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Broadleaf Weed Control and Crop Safety with Premixed Pyrasulfotole and Bromoxynil in Winter Wheat

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ABSTRACT

For more than two decades acetolactate synthase (ALS) inhibiting herbicides have been the major weed control tools in winter wheat which resulted in selection of resistant weeds to those herbicides. Premixed pyrasulfotole & bromoxynil (Huskie®) is a relatively new herbicide registered for use in wheat in 2008. Pyrasulfotole inhibits 4-hydoxyphenylpyruvate dioxygenase (HPPD) enzyme in susceptible plants and is the first significant new mode of action for use in cereals in more than two decades. Field experiments were conducted from 2007 to 2010 at two locations in Kansas, USA to test the efficacy of pyrasulfotole & bromoxynil for broadleaf weed control and crop safety in winter wheat. Treatments included pyrasulfotole & bromoxynil alone at 253 $g·ai·ha^{-1}$ and tank mixtures of pyrasulfotole & bromoxynil at 207 $g·ai·ha^{-1}$ with MCPA at 280 $g·ai·ha^{-1}$, dicamba at 140 $g·ai·ha^{-1}$ or metsulfuron-methyl at 4.2 $g·ai·ha^{-1}$. Herbicides were applied postemergence in fall and spring seasons. Pyrasulfotole & bromoxynil alone or in combination with tank-mix partners, regardless of application time, controlled flixweed, blue mustard, bushy wallflower and field pennycress 98% or more. Henbit control was better when pyrasulfotole & bromoxynil treatments were applied in fall than spring (≥98% vs ≥67%). Pyrasulfotole & bromoxynil alone applied in spring was not effective on wild buckwheat, but tank mixing with dicamba or metsulfuron-methyl controlled wild buckwheat 84% or more. Pyrasulfotole & bromoxynil alone or in tank mixtures caused little (≤7%) or no injury to wheat and the injury did not influence wheat grain yields. Based on excellent control of broadleaf weeds evaluated, pyrasulfotole & bromoxynil is an alternative tool to control ALS-inhibitor resistant weeds in winter wheat. Fall season application and tank mixing with other herbicides are desirable for effective broad spectrum weed control.

Keywords: Huskie®; Henbit; Blue Mustard; Flixweed; Bushy Wallflower; Field Pennycress; Wild Buckwheat; Postemergence; Injury

1. Introduction

Wheat (*Triticum aestivum* L.) is the most important cereal crop in the USA, where it was planted on 23 million ha in 2012 [1]. Most of the wheat grown in the USA is winter wheat (17 million ha). Kansas state ranks first in winter wheat cultivation (4 million ha) in the USA [1]. Winter wheat is not a good competitor with some broadleaf weeds even when wheat emerges before weeds [2]. Common weeds found in winter wheat in the US are blue mustard [*Chorispora tenella* (Pallas) DC.], henbit (*Lamium amplexicaule* L.), flixweed [*Descurainia sophia* (L.) Webb. Ex Prantl], bushy wallflower (*Erysimum repandum* L.), field pennycress (*Thlaspi arvense* L.), wild buckwheat (*Polygonum convolvulus*), shepherd's purse [*Capsella bursa-pastoris* (L.) Medik.], and pinnate tansymustard [*Descurainia pinnata* (Walt.) Britt.]. Their interference can cause significant yield reduction in winter wheat. Season-long competition of 11, 33, and 98 blue mustard $plants·m^{-2}$ reduced wheat grain yields by 28%, 42%, and 51%, respectively [2]. Conley and Bradley (2005) [3] reported yield reductions of 13 and 38% because of henbit interference at 82 and 155 $plants·m^{-2}$, respectively. Northam *et al.* (1993) [4] also reported wheat grain yield loss of 48% with 221 henbit $plants·m^{-2}$. Bushy wallflower at 272 $plants·m^{-2}$ reduced wheat yields by 25% [5]. Hence, winter annual broadleaf weed control is very important for successful wheat production.

