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Control of herbicide resistant *Phalaris minor* by pyroxasulfone in wheat

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ABSTRACT

Evolution of multiple herbicide resistance in *Phalaris minor* in wheat has resulted from the repeated use of herbicides with a similar mode of action which could threaten the sustainability of the rice-wheat cropping system in North-West India. In this context, field studies were conducted at Research Farm, Department of Agronomy, Punjab Agricultural University, Ludhiana during 2011-12, 2012-13 and 2013-14 in randomized block design replicated four times and at farmer's field during 2016-17 and 2017-18 with the objective to evaluate the efficacy of herbicide with alternative mechanism of action for the control of resistant *P. minor* in wheat. The treatments included pyroxasulfone 85, 102, 127.5 g/ha, pendimethalin 750 g/ha as pre-emergence (PE), sulfosulfuron 25 g/ha, clodinafop 60 g/ha as post-emergence (PoE) and unsprayed control. However, the treatments during 2013-14 included pyroxasulfone 85, 102, 127.5 g/ha, pendimethalin 750 g/ha and unsprayed control with pendimethalin 1125 g/ha as PE at farmers' field instead of pendimethalin 750 g/ha. The results indicated that pyroxasulfone at 127.5 g/ha recorded effective control of *P. minor* and its biomass and gave the highest wheat grain yield (4.87, 4.80 and 5.43 t/ha) during 2011-12, 2012-13 and 2013-14, respectively. At farmer's field, pyroxasulfone 127.5 g/ha has been found effective against the resistant populations of *Phalaris* with 5.37 and 5.42 t/ha grain yield. The current study demonstrated that PE application of pyroxasulfone at 127.5 g/ha would be a suitable option for the control of resistant populations of *Phalaris* in wheat in Punjab.

INTRODUCTION

The rice-wheat cropping system is the most commonly followed cropping system in irrigated ecologies of North-West India. Wheat (*Triticum aestivum* L.) is an important cereal crop of Punjab, which is a highly productive zone in the Indo-Gangetic Plains and contributes about 69% of the total food output in the country (about 84% wheat and 54% rice). Punjab is the major wheat growing state in India with an area of 3.5 million ha, 16.1 million tonnes of production and productivity of 4.58 t/ha (Anonymous 2017). In rice-wheat cropping system, *Phalaris minor* Retz. is still the most pernicious and competitive weed in wheat in Punjab, causing significant yield losses in north-west India including Punjab, Haryana, Western Uttar Pradesh states of the north-western Indo-Gangetic Plains of India. Severe reductions in grain yield of wheat have been reported by many researchers.

Being the most problematic weed in wheat, it has a long track record of developing resistance to many herbicides. Continuous use of isoproturon in wheat for more than a decade led to the evolution of resistance in *P. minor* in the early 1990s (Malik and Singh 1993, Walia *et al*. 1997). It was widely used by the farmers due to its cost effectiveness, wider application window, flexibility in the method of application and broad-spectrum weed kill, along with its fair selectivity under wheat-mustard intercropping (Chhokar *et al*. 2009). Number of other herbicides introduced after isoproturon such as clodinafop, fenoxaprop, sulfosulfuron performed fairly well for several years. Unfortunately, the farmers forgot the golden rule of herbicide rotation and it showed resistance to fenoxaprop, clodinafop and sulfosulfuron. In Punjab, *P. minor* is showing resistance to fenoxaprop, clodinafop and sulfosulfuron and pinoxaden. This indicates multiple-herbicide resistance in *P. minor* across three modes of action: photosynthesis at the photosystem II site, acetyl-coA carboxylase (ACCase), and acetolactate synthase (ALS) inhibitors (Heap 2019). Some herbicide mixtures such as mesosulfuron +

iodosulfuron and fenoxaprop + metribuzin were also introduced for controlling resistant *P. minor*. Pre-mix of fenoxaprop + metribuzin have not been widely used due to the sensitivity of some wheat varieties like '*PBW 550*' to this herbicide. Period of continuous repeated sprays with a similar mode of action herbicides, reduced or overdose application, faulty spray techniques, mixing of two or more chemicals, delay in application leads to the evolution of herbicide resistance of *P. minor* in the state.

