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Weed Control With Preemergence Herbicides in Azuki Bean

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Abstract

Three field experiments were completed over a three-year period (2019 to 2021) in Ontario, Canada to develop weed management programs in azuki bean with herbicides (pendimethalin, *S*-metolachlor, halosulfuron, and imazethapyr) applied alone and in combination, and metribuzin, applied preemergence (PRE). At 2 and 4 weeks after emergence (WAE), there was ≤ 8% azuki bean injury from the herbicide treatments evaluated, with the exception of the treatments that included *S*-metolachlor which caused up to 19% azuki bean injury. Pendimethalin (1080 g ai ha^{-1}) and *S*-metolachlor (1600 g ai ha^{-1}) controlled green foxtail 83-94% but provided poor control of common lambsquarters, wild mustard, redroot pigweed, common ragweed, and flower-of-an-hour. Imazethapyr (75 g ai ha^{-1}) controlled common lambsquarters, wild mustard, redroot pigweed, and flower-of-an-hour 90-100% but provided 76-82% control of common ragweed and green foxtail. Halosulfuron (35 g ai ha^{-1}) controlled wild mustard 100%, common ragweed 81-84%, common lambsquarters 77-83%, flower-of-an-hour 72-75%, redroot pigweed 59-72%, and green foxtail 19-23%. The tankmix of pendimethalin + *S*-metolachlor controlled green foxtail and common lambsquarters 87-97% but the control was only 23- 83% on wild mustard, redroot pigweed, common ragweed, and flower-of-an-hour. The tankmixes of pendimethalin + imazethapyr and pendimethalin + *S*-metolachlor + imazethapyr provided 90-100% control of common lambsquarters, wild mustard, redroot pigweed, flower-of-an-hour, and green foxtail, and 78-87% control of common ragweed. The tankmixes of pendimethalin + halosulfuron and pendimethalin + *S*-metolachlor + halosulfuron controlled common lambsquarters and wild mustard 91-100%, green foxtail 76-95%, flower-of-an-hour 70-94%, redroot pigweed 68-91%, and common ragweed 78-79%. Metribuzin (280 g ai ha^{-1}) controlled common lambsquarters, wild mustard, redroot pigweed, common ragweed, flower-of-an-hour, and green foxtail up to 94, 98, 81, 58, 98, and 61% respectively; control improved to 99, 100, 97, 84, 99, and 83%, respectively when the rate was increased to 560 g ai ha^{-1}. Generally, weed density and dry biomass reflected the level of weed control. Weed interference reduced azuki bean yield by 91% in this study. Generally, azuki bean yield reflected the level of weed control.

Keywords: azuki bean yield, broadleaf control, halosulfuron, herbicide tankmix, imazethapyr, pendimethalin, *S*-metolachlor

1. Introduction

Azuki bean [*Vigna angularis* (Willd.) Ohwi & Ohashi] is a small, red bean with a sweet flavor that is mainly used in confectionery food products that are popular with consumers in the orient (Dikshit et al., 2005; Lumpkin et al., 1994). Although azuki bean production occurs mainly in China, Japan, Korea, and India, the production area is limited to about 700,000 ha annually in those countries (Pandiyan et al., 2021). Demand for azuki beans from the Pacific Rim countries has resulted in an increase in azuki bean production in Ontario, Canada for the export market as the province has a suitable environment for azuki bean growth and it is a profitable crop that can be incorporated in current field crop production rotations in the province (Greig, 2019; Lynch, 2019). Azuki bean production increased from 3100 ha in 2017 to 8100 ha in 2019 in Ontario (Greig, 2019). Azuki bean is a short, bushy plant and therefore is vulnerable to weed interference and the associated yields losses which can be as high as 71%, similar to other dry bean market classes (McClary et al., 1993; Pandiyan et al., 2021; Soltani et al., 2018). Presently, only two soil-applied herbicides, pendimethalin and imazethapyr, are registered for weed management in azuki bean production in Ontario (OMAFRA, 2021). More research is needed to find new herbicide options that provide efficacious control of troublesome weeds in azuki bean under Ontario environmental conditions. Halosulfuron, *S*-metolachlor, and metribuzin are additional soil-applied herbicides that have potential for weed management in azuki bean production in Ontario (OMAFRA, 2021).

Pendimethalin is a herbicide from the dinitroaniline chemical family that can be applied preplant incorporated (PPI) for the control of annual grasses and specific broadleaved weeds. Pendimethalin is a microtubule polymerization inhibitor that results in arrested metaphase in susceptible weeds species including barnyardgrass (*Echinochloa crusgalli* (L.) Beauv.), foxtails species (*Setaria* spp.), crabgrass (*Digitaria* spp.), panicums (*Panicum* spp.), field sandbur (*Cenchrus spinifex* Cav.), and johnsongrass (*Sorghum halepense* L.) (Grey et al., 2008; Shaner, 2014). Pendimethalin is also active against broadleaved weeds including common lambsquarters (*Chenopodium album* L.) and redroot pigweed (*Amaranthus retroflexus* L.) including Group 2 and 5 resistant biotypes (Grey et al., 2008; Shaner, 2014).

S-metolachlor is a herbicide from the chloroacetanilide chemical family that controls annual grasses including foxtail species, barnyardgrass, crabgrass species, fall panicum, and witchgrass (*Panicum. Capillare* L.) (Shaner, 2014). *S*-metolachlor is also active against broadleaved weeds including common lambsquarters, pigweeds, and nightshades (*Solanum* spp.) (OMAFRA, 2021; Shaner, 2014).

