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# Broad spectrum weed control in wheat with pyroxsulam and its tank mix combination with sulfosulfuron

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## Abstract

**Field and pot studies were conducted to determine the efficacy of pyroxsulam and tank mix combination of sulfosulfuron + pyroxsulam against diverse weed flora of wheat (*Triticum aestivum* L.). In field studies, pyroxsulam (12, 15 and 18 gha$^{-1}$ ) and tank mix combination of sulfosulfuron + pyroxsulam at 12+12, 15+15 and 18+18 gha$^{-1}$ without and with surfactant were evaluated for weed control in wheat and their carry over effect on succeeding sorghum crop. The weed control, particularly of the *Phalaris minor* was significantly poor, when pyroxsulam or its tank mix combination with sulfosulfuron were applied without surfactant compared to with surfactant (polyglycol 1000 ml ha$^{-1}$). Pyroxsulam alone or in combination with sulfosulfuron provided excellent control of *Avena ludoviciana*. The optimum dose of tank mixture (TM) of sulfosulfuron + pyroxsulam was 18+18 gha$^{-1}$ with 1000 ml ha$^{-1}$ surfactant polyglycol. This combination was superior over sulfosulfuron, due to improved control of *Rumex dentatus*, thereby increased the wheat yield by 10-11% (on three years mean basis). The TM, sulfosulfuron + pyroxsulam with surfactant was similar to ready mixture Atlantis (mesosulfuron + iodosulfuron) at 14.4 (12+ 2.4) g a.i. ha$^{-1}$ in controlling weeds and producing wheat yield. Pyroxsulam at 18 gha$^{-1}$ was effective for control of diverse weed flora (*Avena ludoviciana*, *Phalaris minor*, *Medicago denticulata* and *Lathyrus aphaca*) under field and pot studies. The carry over effect of sulfosulfuron involving treatments (sulfosulfuron, sulfosulfuron + pyroxsulam) was observed on succeeding sorghum crop. At 18+18 gha$^{-1}$ dose of sulfosulfuron + pyroxsulam, the average reduction in sorghum biomass was 44.5% in comparison to no herbicide treatment. Pyroxsulam effectively controlled the *P. minor* populations being susceptible as well as those resistant to fop and / or phenylurea herbicides. However, *P. minor* population resistant to sulfosulfuron showed the cross-resistance to pyroxsulam.**

**Keywords:** Atlantis, *Avena ludoviciana*, herbicide resistance, *Malva parviflora*, Metsulfuron, *Phalaris minor*, *Rumex dentatus*, sorghum

## 1. Introduction

Assured wheat production is essential for food security as it is an important staple food crop for a large population. Weed infestation has been recognized as major constraint in achieving optimum wheat yields. Diverse weed flora infests wheat crop as it is being cultivated under diverse agroclimatic conditions with different soil and agronomic management practices. Inspite of employing weed control measures, still world-wide significant yield losses are caused by weeds in wheat (Kosina *et al*., 2007; Oerke, 2006). For weed control in wheat, herbicides have been found the most effective and widely used due to cost and time effectiveness (Nalewaja, 1974; Chhokar *et. al*., 2012). For efficient management of diverse weed flora, single herbicide may not be effective and therefore we need herbicide combinations.

Sulfosulfuron, a sulfonylurea group herbicide is widely used in wheat (Blackshaw and Hamman, 1998; Chhokar and Malik, 2002; Geier *et al*., 2011) and it is preferred over graminicide (Clodinafop and fenoxaprop) due to additional control of some of the broad-leaved weeds. However, sulfosulfuron is ineffective against some broad-leaved weeds like *Malva parviflora* and *Rumex dentatus* (Chhokar *et al*., 2007a). There is shift in weed flora in fields, where farmers are continuously using either graminicide alone or sulfosulfuron. Under such a situation there is a need to supplement these herbicides with other herbicide options. Pyroxsulam, a new sulphonamide herbicide, is quite effective in controlling many broad-leaved and grassy weeds (DeBoer *et al*., 2011). Combination of pyroxsulam and sulfosulfuron can be an alternative option to control diverse weed flora.

Among grass weeds, *Phalaris minor* and *Avena ludoviciana* are major troublesome weeds in India under irrigated conditions in wheat crop. *P. minor* is of major concern as it infests more than half of wheat area in India and has also evolved multiple herbicide resistance against phenyl urea (Isoproturon), fop (Clodinafop and fenoxaprop) and sulfonylurea (Sulfosulfuron and mesosulfuron) group of herbicides (Chhokar and Sharma, 2008). The response of pyroxsulam against these herbicide resistant populations should also be studied. .

The declining land holding and increasing population have forced the farmers to adopt intensive cropping system, so as to have increased production per unit area and time. However, due to intensification of cropping system there is less intervening period between harvesting and sowing of two crops in sequence. However, under such conditions, the use of persistent herbicides may cause the carry over injury to the succeeding sensitive crops because of longer persistency (Geier *et al*., 200; Shinn *et al*., 1998; Chhokar *et al*., 2006). Therefore, the suitability of persistent herbicides should be examined in systems perspective. Many farmers grow sorghum as fodder crop immediately after wheat harvest and require herbicide carry over effect evaluation on it.