Farmers having an infestation of multiple herbicide resistant populations are facing significant yield reductions in the absence of effective alternative herbicides. Till today, microtubule inhibitors, ACCase and ALS-inhibitors are the key herbicide options available for the control of *Phalaris* in wheat in north-west India. In Punjab, herbicide resistance in *P. minor* continues to escalate in wheat which is threatening the grain production and is adding more to farmers' worry. Diversity of weed management programme by using herbicides with different modes of action is important in preventing or delaying the evolution of herbicide-resistant weeds. There is a dire need to have a PE herbicide with a different mode of action and having sufficient residual activity which can prove as an effective tool for managing herbicide resistant *P. minor* in the state. In this context, a new class of herbicide chemistry pyroxasulfone has provided an alternative to already recommended herbicides (ACCase inhibitors, ALS inhibitors, PSII inhibitors) in wheat in Punjab. Pyroxasulfone has provided effective control of group A and B resistant annual ryegrass in wheat for about 10 years in Australia (Boutsalis *et al*. 2014). Currently, there are relatively few data describing the weed control provided by pyroxasulfone across a diverse spectrum of environments (Knezevic *et al.* 2009). It provides an alternative and unique mode of action which makes it an ideal chemical for herbicide group diversification and resistance management (Yamaji *et al.* 2014).

The objective of this research was to standardize the dose of new herbicide pyroxasulfone (PIH 485 85% WG) for the management of herbicide-resistant *P. minor* in wheat through on-station experiments and farmers' participatory trials.

MATERIALS AND METHODS

A field experiment to investigate the effect of new herbicide pyroxasulfone against resistant *P. minor* in wheat was conducted during 2011-12, 2012-13 and 2013-14 at Research Farm, Department of Agronomy, Punjab Agricultural University (PAU), Ludhiana (30° 56' N, 75° 52' E , 247 m above sea level), Punjab, India. The region is characterized by a sub-tropical and semi-arid climate with a hot dry summer (March–June), wet monsoon season (late June–mid September) and cool, dry winter (October–February). The soil of the experimental site at PAU was a sandy loam in texture, normal in reaction (pH 7.2) and electrical conductivity (0.11dS/m), low in organic carbon (0.42%) and available nitrogen (222.2 kg/ha) and very high in available phosphorus (16.9 kg/ha) and potassium (201.43 kg/ha).

The experimental site had been under a rice-wheat system for more than 10 years and having resistant *P. minor* population. The seven treatments in the study included pyroxasulfone at 85, 102 and 127.5 g/ha applied as pre-emergence (PE), pendimethalin 750 g/ha as PE, sulfosulfuron 25 g/ha, clodinafop 60 g/ha were applied as post-emergence (PoE) and unsprayed control. The pre-emergent herbicides were applied immediately after sowing in moist soil, and other post-emergent herbicides were applied at 35 days after sowing (3-4 leaf stage) with a knapsack sprayer fitted with a flat fan nozzle using a spray volume of 500 L/ha. The experiment was conducted in randomized complete block design replicated four times. The wheat variety *'PBW 550'*, *'PBW 621'* and *'HD 2967'* was sown in mid-November of 2011, 2012 and 2013, respectively, by using seed rate of 112.5 kg/ha by seed cum fertilizer drill at 20 cm row spacing. The recommended doses of fertilizers were applied (125 kg N/ha, 50 kg P_2O_5/ha and 30 kg K_2O/ha) to the crop. The source of NPK used was urea, DAP and muriate of potash, respectively. Half of the recommended dose of N and whole of phosphorus and potassium were applied at the time of sowing and the remaining half dose of N was applied as top dressing at the time of first irrigation. All the recommended plant protection measures were carried out as per the local recommendations of the state. The gross plot size was 7 × 3 m.

The data on weed density was recorded from two randomly selected spots for each plot at 70 days after sowing (DAS) using 0.5 × 0.5 m quadrat. Weed biomass was recorded at 70 days after spray by cutting the weed plants above the ground by randomly placing the two quadrats of 0.5 × 0.5 m and then the samples were oven dried at 60 ±2°C until they reached to a constant weight. The data on plant height was collected from five randomly selected plants per plot at the time of harvest. The data on grain yield was taken from the middle of each plot by manually harvesting and threshing the samples at the time of harvest. The wheat crop was harvested at full maturity in mid-April of 2012, 2013 and 2014. An area of 1 m on each side of the plot and one border row on both sides of the experimental plots were harvested first, thereafter the net area separately. The grain weight was recorded at 14% moisture after threshing, cleaning and drying. The grain yield was expressed as tonnes per hectare.