Halosulfuron is a herbicide from the sulfonylurea chemical family that inhibits the formation of valine, leucine, and isoleucine amino acids within the susceptible plants (Duggleby et al., 2008). Halosulfuron controls broadleaved weeds including wild mustard (*Sinapis arvensis* L.), common lambsquarters, redroot pigweed, velvetleaf (*Abutilon theophrasti* Medic.), and common ragweed (*Ambrosia artemisiifolia* L.) including Group 5 and 9 resistant biotypes. In addition, halosulfuron has activity on yellow nutsedge (*Cyperus esculentus* L.) (Li et al., 2017; OMAFRA, 2021).

Imazethapyr is a herbicide from the imidazolinone chemical family that inhibits acetolactate synthase (ALS) in susceptible plants. Imazethapyr controls broadleaved weeds including common lambsquarters, velvetleaf, common ragweed, *Amaranthus* spp., wild buckwheat (*Polygonum convolulus* L.), ladysthumb (*Polygonum persicaria* L.), wild mustard, and common ragweed, and certain grasses including barnyardgrass and foxtails (Li et al., 2017).

Metribuzin is a herbicide from the triazinone class that inhibits electron transport in photosystem II, resulting in an increase reactive oxygen species and subsequent lipid peroxidation in susceptible plants (Trebst, 2008). Metribuzin controls problematic weeds including common ragweed, common lambsquarters, wild mustard, redroot pigweed, velvetleaf, cocklebur (*Xanthium strumarium* L.), and suppression of annual grasses such as barnyardgrass and green foxtail (OMAFRA, 2021; Shaner, 2014).

Azuki bean producers need to combine grass herbicides such as pendimethalin and *S*-metolachlor with broadleaved herbicides such as imazethapyr and halosulfuron to obtain acceptable broad-spectrum weed control in their production. Few studies have evaluated weed management programs that include metribuzin and two-way or three-way tankmixtures of pendimethalin, *S*-metolachlor, imazethapyr, and halosulfuron applied preemergence in azuki bean. These tankmixtures can potentially increase weed control efficacy and provide consistent broad-spectrum control of troublesome weeds in azuki bean.

The purpose of this study was to evaluate crop injury and weed control efficacy in azuki bean with pendimethalin, *S*-metolachlor, imazethapyr, halosulfuron applied alone and in combination, and metribuzin applied PRE.

2. Materials and Methods

A field study was completed in 2019, 2020, and 2021 at the Huron Research Station near Exeter, Ontario, Canada (43°19′1.21″N, 81°30′3.87″E). The soil was a Brookston clay loam (Orthic Humic Gleysol, mixed, mesic, and poorly drained). Seedbed preparation consisted of fall moldboard plowing followed by seedbed preparation in the spring with a field cultivator with rolling basket harrows.

The experimental design was a randomized complete block design (RCBD) with 4 replicates. Treatments included a weedy and weed-free control and pendimethalin (1080 g ai ha^{-1}), *S*-metolachlor (1600 g ai ha^{-1}), imazethapyr (75 g ai ha^{-1}), halosulfuron (35 g ai ha^{-1}), pendimethalin + *S*-metolachlor (1080 + 1600 g ai ha^{-1}), pendimethalin + imazethapyr (1080 + 75 g ai ha^{-1}), pendimethalin + halosulfuron (1080 + 35 g ai ha^{-1}), pendimethalin + *S*-metolachlor + imazethapyr (1080 + 1600 + 75 g ai ha^{-1}), pendimethalin + *S*-metolachlor + halosulfuron (1080 + 1600 + 35 g ai ha^{-1}), metribuzin (280 g ai ha^{-1}), and metribuzin (560 g ai ha^{-1}) applied PRE. Each plot was 3.0 m wide and 10 m long and consisted of four rows of 'ERIMO' azuki bean seeded in rows spaced 0.75 m apart at approximately 230,000 seeds ha^{-1} in late May to early June of each year.

Herbicide treatments were applied 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 ultra-low drift nozzles (ULD120-02, Hypro, New Brighton, MN) spaced 50 cm apart. The surface area sprayed was the center 2.0 m of each plot. There was a 1.0 m unsprayed area between adjacent plots. Herbicides tested were applied 1-2 days after azuki bean seeding to the soil surface of each plot and were not incorporated.

Azuki bean injury was assessed 2 and 4 weeks after crop emergence (WAE) and weed control for each species was assessed 4 and 8 WAE on a scale of 0-100% with 0 representing no azuki bean injury/weed control and 100 representing complete azuki bean death/weed control. At 8 WAE, weed density and dry weight were determined from two 0.5 m^2 quadrats placed randomly in each plot. Weeds were counted, cut at the soil surface, and were separated by species and dried at 60 °C to constant moisture, and then weighed. A small plot combine was used to harvest azuki beans at maturity. Azuki bean yield was adjusted to 13% seed moisture content.

