American Journal of Plant Sciences, 2016, 7, 1217-1225
Published Online June 2016 in SciRes. http://www.scirp.org/journal/ajps
http://dx.doi.org/10.4236/ajps.2016.78117

Response of Four Dry Bean Market Classes to Pre-Emergence Applications of Pyroxasulfone, Sulfentrazone and Pyroxasulfone plus Sulfentrazone

Allison N. Taziar[1], Nader Soltani[1], Christy Shropshire[1], Darren E. Robinson[1], Mitch Long[2], Chris L. Gillard[1], Peter H. Sikkema[1]

[1]University of Guelph Ridgetown Campus, Ridgetown, Canada
[2]FMC Corporation, Saskatoon, Canada
Email: soltanin@uoguelph.ca

Received 12 May 2016; accepted 11 June 2016; published 15 June 2016

Abstract

Only one herbicide mode of action (ALS inhibitor) is currently available to Ontario dry bean producers for soil-applied broadleaf weed control. Four field studies were conducted over two years (2014, 2015) to examine the tolerance of four market classes of dry beans to sulfentrazone (210 and 420 g·ai·ha^{-1}) and pyroxasulfone (100 and 200 g·ai·ha^{-1}) applied alone and in combination. The registration of these two herbicides would provide Ontario dry bean producers with two additional modes of action for broadleaf weed control. Pyroxasulfone caused up to 23%, 6%, 7% and 10% injury in adzuki, kidney, small red Mexican and white bean, respectively; sulfentrazone caused up to 51%, 12%, 15% and 44% injury and the combination caused up to 90%, 23%, 29% and 62% injury, respectively. Kidney and small red Mexican bean density, height, seed moisture content and yield were not affected. Pyroxasulfone (200 g·ai·ha^{-1}) + sulfentrazone (420 g·ai·ha^{-1}) reduced adzuki and white bean density, shoot dry weight, height and yield. This study concludes that pyroxasulfone (100 g·ai·ha^{-1}) + sulfentrazone (210 g·ai·ha^{-1}) applied PRE can be safely used to control weeds in Ontario kidney and small red Mexican bean production.

Keywords

Adzuki Bean (Erimo), Kidney Bean (Red Hawk), Small Red Mexican Bean (Merlot), White Bean (T9905), Crop Injury, Plant Density, Plant Height, Seed Moisture Content, Tolerance, Yield

How to cite this paper: Taziar, A.N., Soltani, N., Shropshire, C., Robinson, D.E., Long, M., Gillard, C.L. and Sikkema, P.H. (2016) Response of Four Dry Bean Market Classes to Pre-Emergence Applications of Pyroxasulfone, Sulfentrazone and Pyroxasulfone plus Sulfentrazone. *American Journal of Plant Sciences*, **7**, 1217-1225.
http://dx.doi.org/10.4236/ajps.2016.78117

1. Introduction

In 2015, Ontario dry bean growers produced 115,000 tonnes of white and coloured dry beans (*Phaseolus vulgaris* L.) on 52,600 ha [1]. Dry bean market classes commonly grown in Ontario include black, cranberry, kidney, otebo, small red Mexican, white (navy), and adzuki (*Vigna angularis* (Willd) Ohwi & Ohashi) bean. One of the most critical aspects of dry bean production is weed control, as weed interference has been reported to cause up to 68% yield loss [2]-[4]. Currently, Ontario dry bean producers are limited to two acetolactate synthase (ALS) inhibitor herbicides for soil-applied broadleaf weed control, to which there are currently more than ten resistant weed species in the province of Ontario [5]. Therefore, another mode of action is needed for soil-applied broadleaf weed control in order to chemically control these weeds.

Sulfentrazone is a protoporphyrinogen oxidase (PPO) inhibitor herbicide that is recently registered for use in Ontario soybean (*Glycine max* L.). Sulfentrazone inhibits the PPO enzyme, causing an excess of protoporphyrinogen IX in the chloroplast of the cell [6]. The excess then leaks out of the chloroplast into the cyto-phyrinogen, where various reactions convert it to free oxygen radicals. These radicals disrupt cell membranes, resulting in cellular leakage, loss of cell function, and cell death [7]. Sulfentrazone controls broadleaf weeds such as pigweeds (*Amaranthus* spp.), common lambsquarters (*Chenopodium album* L.) and wild buckwheat (*Polygonum convolvulus* L.), and grasses such as giant foxtail (*Setariafaberii* Hermm.), fall panicum (*Panicum dichotomiflorum* Michx.) and witchgrass (*Panicum capillare* L.) [8]-[11].

