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Two-Pass Weed Management Programs for White Bean

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Abstract

It is essential to implement effective weed management programs to minimize white bean yield loss from weed interference. Four field experiments were conducted during 2022 and 2023 to determine the efficacy of one-pass compared to two-pass weed control programs. This study evaluated trifluralin + *S*-metolachlor + imazethapyr or trifluralin + *S*-metolachlor + halosulfuron applied preplant incorporated (PPI), bentazon + fomesafen + quizalofop-p-ethyl applied postemergence (POST), and trifluralin + *S*-metolachlor + imazethapyr or trifluralin + *S*-metolachlor + halosulfuron applied PPI followed by (fb) bentazon + fomesafen + quizalofop-p-ethyl applied POST in white bean. There was minimal white bean injury (≤ 5%) with the herbicide programs evaluated. Weed interference decreased white bean yield 44%. Weed interference with bentazon + fomesafen + quizalofop-p-ethyl applied POST resulted in a 24% decrease in white bean seed yield compared to the weed-free control; however, all other PPI and PPI fb POST herbicide programs resulted in white bean seed yield that was similar to the weed-free control. Weed interference with the one-pass herbicide programs (PPI or POST) resulted in 17% lower white bean seed yield compared to the two-pass herbicide programs (PPI fb POST). Trifluralin + *S*-metolachlor + imazethapyr, applied PPI, controlled velvetleaf 85%, common ragweed 35%, common lambsquarters 96%, and green foxtail 80% at 8 weeks after the POST application (WAT). Trifluralin + *S*-metolachlor + halosulfuron, applied PPI, controlled velvetleaf 68%, common ragweed 87%, common lambsquarters 94% and green foxtail 56% at 8 WAT. Bentazon + fomesafen + quizalofop-p-ethyl, applied POST, controlled velvetleaf 86%, common ragweed 97%, common lambsquarters 34%, and green foxtail 29% at 8 WAT. Trifluralin + *S*-metolachlor + imazethapyr, applied PPI, followed by bentazon + fomesafen + quizalofop-p-ethyl, applied POST, controlled velvetleaf, common ragweed, common lambsquarters, and green foxtail 98, 97, 96, and 94%, respectively at 8 WAT. Trifluralin + *S*-metolachlor + halosulfuron, applied PPI, followed by bentazon + fomesafen + quizalofop-p-ethyl, applied POST, controlled velvetleaf, common ragweed, common lambsquarters, and green foxtail 97, 99, 97 and 93%, respectively at 8 WAT. Based on orthogonal contrast, the two-pass herbicide programs provided 17, 21, 20, and 38% greater control of velvetleaf, common ragweed, common lambsquarters, and green foxtail in comparison to the one-pass herbicide programs, respectively at 8 WAT. This study concludes that the two-pass herbicide programs of trifluralin + *S*-metolachlor + imazethapyr or trifluralin + *S*-metolachlor + halosulfuron applied PPI followed by bentazon + fomesafen + quizalofop-p-ethyl applied POST provides the most consistent weed control in white bean in Ontario.

Keywords: dry bean, efficacy, seed moisture content, two-pass weed control, Weed control, yield, *Phaseolus vulgaris* L.

1. Introduction

White (navy) bean (*Phaseolus vulgaris* L.) is a legume that plays a vital role in human nutrition as it nourishes many people around the globe (Billan, 2023). White bean is the most popular edible bean crop cultivated in Ontario and its production contributes significantly to the agricultural industry of Canada (OBG, 2024). White bean has been grown in Ontario since the early 1900s and over the years producers have refined their cultivation practices to ensure the production of high-quality beans (OBG, 2024). Nearly 80-90% of white bean produced in Ontario are exported to other countries including Europe and Asian countries and the remaining portion is consumed domestically in Canada (OBG, 2024). White bean producers in Ontario annually plant approximately 24,000 ha and produce 67,000 MT of white bean with a value of approximately $70 million (OMAFRA, 2024).

