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Broadleaf Weed Control with Halosulfuron Tankmixes in White Bean

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Abstract

Six field trials were conducted over a four-year (2017-2020) period near Exeter and Ridgetown, Ontario to determine the efficacy of halosulfuron tankmixes applied postemergence to control broadleaf weeds in white bean. Halosulfuron caused up to 4% injury in white bean at 2 and 4 weeks after treatment (WAT). Bentazon, acifluorfen, fomesafen, bentazon/acifluorfen, and bentazon + fomesafen caused 2% - 16% injury at 2 WAT and up to 3% injury at 4 WAT in white bean. The addition of halosulfuron to the aforementioned herbicides did not accentuate white bean injury. Reduced weed interference with the herbicides evaluated increased white been yield 50% - 90% compared to the weedy control; there was no difference in seed yield among herbicide treatments evaluated. At 4 WAT, halosulfuron at 25, 37.5 and 50 g ai ha^{-1} controlled velvetleaf 86%, 93% and 97%; redroot pigweed 83%, 85% and 89%; common ragweed 90%, 93% and 94%; common lambsquarters 27%, 28% and 36%; flower-of-an-hour 66%, 76% and 69%; and wild mustard 100%, 100% and 100%, respectively. Bentazon, acifluorfen, fomesafen, bentazon/acifluorfen, and bentazon + fomesafen controlled velvetleaf 73%, 14%, 52%, 42% and 68%; redroot pigweed 40%, 91%, 85%, 75% and 80%; common ragweed 36%, 81%, 92%, 68% and 84%; common lambsquarters 87%, 39%, 48%, 60% and 76%; flower-of-an-hour 90%, 66%, 63%, 73% and 83%; and wild mustard 97%, 97%, 100%, 99% and 100%, respectively. Halosulfuron tankmixed with bentazon, acifluorfen, fomesafen, bentazon/acifluorfen or bentazon + fomesafen controlled velvetleaf 90%, 51%, 68%, 75% and 90%; redroot pigweed 80%, 99%, 95%, 92% and 91%; common ragweed up to 94%, 97%, 93%, 94% and 95%; common lambsquarters 74%, 62%, 43%, 62% and 66%; flower-of-an-hour 92%, 78%, 74%, 82% and 87%; and wild mustard 100%, 100%, 100%, 100% and 100%, respectively. Weed density and dry biomass followed the same trend. This study concludes that the optimal halosulfuron tankmix is broadleaf weed species specific for weed management in dry bean production.

Keywords

Accentuated Injury, Maturity, Broadleaf Weeds, Yield, White Bean, *Phaseolus vulgaris* L.

1. Introduction

White (navy) bean (*Phaseolus vulgaris* L.) is a small-seeded market class of dry bean that is native to the Americas, where it was first domesticated [1]. White bean with its ample nutritious content has served as a staple food for many people around the world over the years [2]. White bean is a relatively small plant and produces seeds that are oval and flattened in shape and are smaller in size than the seed of many other market classes of dry bean [1]. White bean is the most commonly grown market class of dry bean in Ontario and represents nearly 50% of the dry bean produced in the province [1]. In 2019, white bean producers in Ontario seeded nearly 27,000 ha and produced 56,000,000 kg of white bean with a farm gate value of approximately $46,000,000 [3]. The short physical stature of white bean plants makes the crop sensitive to weed interference. A series of studies conducted by the Weed Science Society of America (WSSA) have concluded that there is an average dry bean yield loss of 71% when weeds were left uncontrolled which was considerably higher than corn (50), soybean (52%) and winter wheat (23%) [4] [5] [6] [7]. Currently, white bean producers have a limited number of herbicides, especially postemergence (POST) herbicides for broadleaf weed control in white bean [8]. Research is needed to identify the optimal herbicide options applied postemergence for broadleaf weed control in white bean [8].

Halosulfuron is a Group 2 sulfonylurea herbicide that inhibits the acetolactate synthase enzyme which is needed for valine, leucine and isoleucine amino acid synthesis in plants [9]. Halosulfuron can control several problematic weeds such as yellow nutsedge (*Cyperus esculentus* L.), velvetleaf (*Abutilon theophrasti* Medic.), redroot pigweed (*Amaranthus retroflexus* L.), common ragweed (*Ambrosia artemisiifolia* L.), common lambsquarters (*Chenopodium album* L.), and wild mustard (*Sinapis arvensis* L.), including Group 5 biotypes [8] [10]. Halosulfuron is active at low rates and has a favorable environmental profile [8] [10].

Bentazon is a POST herbicide from Group 6 (benzothiadiazole) that binds in the place of plastoquinone in photosystem II which results in cell membrane destruction and plant death [10]. Bentazon controls some annual broadleaf weeds such as common lambsquarters, wild mustard and cocklebur (*Xanthium strumarium* L.), including Group 2 and 5 resistant biotypes [10].

Acifluorfen is a POST herbicide from Group 14 (diphenyl ether) that inhibits protoporphyrinogen oxidase (PPO or Protox), needed for the chlorophyll and heme synthesis and can control some broadleaf weeds such as redroot pigweed, common ragweed, wild mustard, ladystumb (*Polygonum persicaria* L.), eastern black nightshade (*Solanum spp.*) and jimsonweed (*Datura stramonium* L.) [8] [10].

Fomesafen is a POST herbicide from Group 14 (diphenyl ether) that inhibits protoporphyrinogen IX oxidase (PPO) and can control annual broadleaf weeds such as pigweeds, common ragweed, mustards, lady's thumb and annual nightshades [11] [12].