Pyroxasulfone is an isoxazoline herbicide that is most effective when applied pre-emergence (PRE) [12] [13]. It is a very-long-chain fatty acid biosynthesis inhibitor that is applied at much lower rates than other group 15 herbicides [14]. Pyroxasulfone primarily controls annual grass species such as barnyard grass (*Echinochloa crusgalli* (L.) Beauv.), large crabgrass (*Digitaria sanguinalis* (L.) Scop.), foxtails (*Setaria* spp.), wild-proso millet (*Panicum miliaceum* L.) and fall panicum (*Panicum dichotomiflorum* Michx.), but also controls broadleaf species such as velvetleaf (*Abutilon theophrasti* Medik.), pigweeds (*Amaranthus* spp.), common lambs quarters, common ragweed (*Ambrosia artemisiifolia* L.), and wild mustard (*Sinapis arvensis* L.) [15] [16]. In Ontario, pyroxasulfone is currently only available in a premix or co-pack with other active ingredients for weed control in maize and soybean crops.

There is little information on dry bean tolerance to sulfentrazone, pyroxasulfone or their combination. The objective of this study was to determine the tolerance of four market classes of dry beans to PRE applications of sulfentrazone, pyroxasulfone, and a combination of the two.

2. Materials and Methods

Four field trials were conducted at the University of Guelph Ridgetown Campus, Ridgetown and Huron Research Station, Exeter in Ontario, Canada over two years (2014, 2015). The 2014 Ridgetown site was a loamy soil with sand, silt and clay content of 40%, 35% and 25%, respectively, pH of 6.6 and organic matter content of 7.1%. The 2014 Exeter site was a Brookston clay loam, with 41% sand, 40% silt, 19% clay, pH of 7.8 and organic matter content of 3.8%. In 2015, soil at Ridgetown was a sandy clay loam with 53% sand, 27% silt, 20% clay, pH of 7.0 and organic matter content of 5.3%. The soil at Exeter in 2015 was a silty clay loam with 18% sand, 46% silt, 36% clay, pH of 7.5 and organic matter content of 4.7%. Seedbeds were prepared by an autumn moldboard ploughing followed by two passes in the spring with a cultivator with rolling basket harrows.

Experiments were arranged in split-plot design, with herbicide as the main plot and bean market class as the sub-plot. Bean market classes included adzuki ("Erimo"), kidney ("Red Hawk"), small red Mexican ("Merlot"), and white ("T9905") bean. Each experiment had four replicates. Plots in Ridgetown were 6 m wide by 8 m long, and consisted of two rows of each market class spaced 75 cm apart. Plots in Exeter were 3 m wide by 10 m long and consisted of 1 row of each market class spaced 75 cm apart. In Ridgetown, kidney bean was seeded at approximately 175,000 seeds ha^{-1} while adzuki, white and small red Mexican beans were seeded at approximately 235,000 seeds ha^{-1}. In Exeter, kidney and small red Mexican beans were seeded at 200,000 seeds ha^{-1}, adzuki bean was seeded at 275,000 ha^{-1}, and white bean was seeded at 250,000 seeds ha^{-1}. All experiments were seeded 4 to 5 cm deep between late May and early June. Herbicide treatments (based on manufacturer's recommended rate) included an untreated control, pyroxasulfone at 100 and 200 $g \cdot ai \cdot ha^{-1}$, sulfentrazone at 210 and 420 $g \cdot ai \cdot ha^{-1}$, pyroxasulfone (100 $g \cdot ai \cdot ha^{-1}$) + sulfentrazone (210 $g \cdot ai \cdot ha^{-1}$), and pyroxasulfone (200 $g \cdot ai \cdot ha^{-1}$) + sulfentrazone (420 $g \cdot ai \cdot ha^{-1}$). Herbicides were applied with a CO_2 pressurized backpack sprayer calibrated to deliver 200 L ha^{-1} at 240 kPA using a 1 m handheld boom with three ULD 110-02 nozzles (Hypro, New Brighton, MN) spaced 0.5 m apart. Plots were not irrigated but were fertilized according to recommended Ontario agronomic crop production practices. All plots were maintained weed-free the entire season by hand-hoeing to eliminate the confounding factor of weed interference.