Weed management is one of the most important aspects of profitable white bean production (Chickoy et al., 1995; Li et al., 2016; Malik et al., 1993). White bean has a short stature and is not very competitive with weeds;

substantial yield losses can occur if weeds are not adequately controlled (Chickoy et al., 1995; Li et al., 2017; Malik et al., 1993). A recent meta-analysis by the yield loss committee of the Weed Science Society of America (WSSA) estimated that there would be a 71% yield loss in North America if weeds were not controlled in dry beans (Soltani et al., 2018). In the same WSSA study, the potential yield loss from uncontrolled weeds in Ontario was 56% in dry beans (Soltani et al., 2018).

There are a limited number of soil-applied and postemergence (POST) herbicides registered for grass and broadleaf weed control in white bean and the registered herbicides do not always provide consistent broad-spectrum control of problematic grass and broadleaf weeds (Li et al., 2017; Soltani et al., 2013 a, b, 2014a, 2020b). Research has demonstrated that relying on a one-pass weed control program can lead to weed escapes and inadequate control of late-emerging weeds (Hartzler, 1996; Loux et al., 2008). A two-pass herbicide program involving both soil-applied herbicides and POST herbicides has several benefits for crop producers including improved weed control, reduced weed interference, increased yield, and enhanced net returns (Gonzini et al., 1999; Hartzler, 1996; Loux et al., 2008; Nurse et al., 2007; Soltani et al., 2013a, 2013b, 2014b; Stewart et al., 2011; Underwood et al., 2017). Preplant-incorporated (PPI) herbicides registered for weed control in white bean in Ontario include trifluralin + *S*-metolachlor + imazethapyr or trifluralin + *S*-metolachlor + halosulfuron, and POST herbicides registered for weed control in white bean in Ontario include bentazon + fomesafen + quizalofop-p-ethyl (OMAFRA, 2023; Soltani et al., 2013a, 2013b, 2020b, 2021).

There is limited information on the efficacy of two-pass weed control programs for control of annual grass and broadleaf weeds where residual herbicides, applied PPI, are followed by (fb) POST herbicides under Ontario environmental conditions. The objective of this study was to determine the efficacy of trifluralin + *S*-metolachlor + imazethapyr or trifluralin + *S*-metolachlor + halosulfuron applied PPI, bentazon + fomesafen + quizalofop-p-ethyl applied POST, and trifluralin + *S*-metolachlor + imazethapyr or trifluralin + *S*-metolachlor + halosulfuron applied PPI fb bentazon + fomesafen + quizalofop-p-ethyl applied POST in white bean.

2. Materials and Methods

Two field experiments were established in 2022 and 2023 at the University of Guelph, Ridgetown Campus, Ridgetown, Ontario, Canada. The soil was Fox sandy loam with 30-51% sand, 26-31% silt, 23-39% clay, 2.7-4.7% organic matter, pH of 6.0-7.9, and cation exchange capacity (CEC) of 12-15. Site preparation included moldboard plowing in the autumn followed by two passes with a field cultivator with rolling basket harrows in the spring.

Experiments were arranged in a randomized complete block design with four replicates. There was a total of seven programs as listed in Tables 1-5. Herbicide application doses and the adjuvant selected were based on the manufacturers' recommendations.

All plots were 3 m wide (4 white bean rows spaced 75 cm apart) and 8 m long. White bean seeds (‘T9905’) were seeded at a density of approximately 225,000 seeds per ha^{-1}. Herbicides were applied using a CO_2-pressurized sprayer calibrated to deliver 200 L per ha^{-1} aqueous solution at 210 kPa. The boom was 1.5 m wide with four ultra-low drift nozzles (ULD120-02, Hypro, New Brighton, MN) spaced 50 cm apart producing a spray width of 2.0 m. PPI herbicides were applied 1-2 days before seeding and immediately incorporated into the soil with two-passes of a field cultivator in opposite directions and POST herbicides were applied when weed escapes were up to 5 cm in height and prior to white bean flowering.