In addition to the experiments at the research farm, farmers' participatory trials were also conducted at farmers' fields in District Moga, India, during 2016-17 and 2017-18 with an objective to assess the performance of new herbicide pyroxasulfone against resistant *P. minor* in real field situations. Based on survey conducted by weed scientists from Punjab Agricultural University, Ludhiana (Punjab) alongwith team from CCS Haryana Agricultural University, Hisar (Haryana) at farmer's field, District Moga (more complaints/ reports of herbicide resistance in wheat from this district), location was chosen at farmer's field where the problem of herbicide resistance was quite high to conduct an experiment. During 2016-17 and 2017-18, the experiment was laid out at the farmer's field. The objective of an experiment was to evaluate the efficacy of new chemistry herbicide pyroxasulfone against resistant *P. minor* in wheat. The soil of the experimental site was loamy sand in texture at farmer's field. The soil was slightly alkaline in reaction (pH 8.2) and electrical conductivity (0.12 dS/m), low in organic carbon (0.33%) and available nitrogen (220 kg/ha) and medium in available phosphorus (16.2 kg/ha) and potassium (271.5 kg/ ha). Wheat variety '*HD 2967*' was sown on 10.11.2016 and 14.11.2017 at farmers' field. The treatments of second experiment at farmers' field included pyroxasulfone 85, 102 and 127.5 g/ha, pendimethalin 1125 g/ha as PE and unsprayed control. The experiments were laid out in a randomized complete block design with three replications, with a plot size of 50 m^2. The observations on weed density and grain yield were taken as explained in Experiment I. The crop was harvested in mid-April 2017 and 2018. The crop was managed according to the standard agronomic practices of the state university. Sampling for grain yield of the crop was done from two random places of 4.0 m × 4.0 m size from each plot at the time of harvesting.

The data of actual number of weeds were transformed by square root transformation for statistical analysis. The data were subjected to the analysis of variance (ANOVA). The significant treatment effect was judged with the help of 'F' test at the 5% level of significance.

RESULTS AND DISCUSSION

Effect on *P. minor*

P. minor was a major grass weed in wheat crop during all the years of investigation. Statistical analysis showed significant differences in weed density and biomass reductions of *P. minor* with pyroxasulfone and pendimethalin. Pyroxasulfone at 102 g and 127.5 g/ha provided effective control of *P. minor* (0 to 5 plants/m^2) during 2011-12 and 2012-13. Sulfosulfuron at 25 g/ha and pyroxasulfone at 85 g/ ha were comparable in providing control of *P. minor* however clodinafop and fenoxaprop recorded significantly more density of *P. minor* but less than unsprayed control (27 and 80 plants/m^2). The highest dose of 127.5 g/ha pyroxasulfone improved the control of *P. minor* (100 and 98.8%) followed by pyroxasulfone 102 g/ha (96.3 and 93.8%) and pendimethalin (96.3 and 93.8%) respectively, in 2011-12 and 2012-13 as compared to unsprayed control. During 2012-13, weed control level increased with the increase in the dose of pyroxasulfone than the other recommended herbicides namely sulfosulfuron and clodinafop. Both sulfosulfuron and clodinafop showed less efficacy on *P. minor*. Pyroxasulfone at 102 and 127.5 g/ha significantly reduced the density of *P. minor* as compared to pyroxasulfone at 85 g/ha and recommended herbicides *i.e.* sulfosulfuron, clodinafop and unsprayed control (**Table 1**). It is clear from the data of weed density that pyroxasulfone 127.5 g/ha had an edge for the control of *P. minor* in wheat. Pyroxasulfone 127.5 g and 102 g/ha gave the best control of *P. minor* as compared to other herbicides. The plots were even free from the second flush of *P. minor*.