Visible crop injury was assessed at 1, 2, 3, 4, 6 and 8 weeks after crop emergence (WAE). Plant density and shoot dry weight were determined at 3 WAE by counting the number of plants in a metre of row for each market class in each treatment, clipping them at the soil surface, placing them in a separate paper bag, drying in a kiln and weighing once dry. At 6 WAE, plant height was determined by randomly selecting ten plants in each market class in each treatment and averaging their heights. Seed moisture content was determined at maturity. Yield was determined at maturity and adjusted to 15% moisture for adzuki bean and 18% moisture for kidney, small red Mexican and white bean.

Statistical Analysis

Statistical Analysis Software (SAS) v. 9.4 (SAS Institute Inc., NC) was used to perform an analysis of variance on all data. Data were partitioned into the fixed effects of herbicide treatment, bean market class and their interaction, and the random effects of environment (year-location combination), block within environment, and interactions between environment and each of the fixed effects. The significance of the fixed and random effects was determined using the F-test and Z-test, respectively. The UNIVARIATE procedure was used to produce residual plots and Shapiro-Wilk statistics to analyze the homogeneity and normality of the residuals under various transformations. The transformation that produced the highest Shapiro-Wilk statistic was used to analyze each data set. Injury, biomass, and seed moisture data were log transformed, while yield and height data were arcsine square root transformed. The MIXED procedure was used to obtain the least squares means and differences of least squares means to achieve means separation between treatments at a Type 1 error of 0.05. Orthogonal contrasts were also performed. Data were back transformed for presentation on the original scale.

3. Results and Discussion

Statistical analysis determined there was no interaction between bean market class and herbicide treatment for injury at 1 and 2 WAE (**Table 1**); therefore the main effect of herbicide will be discussed separately. There was an interaction between dry bean market class and herbicide treatment for plant density, shoot dry weight, plant height, seed moisture content and yield (**Table 2**). Therefore, only the interaction effects will be discussed.

3.1. Crop Injury

Crop injury symptoms included leaf malformation, marginal leaf necrosis, stunting, and reduced plant stand. At 1 and 2 WAE, pyroxasulfone (100 and 200 g·ai·ha^{-1}) caused up to 3% and 7% injury, respectively (**Table 1**). Sulfentrazone (210 g·ai·ha^{-1}) caused up to 8% injury and was equivalent to either rate of pyroxasulfone, whilesulfentrazone (420 g·ai·ha^{-1}) caused up to 23% injury. The combination of pyroxasulfone (100 g·ai·ha^{-1}) and sulfentrazone (210 g·ai·ha^{-1}) caused up to 11% injury, which was equivalent to sulfentrazone alone but greater than pyroxasulfone at 2 WAE. Similarly, pyroxasulfone (200 g·ai·ha^{-1}) + sulfentrazone (420 g·ai·ha^{-1}) produced up to 42% injury which was not different from sulfentrazone (420 g·ai·ha^{-1}) alone.

At 3, 4, 6 and 8 WAE, injury was greatest in adzuki bean, followed by white, small red Mexican, then kidney bean (**Table 1**). Pyroxasulfone (100 g·ai·ha^{-1}) produced the least amount of injury of the herbicide treatments, causing 5% injury or less in all market classes (**Table 3**). Pyroxasulfone (200 g·ai·ha^{-1}) caused greater injury than the 100 g·ai·ha^{-1} rate in adzuki bean at 4 and 6 WAE. Pyroxasulfone (200 g·ai·ha^{-1}) caused up to 23%, 6%, 7%, and 10% injury in adzuki, kidney, small red Mexican and white bean, respectively. The level of injury observed in adzuki and white bean is consistent with other studies examining pyroxasulfone in dry bean, but the injury observed in kidney and small red Mexican bean were much lower than the 10% to 21% injury caused by pyroxasulfone (209 g·ai·ha^{-1}) in other studies using the same cultivars [17] [18]. Weather conditions (rainfall, temperature, etc.) and soil factors affecting herbicide availability may have contributed to the differences among studies.

Sulfentrazone (210 g·ai·ha^{-1}) caused up to 17% injury in adzuki bean, 4% injury in kidney and small red Mexican bean, and 16% injury in white bean (**Table 3**), which is consistent with a study by Soltani *et al*. [19]. The high rate of sulfentrazone (420 g·ai·ha^{-1}) caused greater injury than the 210 g·ai·ha^{-1} rate in small red

Table 1. Visible injury of four market classes of dry bean due to pyroxasulfone and sulfentrazone, alone and in combination, applied PRE in 2014 and 2015 at the Huron Research Station, Exeter, ON and University of Guelph Ridgetown Campus, Ridgetown, ON.