Presently, bentazon, fomesafen and halosulfuron are the only POST herbicides registered for broadleaf weed control in white bean. These herbicides, applied individually, do not provide broad-spectrum control of annual broadleaf weeds in dry beans in Ontario. Halosulfuron in combination bentazon, acifluorfen, fomesafen, bentazon/acifluorfen or bentazon + fomesafen applied POST will increase the spectrum of broadleaf weeds controlled in dry bean production. There is limited information about crop safety and weed control efficacy of these halosulfuron tankmixes in white bean production. The objective of this research was to determine the efficacy of various halosulfuron tankmixes applied POST for the control of annual broadleaf weeds in white bean.

2. Materials and Methods

Six field experiments were established at the Huron Research Station (one in 2017, 2018, 2019 and 2020), Exeter, Ontario (43˚19'1.21"N, 81˚30'3.87"E) and University of Guelph Ridgetown Campus (one in 2019 and 2020), Ridgetown, Ontario (42˚26'26"N, 81˚53'3"W). The soil at Exeter was a Brookston clay loam (Orthic Humic Gleysol, mixed, mesic, and poorly drained) and the soil at the Ridgetown location was a Watford/Brady sandy loam. Seedbed preparation at all sites consisted of fall moldboard plowing followed by seedbed preparation in the spring with a field cultivator with rolling basket harrows.

The experiments were established as a completely randomized block design with four replications. Treatments included a weedy and weed-free control, and halosulfuron at three rates (25, 37.5 and 50 g ai ha^{-1}), bentazon (1080 g ai ha^{-1}), acifluorfen (600 g ai ha^{-1}), fomesafen (240 g ai ha^{-1}), bentazon/acifluorfen (840 g ai ha^{-1}), bentazon + fomesafen (840 + 140 g ai ha^{-1}), halosulfuron + bentazon (1080 + 37.5 g ai ha^{-1}), halosulfuron + acifluorfen (600 + 37.5 g ai ha^{-1}), halosulfuron + fomesafen (240 + 37.5 g ai ha^{-1}), halosulfuron + bentazon/acifluorfen (840 + 37.5 g ai ha^{-1}), and halosulfuron + bentazon + fomesafen (840 + 140 + 37.5 g ai ha^{-1}). All treatments that included halosulfuron had a non-ionic surfactant at 0.25% v/v. Fomesafen included Turbocharge® at 0.5% v/v and bentazon/acifluorfen included Assist® at 1.5 L ha^{-1}. Plots were 3 m wide (4 rows of white bean spaced 0.75 m apart at a seeding rate of 250,000 seed ha^{-1}) and 10 m long at Exeter and 8 m long at Ridgetown.

Herbicides were applied POST at the 2 - 3 trifoliate leaf stage with a CO_2-pressurized backpack sprayer calibrated to deliver 200 L ha^{-1} of spray solution at a pressure of 240 kPa using low drift nozzles (ULD120-02, Spraying Systems Co., P.O. Box 7900. Wheaton, IL 60188). The spray boom was 1.5 m wide with four nozzles spaced 0.5 m apart producing a spray width of 2.0 m.

Crop injury [2 and 4 weeks after treatment (WAT)] and weed control (4 and 8 WAT) were evaluated on a scale of 0 (no injury/control) to 100% (complete plant death). Weed density and dry biomass were determined 4 WAT by counting and harvesting weeds from two 0.5 m^2 quadrats per plot separated by weed species present. Dry biomass was recorded by drying harvested weeds in an oven at 60 C for a minimum of 48 hours. White bean was combined at harvest maturity from the two center rows of each plot with a small plot combine. White bean yield was adjusted to 18% moisture.

The GLIMMIX procedure in SAS (Ver. 9.4, SAS Institute Inc., Cary, NC) was used for data analysis. For the generalized linear mixed model, herbicide treatment was the fixed effect and environment (year-location combinations), environment by treatment interaction and replicate within environment were the random effects; environments were combined for analysis. Distributions for each parameter were evaluated and the one which best met the assumptions of analysis was selected. The assumption of variance homogeneity was confirmed by visual inspection of studentized residual plots and normality was checked using the Shapiro-Wilk statistic and normal probability plot for each parameter. The Poisson distribution was used for white bean injury 2 WAT and the Gaussian distribution was used for white bean injury 4 WAT, velvetleaf and flower-of-an-hour control 4 and 8 WAT, wild mustard control 4 WAT and white bean yield. Redroot pigweed, common ragweed and lambsquarters control 4 and 8 WAT was arcsine square root transformed prior to analysis with the Gaussian distribution. The lognormal distribution was used for wild mustard control 8 WAT, density and dry weight for all weed species and white bean moisture at harvest. Pairwise comparisons of least square means, performed on the model scale, were adjusted using the Tukey-Kramer method prior to determining treatment differences at $P < 0.05$. Where the model and data scale differed, the inverse link function or a back-transformation was used to convert least square means to the data scale for presentation. Treatments were excluded from the analysis if they had zero variance across all environments, including the weedy and weed-free controls for crop injury and weed control, the weed-free control for weed density and dry weight, as well as certain herbicide treatments for wild mustard control, density and dry weight. If an excluded treatment had a value of zero, comparisons with other means were still possible using the p-value produced in the LSMEANS table.