White bean injury was evaluated visually 2 weeks after emergence (WAE) and 1, 2, and 4 weeks after POST herbicide treatment (WAT), using a scale of 0 to 100% where a rating of 0 was defined as no visible white injury and a rating of 100 was defined as total necrosis. Percent weed control was visually assessed 0, 2, 4, and 8 WAT after the POST herbicide treatment (WAT) using a scale of 0 to 100% where a rating of 0 was defined as no weed control and a rating of 100 was defined as complete control. White bean was harvested with a small-plot combine at harvest maturity and seed moisture content and weight were recorded. White bean yield was adjusted to 18% seed moisture content prior to analysis.

Data analysis was carried out using the GLIMMIX procedure in SAS (Ver. 9.4, SAS Institute Inc., Cary, NC), with $P < 0.05$ as the chosen level of significance. The generalized linear mixed model comprised the fixed effect of herbicide treatment and the random effects of environment, environment by treatment interaction, and replicate within environment. A Gaussian distribution was used to analyze white bean yield and visible percent weed control, the latter being arcsine square root transformed prior to analysis. White bean moisture at harvest was analyzed using a lognormal distribution. Treatment least-square means were back-transformed for presentation or results where necessary. Tukey’s adjustment was applied to pairwise comparisons among treatment least-square means. A contrast was constructed to compare one-pass to two-pass weed control programs for each variable except the visible percent weed control evaluated just prior to the postemergence application.

3. Results and Discussion

The dominant weed species in this study were velvetleaf (*Abutilon theophrasti* Medic.; ABUTH); common ragweed (*Ambrosia artemisiifolia* L.; AMBEL), common lambsquarters (*Chenopodium album* L.; CHEAL), and green foxtail (*Setaria viridis* L.; SETVI). There was no significant interaction between environments and programs, therefore data were pooled and averaged over environments.

3.1 White Bean Injury and Yield

There no, or minimal, visible white bean injury (≤ 5%) at 2 WAE or 0, 2, and 4 WAT with the PPI, POST, or PPI fb POST herbicide programs evaluated (data not presented).

Weed interference increased seed moisture content 0.7% (delayed white bean maturity) in the non-treated control compared to the weed-free control (Table 1). There were no differences in white bean seed moisture content treated with the herbicide programs evaluated (Table 1). However, weed interference with the one-pass herbicide programs increased seed moisture content 0.3% compared to two-pass herbicide programs which indicates delayed white bean maturity with the one-pass herbicide programs (Table 1).

Table 1. White bean seed moisture content and yield for PPI, POST, or two-pass herbicide programs from four experiments conducted at Ridgetown, Ontario in 2022 and 2023 (n = 4)

Herbicide treatment	Rate	Timing	Moisture	Yield
	g ai ha^{-1}		%	T ha^{-1}
Weed-free control			17.5 a	1.63 a
Non-treated control			18.2 b	0.91 c
Trifluralin + *S*-metolachlor + imazethapyr	840 + 1373 + 45	PPI	17.8 ab	1.33 ab
Trifluralin + *S*-metolachlor + halosulfuron	840 + 1373 + 35	PPI	17.6 a	1.35 ab
Bentazon + fomesafen + quizalofop-p-ethyl	840 + 240 + 48	POST	17.7 a	1.24 bc
Trifluralin + *S*-metolachlor + imazethapyr + bentazon + fomesafen + quizalofop-p-ethyl	840 + 1373 + 45 + 840 + 240 + 48	PPI + POST	17.4 a	1.54 ab
Trifluralin + *S*-metolachlor + halosulfuron + bentazon + fomesafen + quizalofop-p-ethyl	840 + 1373 + 35 + 840 + 240 + 48	PPI + POST	17.5 a	1.62 a
Contrast				
1-pass *vs* 2-pass			17.7 *vs* 17.4*	1.31 *vs* 1.58*

Note. Means within a column followed by the same lowercase letter do not differ significantly according to Tukey's HSD at P < 0.05.

* and ** denote significance at P < 0.05 and P < 0.001, respectively.

Abbreviations: POST, postemergence up to 5 cm weed escapes and prior to white bean flowering; PPI, preplant incorporated.