Data analysis was conducted using the GLIMMIX procedure in SAS (Ver. 9.4, SAS Institute Inc., Cary, NC) and the level of significance was set at 0.05 for all comparisons. Herbicide treatment was the fixed effect and site-year (environment), environment by treatment interaction, and replicate within environment were the random effects for the generalized linear mixed model. The distribution selected for each parameter was the one that most closely met the assumptions of analysis, based on visual examination of studentized residual plots for the assumption of homogeneity of variance, and the normal probability plot and Shapiro-Wilk statistic for normality. The Gaussian distribution was used for azuki bean injury 2 WAE, redroot pigweed control, common ragweed control, and azuki bean yield. Azuki bean injury 4 WAE, lambsquarters control, wild mustard control, and flower-of-an-hour control were arcsine square-root transformed prior to analysis with the Gaussian distribution. The lognormal distribution was used for density and dry biomass for all weed species and azuki bean moisture at harvest. The least-square means were subjected to the Tukey-Kramer adjustment prior to pairwise comparisons of least-square means. Treatments with zero variance across all environments were excluded from the analysis, including the non-treated and weed-free controls for crop injury and weed control, the weed-free control for weed density and dry biomass, as well as certain herbicide treatments for density and dry biomass. The P-value that is shown in the LSMEANS table still allowed comparisons of each treatment with the value of zero. The least-square means were back-transformed, if necessary, for presentation.

3. Results and Discussion

3.1 Azuki Bean Injury and Yield

Pendimethalin, imazethapyr, halosulfuron, pendimethalin + imazethapyr, pendimethalin + halosulfuron, and metribuzin caused ≤ 8 and 3% azuki bean injury at 2 and 4 WAE, respectively. In contrast, the herbicide treatments that included *S*-metolachlor (*S*-metolachlor, pendimethalin + *S*-metolachlor, pendimethalin + *S*-metolachlor + imazethapyr, and pendimethalin + *S*-metolachlor + halosulfuron) cause ≥ 15 and 5% azuki bean injury at 2 and 4 WAE, respectively (Table 1). Weed interference reduced azuki bean yield by 91% in this study. Reduced weed interference with imazethapyr, pendimethalin + imazethapyr, pendimethalin + halosulfuron, pendimethalin + *S*-metolachlor + imazethapyr, pendimethalin + *S*-metolachlor + halosulfuron, and metribuzin (560 g ai ha^{-1}) resulted in azuki seed yield that was similar to the weed-free control (Table 1). However, weed interference with pendimethalin, *S*-metolachlor, halosulfuron, pendimethalin + *S*-metolachlor, pendimethalin + halosulfuron, and metribuzin (280 g ai ha^{-1}) reduced azuki bean yield by 77, 82, 71, 59, 48, and 58% relative to the weed-free control, respectively (Table 1).

Table 1. Effect of various herbicides applied PRE on azuki bean visible injury 2 and 4 WAE in 2019-2021 (n = 3), percent moisture at maturity and yield in 2019 and 2020 (n = 2) near Exeter, ON. Means followed by the same letter within a column are not significantly different according to a Tukey-Kramer multiple range test at $P < 0.05^a$

Treatment	Rate (g ai ha^{-1})	Injury (%)		Moisture (%)	Yield (T ha^{-1})
		2 WAE	4 WAE		
Weed-free control		0 a	0 a	14.6 abc	1.88 a
Non-treated control		0 a	0 a	14.8 abc	0.16 d
Pendimethalin	1080	3 ab	0 a	15.1 abc	0.44 cd
S-metolachlor	1600	15 c	5 b	15.3 c	0.34 cd
Imazethapyr	75	4 b	1 ab	14.4 a	1.35 abc
Halosulfuron	35	4 b	1 ab	14.9 abc	0.55 bcd
Pendimethalin + *S*-metolachlor	1080 + 1600	18 c	6 b	15.2 bc	0.78 bcd
Pendimethalin + imazethapyr	1080 + 75	7 b	2 ab	14.4 a	1.55 ab
Pendimethalin + halosulfuron	1080 + 35	8 b	1 ab	14.8 abc	0.98 abcd
Pendimethalin + *S*-metolachlor + imazethapyr	1080 + 1600 + 75	19 c	6 b	14.7 abc	1.58 ab
Pendimethalin + *S*-metolachlor + halosulfuron	1080 + 1600 + 35	18 c	6 b	14.6 abc	1.36 ab
Metribuzin	280	4 b	2 ab	14.8 abc	0.79 bcd
Metribuzin	560	8 b	3 b	14.5 ab	1.35 abc

Note. [1] Abbreviations: PRE, preemergence; WAE, weeks after crop emergence.

Results are similar to another study in which pendimethalin, *S*-metolachlor, imazethapyr, and halosulfuron applied PPI alone and in combination, and metribuzin applied PPI caused up to 6% injury in azuki bean (Soltani et al., 2021a). In the same study, reduced weed interference with imazethapyr, pendimethalin + imazethapyr, pendimethalin + *S*-metolachlor + imazethapyr, pendimethalin + *S*-metolachlor + halosulfuron, and metribuzin at the high rate resulted in azuki seed yield comparable to the weed-free control. Poor weed control and subsequent greater weed interference with pendimethalin, halosulfuron, and metribuzin (low rate) decreased azuki bean yield by 50%, 56%, and 44%, respectively (Soltani et al., 2021a). In other studies, reduction of weed interference with trifluralin, *S*-metolachlor, halosulfuron, or imazethapyr applied alone or in two-, three- or four-way tankmixtures resulted in dry bean yield comparable to the weed-free control (Soltani et al., 2020).

3.2 Weed Control

Weeds selected for analysis were in at least 2 out of the 3 environments and included common lambsquarters (3/3), wild mustard (3/3), redroot pigweed (2/3), common ragweed (2/3), flower-of-an-hour (3/3), and green foxtail (3/3).