Main Effects[a]	Dry Bean Injury					
	1 WAE[a]	2 WAE[b]	3 WAE	4 WAE	6 WAE	8 WAE
	%					
Dry Bean Market Class	*	**	**	**	**	*
Adzuki	14[b]	21[b]	27	25	16	11
Kidney	5[a]	6[a]	7	7	3	3
Small Red Mexican	8[ab]	7[a]	7	7	4	2
White	15[b]	15[b]	16	14	7	4
Herbicide Treatment (g·ai·ha^{-1})	**	**	**	**	**	**
Untreated	0[a]	0[a]	0	0	0	0
Pyroxasulfone (100)	3[b]	3[b]	3	3	1	1
Pyroxasulfone (200)	6[bc]	7[bc]	10	10	5	4
Sulfentrazone (210)	6[bc]	8[bc]	9	7	4	3
Sulfentrazone (420)	16[cd]	23[de]	25	23	12	7
Pyroxasulfone + Sulfentrazone (100 + 210)	11[bcd]	10[cd]	11	9	5	3
Pyroxasulfone + Sulfentrazone (200 + 420)	40[d]	42[e]	43	42	28	15
Interaction						
B × H	NS	NS	**	*	**	**
Contrasts						
Pyroxasulfone vs pyroxasulfone + sulfentrazone	4 vs 22**	4 vs 21**	6 vs 22**	6 vs 20**	3 vs 12**	2 vs 7**
Sulfentrazone vs pyroxasulfone + sulfentrazone	10 vs 22**	13 vs 21	15 vs 22	13 vs 20*	7 vs 12*	4 vs 7

[a]Abbreviations: B, bean market class; H, herbicide treatment; NS, not significant at α = 0.05; PRE, pre-emergence; WAE, weeks after emergence. [b]Means of main effects were only separated when the interaction was not significant. Significance of main effects, interactions and contrasts are denoted by * for $P < 0.05$ and ** for $P < 0.01$. [b]Means followed by the same letter in each column are not significantly different according to Fisher's Protected LSD at $P < 0.05$.

Table 2. Plant density, shoot dry weight, plant height, seed moisture content and yield of four market classes of dry bean treated PRE with sulfentrazone and pyroxasulfone, alone and in combination, near Ridgetown and Exeter, ON, Canada over two years (2014, 2015).

Main Effects[a]	Plant Density # m^{-1} row	Shoot Dry Weight g·plant^{-1}	Plant Height cm	Seed Moisture Content %	Yield T·ha^{-1}
Dry Bean Market Class	*	**	**	*	**
Adzuki	14	0.7	33.8	15.3	1.70
Kidney	15	3.2	59.2	19.5	2.71
Small Red Mexican	17	2.4	61.1	21.0	3.39
White	17	1.5	52.1	19.5	3.60
Herbicide Treatment (g·ai·ha^{-1})	**	**	**	**	**
Untreated	17	2.2	56.4	18.4	3.16
Pyroxasulfone (100)	17	2.0	54.8	18.0	2.93
Pyroxasulfone (200)	17	1.7	51.7	18.7	2.78
Sulfentrazone (210)	16	2.0	53.2	18.4	2.93
Sulfentrazone (420)	15	1.6	47.7	19.3	2.57
Pyroxasulfone + Sulfentrazone (100 + 210)	16	1.9	53.2	18.5	3.05
Pyroxasulfone + Sulfentrazone (200 + 420)	13	1.3	43.4	19.9	2.33

Continued

Interaction					
B × H	**	**	**	*	**
Contrasts					
Pyroxasulfone vs pyroxasulfone + sulfentrazone	17 vs 15**	1.9 vs 1.6**	53.3 vs 48.3**	18.3 vs 19.2**	2.85 vs 2.68
Sulfentrazone vs pyroxasulfone + sulfentrazone	16 vs 15	1.8 vs 1.6	50.5 vs 48.3	18.8 vs 19.2	2.75 vs 2.68

[a]Significance of main effects, interactions and contrasts indicated by * for $P < 0.05$ and ** for $P < 0.01$. Means were not separated as the interaction was significant.

Table 3. Visible injury (%) of four market classes of dry bean treated PRE with sulfentrazone and pyroxasulfone, alone and in combination, near Ridgetown and Exeter, ON, Canada over two years (2014, 2015). Means followed by the same letter in a row (Y-Z) or column (a-d) for each rating are not significantly different according to Fisher's Protected LSD at $P < 0.05$[a].