3. Results and Discussion

3.1. White Bean Injury and Yield

Halosulfuron at 25, 37.5 and 50 g ai ha^{-1} applied POST caused 2%, 3% and 4% white bean injury at 2 WAT, respectively; the injury was transient with no injury at 4 WAT (**Table 1**). Bentazon, acifluorfen, fomesafen, bentazon/acifluorfen, and bentazon + fomesafen caused 2%, 13%, 5%, 16% and 4% white bean injury

Table 1. Visible injury 2 and 4 WAT, percent moisture at maturity and yield of white bean treated with halosulfuron tankmixes applied POST at Exeter (2017-2020) and Ridgetown (2019-2020). Means followed by a different letter within a column are significantly different according to a Tukey-Kramer multiple range test at $P < 0.05$.[a]

Treatment[b]	Rate	Injury (%)		Moisture (%)	Yield (T ha^{-1})
	(g a.i. ha^{-1})	2 WAT	4 WAT[c]		
Weed-free control		0 a	0 a	16.6 a	2.85 a
Weedy control		0 a	0 a	18.1 b	1.15 c
Halosulfuron	25	2 b	0 a	17.9 b	1.83 b
Halosulfuron	37.5	3 b	0 a	17.8 b	1.87 b
Halosulfuron	50	4 b	0 a	17.4 ab	1.95 b
Bentazon	1080	2 b	0 a	18.0 b	1.84 b
Acifluorfen	600	13 de	2 ab	17.8 b	1.74 b
Fomesafen[d]	240	5 bc	0 a	17.4 ab	2.02 b
Bentazon/acifluorfen[e]	840	16 e	3 b	17.6 b	1.88 b
Bentazon + fomesafen	840 + 140	4 b	0 a	17.5 ab	2.04 b
Halosulfuron + bentazon	1080 + 37.5	3 b	0 a	17.5 ab	2.19 b
Halosulfuron + acifluorfen	600 + 37.5	16 e	2 ab	17.5 ab	2.12 b
Halosulfuron + fomesafen	240 + 37.5	6 bcd	1 ab	17.5 ab	2.04 b
Halosulfuron + bentazon/acifluorfen	840 + 37.5	12 cde	2 ab	17.6 ab	2.09 b
Halosulfuron + bentazon + fomesafen	840 + 140 + 37.5	5 bc	1 ab	17.4 ab	2.25 b

[a]Abbreviations: POST, postemergence; WAT, weeks after herbicide application. [b]All halosulfuron treatments included non-ionic surfactant (0.25% v/v). [c]Zero injury for Exeter (2017-2018); only Exeter and Ridgetown (2019-2020) were analyzed. [d]Included Turbocharge (0.5% v/v). [e]Included Assist (1.5 l ha^{-1}).

at 2 WAT and 0, 2%, 0, 3% and 0% white bean injury at 4 WAT, respectively. The addition of halosulfuron to bentazon, acifluorfen, fomesafen, bentazon/acifluorfen or bentazon + fomesafen did not exacerbate white bean injury and caused 3%, 16%, 6%, 12% and 5% injury at 2 WAT, and 0, 2%, 1%, 2%, and 1% injury at 4 WAT, respectively (**Table 1**). Responses with herbicides evaluated have been variable in other studies. Halosulfuron applied POST at 35 and 70 g ai ha^{-1} was shown to caused 5% injury in white bean [13] but caused no visible injury or yield reduction in other studies [14] [15]. VanGessel *et al.* [16] reported as much as 20% injury with bentazon in dry bean, but as little as 3% visible injury was reported in another study [17].

Weed interference reduced white bean yield 60% (**Table 1**). Reduced weed interference with the herbicides evaluated increased white been yield 50% - 90% compared to the weedy control, but white bean yield was still less than the weed-free control by 21% - 39%. There was no difference in white bean seed yield among herbicide treatments evaluated (**Table 1**). Wall [18] found a 21% yield reduction in seed yield with bentazon applied POST, but Blackshaw *et al.* [19] and Burnside *et al.* [20] found no yield reduction with bentazon applied POST in dry bean. Minimal injury and no adverse effects on seed yields were reported by other studies with POST application of halosulfuron, bentazon and fomesafen in dry bean [11] [14] [21].

3.2. Velvetleaf

Halosulfuron at 25, 37.5 and 50 g ai ha^{-1} applied POST controlled velvetleaf 86%, 93% and 97% at 4 WAT and 78%, 87% and 92% at 8 WAT, respectively (Table 2). Bentazon, acifluorfen, fomesafen, bentazon/acifluorfen, and bentazon + fomesafen controlled velvetleaf 73%, 14%, 52%, 42% and 68% at 4 WAT and 72%, 15%, 48%, 38% and 62% at 8 WAT, respectively. The addition of halosulfuron to bentazon, acifluorfen, fomesafen, bentazon/acifluorfen, or bentazon + fomesafen numerically improved velvetleaf control to 90%, 51%, 68%, 75% and 90% at 4 WAT, and 86%, 49%, 63%, 69% and 86% at 8 WAT, respectively (Table 2). Halosulfuron (37.5 and 50 g ai ha^{-1}), bentazon, bentazon + fomesafen, halosulfuron + fomesafen, halosulfuron + bentazon/acifluorfen and halosulfuron + bentazon +

Table 2. Percent visible control 4 and 8 WAT, density and dry weight of velvetleaf treated with halosulfuron tankmixes applied POST at Ridgetown (2019-2020). Means followed by a different letter within a column are significantly different according to a Tukey-Kramer multiple range test at $P < 0.05$[a].