3.2.1 Common Lambsquarters

Pendimethalin, *S*-metolachlor, imazethapyr, halosulfuron, pendimethalin + *S*-metolachlor, pendimethalin + imazethapyr, pendimethalin + halosulfuron, pendimethalin + *S*-metolachlor + imazethapyr, pendimethalin + *S*-metolachlor + halosulfuron, metribuzin (280 g ai ha^{-1}), and metribuzin (560 g ai ha^{-1}) applied PRE controlled common lambsquarters 78, 44, 98, 83, 87, 100, 91, 100, 92, 94, and 99% at 4 WAE; and 89, 39, 98, 77, 94, 100, 92, 99, 92, 90, and 99% at 8 WAE in azuki bean, respectively (Table 2). Among the herbicide treatments evaluated, imazethapyr, pendimethalin + imazethapyr, pendimethalin + *S*-metolachlor + imazethapyr, and metribuzin at the high rate were the only treatments that reduced common lambsquarters density and dry biomass that was similar to the weed-free control.

Table 2. Effect of PRE herbicides on common lambsquarters visible control 4 and 8 WAE, density and dry biomass in 2019-2021 (n = 3) near Exeter, ON. Means followed by the same letter within a column are not significantly different according to a Tukey-Kramer multiple range test at $P < 0.05$[a]

Treatment	Rate (g ai ha^{-1})	Control (%)		Density	Dry biomass
		4 WAE	8 WAE	(plants m^{-2})	(g m^{-2})
Weed-free control		100	100	0.0 a	0.0 a
Non-treated control		0 d	0 c	56.2 e	38.2 c
Pendimethalin	1080	78 bc	89 a	19.6 cde	9.2 bc
S-metolachlor	1600	44 c	39 b	24.0 de	59.3 c
Imazethapyr	75	98 ab	98 a	1.1 abc	2.3 ab
Halosulfuron	35	83 ab	77 ab	12.7 cd	76.4 c
Pendimethalin + *S*-metolachlor	1080 + 1600	87 ab	94 a	4.7 bcd	7.9 bc
Pendimethalin + imazethapyr	1080 + 75	100 a	100 a	0.4 ab	0.6 ab
Pendimethalin + halosulfuron	1080 + 35	91 ab	92 a	6.4 bcd	6.2 abc
Pendimethalin + *S*-metolachlor + imazethapyr	1080 + 1600 + 75	100 a	99 a	0.2 ab	0.2 ab
Pendimethalin + *S*-metolachlor + halosulfuron	1080 + 1600 + 35	92 ab	92 a	4.8 bcd	10.0 bc
Metribuzin	280	94 ab	90 a	1.7 abc	18.5 bc
Metribuzin	560	99 a	99 a	0.1 ab	0.6 ab

Note. [1] Abbreviations: PRE, preemergence; WAE, weeks after crop emergence.

Results are similar to another study in which pendimethalin, *S*-metolachlor, imazethapyr, halosulfuron, pendimethalin + *S*-metolachlor, pendimethalin + imazethapyr, pendimethalin + halosulfuron, pendimethalin + *S*-metolachlor + imazethapyr, pendimethalin + *S*-metolachlor + halosulfuron, metribuzin (280 g ai ha^{-1}), and metribuzin (560 g ai ha^{-1}) applied PPI controlled common lambsquarter 98-99, 78-83, 100, 96-99, 99, 100, 100, 100, 100, 99, and 100%, respectively in azuki bean (Soltani et al., 2021a). In other studies, common lambsquarters were controlled 84-98% with pendimethalin PRE (Li et al., 2016, 2017; Taziar et al., 2016a, 2016b, 2016c); 7-27% with *S*-metolachlor PRE (Li et al., 2016, 2017; Taziar et al., 2016b, 2016c); 97-99% with imazethapyr PRE (Taziar et al., 2016c); and 87-99% with halosulfuron PRE (Li et al., 2016, 2017; Soltani et al., 2014; Taziar et al., 2016b). In addition, the two-way tankmixture of *S*-metolachlor + halosulfuron was shown to control common lambsquarters 99-100% control in dry bean (Soltani et al., 2020).

3.2.2 Wild Mustard

S-metolachlor, pendimethalin, and pendimethalin + *S*-metolachlor controlled wild mustard 9, 34, and 54% at 4 WAE and 5, 9, and 31%, at 8 WAE, respectively (Table 3). In contrast, herbicide treatments that included imazethapyr, halosulfuron, or metribuzin controlled wild mustard > 90 and 98% at 4 and 8 WAE, respectively. Imazethapyr, halosulfuron, pendimethalin + imazethapyr, pendimethalin + halosulfuron, pendimethalin + *S*-metolachlor + imazethapyr, pendimethalin + *S*-metolachlor + halosulfuron, and metribuzin (560 g ai ha^{-1}) reduced wild mustard density and dry biomass 100%. Metribuzin (280 g ai ha^{-1}) reduced the density and dry biomass of wild mustard by 94 and 83%, respectively. In contrast, *S*-metolachlor, pendimethalin, and pendimethalin + *S*-metolachlor did not reduce wild mustard density and biomass compared to the weedy control.