Herbicide Treatment (g·ai·ha^{-1})	Adzuki Bean			Kidney Bean			Small Red Mexican Bean			White Bean		
Injury 3 *WAE*						%						
Untreated	0	a		0	a		0	a		0	a	
Pyroxasulfone (100)	5	b	Z	3	b	Z	2	b	Z	3	b	Z
Pyroxasulfone (200)	22	bc	Z	5	bc	Z	7	bc	Z	10	bc	Z
Sulfentrazone (210)	17	bc	Z	4	b	Z	4	bc	Z	16	cde	Z
Sulfentrazone (420)	51	cd	Y	12	bc	Z	15	cd	YZ	44	de	YZ
Pyroxasulfone + Sulfentrazone (100 + 210)	41	cd	Y	6	bc	Z	5	bc	Z	12	bcd	YZ
Pyroxasulfone + Sulfentrazone (200 + 420)	86	d	Z	23	c	Z	29	d	Z	59	e	Z
Injury 4 *WAE*						%						
Untreated	0	a		0	a		0	a		0	a	
Pyroxasulfone (100)	5	b	Z	3	b	Z	2	b	Z	2	b	Z
Pyroxasulfone (200)	23	cd	Z	6	bc	Z	6	bcd	Z	9	bc	Z
Sulfentrazone (210)	14	bc	Y	4	b	YZ	2	b	Z	12	bc	YZ
Sulfentrazone (420)	49	cd	Z	11	bc	Z	14	cd	Z	37	cd	Z
Pyroxasulfone + Sulfentrazone (100 + 210)	28	cd	Y	5	bc	Z	4	bc	Z	11	bc	YZ
Pyroxasulfone + Sulfentrazone (200 + 420)	90	d	Z	21	c	Z	26	d	Z	62	d	Z
Injury 6 *WAE*						%						
Untreated	0	a		0	a		0	a		0	a	
Pyroxasulfone (100)	1	b	Z	1	ab	Z	1	b	Z	2	b	Z
Pyroxasulfone (200)	14	c	Z	3	bc	Z	3	bc	Z	4	b	Z
Sulfentrazone (210)	9	bc	Z	2	bc	Z	2	bc	Z	4	b	Z
Sulfentrazone (420)	39	cd	Y	4	bc	Z	6	bc	Z	22	b	YZ
Pyroxasulfone + Sulfentrazone (100 + 210)	17	cd	Z	3	bc	Z	3	bc	Z	4	b	Z
Pyroxasulfone + Sulfentrazone (200 + 420)	86	d	Y	11	c	Z	12	c	Z	49	c	YZ
Injury 8 *WAE*						%						
Untreated	0	a		0	a		0	a		0	a	
Pyroxasulfone (100)	1	ab	Z	2	b	Z	1	ab	Z	1	ab	Z
Pyroxasulfone (200)	8	bc	Z	3	b	Z	3	b	Z	2	b	Z
Sulfentrazone (210)	6	bc	Z	2	b	Z	1	b	Z	2	b	Z
Sulfentrazone (420)	33	cd	Y	4	b	Z	2	b	Z	9	bc	YZ
Pyroxasulfone + Sulfentrazone (100 + 210)	11	c	Z	2	b	Z	1	b	Z	2	b	Z
Pyroxasulfone + Sulfentrazone (200 + 420)	67	d	Y	9	b	Z	4	b	Z	20	c	YZ

[a]Abbreviations: PRE, pre-emergence; WAE, weeks after emergence.

Mexican bean at 4 WAE, but injury was equivalent for both rates in the other market classes. Sulfentrazone (420 g·ai·ha^{-1}) caused up to 51%, 12%, 15% and 44% injury in adzuki, kidney, small red Mexican and white bean, respectively.

Pyroxasulfone (100 g·ai·ha^{-1}) + sulfentrazone (210 g·ai·ha^{-1}) caused up to 41, 6, 5, and 12% injury in adzuki, kidney, small red Mexican and white bean, respectively, and pyroxasulfone (200 g·ai·ha^{-1}) + sulfentrazone (420 g·ai·ha^{-1}) caused up to 90, 23, 29, and 62% injury, respectively (**Table 3**). In other studies examining PRE tank mixtures of a group 14 plus a group 15 herbicide on dry bean, dimethenamid-p/saflufenacil at the 1X rate caused up to 18% injury in dry bean, while the 2X rate caused up to 45% injury [20]. Fomesafen + s-metolachlor only caused up to 6.4% injury [21]. With the exception of white bean at 6 WAE, the level of injury produced by either herbicide combination was not greater than the injury produced by the respective rate of sulfentrazone on its own. Based on orthogonal contrasts, the addition of sulfentrazone to pyroxasulfone caused an increase in bean injury of 5% to 18% at 1, 2, 3, 4, 6 and 8 WAE (**Table 1**). In contrast, the addition of pyroxasulfone to sulfentrazone caused an increase in bean injury of 5% to 12% at 1, 4 and 6 WAE.