Weed interference decreased white bean seed yield 44% in the non-treated weedy control compared to the weed-free control (Table 1). Additionally, weed interference with bentazon + fomesafen + quizalofop-p-ethyl applied POST decreased seed yield 12% compared to the weed-free control; reduced weed interference with all other PPI and PPI fb POST herbicide programs resulted in white bean seed yield that was similar to the weed-free control (Table 1). Weed interference with the one-pass herbicide programs resulted in 17% lower white bean seed yield compared to the two-pass herbicide programs (PPI fb POST) (Table 1). In other studies, trifluralin, *S*-metolachlor, halosulfuron, or imazethapyr applied alone or in a two-, three- or four-way tank-mixtures applied PPI caused up to 4% visible white bean injury (Soltani et al., 2021). Trifluralin + halosulfuron applied PPI caused as much as 8% visible white bean injury; however, seed yield with the trifluralin + halosulfuron tankmixes was similar to the weed-free control (Soltani et al., 2020b). Li et al. (2016) and Soltani et al. (2020a) reported that reduced weed interference with trifluralin + halosulfuron applied PPI resulted in white bean yield that was similar to the weed-free control. Another study observed minimal injury (< 5%) and no yield reduction in white bean with the sequential application of a PPI herbicide (pendimethalin) followed by bentazon, fomesafen, bentazon + fomesafen or halosulfuron applied POST in white bean (Soltani et al., 2013b).

3.2 Velvetleaf Control

Trifluralin + *S*-metolachlor + imazethapyr, applied PPI, controlled velvetleaf 93, 91, 88, and 85% at 0, 2, 4, and 8 WAT, respectively (Table 2). Trifluralin + *S*-metolachlor + halosulfuron, applied PPI, controlled velvetleaf 90, 83, 75, and 68% at 0, 2, 4, and 8 WAT, respectively (Table 2). Bentazon + fomesafen + quizalofop-p-ethyl, applied POST, controlled velvetleaf 90, 87, and 86% at 2, 4, and 8 WAT, respectively (Table 2). Trifluralin + *S*-metolachlor + imazethapyr, applied PPI, followed by bentazon + fomesafen + quizalofop-p-ethyl, applied POST, controlled velvetleaf 90, 99, 98, and 98% at 0, 2, 4, and 8 WAT, respectively (Table 2). Trifluralin + *S*-metolachlor + halosulfuron, applied PPI, followed by bentazon + fomesafen + quizalofop-p-ethyl, applied POST, controlled velvetleaf 92, 99, 98, and 97% at 0, 2, 4, and 8 WAT, respectively (Table 2). Based on orthogonal contrasts, two-pass herbicide programs, provided 11, 14, and 17% greater control of velvetleaf in comparison to the one-pass herbicide programs at 2, 4, and 8 WAT, respectively (Table 2). Results are similar to other studies in which trifluralin + halosulfuron applied PPI provided 71-95% control of velvetleaf in white bean (Soltani et al., 2020a). In another study, trifluralin + halosulfuron and *S*-metolachlor + halosulfuron applied PPI provided 96-97% control of velvetleaf in white bean (Soltani et al., 2020b). Brown and Masiunas (2002) reported that trifluralin and *S*-metolachlor applied PPI did not control velvetleaf but imazethapyr and halosulfuron applied PPI controlled velvetleaf > 95%. In another study, three-way herbicide mixtures of trifluralin + *S*-metolachlor + halosulfuron or imazethapyr applied PPI provided 62-73% and 97-99% control of velvetleaf in white bean, respectively (Soltani et al., 2021).

Table 2. Visible velvetleaf control for PPI, POST, or two-pass herbicide programs from three experiments conducted at Ridgetown, Ontario in 2022 and 2023 (n = 3)

