide >90% green foxtail control in white bean [17].

Table 5: Percent control, density, and dry weight of green foxtail 2 and 4 weeks after herbicide treatment (WAT) in white bean treated with pethoxamid applied PRE in 2015, 2016, and 2017.

Treatment	Rate (g·ai/ha)	Control (%) 2 WAT	Control (%) 4 WAT	Density (#/m^2)	Dry weight (g/m^2)
Weedy check		0^{d}	0^{d}	62.6^{d}	38.3^{e}
Weed-free check		100	100	0.0^{a}	0.0^{a}
Pethoxamid	840	78^{ab}	71^{ab}	12.2^{bc}	4.4^{bc}
s-metolachlor	1050	90^{a}	87^{a}	4.2^{b}	2.0^{bc}
Halosulfuron	35	46^{c}	47^{c}	44.1^{cd}	17.5^{de}
Imazethapyr	75	88^{ab}	85^{a}	9.2^{b}	2.6^{bc}
Sulfentrazone	140	64^{bc}	51^{bc}	14.8^{bcd}	8.3^{cd}
Pethoxamid + halosulfuron	840 + 35	81^{ab}	72^{a}	11.4^{bc}	5.3^{bcd}
Pethoxamid + imazethapyr	840 + 75	92^{a}	89^{a}	3.2^{b}	1.0^{ab}
Pethoxamid + sulfentrazone	840 + 140	89^{a}	76^{a}	7.7^{b}	3.2^{bc}

Data are combined over environments and years. Means followed by the same letter within a column are not significantly different according to the Tukey–Kramer multiple range test at $P < 0.05$.

4. Conclusion

There was minimal visible injury with most of the herbicides evaluated. Pethoxamid + sulfentrazone caused the most visible injury (8%) in white bean; however, plants recovered and had no yield reduction at harvest time. Weed control was variable depending on the weed species evaluated. Pethoxamid, *S*-metolachlor, halosulfuron, imazethapyr, sulfentrazone, pethoxamid + halosulfuron, pethoxamid + imazethapyr, and pethoxamid + sulfentrazone controlled redroot pigweed 82 to 98%; common ragweed 19 to 93%; common lambsquarters 49 to 84%; and green foxtail 47 to 92%. Weed interference with pethoxamid, *S*-metolachlor, and sulfentrazone reduced white bean seed yield 36%. Generally, there was no difference in the efficacy of pethoxamid compared to *S*-metolachlor-applied PRE. The spectrum of broadleaf weeds controlled was generally increased with the addition of halosulfuron, imazethapyr, or sulfentrazone to pethoxamid-applied PRE. Results indicate that there is potential for the tank-mix of pethoxamid plus halosulfuron, imazethapyr, or sulfentrazone for the control of annual grass and broadleaf weeds in white navy bean. Pethoxamid has superior activity than *S*-metolachlor against some Group 2, 5, and 9 herbicide-resistant weeds including palmer amaranth and common waterhemp and can be used as an additional option for managing these weeds in white bean.

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.

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