3.2. Plant Density

Kidney bean and small red Mexican bean densities were not reduced by any of the herbicide treatments (**Table 4**). Pyroxasulfone (100 and 200 g·ai·ha^{-1}), sulfentrazone (210 and 420 g·ai·ha^{-1}), and pyroxasulfone (100 g·ai·ha^{-1}) + sulfentrazone (210 g·ai·ha^{-1}) did not reduce adzuki or white bean density relative to the control. In

Table 4. Plant density, shoot dry weight and plant height (expressed as percentages of the untreated control) of four market classes of dry bean treated PRE with sulfentrazone and pyroxasulfone, alone and in combination, near Ridgetown and Exeter, ON, Canada over two years (2014, 2015). Means followed by the same letter in a row (W-Z) or column (a-c) for each variable are not significantly different according to Fisher's Protected LSD at $P < 0.05$.

Herbicide Treatment (g·ai·ha^{-1})	Adzuki Bean			Kidney Bean			Small Red Mexican Bean			White Bean		
Plant Density						%						
Untreated	100	a	Z	100	a	Z	100	a	Z	100	a	Z
Pyroxasulfone (100)	100	a	Z	105	a	Z	98	a	Z	86	ab	Z
Pyroxasulfone (200)	92	a	Z	104	a	Z	98	a	Z	97	a	Z
Sulfentrazone (210)	84	ab	Z	102	a	Z	98	a	Z	98	a	Z
Sulfentrazone (420)	71	ab	Z	98	a	Z	93	a	Z	84	ab	Z
Pyroxasulfone + Sulfentrazone (100 + 210)	78	ab	Z	100	a	Z	96	a	Z	98	a	Z
Pyroxasulfone + Sulfentrazone (200 + 420)	55	b	Y	90	a	YZ	101	a	Z	67	b	YZ
Shoot Dry Weight						%						
Untreated	100	a	X	100	a	Z	100	a	YZ	100	a	Y
Pyroxasulfone (100)	95	a	X	93	a	Z	92	ab	YZ	83	ab	Y
Pyroxasulfone (200)	79	a	X	85	a	Z	78	ab	YZ	67	abc	Y
Sulfentrazone (210)	102	a	X	90	a	Z	90	ab	YZ	78	ab	Y
Sulfentrazone (420)	67	ab	X	82	a	Z	70	ab	YZ	64	bc	Y
Pyroxasulfone + Sulfentrazone (100 + 210)	70	ab	X	99	a	Z	89	ab	Z	71	ab	Y
Pyroxasulfone + Sulfentrazone (200 + 420)	31	b	W	86	a	Z	64	b	Y	40	c	X
Plant Height						%						
Untreated	100	a	Y	100	a	Z	100	a	Z	100	a	Z
Pyroxasulfone (100)	97	a	Y	97	a	Z	98	a	Z	96	a	YZ
Pyroxasulfone (200)	84	ab	Y	96	a	Z	95	a	Z	90	ab	Z
Sulfentrazone (210)	90	ab	Y	97	a	Z	98	a	Z	91	ab	YZ
Sulfentrazone (420)	72	bc	Y	96	a	Z	91	a	Z	76	bc	YZ
Pyroxasulfone + Sulfentrazone (100 + 210)	87	ab	Y	98	a	Z	97	a	Z	92	ab	Z
Pyroxasulfone + Sulfentrazone (200 + 420)	54	c	Y	91	a	Z	87	a	Z	71	c	Z

contrast, pyroxasulfone (200 g·ai·ha^{-1}) + sulfentrazone (420 g·ai·ha^{-1}) reduced adzuki and white bean density by 45% and 33%, respectively. Dimethenamid-p/saflufenacil also reduced plant density by 49% [20]. Based on orthogonal contrasts, the addition of sulfentrazone to pyroxasulfone reduced dry bean density by 2 plants m^{-1} of row; however, there was no impact on dry bean density when pyroxasulfone was added to sulfentrazone (**Table 2**).