Herbicide treatment	Rate	Timing	Velvetleaf control			
			0 WAT	2 WAT	4 WAT	8 WAT
	g ai ha^{-1}		---------------------- % ----------------------			
Weed-free control			100 a	100 a	100 a	100 a
Non-treated control			0 c	0 b	0 b	0 c
Trifluralin + *S*-metolachlor + imazethapyr	840 + 1373 + 45	PPI	93 b	91 a	88 a	85 ab
Trifluralin + *S*-metolachlor + halosulfuron	840 + 1373 + 35	PPI	90 b	83 a	75 a	68 b
Bentazon + fomesafen + quizalofop-p-ethyl	840 + 240 + 48	POST	0 c	90 a	87 a	86 ab
Trifluralin + *S*-metolachlor + imazethapyr + bentazon + fomesafen + quizalofop-p-ethyl	840 + 1373 + 45 + 840 + 240 + 48	PPI + POST	90 b	99 a	98 a	98 ab
Trifluralin + *S*-metolachlor + halosulfuron + bentazon + fomesafen + quizalofop-p-ethyl	840 + 1373 + 35 + 840 + 240 + 48	PPI + POST	92 b	99 a	98 a	97 ab
Contrast						
1-pass *vs* 2-pass			-	88 *vs* 99*	84 *vs* 98*	80 *vs* 97*

Note. Means within a column followed by the same lowercase letter do not differ significantly according to Tukey's HSD at P < 0.05.

* and ** denote significance at P < 0.05 and P < 0.001, respectively.

Abbreviations: POST, postemergence up to 5 cm weed escapes and prior to white bean flowering; PPI, preplant incorporated.

3.3 Common Ragweed

Trifluralin + *S*-metolachlor + imazethapyr, applied PPI, controlled common ragweed 93, 71, 55, and 35% at 0, 2, 4, and 8 WAT, respectively (Table 3). Trifluralin + *S*-metolachlor + halosulfuron, applied PPI, controlled common ragweed 98, 96, 92, and 87% at 0, 2, 4, and 8 WAT, respectively (Table 3). Bentazon + fomesafen + quizalofop-p-ethyl, applied POST, controlled common ragweed 97% at 2, 4, and 8 WAT (Table 3). Trifluralin + *S*-metolachlor + imazethapyr, applied PPI, followed by bentazon + fomesafen + quizalofop-p-ethyl, applied POST, controlled common ragweed 95, 99, 99, and 97% at 0, 2, 4, and 8 WAT, respectively (Table 3). Trifluralin + *S*-metolachlor + halosulfuron, applied PPI, followed by bentazon + fomesafen + quizalofop-p-ethyl, applied POST, controlled common ragweed 97, 100, 99, and 99% at 0, 2, 4, and 8 WAT, respectively (Table 3). Based on orthogonal contrasts, two-pass herbicide programs provided 10, 14, and 21% greater control of common ragweed in comparison to the one-pass herbicide programs, at 2, 4 and 8 WAT, respectively (Table 3). Results are similar to other studies in which mixtures of trifluralin + *S*-metolachlor with halosulfuron, imazethapyr, or halosulfuron

+ imazethapyr applied PPI provided 95, 75, and 95% control of common ragweed in white bean, respectively (Soltani et al., 2021). In another study, trifluralin + halosulfuron applied PPI provided 90 to 97% control of common ragweed in white bean (Soltani et al., 2020a). Also, trifluralin + halosulfuron and *S*-metolachlor + halosulfuron applied PPI provided 93-94% and 91-96% control of common ragweed in white bean, respectively (Soltani et al., 2020b). Li et al. (2016) reported 97% control of common ragweed in white bean with halosulfuron + trifluralin applied PPI. Additionally, POST application of bentazon + fomesafen and halosulfuron + bentazon + fomesafen controlled common ragweed 84-87% and 79-82% in white bean, respectively (Soltani et al., 2013a). Soltani et al. (2013b) reported that the sequential application of a PPI herbicide (pendimethalin) followed by bentazon, fomesafen, bentazon + fomesafen or halosulfuron applied POST controlled common ragweed as much as 60, 98, 95, and 96%, respectively in white bean.