Table 3. Effect of PRE herbicides on wild mustard visible control 4 and 8 WAE, density and dry biomass in 2019-2021 (n = 3) near Exeter, ON. Means followed by the same letter within a column are not significantly different according to a Tukey-Kramer multiple range test at $P < 0.05^a$

Treatment	Rate (g ai ha^{-1})	Control (%)		Density	Dry biomass
		4 WAE	8 WAE	(plants m^{-2})	(g m^{-2})
Weed-free control		100	100	0.0 a	0.0 a
Non-treated control		0 e	0 c	21.7 b	19.0 b
Pendimethalin	1080	34 c	9 b	20.3 b	27.7 b
S-metolachlor	1600	9 d	5 bc	28.8 b	37.0 b
Imazethapyr	75	100 a	100 a	0.0 a	0.0 a
Halosulfuron	35	100 a	100 a	0.0 a	0.0 a
Pendimethalin + *S*-metolachlor	1080 + 1600	54 c	31 b	18.6 b	35.2 b
Pendimethalin + imazethapyr	1080 + 75	100 a	100 a	0.0 a	0.0 a
Pendimethalin + halosulfuron	1080 + 35	100 a	100 a	0.0 a	0.0 a
Pendimethalin + *S*-metolachlor + imazethapyr	1080 + 1600 + 75	100 a	100 a	0.0 a	0.0 a
Pendimethalin + *S*-metolachlor + halosulfuron	1080 + 1600 + 35	100 a	100 a	0.0 a	0.0 a
Metribuzin	280	90 b	98 a	1.2 a	3.3 a
Metribuzin	560	100 a	100 a	0.0 a	0.0 a

Note. [1] Abbreviations: PRE, preemergence; WAE, weeks after crop emergence.

Results are similar to another study in which pendimethalin, *S*-metolachlor, imazethapyr, halosulfuron, pendimethalin + *S*-metolachlor, pendimethalin + imazethapyr, pendimethalin + halosulfuron, pendimethalin + *S*-metolachlor + imazethapyr, pendimethalin + *S*-metolachlor + halosulfuron, metribuzin (280 g ai ha^{-1}), and metribuzin (560 g ai ha^{-1}) applied PPI controlled wild mustard 30-40, 46-58, 100, 100, 62-63, 100, 100, 100, 99-100, 97-99, and 99%, respectively in azuki bean (Soltani et al., 2021a). In other studies, wild mustard was controlled 13-48% with pendimethalin PRE (Li et al., 2016, 2017; Taziar et al., 2016c); 2-50% with *S*-metolachlor PRE (Li et al., 2016, 2017; Taziar et al., 2016b, 2016c); 97-99% with imazethapyr PRE (Taziar et al., 2016d); and 98-100% with halosulfuron PRE (Li et al., 2017; Soltani et al., 2014; Taziar et al., 2016d). The two-way mixture of *S*-metolachlor + halosulfuron applied PPI controlled wild mustard 99-100% in dry bean (Soltani et al., 2020). In another study, halosulfuron, imazethapyr, and halosulfuron + imazethapyr controlled wild mustard 96-100% and 97-100% at 4 and 8 weeks after treatment application (WAA), respectively in dry bean (Soltani et al., 2021b).

3.2.3 Redroot Pigweed

Pendimethalin, *S*-metolachlor, imazethapyr, halosulfuron, pendimethalin + *S*-metolachlor, pendimethalin + imazethapyr, pendimethalin + halosulfuron, pendimethalin + *S*-metolachlor + imazethapyr, pendimethalin + *S*-metolachlor + halosulfuron, metribuzin (280 g ai ha^{-1}), and metribuzin (560 g ai ha^{-1}) controlled redroot pigweed 41, 48, 93, 72, 83, 96, 82, 99, 91, 81 and 97% at 4 WAE; and 31, 33, 90, 59, 72, 91, 68, 96, 83, 65, and 90% at 8 WAE in azuki bean, respectively (Table 4). Pendimethalin and *S*-metolachlor did not reduce redroot pigweed density but imazethapyr, halosulfuron, pendimethalin + *S*-metolachlor, pendimethalin + imazethapyr, pendimethalin + halosulfuron, pendimethalin + *S*-metolachlor + imazethapyr, pendimethalin + *S*-metolachlor + halosulfuron, metribuzin (280 g ai ha^{-1}), and metribuzin (560 g ai ha^{-1}) reduced redroot pigweed density 96, 82, 82, 97, 84, 99, 95, 94 and 99%, respectively. Imazethapyr, pendimethalin + imazethapyr, pendimethalin + *S*-metolachlor + imazethapyr, and metribuzin (560 g ai ha^{-1}) reduced redroot pigweed dry biomass 73, 91, 98, and 94%, respectively. However, other herbicide treatments evaluated had no effect on the dry biomass of redroot pigweed in azuki bean.

Table 4. Effect of PRE herbicides on redroot pigweed visible control 4 and 8 WAE, density, and dry biomass in 2020-2021 (n = 2) near Exeter, ON. Means followed by the same letter within a column are not significantly different according to a Tukey-Kramer multiple range test at P < 0.05[a]

Treatment	Rate (g ai ha^{-1})	Control (%)		Density (plants m^{-2})	Dry biomass (g m^{-2})
		4 WAE	8 WAE		
Weed-free control		100	100	0.0 a	0.0 a
Non-treated control		0 d	0 e	85.5 gh	142.8 f
Pendimethalin	1080	41 c	31 d	121.4 h	208.8 f
S-metolachlor	1600	48 c	33 d	29.2 fg	150.4 f
Imazethapyr	75	93 ab	90 ab	3.1 bc	38.0 bcde
Halosulfuron	35	72 b	59 cd	15.4 ef	127.5 f
Pendimethalin + *S*-metolachlor	1080 + 1600	83 ab	72 abc	12.0 de	55.2 def
Pendimethalin + imazethapyr	1080 + 75	96 a	91 ab	2.3 bc	12.4 bcd
Pendimethalin + halosulfuron	1080 + 35	82 ab	68 abc	14.0 de	125.6 ef
Pendimethalin + *S*-metolachlor + imazethapyr	1080 + 1600 + 75	99 a	96 a	0.5 ab	2.4 ab
Pendimethalin + *S*-metolachlor + halosulfuron	1080 + 1600 + 35	91 ab	83 abc	4.7 cd	48.8 cdef
Metribuzin	280	81 ab	65 bc	4.9 cd	171.0 f
Metribuzin	560	97 a	90 ab	0.8 ab	8.0 abc

Note. [1] Abbreviations: PRE, preemergence; WAE, weeks after crop emergence.