For more than two decades acetolactate synthase (ALS)-inhibiting herbicides have been primary herbicides used in winter wheat, however continuous usage of those herbicides led to selection of ALS-inhibitor resistant weeds. Currently 126 ALS-inhibitor resistant weed species have been reported worldwide; 45 in the USA [6]. Bushy wallflower and flixweed, two common broadleaf

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weeds in winter wheat, were reported ALS-inhibitor resistant in 2005 and 2006, respectively in Kansas [6-8]. Rotating herbicides with different modes of action can avoid selection for weeds biotypes that are resistant to certain herbicides. Hence, there is a need for herbicides with alternative modes of action to ALS-inhibitor herbicides in wheat.

Pyrasulfotole is a new herbicidal active ingredient belonging to the pyrazoles family of herbicides. Pyrasulfotole inhibits 4-hydoxyphenylpyruvate dioxygenase (HPPD) and blocks the pathway of prenylquinone biosynthesis in plants [9]. This leads to decreased levels of plastoquinone in plant tissue and reduced photosynthetic yield [10]. Indirect inhibition of phytoene desaturase as a consequence of blocked plastoquinone biosynthesis subsequently leads to a decrease in carotenoids [11] and consequently prevents stabilization of the photosynthetic apparatus so that chlorophyll molecules are destroyed by excessive light energy. Inhibition of HPPD also prevents biosynthesis of tocopherols that leads to reduced vitamin E synthesis, which means loss of protection against oxidative stress and against photo inactivation of the photosynthesis apparatus. The whole process will result in typical bleaching symptoms in the newly developing leaves during the first week after application. These bleaching symptoms progress toward necrosis and susceptible plants generally die within two to three weeks after treatment. Pyrasulfotale is the first significant compound with a new mode of action for broadleaf weed control in wheat, barley and triticale in more than 20 years.

The prepacked mixture of pyrasulfotole & bromoxynil (Huskie®, Bayer CropScience, P.O. Box 12014, 2 T.W. Alexander Drive, Research Triangle Park, North Carolina 27709, USA) received US registration for use in wheat in 2008. Bromoxynil belongs to the nitrile group and inhibits photosynthesis at photosystem II in susceptible plants. The premix also contains the safener mefenpyr-diethyl. The recommended dose of pyrasulfotole & bromoxynil is 207 to 282 $g \cdot ai \cdot ha^{-1}$ and recommended stage of application in wheat is first leaf to flag leaf emergence. The herbicide label recommends tank mixing pyrasulfotole & bromoxynil with dicamba, MCPA, metsulfuron-methyl or 2,4-D for broad spectrum weed control. Currently not much information on use of pyrasulfotole & bromoxynil in winter wheat is available. The objectives of the study were 1) to evaluate premixed pyrasulfotole & bromoxynil with and without other herbicides for efficacy and safety in winter wheat and 2) to determine the optimum time for its application.

2. Material and Methods

Field experiments were conducted for two years near Hays (2007-2009) and for three years near Manhattan (2007-2010) in Kansas in the central USA. Soil characteristics of the sites are given in **Table 1**. Experimental design was a randomized complete block with four treatment replications. The pyrasulfotole & bromoxynil premix was tested alone or in tank mix combinations with other herbicides applied postemergence (POST) at two timings. The rate of pyrasulfotole & bromoxynil used was 253 $g \cdot ai \cdot ha^{-1}$ without other herbicides and 207 $g \cdot ai \cdot ha^{-1}$ when tank mixed. Tank mixture partners tested were MCPA ester at 280 $g \cdot ai \cdot ha^{-1}$, dicamba at 140 $g \cdot ai \cdot ha^{-1}$,

Table 1. Soil characteristics and planting and spraying information, Hays and Manhattan, KS, 2007-2010.