Table 3. Visible common ragweed control for PPI, POST, or two-pass herbicide programs from four experiments conducted at Ridgetown, Ontario in 2022 and 2023 (n = 4)

Herbicide treatment	Rate	Timing	Common ragweed control			
			0 WAT	2 WAT	4 WAT	8 WAT
	g ai ha^{-1}		------------------------ % ------------------------			
Weed-free control			100 a	100 a	100 a	100 a
Non-treated control			0 c	0 c	0 c	0 c
Trifluralin + *S*-metolachlor + imazethapyr	840 + 1373 + 45	PPI	93 b	71 b	55 b	35 b
Trifluralin + *S*-metolachlor + halosulfuron	840 + 1373 + 35	PPI	98 ab	96 ab	92 ab	87 a
Bentazon + fomesafen + quizalofop-p-ethyl	840 + 240 + 48	POST	0 c	97 ab	97 a	97 a
Trifluralin + *S*-metolachlor + imazethapyr + bentazon + fomesafen + quizalofop-p-ethyl	840 + 1373 + 45 + 840 + 240 + 48	PPI + POST	95 b	99 a	99 a	97 a
Trifluralin + *S*-metolachlor + halosulfuron + bentazon + fomesafen + quizalofop-p-ethyl	840 + 1373 + 35 + 840 + 240 + 48	PPI + POST	97 ab	100 a	99 a	99 a
Contrast						
1-pass *vs* 2-pass			-	90 *vs* 100*	85 *vs* 99*	77 *vs* 98*

Note. Means within a column followed by the same lowercase letter do not differ significantly according to Tukey's HSD at P < 0.05.

* and ** denote significance at P < 0.05 and P < 0.001, respectively.

Abbreviations: POST, postemergence up to 5 cm weed escapes and prior to white bean flowering; PPI, preplant incorporated.

3.4 Common Lambsquarters

Trifluralin + *S*-metolachlor + imazethapyr, applied PPI, controlled common lambsquarters 99, 98, 97, and 96% at 0, 2, 4, and 8 WAT, respectively (Table 4). Trifluralin + *S*-metolachlor + halosulfuron, applied PPI, controlled common lambsquarters 99, 97, 95, and 94% at 0, 2, 4, and 8 WAT, respectively (Table 4). Bentazon + fomesafen + quizalofop-p-ethyl, applied POST, controlled common lambsquarters 42, 36, and 34% at 2, 4, and 8 WAT, respectively (Table 4). Trifluralin + *S*-metolachlor + imazethapyr, applied PPI, followed by bentazon + fomesafen + quizalofop-p-ethyl, applied POST, controlled common lambsquarters 99, 99, 97, and 96% at 0, 2, 4, and 8 WAT, respectively (Table 4). Trifluralin + *S*-metolachlor + halosulfuron, applied PPI, followed by bentazon + fomesafen + quizalofop-p-ethyl, applied POST, controlled common lambsquarters 98, 99, 98, and 97% at 0, 2, 4, and 8 WAT, respectively (Table 4). Based on orthogonal contrasts, two-pass herbicide programs provided 14, 16, and 20% greater control of common lambsquarters in comparison to the one-pass herbicide programs, at 2, 4 and 8 WAT, respectively (Table 4). Results are similar to other studies in which herbicide mixtures of trifluralin + *S*-metolachlor with halosulfuron, imazethapyr and halosulfuron + imazethapyr applied PPI provided 100% control of common lambsquarters in white bean (Soltani et al., 2021). In another study, trifluralin + halosulfuron applied PPI provided 95-99% control of common lambsquarters in white bean (Soltani et al., 2020a). Li et al. (2016) reported ≥ 98% control of common lambsquarters in white bean with halosulfuron + trifluralin applied PPI. Soltani et al. (2020b) found 99-100% control common lambsquarters with trifluralin + halosulfuron and *S*-metolachlor + halosulfuron applied PPI in white bean. In another study, bentazon + fomesafen and halosulfuron + bentazon + fomesafen applied POST controlled common lambsquarters 91-93 and 97-98% in white bean, respectively (Soltani et al., 2013a). Wilson (2005) reported 97% control of common lambsquarters with fomesafen plus imazamox applied POST in dry bean. Bailey et al. (2003) observed > 90% control of common lambsquarters with fomesafen and fomesafen plus bentazon in snap bean. The sequential application of a PPI herbicide (pendimethalin) followed by bentazon, fomesafen, bentazon plus fomesafen, or halosulfuron applied POST controlled common lambsquarters 99, 87, 92, and 83% in white bean, respectively (Soltani et al., 2013b).