In other studies, redroot pigweed was controlled 59-69% with pendimethalin PRE (Li et al., 2016, 2017; Taziar et al., 2016c), 89-100% with *S*-metolachlor PRE (Li et al., 2016, 2017; Taziar et al., 2016b, 2016c); 87-92% with imazethapyr PRE (Taziar et al., 2016d); and 89-100% with halosulfuron PRE (Li et al., 2016, 2017; Soltani et al., 2014; Taziar et al., 2016b) in dry bean. In another study, *S*-metolachlor and halosulfuron applied PRE controlled pigweeds as much as 97% while the two-way tankmix of *S*-metolachlor + halosulfuron applied PRE controlled pigweeds as much as 100% in white bean (Soltani et al., 2020). Another study showed that the control redroot pigweed increases from 90% to 99-100% with the addition of halosulfuron, imazethapyr, or halosulfuron + imazethapyr to *S*-metolachlor in dry bean (Soltani et al., 2021b).

3.2.4 Common Ragweed

Pendimethalin, *S*-metolachlor, imazethapyr, halosulfuron, pendimethalin + *S*-metolachlor, pendimethalin + imazethapyr, pendimethalin + halosulfuron, pendimethalin + *S*-metolachlor + imazethapyr, pendimethalin + *S*-metolachlor + halosulfuron, metribuzin (280 g ai ha^{-1}), and metribuzin (560 g ai ha^{-1}) controlled common ragweed 9, 20, 80, 84, 31, 87, 78, 78, 78, 57, and 83% at 4 WAE; and 3, 36, 76, 81, 23, 81, 79, 78, 78, 58, and 84% at 8 WAE in azuki bean, respectively (Table 5). Pendimethalin, *S*-metolachlor, and pendimethalin + *S*-metolachlor did not reduce the density of common ragweed but imazethapyr, halosulfuron, pendimethalin + imazethapyr, pendimethalin + halosulfuron, pendimethalin + *S*-metolachlor + imazethapyr, pendimethalin + *S*-metolachlor + halosulfuron, metribuzin (280 g ai ha^{-1}), and metribuzin (560 g ai ha^{-1}) reduced common ragweed density 92, 93, 93, 69, 84, 84, 89, g ai ha^{-1} and 93%, respectively. None of the herbicide treatments evaluated had a significant effect on common ragweed biomass relative to the weedy control.

Table 5. Effect of PRE herbicides on common ragweed visible control 4 and 8 WAE, density, and dry biomass in 2019 and 2021 (n = 2) near Exeter, ON. Means followed by the same letter within a column are not significantly different according to a Tukey-Kramer multiple range test at $P < 0.05$[a]

Treatment	Rate (g ai ha^{-1})	Control (%)		Density	Dry biomass
		4 WAE	8 WAE	(plants m^{-2})	(g m^{-2})
Weed-free control		100	100	0.0 a	0.0 a
Non-treated control		0 d	0 e	9.6 d	71.3 bcd
Pendimethalin	1080	9 c	3 de	6.1 d	92.0 cd
S-metolachlor	1600	20 c	36 c	6.2 d	90.0 cd
Imazethapyr	75	80 a	76 ab	0.8 b	38.8 bcd
Halosulfuron	35	84 a	81 a	0.7 b	7.3 ab
Pendimethalin + *S*-metolachlor	1080 + 1600	31 c	23 cd	9.2 d	140.7 d
Pendimethalin + imazethapyr	1080 + 75	87 a	81 a	0.7 b	32.5 bcd
Pendimethalin + halosulfuron	1080 + 35	78 ab	79 a	3.0 c	58.9 bcd
Pendimethalin + *S*-metolachlor + imazethapyr	1080 + 1600 + 75	78 ab	78 ab	1.5 bc	26.4 abc
Pendimethalin + *S*-metolachlor + halosulfuron	1080 + 1600 + 35	78 ab	78 ab	1.5 bc	65.6 bcd
Metribuzin	280	57 b	58 b	1.1 bc	31.0 bcd
Metribuzin	560	83 a	84 a	0.7 b	30.5 bcd

Note. [1] Abbreviations: PRE, preemergence; WAE, weeks after crop emergence.

Results are similar to another study in which pendimethalin, *S*-metolachlor, imazethapyr, halosulfuron, pendimethalin + *S*-metolachlor, pendimethalin + imazethapyr, pendimethalin + halosulfuron, pendimethalin + *S*-metolachlor + imazethapyr, pendimethalin + *S*-metolachlor + halosulfuron, metribuzin (280 g ai ha^{-1}), and metribuzin (560 g ai ha^{-1}) applied PPI controlled common ragweed 5-10, 26-27, 77, 94, 40-48, 78-83, 89-91, 73-76, 93-94, 88-89, and 98-99%, respectively in azuki bean (Soltani et al., 2021). In other studies, common ragweed was controlled 9-92% with pendimethalin PRE (Li et al., 2016, 2017; Taziar et al., 2016c); 3-27% with *S*-metolachlor PRE (Li et al., 2016, 2017; Taziar et al., 2016b, 2016c); 23-37% with imazethapyr PRE (Li et al., 2017; Taziar et al., 2016d); and 83-96% with halosulfuron PRE (Li et al., 2016, 2017; Taziar et al., 2016b). The two-way tankmixes of *S*-metolachlor + halosulfuron was shown to control common ragweed 96% in white bean (Soltani et al., 2020). Another study showed that halosulfuron, imazethapyr, or halosulfuron + imazethapyr controlled common ragweed 93%, 67%, and 97%, respectively; there was no improvement in common ragweed control with the addition of *S*-metolachlor (Soltani et al., 2021b).