	Hays, KS		Manhattan, KS		
	2007-2008	2008-2009	2007-2008	2008-2009	2009-2010
Soil type	Roxbury silt loam	Crete silty clay loam	Reading silt loam	Reading silt loam	Reading silt loam
Soil pH	7.7	6.3	5.7	5.7	5.7
Organic matter (%)	2.5	2	2.9	2.9	2.9
Wheat cultivar	Danby	KS08HW35-1	Overley	Overley	Fuller
Seed rate ($kg \cdot ha^{-1}$)	73	63	78	78	78
Planting date	10/02/2007	10/01/2008	10/11/2007	10/08/2008	10/19/2009
Row spacing (cm)	25	25	25	25	19
Plot size	2.5 × 6.7	2.5 × 6.7	1.9 × 6	1.9 × 6	1.9 × 6
Fall-POST spray date	11/04/2007	11/07/2008	11/27/2007	11/25/2008	12/04/2009
Spring-Post spray date	03/13/2008	03/16/2009	03/28/2008	03/17/2009	03/29/2010

and metsulfuron-methyl at 4.2 $g \cdot ai \cdot ha^{-1}$. A commercial standard of premixed triasulfuron & dicamba at 165 $g \cdot ai \cdot ha^{-1}$ and a non-treated control were also included in the study. Non-ionic surfactant at 0.5% v/v and 28% urea ammonium nitrate at 4.7 $L \cdot ha^{-1}$ were included with all herbicide treatments. Treatments were applied postemergence to winter wheat at two timings, *i.e.* fall postemergence (fall-POST) and spring postemergence (spring-POST). Herbicides were applied broadcast using backpack or tractor-mounted plot sprayers, calibrated to deliver 121 to 139 $L \cdot ha^{-1}$ at 172 to 207 kPa. Henbit, flixweed and blue mustard were predominate weed species at Hays, and henbit, flixweed, bushy wallflower, field pennycress and wild buckwheat were predominate at Manhattan. Wheat variety, seeding rate, plot size, row spacing, planting and application dates are presented in **Table 1**. Generally, wheat was 5 - 10 cm tall with 1 - 2 tillers at fall-POST application and 7.5 - 15 cm tall with 2 - 5 tillers at spring-POST application. Likewise, except wild buckwheat, weeds were 1 - 2.5 cm tall at fall-POST and 2.5 - 7.5 cm at spring-POST application. Wild buckwheat had not emerged by the time of fall-POST applications at Manhattan; they emerged in spring and were at cotyledon to 4 leaf stage when spring-POST treatments were applied.

Weed control and crop injury were rated based on composite visual estimations of density reduction, growth inhibition, and foliar injury on a scale of 0 (no effect) to 100 (plant death). Henbit, flixweed and blue mustard control ratings were determined 195 to 224 days after planting (DAP) at Hays. Similarly, henbit, flixweed, bushy wallflower and field pennycress control ratings were determined 190 to 206 DAP at Manhattan. Wild buckwheat control was determined 236 to 258 DAP at Manhattan. Wheat injury was visually assessed 2 weeks after fall-POST and spring-POST applications at each location. Grain yield was determined by harvesting the six center rows of each plot with a plot combine and adjusting seed weight to 12.5% moisture content. Yields were not determined at Manhattan in 2008 due to hail damage. Data were analyzed using the general linear model procedure of SAS (Statistical Analysis Systems Institute, Cary, NC, USA) and means were separated at the 5% significance level using Fisher's protected LSD. Percent weed control and wheat injury were arcsine transformed before analysis. The control treatment was omitted from weed control and crop injury analyses, but included in the analysis of wheat grain yield. Because there was significant year by location by treatment interaction for henbit and flixweed control data are presented year wise for each location (**Table 2**). Year by treatment interactions were significant for blue mustard, bushy wallflower and field pennycress and hence data are presented year wise for respective locations. Wild buckwheat control ratings at Manhattan were pooled over years 2007-2008 and 2008-2009 because year by treatment interaction was non-significant. Wheat injury rating were pooled over years and presented separately for each site because site by treatment interactions were significant.