Table 4. Visible common lambsquarters control for PPI, POST, or two-pass herbicide programs from four experiments conducted at Ridgetown, Ontario in 2022 and 2023 (n = 4)

Herbicide treatment	Rate	Timing	Common lambsquarters control			
			0 WAT	2 WAT	4 WAT	8 WAT
	g ai ha^{-1}		---------------------- % ----------------------			
Weed-free control			100 a	100 a	100 a	100 a
Non-treated control			0 c	0 c	0 c	0 c
Trifluralin + *S*-metolachlor + imazethapyr	840 + 1373 + 45	PPI	99 ab	98 a	97 a	96 a
Trifluralin + *S*-metolachlor + halosulfuron	840 + 1373 + 35	PPI	99 ab	97 a	95 a	94 a
Bentazon + fomesafen + quizalofop-p-ethyl	840 + 240 + 48	POST	0 c	42 b	36 b	34 b
Trifluralin + *S*-metolachlor + imazethapyr + bentazon + fomesafen + quizalofop-p-ethyl	840 + 1373 + 45 + 840 + 240 + 48	PPI + POST	99 ab	99 a	97 a	96 a
Trifluralin + *S*-metolachlor + halosulfuron + bentazon + fomesafen + quizalofop-p-ethyl	840 + 1373 + 35 + 840 + 240 + 48	PPI + POST	98 b	99 a	98 a	97 a
Contrast						
1-pass *vs* 2-pass			-	85 *vs* 99*	82 *vs* 98*	79 *vs* 97*

Note. Means within a column followed by the same lowercase letter do not differ significantly according to Tukey's HSD at P < 0.05.

* and ** denote significance at P < 0.05 and P < 0.001, respectively.

Abbreviations: POST, postemergence up to 5 cm weed escapes and prior to white bean flowering; PPI, preplant incorporated.

3.5 Green Foxtail

Trifluralin + *S*-metolachlor + imazethapyr, applied PPI, controlled green foxtail 91, 87, 84, and 80% at 0, 2, 4, and 8 WAT, respectively (Table 5). Trifluralin + *S*-metolachlor + halosulfuron, applied PPI, controlled green foxtail 89, 84, 72, and 56% at 0, 2, 4, and 8 WAT, respectively (Table 4). Bentazon + fomesafen + quizalofop-p-ethyl, applied POST, controlled green foxtail 58, 46, and 29% at 2, 4, and 8 WAT, respectively (Table 5). Trifluralin + *S*-metolachlor + imazethapyr, applied PPI, followed by bentazon + fomesafen + quizalofop-p-ethyl, applied POST, controlled green foxtail 92, 97, 96, and 94% at 0, 2, 4, and 8 WAT, respectively (Table 5). Trifluralin + *S*-metolachlor + halosulfuron, applied PPI, followed by bentazon + fomesafen + quizalofop-p-ethyl, applied POST, controlled green foxtail 89, 97, 96, and 93% at 0, 2, 4, and 8 WAT, respectively (Table 5). Based on orthogonal contrasts, two-pass herbicide programs provided 20, 28, and 38% greater control of green foxtail in comparison to the one-pass herbicide programs, at 2, 4, and 8 WAT, respectively (Table 5). Results are similar to other studies in which the mixtures of trifluralin + *S*-metolachlor with halosulfuron, imazethapyr, and halosulfuron + imazethapyr applied PPI provided 97-98, 98-99, and 98-99% control of green foxtail in white bean, respectively (Soltani et al., 2021). Soltani et al. (2020a) reported 93-98% control of green foxtail with trifluralin + halosulfuron applied PPI in white bean. Additionally, Li et al. (2016) observed 93% control of green foxtail in white bean with halosulfuron + trifluralin applied PPI. In another study, trifluralin + halosulfuron and *S*-metolachlor + halosulfuron applied PPI provided 94-95% control of green foxtail in white bean (Soltani et al., 2020b). In addition, two-pass programs of pendimethalin applied PPI followed by bentazon, fomesafen, bentazon plus fomesafen, or halosulfuron applied POST controlled green foxtail as much as 94, 97, 94, and 96% in white bean, respectively (Soltani et al., 2013b).