3.2.5 Flower-of-an-Hour

Pendimethalin, *S*-metolachlor, and halosulfuron controlled flower-of-an-hour 50 to 75% and 52 to 72% at 4 and 8 WAE, respectively (Table 6). Herbicide treatments that included imazethapyr or metrbibuzin controlled flower-of-an-hour 98 to 100% and 95 to 99% at 4 and 8 WAE, respectively. Pendimethalin, *S*-metolachlor, and pendimethalin + *S*-metolachlor did not reduce flower-of-an-hour density but imazethapyr, pendimethalin + imazethapyr, pendimethalin + *S*-metolachlor + imazethapyr, metribuzin (280 g ai ha^{-1}), and metribuzin (560 g ai ha^{-1}) reduced flower-of-an-hour density 91, 98, 95, 87, and 100%, respectively. Other herbicide treatments evaluated had no significant effect on the flower-of-an-hour density. None of the herbicide treatments evaluated had a significant effect on flower-of-an-hour dry biomass except for pendimethalin + imazethapyr and metribuzin (560 g ai ha^{-1}) that reduced flower-of-an-hour dry biomass 89 and 100%, respectively compared to the weedy control in azuki bean.

Table 6. Effect of PRE herbicides on flower-of-an-hour visible control 4 and 8 WAE, density, and dry biomass in 2019-2021 (n = 3) near Exeter, ON. Means followed by the same letter within a column are not significantly different according to a Tukey-Kramer multiple range test at P < 0.05[a]

Treatment	Rate (g ai ha^{-1})	Control (%)		Density (plants m^{-2})	Dry biomass (g m^{-2})
		4 WAE	8 WAE		
Weed-free control		100	100	0.0 a	0.0 a
Non-treated control		0 e	0 c	11.0 ef	9.1 cd
Pendimethalin	1080	65 cd	52 b	24.5 f	12.6 cd
S-metolachlor	1600	50 d	53 b	8.4 ef	19.1 d
Imazethapyr	75	98 ab	95 ab	1.0 abc	3.3 abc
Halosulfuron	35	75 bcd	72 ab	3.4 bcde	8.9 bcd
Pendimethalin + *S*-metolachlor	1080 + 1600	74 bcd	71 ab	4.2 cdef	13.5 d
Pendimethalin + imazethapyr	1080 + 75	100 a	99 a	0.2 ab	1.0 ab
Pendimethalin + halosulfuron	1080 + 35	94 abc	82 ab	1.8 bcde	4.0 bcd
Pendimethalin + *S*-metolachlor + imazethapyr	1080 + 1600 + 75	99 a	96 ab	0.5 abc	2.8 abc
Pendimethalin + *S*-metolachlor + halosulfuron	1080 + 1600 + 35	88 abc	70 ab	3.7 bcdef	11.2 cd
Metribuzin	280	98 ab	96 ab	1.4 bcd	4.7 bcd
Metribuzin	560	99 a	99 a	0.0 a	0.0 a

Note. [1] Abbreviations: PRE, preemergence; WAE, weeks after crop emergence.

3.2.6 Green Foxtail

Pendimethalin, *S*-metolachlor, imazethapyr, halosulfuron, pendimethalin + *S*-metolachlor, pendimethalin + imazethapyr, pendimethalin + halosulfuron, pendimethalin + *S*-metolachlor + imazethapyr, pendimethalin + *S*-metolachlor + halosulfuron, metribuzin (280 g ai ha^{-1}), and metribuzin (560 g ai ha^{-1}) controlled green foxtail 83, 90, 78, 19, 94, 90, 76, 94, 91, 61, and 83% at 4 WAE; and 94, 94, 82, 23, 97, 93, 81, 97, 95, 42, and 73% at 8 WAE in azuki bean, respectively (Table 7). Halosulfuron, pendimethalin + halosulfuron, and metribuzin (280 g ai ha^{-1}) did not reduce green foxtail density relative to the weedy control but pendimethalin, *S*-metolachlor, imazethapyr, pendimethalin + *S*-metolachlor, pendimethalin + imazethapyr, pendimethalin + *S*-metolachlor + imazethapyr, pendimethalin + *S*-metolachlor + halosulfuron, and metribuzin (560 g ai ha^{-1}) reduced green foxtail density 80, 85, 70, 94, 86, 95, 94, and 90%, respectively. Similarly, halosulfuron, pendimethalin + halosulfuron, and metribuzin at both rates (280 and 560 g ai ha^{-1}) did not reduce green foxtail dry biomass relative to the weedy control but pendimethalin, *S*-metolachlor, imazethapyr, pendimethalin + *S*-metolachlor, pendimethalin + imazethapyr, pendimethalin + *S*-metolachlor + imazethapyr, and pendimethalin + *S*-metolachlor + halosulfuron reduced green foxtail dry biomass 81, 94, 66, 96, 95, 95, and 95%, respectively (Table 7).