Treatment[b]	Rate	Control (%)			
		4 WAT	8 WAT	Density	Dry weight
	(g a.i. ha^{-1})			(plants m^{-2})	(g m^{-2})
Weed-free control		100	100	0 a	0 a
Weedy control		0 d	0 d	5.0 c	7.5 c
Halosulfuron	25	86 ab	78 ab	1.3 abc	0.5 ab
Halosulfuron	37.5	93 a	87 a	0.5 ab	0.1 ab
Halosulfuron	50	97 a	92 a	0.6 ab	0.1 ab
Bentazon	1080	73 ab	72 ab	1.0 ab	0.2 ab
Acifluorfen	600	14 cd	15 cd	2.8 bc	5.5 c
Fomesafen[c]	240	52 abc	48 abc	1.7 bc	2.0 bc
Bentazon/acifluorfen[d]	840	42 bc	38 bc	2.4 bc	2.7 bc
Bentazon + fomesafen	840 + 140	68 ab	62 abc	0.8 ab	1.0 ab
Halosulfuron + bentazon	1080 + 37.5	90 a	86 ab	1.9 bc	0.7 ab
Halosulfuron + acifluorfen	600 + 37.5	51 abc	49 abc	1.5 bc	1.1 bc
Halosulfuron + fomesafen	240 + 37.5	68 ab	63 abc	0.9 ab	0.7 ab
Halosulfuron+ entazon/acifluorfen	840 + 37.5	75 ab	69 ab	0.7 ab	0.2 ab
Halosulfuron + bentazon + omesafen	840 + 140 + 37.5	90 a	86 ab	0.7 ab	0.1 ab

[a]Abbreviations: POST, postemergence; WAT, weeks after herbicide application. [b]All halosulfuron treatments included non-ionic surfactant (0.25% v/v). [c]Included Turbocharge (0.5% v/v). [d]Included Assist (1.5 l ha^{-1}).

fomesafen reduced velvetleaf density 90%, 88%, 80%, 84%, 82%, 86% and 86%, respectively. Other treatments evaluated resulted in velvetleaf density that was similar to the weedy control (**Table 2**). Halosulfuron (25, 37.5 and 50 g ai ha^{-1}), bentazon, bentazon + fomesafen, halosulfuron + bentazon, halosulfuron + fomesafen, halosulfuron + bentazon/acifluorfen and halosulfuron + bentazon + fomesafen reduced velvetleaf dry biomass 90%, 98%, 98%, 96%, 80%, 86%, 86%, 96% and 98%, respectively. Other herbicide treatments resulted in velvetleaf dry biomass that was similar to the weedy control (**Table 2**).

3.3. Redroot Pigweed

Halosulfuron at 25, 37.5 and 50 g ai ha^{-1} applied POST controlled redroot pigweed 83%, 85% and 89% at 4 WAT and 72%, 79% and 83% at 8 WAT, respectively (**Table 3**). Bentazon, acifluorfen, fomesafen, bentazon/acifluorfen, and bentazon + fomesafen controlled redroot pigweed 40%, 91%, 85%, 75% and 80% at 4 WAT and 31%, 85%, 81%, 63% and 72% at 8 WAT, respectively. The addition of halosulfuron to bentazon, acifluorfen, fomesafen, bentazon/acifluorfen or bentazon + fomesafen numerically improved redroot pigweed control to 80%, 99%, 95%, 92% and 91% at 4 WAT, and 74%, 96%, 91%, 88% and 89% at 8 WAT, respectively (**Table 3**). Acifluorfen, fomesafen, halosulfuron + acifluorfen, halosulfuron + fomesafen, halosulfuron + bentazon/acifluorfen and halosulfuron + bentazon + fomesafen reduced redroot pigweed density 58%, 67%, 92%, 56%, 64% and 67%, respectively. Other treatments resulted in redroot pigweed density that was similar to the weedy control. Herbicide treatments evaluated reduced redroot pigweed dry biomass 71% - 97% except bentazon which resulted in redroot pigweed dry biomass that was similar to the weedy control (**Table 3**). Halosulfuron + acifluorfen reduced redroot pigweed biomass 97% which was similar to the weed-free control. Results are similar to other studies in which halosulfuron, bentazon and fomesafen applied POST controlled redroot pigweed 54% - 100%, 54% - 76%, and 85% - 99% in white bean, respectively [14] [21].

3.4. Common Ragweed

Halosulfuron at 25, 37.5 and 50 g ai ha^{-1} applied POST controlled common ragweed 90%, 93% and 94% at 4 WAT and 84%, 90% and 92% at 8 WAT, respectively (**Table 4**). Bentazon, acifluorfen, fomesafen, bentazon/acifluorfen, and bentazon + fomesafen controlled common ragweed 36%, 81%, 92%, 68% and 84% at 4 WAT and 25%, 67%, 88%, 58% and 78% at 8 WAT, respectively. The addition of halosulfuron to bentazon, acifluorfen, fomesafen, bentazon/acifluorfen or bentazon + fomesafen numerically improved common ragweed control to 94%, 97%, 93%, 94% and 95% at 4 WAT, and 91%, 94%, 90%, 88% and 91% at 8 WAT, respectively (**Table 4**). Halosulfuron at 25, 37.5 and 50 g ai ha^{-1}, fomesafen, halosulfuron + bentazon, halosulfuron + acifluorfen, halosulfuron + fomesafen, halosulfuron + bentazon/acifluorfen and halosulfuron +

Table 3. Percent visible control 4 and 8 WAT, density and dry weight of redroot pigweed treated with halosulfuron tankmixes applied POST at Exeter (2017-2020) and Ridgetown (2019-2020). Means followed by a different letter within a column are significantly different according to a Tukey-Kramer multiple range test at P < 0.05[a].