3. Results and Discussion

3.1. Weed Control

3.1.1. Henbit

In 2007-2008, at Hays, fall-POST application of all herbicides controlled henbit better than spring-POST treatments (**Table 3**). Complete control of henbit was achieved with all fall-POST treatments. Among spring-POST treatments henbit control was lowest with tank mixture of pyrasulfotole & bromoxynil + metsulfuron-methyl (86%) and premixed triasulfuron & dicamba (84%). Henbit control was essentially complete, regardless of herbicide or application timing at Hays in 2008-2009. At Manhattan, all pyrasulfotole & bromoxynil treatments applied fall-POST controlled henbit ≥ 98%, but control varied significantly among spring-POST treatments (67% - 100%). Lowest henbit control was observed with triasulfuron & dicamba applied either fall-POST or spring-POST compared to pyrasulfotole & bromoxynil treatments, however fall-POST treatment was much better than spring-POST treatment (88% - 95% vs 53% - 63%). These results indicate that pyrasulfotole & bromoxynil with or without tank mixtures controlled henbit better than commercial standard triasulfuron & dicamba. However, fall applications of pyrasulfotole & bromoxynil were better than spring applications. This could be due to the fact that henbit was smaller in size in fall (1 - 2.5 cm) compared to spring (2.5 - 7.5 cm). Contrary to our results, Martin *et al.* (2008) [12] reported complete control of henbit with pyrasulfotole & bromoxynil alone or in combination with dicamba regardless of application timing (fall or spring). In our experiment it was also noticed that, in two instances, pyrasulfotole & bromoxynil + metsulfuron-methyl applied spring-POST controlled henbit less compared to pyrasulfotole & bromoxynil alone or in combination with MCPA. Generally, ALS-inhibiting herbicides (triasulfuron and metsulfuron-methyl) control henbit better when applied in fall than spring.

3.1.2. Flixweed, Blue Mustard, Bushy Wallflower and Field Pennycress

The premix of pyrasulfotole & bromoxynil alone or in combination with MCPA, dicamba or metsulfuron-methyl, across locations, controlled flixweed and blue mustard, 98% or more regardless of application timing (**Table 4**). Data on flixweed at Hays in 2008-2009 and at Manhattan in 2007-2008 and 2009-2010, and on blue mustard at Hays in 2007-2008 are not presented here

Table 2. Analysis of variance (ANOVA) results for weed control and crop injury[a,b].

Source	Henbit	Flixweed	Blue mustard	Bushy wallflower	Field pennycress	Wild buckwheat	Injury-F	Injury-S
Year	***	**	*	**	***	NS	***	NS
Location	***	NS	-	-	-	-	***	***
Year × location	***	***	-	-	-	-	***	***
Treatment	***	***	***	***	***	***	**	***
Year × treatment	***	***	***	***	***	NS	NS	**
Location × treatment	***	***	-	-	-	-	**	***
Year × location × treatment	***	***	-	-	-	-	**	NS

[a]Abbreviation: NS, not significant; injury-F, injury due to fall treatments; injury-S, injury due to spring treatments; [b]Results of ANOVA based upon arcsine-transformed data; *P = 0.05 - 0.01; **P = 0.01 - 0.001; ***P = 0.001 - 0.0001.

Table 3. Henbit control with POST application of premixed pyrasulfotole & bromoxynil and its tank mixtures, Hays and Manhattan, KS[a].

Treatments[b]	Time of application	Rate	Hays		Manhattan		
			2007-2008	2008-2009	2007-2008	2008-2009	2009-2010
		g·ha^{-1}	%				
Pyrasulfotole[c]	Fall	253	100	99	98	98	100
Pyrasulfotole + MCPA	Fall	207 + 280	100	100	99	100	100
Pyrasulfotole + dicamba	Fall	207 + 140	100	100	98	100	100
Pyrasulfotole + metsulfuron-methyl	Fall	207 + 4.2	100	100	100	100	100
Triasulfuron & dicamba	Fall	165	100	100	88	92	95
Pyrasulfotole	Spring	253	94	100	99	80	97
Pyrasulfotole + MCPA	Spring	207 + 280	95	99	99	82	100
Pyrasulfotole + dicamba	Spring	207 + 140	93	99	92	72	100
Pyrasulfotole + metsulfuron-methyl	Spring	207 + 4.2	86	100	93	67	97
Triasulfuron & dicamba	Spring	165	84	100	63	53	53
LSD (0.05)			4	NS	4	10	5