Table 5. Visible green foxtail control for PPI, POST, or two-pass herbicide programs from four experiments conducted at Ridgetown, Ontario in 2022 and 2023 (n = 4)

Herbicide treatment	Rate	Timing	Green foxtail control			
			0 WAT	2 WAT	4 WAT	8 WAT
	g ai ha^{-1}		---------------------- % ----------------------			
Weed-free control			100 a	100 a	100 a	100 a
Non-treated control			0 c	0 c	0 d	0 d
Trifluralin + *S*-metolachlor + imazethapyr	840 + 1373 + 45	PPI	91 b	87 ab	84 abc	80 abc
Trifluralin + *S*-metolachlor + halosulfuron	840 + 1373 + 35	PPI	89 b	84 ab	72 bc	56 bc
Bentazon + fomesafen + quizalofop-p-ethyl	840 + 240 + 48	POST	0 c	58 b	46 c	29 c
Trifluralin + *S*-metolachlor + imazethapyr + bentazon + fomesafen + quizalofop-p-ethyl	840 + 1373 + 45 + 840 + 240 + 48	PPI + POST	92 b	97 a	96 ab	94 ab
Trifluralin + *S*-metolachlor + halosulfuron + bentazon + fomesafen + quizalofop-p-ethyl	840 + 1373 + 35 + 840 + 240 + 48	PPI + POST	89 b	97 a	96 ab	93 ab
Contrast						
1-pass *vs* 2-pass			-	77 *vs* 97*	68 *vs* 96*	55 *vs* 93*

Note. Means within a column followed by the same lowercase letter do not differ significantly according to Tukey's HSD at $P < 0.05$.

* and ** denote significance at $P < 0.05$ and $P < 0.001$, respectively.

Abbreviations: POST, postemergence up to 5 cm weed escapes and prior to white bean flowering; PPI, preplant incorporated.

4. Conclusions

Trifluralin + *S*-metolachlor + imazethapyr or trifluralin + *S*-metolachlor + halosulfuron applied PPI, bentazon + fomesafen + quizalofop-p-ethyl applied POST, and trifluralin + *S*-metolachlor + imazethapyr or trifluralin + *S*-metolachlor + halosulfuron applied PPI followed by bentazon + fomesafen + quizalofop-p-ethyl applied POST caused minimal white bean injury. Weed interference with one-pass herbicide programs decreased white bean yield 17% compared to the two-pass herbicide programs (PPI fb POST).

Weed control with the herbicide programs evaluated was weed species-specific. Velvetleaf was controlled the best (≥ 97%) with trifluralin + *S*-metolachlor + imazethapyr or trifluralin + *S*-metolachlor + halosulfuron applied PPI followed by bentazon + fomesafen + quizalofop-p-ethyl applied POST.

Common ragweed was best controlled (≥ 97%) with bentazon + fomesafen + quizalofop-p-ethyl applied POST and trifluralin + *S*-metolachlor + imazethapyr or trifluralin + *S*-metolachlor + halosulfuron applied PPI followed by bentazon + fomesafen + quizalofop-p-ethyl applied POST.

Common lambsquarters was controlled ≥94% with trifluralin + *S*-metolachlor + imazethapyr or trifluralin + *S*-metolachlor + halosulfuron applied PPI and when followed by bentazon + fomesafen + quizalofop-p-ethyl applied POST.

Green foxtail was controlled the best (≥ 93%) with trifluralin + *S*-metolachlor + imazethapyr or trifluralin + *S*-metolachlor + halosulfuron applied PPI followed by bentazon + fomesafen + quizalofop-p-ethyl applied POST.

In summary, the two-pass herbicide programs of trifluralin + *S*-metolachlor + imazethapyr or trifluralin + *S*-metolachlor + halosulfuron applied PPI followed by bentazon + fomesafen + quizalofop-p-ethyl applied POST can be utilized to effectively manage a wide range of common annual grass and broadleaf weeds in Ontario. Combining herbicides with diverse modes of action can help mitigate the selection pressure that drives the evolution of herbicide-resistant weeds.

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Drs. Peter Sikkema and Nader Soltani were responsible for the study design and writing of this manuscript. Christy Shropshire conducted the statistical analysis of the data collected.

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