Treatment[b]	Rate	Control (%)			
		4 WAT	8 WAT	Density	Dry weight
	(g a.i. ha^{-1})			(plants m^{-2})	($g{\cdot}m^{-2}$)
Weed-free control		100	100	0 a	0 a
Weedy control		0 e	0 e	36 d	82.5 f
Halosulfuron	25	83 bc	72 bc	30 cd	23.4 de
Halosulfuron	37.5	85 abc	79 bc	35 cd	22.5 de
Halosulfuron	50	89 abc	83 abc	18 cd	12.4 cd
Bentazon	1080	40 d	31 d	29 cd	65.8 ef
Acifluorfen	600	91 abc	85 abc	15 c	7.5 bcd
Fomesafen[c]	240	85 abc	81 abc	12 c	6.8 bcd
Bentazon/acifluorfen[d]	840	75 c	63 c	21 cd	17.8 cd
Bentazon + fomesafen	840 + 140	80 bc	72 bc	25 cd	23.9 de
Halosulfuron + bentazon	1080 + 37.5	80 bc	74 bc	30 cd	22.1 cd
Halosulfuron + acifluorfen	600 + 37.5	99 a	96 a	3 b	2.5 ab
Halosulfuron + fomesafen	240 + 37.5	95 ab	91 ab	16 c	5.5 bc
Halosulfuron + entazon/acifluorfen	840 + 37.5	92 abc	88 ab	13 c	8.2 bcd
Halosulfuron + bentazon + fomesafen	840 + 140 + 37.5	91 abc	89 ab	12 c	6.1 bcd

[a]Abbreviations: POST, postemergence; WAT, weeks after herbicide application. [b]All halosulfuron treatments included non-ionic surfactant (0.25% v/v). [c]Included Turbocharge (0.5% v/v). [d]Included Assist (1.5 l ha^{-1}).

bentazon + fomesafen reduced common ragweed density 75%, 85%, 84%, 78%, 88%, 81%, 79%, 75% and 84%, respectively. Other treatments resulted in common ragweed density that was similar to the weedy control (**Table 4**). Halosulfuron at 25, 37.5 and 50 g ai ha^{-1}, acifluorfen, fomesafen, bentazon/acifluorfen, bentazon + fomesafen, halosulfuron + bentazon, halosulfuron + acifluorfen, halosulfuron + fomesafen, halosulfuron + bentazon/acifluorfen and halosulfuron + bentazon + fomesafen reduced common ragweed biomass 72% - 98%; bentazon was the only herbicide that did not reduce common ragweed biomass. (**Table 4**). In other studies, halosulfuron applied POST provided 91% - 99% control of common ragweed in white bean [14] [15]. Bentazon applied POST provided 50% - 66% control of common ragweed in white bean [14] [15]. Fomesafen applied POST provided 90% - 98% control of common ragweed in white bean [11] [14].

Table 4. Percent visible control 4 and 8 WAT, density and dry weight of common ragweed treated with halosulfuron tankmixes applied POST at Exeter (2017, 2019) and Ridgetown (2019-2020). Means followed by a different letter within a column are significantly different according to a Tukey-Kramer multiple range test at P < 0.05[a].

Treatment[b]	Rate	Control (%)			
		4 WAT	8 WAT	Density	Dry weight
	(g a.i. ha^{-1})			(plants m^{-2})	($g{\cdot}m^{-2}$)
Weed-free control		100	100	0 a	0 a
Weedy control		0 d	0 d	18.5 d	28.2 e
Halosulfuron	25	90 ab	84 ab	4.7 bc	1.0 abc
Halosulfuron	37.5	93 ab	90 a	2.8 b	0.5 ab
Halosulfuron	50	94 ab	92 a	3.0 bc	2.0 bcd
Bentazon	1080	36 c	25 c	9.5 cd	9.6 de
Acifluorfen	600	81 ab	67 ab	13.4 cd	5.9 bcd
Fomesafen[c]	240	92 ab	88 ab	4.1 bc	1.3 abc
Bentazon/acifluorfen[d]	840	68 bc	58 bc	11.0 cd	7.8 cd
Bentazon + fomesafen	840 + 140	84 ab	78 ab	7.1 cd	3.8 bcd
Halosulfuron + bentazon	1080 + 37.5	94 ab	91 a	2.2 b	0.5 ab
Halosulfuron + acifluorfen	600 + 37.5	97 a	94 a	3.6 bc	0.7 ab
Halosulfuron + fomesafen	240 + 37.5	93 ab	90 a	3.8 bc	1.3 abc
Halosulfuron + bentazon/acifluorfen	840 + 37.5	94 ab	88 ab	4.7 bc	1.7 bcd
Halosulfuron + bentazon + fomesafen	840 + 140 + 37.5	95 ab	91 a	3.0 bc	0.7 ab

[a]Abbreviations: POST, postemergence; WAT, weeks after herbicide application. [b]All halosulfuron treatments included non-ionic surfactant (0.25% v/v). [c]Included Turbocharge (0.5% v/v). [d]Included Assist (1.5 l ha^{-1}).