[a]Abbreviations: NS, non-significant; [b]All herbicide treatments include non-ionic surfactant at 0.5% v/v and 28% urea ammonium nitrate at 4.7 L·ha^{-1}; [c]Pyrasulfotole has bromoxynil as premix partner.

because weed control was almost complete and treatment differences were not significant. These results are consistent with reports of 98% - 99% control of flixweed and 96% - 99% control of blue mustard in Oregon with spring-applied pyrasulfotole & bromoxynil [13]. In our study, bushy wallflower and field pennycress were controlled 90% or more, regardless of application time, and there were no significant differences among treatments (data not shown). The commercial standard triasulfuron & dicamba controlled all four weeds completely when applied fall-POST, but control was occasionally lower than pyrasulfotole & bromoxynil treatments when applied in spring. Across locations, triasulfuron & dicamba applied spring-POST controlled flixweed by 83% - 100%, blue mustard 89% - 100%, bushy wallflower 90% - 100% and field pennycress 90% - 100%.

3.1.3. Wild Buckwheat

At Manhattan, wild buckwheat emerged late after fall-POST application and plants were small at the time of spring-POST application. Spring-applied pyrasulfotole & bromoxynil alone or in combination with MCPA provided poor wild buckwheat control (3% and 12%, respectively) (**Table 4**). However, when pyrasulfotole & bromoxynil was tank mixed with dicamba or metsulfuronmethyl control of wild buckwheat was 84% or more. Spring applied triasulfuron & dicamba controlled wild buckwheat 94%. Even though wild buckwheat had not emerged at the time of fall-POST application, pyrasulfotole & bromoxynil + metsulfuron-methyl and triasulfuron & dicamba applied in fall controlled wild buckwheat 73% and 87%, respectively. This might be due to residual activity of metsulfuron and triasulfuron in the soil. Metsulfuron-methyl and triasulfuron can persist in the soil up 4 and 12 weeks, respectively [14]. These results indicated that pyrasulfotole & bromoxynil premix alone applied in spring has very little effect on wild buckwheat.

3.2. Crop Injury and Grain Yields

At Hays, averaged over years, pyrasulfotole & bromoxynil alone or in combination with MCPA or dicamba or metsulfuron-methyl applied in fall or spring caused 1 to 4% wheat injury, but the injury was not significant among treatments (**Table 5**). At Manhattan, no injury was obesrved with pyrasulfotole & bromoxynil treatments when applied in fall, but up to 7% injury was observed when applied in spring. Triasulfuron & dicamba caused 0% to 6% injury. However, injury symptoms disappeared within 3 to 4 weeks and did not influence wheat grain yields (data not shown). In a study conducted at Oregon, no wheat injury was observed with pyrasulfotole & bromoxynil applied in spring at 282 $g \cdot ai \cdot ha^{-1}$ [13]. This tolerance in wheat might be due to faster metabolic degradation of the herbicide inside the plant. Wheat grain

Table 4. Fixweed, blue mustard and wild buckwheat control with POST application of premixed pyrasulfotole & bromoxynil and its tank mixtures.