3.3. Shoot Dry Weight

Pyroxasulfone (100 g·ai·ha^{-1}) and sulfentrazone (210 g·ai·ha^{-1}) alone did not affect shoot dry weight for any of the dry bean market classes (**Table 4**). Pyroxasulfone (200 g·ai·ha^{-1}), sulfentrazone (420 g·ai·ha^{-1}), and pyroxasulfone (100 g·ai·ha^{-1}) + sulfentrazone (210 g·ai·ha^{-1}) numerically reduced adzuki shoot dry weight by 21%, 33%, and 30%, respectively, but not relative to the control. Pyroxasulfone (200 g·ai·ha^{-1}) + sulfentrazone (420 g·ai·ha^{-1}) reduced adzuki shoot dry weight by 69%. Kidney bean shoot dry weight was not reduced by any of the herbicide treatments compared to the control. Pyroxasulfone (200 g·ai·ha^{-1}) + sulfentrazone (420 g·ai·ha^{-1}) reduced small red Mexican bean shoot dry weight by 36%. White bean shoot dry weight was not reduced compared to the control by pyroxasulfone (100 and 200 g·ai·ha^{-1}), sulfentrazone (210 g·ai·ha^{-1}), or pyroxasulfone (100 g·ai·ha^{-1}) + sulfentrazone (210 g·ai·ha^{-1}), but sulfentrazone (420 g·ai·ha^{-1}) and pyroxasulfone (200 g·ai·ha^{-1}) + sulfentrazone (420 g·ai·ha^{-1}) reduced shoot dry weight by 36% and 60%, respectively. In other studies, pyroxasulfone (209 g·ai·ha^{-1}) reduced shoot dry weight by up to 30%, and sulfentrazone (280 g·ai·ha^{-1}) reduced shoot dry weight by up to 19% [18] [20]. Orthogonal contrasts indicate the addition of sulfentrazone to pyroxasulfone reduced bean shoot dry weight; however, there was no impact on shoot dry weight when pyroxasulfone was added to sulfentrazone (**Table 2**).

3.4. Plant Height

Taller plants are desirable for dry bean crops to reduce harvest losses. Pyroxasulfone and sulfentrazone, alone and in combination, did not reduce kidney or small red Mexican bean height. This contrasts other studies which found a 20% decrease in pinto and small red Mexican bean height, and a 13% decrease in kidney bean height when treated with 209 g·ai·ha^{-1} pyroxasulfone PRE [17] [21]. Pyroxasulfone (100 and 200 g·ai·ha^{-1}), sulfentrazone (210 g·ai·ha^{-1}), and pyroxasulfone (100 g·ai·ha^{-1}) + sulfentrazone (210 g·ai·ha^{-1}) also did not reduce adzuki or white bean height compared to the control. Sulfentrazone (420 g·ai·ha^{-1}) reduced adzuki and white bean height by 28% and 24%, respectively, and pyroxasulfone (200 g·ai·ha^{-1}) + sulfentrazone (420 g·ai·ha^{-1}) reduced adzuki and white bean height by 46% and 29%, respectively. This is higher than in other studies, which found sulfentrazone (420 g·ai·ha^{-1}) caused a 6% to 15% height reduction in black, brown, cranberry, kidney, otebo, pinto, white, and yellow eye beans [22]. Based on orthogonal contrasts, the addition of sulfentrazone to pyroxasulfone reduced bean height 5 cm. However, there was no impact on bean height when pyroxasulfone was added to sulfentrazone (**Table 2**).

3.5. Seed Moisture Content

Elevated seed moisture content indicates a delay in crop maturity, which will cause increased drying costs. In this study, kidney, small red Mexican and white bean seed moisture content was not affected by any of the herbicide treatments compared to the control (**Table 5**). Pyroxasulfone (200 g·ai·ha^{-1}) + sulfentrazone (420 g·ai·ha^{-1}) increased adzuki bean seed moisture by 2.4%. Given that the seed moisture content of adzuki bean treated with sulfentrazone (420 g·ai·ha^{-1}) was not different from this combination, the delayed maturity can be attributed to the sulfentrazone rather than the pyroxasulfone. This is reflected by the orthogonal contrasts, which show the addition of sulfentrazone to pyroxasulfone increased bean moisture content (delayed maturity) at harvest by 0.9%; however, there was no impact on bean maturity when pyroxasulfone was added to sulfentrazone (**Table 2**).