3.5. Common Lambsquarters

Halosulfuron at 25, 37.5 and 50 g ai ha^{-1} applied POST controlled common lambsquarters 27%, 28% and 36% at 4 WAT and 18%, 21% and 27% at 8 WAT, respectively (Table 5). Bentazon, acifluorfen, fomesafen, bentazon/acifluorfen, and bentazon + fomesafen controlled common lambsquarters 87%, 39%, 48%, 60% and 76% at 4 WAT and 85%, 28%, 39%, 53% and 72% at 8 WAT, respectively. The addition of halosulfuron to bentazon, acifluorfen, fomesafen, bentazon/acifluorfen or bentazon + fomesafen controlled common lambsquarters 74%, 62%, 43%, 62% and 66% at 4 WAT, and 67%, 49%, 32%, 52% and 60% at 8 WAT, respectively (Table 5). Bentazon reduced common lambsquarters density 66% and tankmixes/premixes of bentazon with acifluorfen, fomesafen, halosulfuron, halosulfuron + acifluorfen and halosulfuron + fomesafen reduced common lambsquarters density 37% - 53%, but other herbicide treatments resulted in common lambsquarters density that was similar to the weedy control (Table 5). Similarly, herbicide treatments that included bentazon reduced common

Table 5. Percent visible control 4 and 8 WAT, density and dry weight of common lambsquarters treated with halosulfuron tankmixes applied POST at Exeter (2017-2020) and Ridgetown (2019-2020). Means followed by a different letter within a column are significantly different according to a Tukey-Kramer multiple range test at P < 0.05.

Treatment[b]	Rate	Control (%)			
		4 WAT	8 WAT	Density	Dry weight
	(g a.i. ha^{-1})			(plants m^{-2})	($g \cdot m^{-2}$)
Weed-free control		100	100	0 a	0 a
Weedy control		0 e	0 f	38 def	25.8 gh
Halosulfuron	25	27 d	18 e	43 ef	29.3 h
Halosulfuron	37.5	28 d	21 de	41 ef	27.8 h
Halosulfuron	50	36 cd	27 cde	36 def	28.2 h
Bentazon	1080	87 a	85 a	13 b	2.7 b
Acifluorfen	600	39 cd	28 cde	44 f	23.6 efgh
Fomesafen[c]	240	48 bcd	39 bcde	27 cdef	16.0 efgh
Bentazon/acifluorfen[d]	840	60 bc	53 bc	24 bcde	11.4 cdefg
Bentazon + fomesafen	840 + 140	76 ab	72 ab	19 bcd	5.6 bcd
Halosulfuron + bentazon	1080 + 37.5	74 ab	67 ab	18 bc	5.2 bc
Halosulfuron + acifluorfen	600 + 37.5	62 abc	49 bcde	27 cdef	13.4 defgh
Halosulfuron + fomesafen	240 + 37.5	43 cd	32 cde	39 def	25.4 fgh
Halosulfuron + bentazon/acifluorfen	840 + 37.5	62 abc	52 bcd	22 bcde	9.4 cde
Halosulfuron + bentazon + fomesafen	840 + 140 + 37.5	66 abc	60 ab	19 bcd	10.7 cdef

[a]Abbreviations: POST, postemergence; WAT, weeks after herbicide application. [b]All halosulfuron treatments included non-ionic surfactant (0.25% v/v). [c]Included Turbocharge (0.5% v/v). [d]Included Assist (1.5 l ha^{-1}).

lambsquarters dry biomass by 56% - 90%, but other herbicide treatments resulted in common lambsquarters dry biomass that was similar to the weedy control (Table 5). In other studies, halosulfuron applied POST provided only 8% - 41% control of common lambsquarters in white bean [14] [15]. Bentazon applied POST provided 85% - 90% control of common lambsquarters in white bean [14] [15]. Fomesafen applied POST provided 53% - 75% control of common lambsquarters in white bean [14] [15].

3.6. Flower-of-an-Hour

The control of flower-of-an-hour ranged from 63% - 92% at 4 WAT, there was no difference among the treatments evaluated and 39% - 97% at 8 WAT (Table 6). Bentazon, bentazon + fomesafen and halosulfuron + bentazon reduced flower-of-an-hour density 94%, 80% and 85% respectively; other herbicide treatments resulted in flower-of-an-hour density that was similar to the weedy control (Table 6). All herbicide treatments resulted in flower-of-an-hour dry

Table 6. Percent visible control 4 and 8 WAT, density and dry weight of flower-of-an-hour treated with halosulfuron tankmixes applied POST at Exeter (2017, 2019). Means followed by a different letter within a column are significantly different according to a Tukey-Kramer multiple range test at $P < 0.05$[a].

Treatment[b]	Rate	Control (%)		Density	Dry weight
		4 WAT	8 WAT		
	(g a.i. ha^{-1})			(plants m^{-2})	($g \cdot m^{-2}$)
Weed-free control		100	100	0 a	0 a
Weedy control		0 b	0 d	13.9 e	5.0 b
Halosulfuron	25	66 a	43 bc	8.1 cde	2.6 ab
Halosulfuron	37.5	76 a	39 c	12.4 de	3.8 b
Halosulfuron	50	69 a	49 abc	6.8 bcde	1.5 ab
Bentazon	1080	90 a	97 a	0.9 ab	0.7 ab
Acifluorfen	600	66 a	44 bc	17.9 e	5.9 b
Fomesafen[c]	240	63 a	54 abc	6.4 bcde	2.6 ab
Bentazon/acifluorfen[d]	840	73 a	63 abc	6.2 bcde	3.0 b
Bentazon + fomesafen	840 + 140	83 a	83 abc	2.8 abcd	2.5 ab
Halosulfuron + bentazon	1080 + 37.5	92 a	93 ab	2.1 abc	0.5 ab
Halosulfuron + acifluorfen	600 + 37.5	78 a	51 abc	15.7 e	3.1 b
Halosulfuron + fomesafen	240 + 37.5	74 a	51 abc	14.1 e	2.7 b
Halosulfuron + bentazon/acifluorfen	840 + 37.5	82 a	77 abc	4.2 abcde	1.3 ab
Halosulfuron + bentazon + fomesafen	840 + 140 + 37.5	87 a	84 abc	4.3 bcde	2.0 ab

[a]Abbreviations: POST, postemergence; WAT, weeks after herbicide application. [b]All halosulfuron treatments included non-ionic surfactant (0.25% v/v). [c]Included Turbocharge (0.5% v/v). [d]Included Assist (1.5 l ha^{-1}).

biomass that was similar to the weedy control (Table 6).