Table 7. Effect of PRE herbicides on green foxtail visible control 4 and 8 WAE, density, and dry biomass in 2019-2021 (n = 3) near Exeter, ON. Means followed by the same letter within a column are not significantly different according to a Tukey-Kramer multiple range test at $P < 0.05$[a]

Treatment	Rate (g ai ha^{-1})	Control (%)		Density (plants m^{-2})	Dry biomass (g m^{-2})
		4 WAE	8 WAE		
Weed-free control		100	100	0.0 a	0.0 a
Non-treated control		0 d	0 e	119.1 e	184.7 f
Pendimethalin	1080	83 ab	94 ab	23.3 bcd	35.8 bcde
S-metolachlor	1600	90 a	94 ab	17.8 bcd	10.2 bcd
Imazethapyr	75	78 ab	82 ab	36.0 bcd	63.7 bcde
Halosulfuron	35	19 c	23 d	89.3 de	138.9 ef
Pendimethalin + *S*-metolachlor	1080 + 1600	94 a	97 a	7.1 b	8.0 b
Pendimethalin + imazethapyr	1080 + 75	90 a	93 ab	16.6 bc	9.0 b
Pendimethalin + halosulfuron	1080 + 35	76 ab	81 ab	37.2 cde	67.5 ef
Pendimethalin + *S*-metolachlor + imazethapyr	1080 + 1600 + 75	94 a	97 a	6.3 b	8.6 b
Pendimethalin + *S*-metolachlor + halosulfuron	1080 + 1600 + 35	91 a	95 ab	7.3 b	9.8 bc
Metribuzin	280	61 b	42 cd	39.6 cde	160.4 ef
Metribuzin	560	83 ab	73 bc	12.0 bc	64.2 cdef

Note. [1] Abbreviations: PRE, preemergence; WAE, weeks after crop emergence.

Results are similar to another study in which pendimethalin, *S*-metolachlor, imazethapyr, halosulfuron, pendimethalin + *S*-metolachlor, pendimethalin + imazethapyr, pendimethalin + halosulfuron, pendimethalin + *S*-metolachlor + imazethapyr, pendimethalin + *S*-metolachlor + halosulfuron, metribuzin (280 g ai ha^{-1}), and metribuzin (560 g ai ha^{-1}) applied PPI controlled green foxtail 98-99, 96-97, 76-80, 26-29, 99-100, 99, 94-97, 99, 98-99, 51-68, and 83-87%, respectively in azuki bean (Soltani et al., 2021a). In other studies, green foxtail was controlled 80-88% with pendimethalin PRE (Li et al., 2016, 2017); 93-99% with *S*-metolachlor PRE (Li et al., 2016, 2017; Soltani et al., 2014); 85-92% with imazethapyr PRE (Li et al., 2017); and 11-53% with halosulfuron PRE (Li et al., 2016, 2017; Soltani et al., 2014) in dry bean. The tankmixture of *S*-metolachlor + halosulfuron was also shown to control green foxtail as much as 95% in dry bean (Soltani et al., 2020).

4. Conclusions

Based on these results, there was ≤ 8% azuki bean injury from the herbicide treatments evaluated, with the exception of the treatments that included *S*-metolachlor which caused up to 19% azuki bean injury. Pendimethalin (1080 g ai ha^{-1}) and *S*-metolachlor (1600 g ai ha^{-1}) provided good to excellent control of green foxtail but provided poor control of common lambsquarters, wild mustard, redroot pigweed, common ragweed, and flower-of-an-hour. Imazethapyr (75 g ai ha^{-1}) provided excellent control of common lambsquarters, wild mustard, redroot pigweed, and flower-of-an-hour, and fair to good control of common ragweed and green foxtail. Halosulfuron (35 g ai ha^{-1}) provided excellent control of wild mustard, fair to good control of common ragweed, common lambsquarters, and flower-of-an-hour, and poor control of redroot pigweed, and green foxtail. The tankmix of pendimethalin + *S*-metolachlor provided good to excellent control of green foxtail and common lambsquarters but the control was inconsistent (23- 83%) on wild mustard, redroot pigweed, common ragweed, and flower-of-an-hour. The tankmixes of pendimethalin + imazethapyr and pendimethalin + *S*-metolachlor + imazethapyr provided excellent control of common lambsquarters, wild mustard, redroot pigweed, flower-of-an-hour, and green foxtail and good control of common ragweed. The tankmixes of pendimethalin + halosulfuron and pendimethalin + *S*-metolachlor + halosulfuron provided excellent control of common lambsquarters and wild mustard, fair to good control of green foxtail, flower-of-an-hour, redroot pigweed, and common ragweed. Metribuzin (280 g ai ha^{-1}) controlled common lambsquarters, wild mustard, redroot pigweed, common ragweed, flower-of-an-hour, and green foxtail up to 94, 98, 81, 58, 98, and 61% respectively; control improved to as much as 99, 100, 97, 84, 99, and 83%, respectively when the rate was increased to 560 g ai ha^{-1}. Generally, weed density and dry biomass reflected the level of weed control. Weed interference reduced azuki bean yield by 91% in this study. Generally, azuki bean yield reflected the level of weed control. Reduced weed interference with imazethapyr, pendimethalin + imazethapyr, pendimethalin + halosulfuron, pendimethalin + *S*-metolachlor + imazethapyr, pendimethalin + *S*-metolachlor + halosulfuron, and metribuzin (560 g ai ha^{-1}) resulted in azuki seed yield that was similar to weed-free control.

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