3.6. Yield

Kidney and small red Mexican bean yield were not affected by any of the herbicide treatments evaluated (**Table 5**). Pyroxasulfone and sulfentrazone applied on their own did not reduce white bean yield relative to the control, although yield was numerically reduced by 23% by sulfentrazone at 420 g·ai·ha^{-1}. This is similar to other studies, where sulfentrazone (420 g·ai·ha^{-1}) reduced black, brown, cranberry, kidney, otebo, pinto, white and yellow eye

Table 5. Seed moisture content (%) and yield (as a percent of the untreated control) of four market classes of dry bean treated PRE with sulfentrazone and pyroxasulfone, alone and in combination, near Ridgetown and Exeter, ON, Canada over two years (2014, 2015). Means followed by the same letter in a row (Y-Z) or column (a-c) are not significantly different according to Fisher's Protected LSD at $P < 0.05$.

Herbicide Treatment (g·ai·ha^{-1})	Adzuki Bean			Kidney Bean			Small Red Mexican Bean			White Bean		
Seed Moisture Content							%					
Untreated	14.9	a	Z	19.7	a	Z	20.2	a	Z	19.1	a	Z
Pyroxasulfone (100)	14.6	a	Z	19.1	a	Z	20.0	a	Z	18.9	a	Z
Pyroxasulfone (200)	15.1	a	Z	20.2	a	Z	20.8	a	Z	19.1	a	Z
Sulfentrazone (210)	14.9	a	Z	19.3	a	Z	20.8	a	Z	19.3	a	Z
Sulfentrazone (420)	15.5	ab	Z	19.7	a	YZ	22.4	a	Y	20.1	a	YZ
Pyroxasulfone + Sulfentrazone (100 + 210)	15.3	a	Z	19.1	a	Z	20.5	a	Z	19.4	a	Z
Pyroxasulfone + Sulfentrazone (200 + 420)	17.3	b	Z	19.8	a	Z	22.1	a	Z	20.8	a	Z
Yield							%					
Untreated	100	a	Y	100	a	YZ	100	a	YZ	100	a	Z
Pyroxasulfone (100)	95	a	Z	95	a	Z	92	a	Z	90	ab	Z
Pyroxasulfone (200)	83	ab	Y	89	a	YZ	89	a	YZ	89	ab	Z
Sulfentrazone (210)	82	ab	Y	98	a	YZ	99	a	Z	90	ab	Z
Sulfentrazone (420)	57	bc	Y	96	a	Z	93	a	Z	77	ab	Z
Pyroxasulfone + Sulfentrazone (100 + 210)	78	ab	Y	104	a	YZ	102	a	Z	98	a	Z
Pyroxasulfone + Sulfentrazone (200 + 420)	41	c	Y	87	a	Z	91	a	Z	72	b	Z

bean yield by 15%, 0%, 11%, 0%, 3%, 0%, 17% and 0%, respectively [22]. Pyroxasulfone (100 g·ai·ha^{-1}) + sulfentrazone (210 g·ai·ha^{-1}) also did not reduce white bean yield relative to the control, but pyroxasulfone (200 g·ai·ha^{-1}) + sulfentrazone (420 g·aiha^{-1}) reduced yield by 28%. Adzuki bean yield was the most affected of all the market classes evaluated. Sulfentrazone (420 g·ai·ha^{-1}) reduced yield by 43% and pyroxasulfone (200 g·ai·ha^{-1}) + sulfentrazone (420 g·ai·ha^{-1}) reduced yield by 59%. The yield reduction caused by pyroxasulfone + sulfentrazone in this study is lower than that caused by dimethenamid-p/saflufenacil, which caused up to 61% yield loss in white bean [20]. Based on orthogonal contrasts, there was no effect on bean yield when sulfentrazone was added to pyroxasulfone or when pyroxasulfone was added to sulfentrazone (**Table 2**).

4. Conclusion

In general, the level of injury caused by pyroxasulfone was lower and sulfentrazone was higher in this study than that reported in other studies, which might be a result of differential weather and soil conditions. Adzuki bean was the least tolerant to PRE mixtures of pyroxasulfone + sulfentrazone, with up to 90% injury and a 59% yield loss. White bean was the second most sensitive, with a narrow margin of crop safety at the low rates, and kidney and small red Mexican bean had acceptable tolerance at the low rates. Based on the results of this study, pyroxasulfone (100 g·ai·ha^{-1}) + sulfentrazone (210 g·ai·ha^{-1}) applied PRE is a safe herbicide combination for kidney and small red Mexican beans in Ontario.

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