Treatments[a]	Time of application	Rate	Flixweed		Blue mustard	Wild buckwheat
			Hays	Manhattan	Hays	Manhattan
			2007-2008	2008-2009	2007-2008	Pooled[c&d]
		$g \cdot ha^{-1}$	%			
Pyrasulfotole[b]	Fall	253	100	100	99	0
Pyrasulfotole + MCPA	Fall	207 + 280	100	100	99	0
Pyrasulfotole + dicamba	Fall	207 + 140	100	100	98	0
Pyrasulfotole + metsulfuron-methyl	Fall	207 + 4.2	100	100	100	73
Triasulfuron & dicamba	Fall	165	100	100	100	87
Pyrasulfotole	Spring	253	100	100	99	3
Pyrasulfotole + MCPA	Spring	207 + 280	100	100	100	12
Pyrasulfotole + dicamba	Spring	207 + 140	100	100	100	84
Pyrasulfotole + metsulfuron-methyl	Spring	207 + 4.2	100	100	100	92
Triasulfuron & dicamba	Spring	165	96	83	89	94
LSD (0.05)			1	3	2	12

[a]All herbicide treatments include non-ionic surfactant at 0.5% v/v and 28% urea ammonium nitrate at 4.7 $L \cdot ha^{-1}$; [b]Pyrasulfotole has bromoxynil as premix partner; [c]Data pooled over years 2007-2008 and 2008-2009; [d]Wild buckwheat did not emerge at the time of fall applications.

Table 5. Wheat injury caused by premixed pyrasulfotole & bromoxynil and its tank mixtures applied in fall and spring seasons, Hays and Manhattan, KS[a].

Treatments[b]	Rate	14 DAFT		14 DAST	
		Hays	Manhattan	Hays	Manhattan
	$g \cdot ha^{-1}$	%			
Pyrasulfotole[c]	253	2	0	2	0
Pyrasulfotole + MCPA	207 + 280	1	0	1	0
Pyrasulfotole + dicamba	207 + 140	4	0	1	7
Pyrasulfotole + metsulfuron-methyl	207 + 4.2	3	0	2	1
Triasulfuron & dicamba	165	4	0	0	6
LSD (0.05)		NS	NS	NS	2

[a]Abbreviations: DAFT, days after fall treatments; DAST, days after spring treatments; NS, non-significant; [b]All herbicide treatments include non-ionic surfactant at 0.5% v/v and 28% urea ammonium nitrate at 4.7 $L \cdot ha^{-1}$. [c]Pyrasulfotole has bromoxynil as premix partner.

yields were not influenced by any treatment compared to untreated control (data not shown). High densities of winter annual broadleaf species often reduce wheat yields, sometimes dramatically, but controlling low to medium density weed populations does not always result in higher grain yields [15,16]. Analysis of 25 experiments conducted over a several year period in Oklahoma found that effective herbicidal control of weeds did not increase wheat yields most of the time; yield increased when bushy wallflower density was as much as 830 plants·m^{-2} [16]. Still good weed control is necessary in winter wheat to prevent multiplication of weed density in future.

4. Conclusion

Premixed pyrasulfotole & bromoxynil alone at 253 g·ai·ha^{-1} or pyrasulfotole & bromoxynil at 207 g·ai·ha^{-1} in combination with MCPA, dicamba or metsulfuron-methyl applied postemergence either in fall or spring controlled blue mustard, flixweed, bushy wallflower and field pennycress 98% or more. Henbit control with pyrasulfotole & bromoxynil treatments was much better when they were applied in fall than spring (≥98% vs ≥67%). Pyrasulfotole & bromoxynil applied alone in spring was not effective on wild buckwheat, but tank mixing with dicamba or metsulfuron-methyl controlled wild buckwheat 84% or more. Hence, tank mixing pyrasulfotole & bromoxynil with other herbicides is desirable for broad spectrum of weed control. Minor (≤7%) or no crop injury was noticed with pyrasulfotole & bromoxynil treatments regardless of application time. It can be concluded that the new herbicide pyrasulfotole & bromoxynil can safely be used in wheat for broadleaf weed control in spring or fall season, but fall application is desirable for better weed control. With a new and unique mode of action, premix of pyrasulfotole & bromoxynil is an effective alternative herbicide for wheat growers to combat weeds resistant to ALS-inhibiting herbicides.

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