Weed biomass also showed a decreasing trend with the increase in the dose of pyroxasulfone during both the years. This could be explained by the evidence that better control of weeds in pyroxasulfone treated plots resulted in significantly less accumulation of weed biomass. Weed biomass at 70 days after spray (DAS) varied significantly among weed control treatments during both the cropping seasons (**Table 1**). In both the years, plots treated with clodinafop, sulfosulfuron and pyroxasulfone 85 g/ha had the highest weed biomass, which was higher than the plots treated with pyroxasulfone 102 g and 127.5 g/ha and pendimethalin 750 g/ha. Pyroxasulfone 127.5 g/ha had the lowest weed biomass (2 g/m^2) than all other treatments during

2011-12 and 2012-13. Weed control efficiency being the highest 88.9 and 99% obtained in pyroxasulfone 127.5 g/ha (**Table 1**). Weed control efficiency followed the trend pyroxasulfone 127.5 g/ha > pyroxasulfone 102 g/ha > pendimethalin 750 g/ha. Pyroxasulfone provided longer weed control than pendimethalin. Weed control efficiency was highest in pyroxasulfone at 127.5 g/ha as it recorded the least density of *P. minor* (**Table 1**) so less weed biomass was obtained. PE application of pyroxasulfone prevented the germination and establishment of resistant *P. minor*. Similarly, pendimethalin also helped in giving weed free environment in the initial days of crop establishment. Therefore, PE herbicides provided weed free environment which gave a strong edge to the crop to flourish. This helps the crop to utilize all the available resources efficiently. Another factor could be that wheat foliage has covered the ground completely which allowed less penetration of light from the wheat foliage, so very less germination of later flush of weeds took place. In PoE applied herbicides *P. minor* compete with the crop for all the available resources in the field nearly for the first 30 days. During 2013-14, pyroxasulfone at 127.5 g/ha had an edge for the control of *P. minor* as compared to its lower doses of 102 and 85 g/ha (**Table 3**).

Pyroxasulfone at 100 g/ha provides efficient control of both herbicide-resistant and susceptible annual ryegrass (*Lolium multiflorum*) populations in wheat (Tanetani *et al.* 2009). Pyroxasulfone provided 88% or better control of kochia (*Kochia scoparia*) and velvetleaf (*Abutilon theophrasti* Medik.) four months after planting, which was greater than metolachlor in furrow-irrigated corn (*Zea mays* L.) (King and Garcia 2008). Pyroxasulfone 200 to 300 g/ha provided excellent control of green foxtail (*Setaria viridis*), field sandbur (*Cenchrus spinifex* Cav.), large crabgrass *(Digitaria sanguinalis*), palmer amaranth (*Amaranthus palmeri*), puncturevine (*Tribulus terrestris* L.), *Texas panicum* (*Panicum texanum*) and velvetleaf (*Abutilon theophrasti* Medik.) (Knezevic *et al.* 2009, Geier *et al.* 2006, Gregory *et al.* 2005).

Effect on crop

There was no significant effect observed on plant height of the crop (**Table 2**). Spike length is an important yield attributing character which is directly related to the number of grains per ear and thus holds significance in determining the grain yield. The herbicide sprayed plots produced significantly more spike length as compared with unsprayed plots. Higher spike length (12 and 11.7 cm) was recorded in pyroxasulfone 127.5 g/ha as compared to check herbicides viz. sulfosulfuron (11.7 and 10.8 cm) and clodinafop (11.6 and 10.5 cm). The differences in spike length were reflected in variation in wheat grain yield under different treatments. All the herbicidal

Table 1. Effect of different weed control treatments on weed density and biomass of *P. minor* in wheat at 70 DAS at Ludhiana

Treatment	Dose (g/ha)	Application time	Weed density (no./m^2)		Weed biomass (g/m^2)		WCE (%)	
			2011-12	2012-13	2011-12	2012-13	2011-12	2012-13
Pyroxasulfone	85	PE	2.07 (3)*	3.33 (10)	3.21 (9)	5.0 (24)	50.0	88.3
Pyroxasulfone	102	PE	1.24 (1)	2.38 (5)	2.18 (5)	3.87 (14)	72.2	93.2
Pyroxasulfone	127.5	PE	1.07 (0)	1.38 (1)	1.73 (2)	1.73 (2)	88.9	99.0
Pendimethalin	750	PE	1.30 (1)	2.42 (5)	2.20 (5)	3.83 (14)	72.2	93.2
Sulfosulfuron	25	PoE	2.13 (4)	4.86 (23)	3.44 (11)	5.13 (26)	38.9	87.3
Clodinafop	60	PoE	3.89 (14)	6.28 (39)	3.69 (13)	7.28 (52)	27.8	74.6
Unsprayed control	-	-	5.25 (27)	9.00 (80)	4.35 (18)	14.37(205)	-	-
LSD (p=0.05)			0.61	0.77	0.87	0.56	-	-