3.7. Wild Mustard

Herbicide treatments evaluated controlled wild mustard 97% - 100% at 4 WAT and 99% - 100% at 8 WAT (Table 7). Herbicide treatments reduced wild mustard density 96% - 100% and dry biomass 99% - 100%. Wild mustard density was similar to the weed-free control except for bentazon and acifluorfen and wild mustard biomass was similar to the weed-free control except acifluorfen (Table 7). Results are similar to other studies in which halosulfuron, bentazon and fomesafen provided 96% - 100%, 50% - 66% and 90% - 98% control of wild mustard in white bean [14] [15] [21].

4. Conclusion

Halosulfuron applied POST alone caused minimal injury in white bean. Herbicide tankmixes that included acifluorfen caused 12% - 16% white bean injury.

Table 7. Percent visible control 4 and 8 WAT, density and dry weight of wild mustard treated with halosulfuron tankmixes applied POST at Exeter (2017-2019). Means followed by a different letter within a column are significantly different according to a Tukey-Kramer multiple range test at P < 0.05[a].

Treatment[b]	Rate	Control[c] (%)			
		4 WAT	8 WAT	Density	Dry weight
	(g a.i. ha^{-1})			(plants m^{-2})	($g \cdot m^{-2}$)
Weed-free control		100	100	0 a	0 a
Weedy control		0 b	0 b	100 c	85.1 c
Halosulfuron	25	100	100	0 a	0 a
Halosulfuron	37.5	100	100	0 a	0 a
Halosulfuron	50	100	100	0 a	0 a
Bentazon	1080	97 a	99 a	4 b	0.4 ab
Acifluorfen	600	97 a	100	4 b	0.9 b
Fomesafen[d]	240	100	100	0 a	0 a
Bentazon/acifluorfen[e]	840	99 a	99 a	1 ab	0.3 ab
Bentazon + fomesafen	840 + 140	100	100	0 a	0 a
Halosulfuron + bentazon	1080 + 37.5	100	100	0 a	0 a
Halosulfuron + acifluorfen	600 + 37.5	100	100	0 a	0 a
Halosulfuron + fomesafen	240 + 37.5	100	100	0 a	0 a
Halosulfuron + bentazon/acifluorfen	840 + 37.5	100	100	0 a	0 a
Halosulfuron + bentazon + fomesafen	840 + 140 + 37.5	100	100	0 a	0 a

[a]Abbreviations: POST, postemergence; WAT, weeks after herbicide application. [b]All halosulfuron treatments included non-ionic surfactant (0.25% v/v). [c]Non-check treatments with 100% control and zero variance across all environments were excluded from the analysis and therefore not included in the means comparisons. [d]Included Turbocharge (0.5% v/v). [e]Included Assist (1.5 l ha^{-1})

All other herbicide treatments caused ≤6% white bean injury. White bean plants exhibited minimal injury (≤3%) at 4 WAT from all herbicide treatments evaluated. Weed interference reduced white bean yield by 60%. Reduced weed interference with the herbicide treatments evaluated increased white been yield 50% - 90% compared to the weedy control; there was no difference in white bean seed yield among herbicide treatments evaluated. Halosulfuron applied POST alone at 25, 37.5 and 50 g ai ha^{-1} provided poor control of common lambsquarters and flower-of-an-hour and adequate to excellent control of velvetleaf, redroot pigweed, common ragweed and wild mustard. Bentazon alone applied POST provided poor control of velvetleaf, redroot pigweed and common ragweed but, adequately controlled common lamb-squarters, flower-of-an-hour and wild mustard. Acifluorfen applied POST provided poor control of velvetleaf, common ragweed, common lambsquarters, and flower-an-hour but, provided adequate control of redroot pigweed and wild mustard. Fomesafen applied POST provided poor control of velvetleaf, common lambsquarters and flower-an-hour but, provided adequate to excellent control of redroot pigweed, common ragweed and wild mustard. Bentazon/acifluorfen applied POST provided poor control of velvetleaf, redroot pigweed, common ragweed, common lambsquarters and flower-an-hour but, provided excellent control of wild mustard. Bentazon + fomesafen applied POST provided poor control of velvetleaf, common lambsquarters and flower-an-hour but, provided adequate to excellent control of redroot pigweed, common ragweed and wild mustard. The addition of halosulfuron to bentazon, acifluorfen, fomesafen, bentazon/acifluorfen or bentazon + fomesafen generally improved the control of the broadleaf species evaluated but, the results were not always statistically significant. This study concludes that halosulfuron tankmixed with bentazon, acifluorfen, fomesafen, bentazon/acifluorfen or bentazon + fomesafen has the potential for problematic broadleaf weed control in white bean production, however the optimal herbicide program is weed species specific.

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Conflicts of Interest

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

References

[1] Hensall District Co-Operative (2020) Coloured Beans Seed. https://www.hdc.on.ca

[2] Messina, V. (2014) Nutritional and Health Benefits of Dried Beans. *The American Journal of Clinical Nutrition*, **100**, 437-442. https://doi.org/10.3945/ajcn.113.071472

[3] [OMAFRA] Ontario Ministry of Agriculture and Food and Rural Affairs (2021) Area, Yield, Production and Farm Value of Specified Field Crops, Ontario, 2012-2021.