*Figures in parentheses are original means and data is subjected to square root transformation; PE - pre-emergence; PoE - Post-emergence

Table 2. Effect of different weed control treatments on growth, yield and yield attributes of wheat at Ludhiana

Treatment	Dose (g/ha)	Application time	Plant height (cm)		Spike length (cm)		Grain yield (t/ha)	
			2011-12	2012-13	2011-12	2012-13	2011-12	2012-13
Pyroxasulfone	85	PE	72.5	76.7	11.6	10.8	4.49	4.15
Pyroxasulfone	102	PE	73.1	78.4	11.8	10.9	4.68	4.79
Pyroxasulfone	127.5	PE	72.9	77.3	12.0	11.7	4.87	4.80
Pendimethalin	750	PE	72.4	77.9	11.9	10.9	4.70	4.79
Sulfosulfuron	25	PoE	73.4	76.4	11.7	10.8	4.47	4.39
Clodinafop	60	PoE	74.5	77.2	11.6	10.5	3.66	3.84
Unsprayed control	-	-	70.4	77.3	11.1	8.9	2.89	2.62
LSD (p=0.05)			NS	NS	0.3	0.5	0.19	0.28

PE - pre-emergence; PoE - Post-emergence treatments recorded significantly higher wheat grain yield and yield attributes (spike length) than the unsprayed control during both the years. The grain yield in pyroxasulfone at 102 g and 127.5 g/ha was higher than pyroxasulfone 85 g/ha, sulfosulfuron and clodinafop. In both the years, pyroxasulfone 127.5 g/ha recorded similar wheat grain yield (4.87 t and 4.80 t/ha, respectively in 2011-12 and 2012-13) in the plots treated with 102 g/ha pyroxasulfone (4.68 and 4.79 t/ha, respectively in 2011-12 and 2012-13) (**Table 2**). The data with respect to sulfosulfuron and clodinafop was statistically at par with pyroxasulfone at 102 g/ha and pendimethalin 750 g/ha. It was due to more spike length (**Table 2**) and less *P. minor* density and biomass (**Table 1**). The grain yield was found to be 61.9 and 82.8% more in pyroxasulfone at 102 g/ha than unsprayed plots. The higher grain yield obtained in pyroxasulfone at 102, 127.5 and pendimethalin 750 g/ha might be due to better weed control which resulted in better utilization of available resources. Significantly less grain yield in PoE herbicide sprayed plots was mainly due to more *P. minor* density and weed biomass (**Table 1**). Uncontrolled weed competition throughout the season resulted in the lowest grain yield (2.89 and 2.62 t/ha, respectively) in unsprayed plots (**Table 1**). During 2013-14, pyroxasulfone 127.5 g/ha recorded significantly higher grain yield (5.43 t/ha) than all other herbicide treatments due to better control of *P. minor* (**Table 3**).

Correlation matrix

The data based on 2011-12 and 2012-13 depicted in **Table 5** on the correlation matrix revealed that weed biomass showed negative coefficients. All the yield attributes were found significant with grain yield of wheat. The mean spike length (r=0.94) was found a highly significant and positive correlation with grain yield (**Table 3**). This suggests the inter-dependence of these characters as important yield determinants. The effective control of weeds also led to higher correlation between yield and yield parameters. However, weed biomass has negative relation (r=-0.95) on grain yield. Grain yield of wheat decreased linearly as the weed biomass increased and infestation of *P. minor* accounted for 91.3% variation in grain yield (**Figure 1**).

At farmer's field, during 2016-17 and 2017-18, pyroxasulfone at both 102 and 127.5 g/ha gave effective control of *P. minor* and gave statistically similar wheat grain yield and were at par to pendimethalin 1125 g/ha. PE herbicides pendimethalin 1125 g/ha and pyroxasulfone 127.5 g/ha provided good control of *P. minor* (**Table 4**).

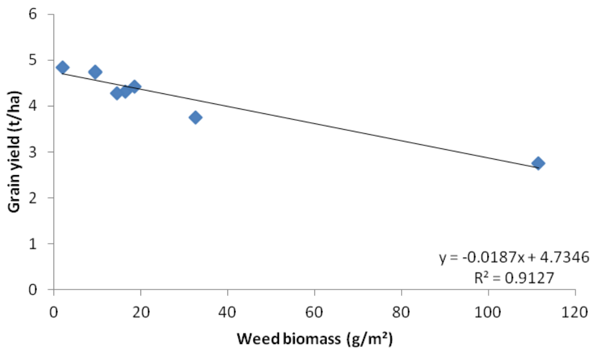

Figure 1. Relationship between weed biomass of *P. minor* and grain yield of wheat (mean of 2011-12 and 2012-13)

Table 3. Effect of different weed control treatments on *P. minor* density and biomass at Ludhiana (2013-14)

Treatment	Dose (g/ha)	*P. minor* density (no./m^2)	*P. minor* biomass (g/m^2)	Wheat grain yield (t/ha)
Pyroxasulfone	85	3.67 (13)*	6.16 (37)	4.31
Pyroxasulfone	102	2.87 (7)	4.21 (17)	5.22
Pyroxasulfone	127.5	1.71 (2)	3.26 (10)	5.43
Pendimethalin	750	3.00 (8)	4.35 (18)	5.19
Unsprayed control	-	9.38 (87)	11.1(122)	3.12
LSD (p=0.05)		0.79	0.44	0.15

*Figures in parentheses are original means and data is subjected to square root transformation

Table 4. Effect of different weed control treatments on *P. minor* density and wheat grain yield at farmer's field (district Moga) in 2016-17 and 2017-18

Treatment	Dose (g/ha)	*P. minor* density at 45 DAS (no./m^2)		Wheat grain yield (t/ha)	
		2016-17	2017-18	2016-17	2017-18
Pyroxasulfone	85	3.59 (12)*	2.99 (8)	4.85	5.03
Pyroxasulfone	102	1.75 (2)	1.63 (2)	5.18	5.36
Pyroxasulfone	127.5	1.49 (1)	1.28 (0.7)	5.37	5.42
Pendimethalin	1125	1.63 (2)	1.82 (2)	5.57	5.40
Unsprayed control	-	16.9 (284)	16.0 (257)	3.92	4.13
LSD (p=0.05)	-	1.06	0.65	0.21	0.11

*Figures in parentheses are original means and data is subjected to square root transformation

Table 5. Correlation matrix among growth and yield attributes, grain yield and weed biomass in wheat (mean of 2011-12 and 2012-13 at Ludhiana)

	Grain yield	1000 grain wt.	Spike length	Plant height	Weed Biomass
Grain yield	1				
1000 grain weight	0.85498**				
Spike length	0.94325**	0.79497**			
Plant height	0.559032	0.237704	0.608222		
Weed biomass	-0.95535	-0. 76495	-0.94509	0.69044	1

**Correlation is significant at 0.01 level (two-tailed)

The findings of the present study provide herbicide options for the management of herbicide resistant *P. minor*. Pre-emergence application of pyroxasulfone at 127.5 g/ha recorded effective control of *P. minor* and gave the highest wheat grain yield during all the years. Pyroxasulfone 127.5 g/ha and pendimethalin 1125 g/ha, as a single pre-emergence herbicide, has proved quite effective against resistant *P. minor* at farmers' field. PE herbicides emerged from this study will help in delaying the process of cross and multiple resistance development in *P. minor* particularly in Punjab. However, there is a need to evaluate pyroxasulfone under different soil textures and moisture conditions for the management of multiple herbicide-resistant *P. minor*. Its field efficacy will depend on its large scale field use after availability to the farmers. These results indicate that pyroxasulfone has the potential being a PE herbicide to be a valuable tool for wheat growers to control resistant *P. minor* populations in wheat in future.

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