[4] Soltani, N., Dille, J.A., Burke, I.C., Everman, W.J., VanGessel, M.J., Davis, V.M. and Sikkema, P.H. (2018) Potential Yield Loss in Dry Bean Crops Due to Weeds in the United States and Canada. *Weed Technology*, **32**, 342-346. https://doi.org/10.1017/wet.2017.116

[5] Soltani, N., Dille, J.A., Burke, I.C., Everman, W.J., VanGessel, M.J., Davis, V.M. and Sikkema, P.H. (2017) Perspectives on Potential Soybean Yield Losses from Weeds in North America. *Weed Technology*, **31**, 148. https://doi.org/10.1017/wet.2016.2

[6] Soltani, N., Dille, J.A., Burke, I.C., Everman, W.J., VanGessel, M.J., Davis, V.M. and Sikkema, P.H. (2016) Potential Corn Yield Losses from Weeds in North America. *Weed Technology*, **30**, 979-984. https://doi.org/10.1614/WT-D-16-00046.1

[7] Flessner, M.L., Burke I.C., Dille, J.A., Everman, W.J., VanGessel, M.J., Tidemann, B., Soltani, N., and Sikkema, P.H. (2021) Potential Wheat Yield Loss Due to Weeds in the United States and Canada. *Weed Technology*. (Under Review)

[8] [OMAFRA] Ontario Ministry of Agriculture and Food and Rural Affairs (2020) Guide to Weed Control, Publication 75. Toronto, 1-457.

[9] Duggleby, R.G., McCourt, J.A. and Guddat, L.W. (2008) Structure and Mechanism

of Inhibition of Plant Acetohydroxyacid Synthase. *Plant Physiology and Biochemistry*, **46**, 309-324. https://doi.org/10.1016/j.plaphy.2007.12.004

[10] Shaner, D.L. (2014) Herbicide Handbook. Tenth Edition, Weed Science Society of America, Champaign, 513 p.

[11] Wilson, R.G. (2005) Response of Dry Bean and Weeds to Fomesafen and Fomesafen Tank Mixtures. *Weed Technology*, **19**, 201-206. https://doi.org/10.1614/WT-04-166R

[12] Peachey, E., Doohan, D. and Koch, T. (2012) Selectivity of Fomesafen Based Systems for Preemergence Weed Control in Cucurbit Crops. *Crop Protection*, **40**, 91-97. https://doi.org/10.1016/j.cropro.2012.04.003

[13] Soltani, N., Shropshire, C. and Sikkema, P.H. (2012) Response of Dry Bean to Halosulfuron Applied Postemergence. *Canadian Journal of Plant Science*, **92**, 723-728. https://doi.org/10.4141/cjps2011-220

[14] Soltani, N., Nurse, R.E. and Sikkema, P.H. (2013) Weed Management in White Beans with Postemergence Herbicide Tankmixes. *Canadian Journal of Plant Science*, **93**, 669-674. https://doi.org/10.4141/cjps2012-273

[15] Soltani, N., Nurse, R.E., Shropshire, C. and Sikkema, P.H. (2013) Weed Control in White Bean with Pendimethalin Applied Preplant Followed by Postemergence Broadleaved Herbicides. *The Open Plant Science Journal*, **7**, 24-30. https://doi.org/10.2174/1874294701307010024

[16] VanGessel, J.M., Monks, W.D. and Quintin, R.J. (2000) Herbicides for Potential Use in Lima Bean (*Phaseolus lunatus*) Production. *Weed Technology*, **14**, 279-286. https://doi.org/10.1614/0890-037X(2000)014[0279:HFPUIL]2.0.CO;2

[17] Soltani, N., Bowley, S. and Sikkema, P.H. (2005) Responses of Black and Cranberry Beans (*Phaseolus vulgaris*) to Postemergence Herbicides. *Crop Protection*, **24**, 15-21. https://doi.org/10.1016/j.cropro.2004.06.003

[18] Wall, D.A. (1995) Bentazon Tank-Mixtures for Improved Redroot Pigweed (*Amaranthus retroflexus*) and Common Lambsquarters (*Chenopodium album*) Control in Navy Beans (*Phaseolus vulgaris*). *Weed Technology*, **9**, 610-616. https://doi.org/10.1017/S0890037X00023927

[19] Blackshaw, R.E., Molnar, J.L., Muendel, H.H., Saindon, G. and Li, X. (2000) Integration of Cropping Practices and Herbicides Improves Weed Management in Dry Bean (*Phaseolus vulgaris*). *Weed Technology*, **14**, 327-336. https://doi.org/10.1614/0890-037X(2000)014[0327:IOCPAH]2.0.CO;2

[20] Burnside, O.C., Ahrens, W.H., Holder, B.J., Wiens, M.J., Johnson, M.M. and Ristau, E.A. (1994) Efficacy and Economics of Various Mechanical plus Chemical Weed Control Systems in Dry Beans (*Phaseolus vulgaris*). *Weed Technology*, **8**, 238-244. https://doi.org/10.1017/S0890037X00038719

[21] Soltani, N., Nurse, R.E., Shropshire, C. and Sikkema, P.H. (2014) Weed Control with Halosulfuron Applied Preplant Incorporated, Preemergence or Postemergence in White Bean. *Agricultural Sciences*, **5**, 875-881. https://doi.org/10.4236/as.2014.510094