Considering these facts, field and pot studies were carried out with the aims (1) to determine the effectiveness of pyroxsulam, and its combination with sulfosulfuron without and with surfactant (Polyglycol) against grassy and broad-leaved weeds in wheat; (2) to find out the residual effect of pyroxsulam and pyroxsulam + sulfosulfuron applied in wheat on the succeeding crop of sorghum; and (3) to evaluate the performance of pyroxsulam against the fop (clodinafop/fenoxaprop), phenylurea (Isoproturon) and/or sulfonylurea (sulfosulfuron) resistant and sensitive populations of *P. minor* so as to determine the alternative management strategies.

## 2. Materials and Methods

Field and pot studies were conducted at Resource Management Block, Indian Institute of Wheat and Barley Research, Karnal, Haryana, India located at latitude of 29° 43' North latitude, 76° 58' East longitude and at an altitude of 245 m above MSL to determine the optimum dose of pyroxsulam and its tank mix combination with sulfosulfuron for effective weed control in wheat crop and better wheat grain yield. The experimental field soil was sandy clay loam in texture with pH of 8.0-8.2 and organic carbon content 0.39-0.42%. The experimental field had been under a rice-wheat cropping system for several years. The details of the studies undertaken are given under the following heads.

*2.1 Efficacy of pyroxsulam alone and in combination with sulfosulfuron aganst weeds in wheat:* During the four winter seasons, different formulations of pyroxsulam alone and in combination with sulfosulfuron were evaluated for control of grassy and broadleaved weeds in two set of field experiments. During first two winter seasons (2010-11 and 2011-12), wheat cv. DBW-17 was sown and during the next two seasons (2012-13 and 2013-14) cv. HD 2967 was sown.

*2.1.1. Efficacy of pyroxsulam:* Different pyroxsulam formulation evaluated during 2011-12 and 2012-13 to 2013-14 were pyroxsulam 5%WDG and pyroxsulam 4.5%OD, respectively. Crop was sown on 16th November 2011, 20th November 2012 and 10th November 2013. Weed control treatments which included pyroxsulam at 12, 15 and 18 gha$^{-1}$ without and with surfactant (Polyglycol @ 1000 mlha$^{-1}$ ) along with standard treatments of sulfosulfuron 25 gha$^{-1}$ , metsulfuron 4 gha$^{-1}$ and untreated weedy control were evaluated (Table 2). Surfactants used with sulfosulfuron and metsulfuron treatments were cationic surfactant, Leader mix 1250 mlha$^{-1}$ and Dupont non-ionic surfactant (Iso-Octyl-phenoxy-polyxethanol 12.5%) 500 mlha$^{-1}$ , respectively.

*2.1.2. Efficacy of tank mix combination of pyroxsulam + sulfosulfuron:* Different herbicide formulations evaluated during 2010-11 and 2012-13 to 2013-14 were pyroxsulam 9%WDG + sulfosulfuron 75%WG, and pyroxsulam 4.5%OD+ sulfosulfuron 75%WG, respectively. Crop was sown on 24th November, 2010; 20th November 2012 and 10th November 2013 during the three winter crop seasons. The experimental treatments consisting of pyroxsulam + sulfosulfuron without and with surfactant (Polyglycol at 1000 ml ha$^{-1}$) at 12+12, 15+15 and 18+18 gha$^{-1}$ along with standard treatments of Atlantis 3.6% WDG 400 gha$^{-1}$ (Mesosulfuron + Iodosulfuron-12.0 + 2.4 g a.i. ha$^{-1}$), sulfosulfuron 25 gha$^{-1}$ , pyroxsulam 18 gha$^{-1}$ , and untreated weedy control were evaluated (Table 3).

The field experiments were conducted in Randomized Block Design with three replications. The crop was sown using a seed rate of 100 kg $ha^{-1}$. The herbicide spraying was done at around 39-44 days after sowing (DAS) with knap sack sprayer fitted with flat fan nozzles using 375 litres water/ha. Fertilizers (150 kg N, 60 kg $P_2O_5$ and 40 $kgha^{-1}$ $K_2O$) and irrigations (5-6) were applied according to recommendations for wheat. Full doses of $P_2O_5$ and $K_2O$, were applied at the time of sowing. N (150 kg $ha^{-1}$), as urea, was applied in three equal splits (50 kg N at sowing, 50 kg N at first irrigation and 50 kg N at second irrigation around 45 DAS). The field was irrigated by surface method of irrigation as and when required by the crop. The weed dry weight in $g/m^2$ was recorded at around 120 DAS by harvesting weeds using 0.25 $m^2$ quadrate placed randomly at two places in each plot. The harvested weeds after sun drying were dried in oven at 60 °C temperature for 3-4 days till constant weight and then the dry weight recorded and converted to g $m^{-2}$. The crop was manually harvested and threshed using a small plot thresher. Weed Control Efficiency (WCE) was calculated using the formula

WCE= (WDC-WDT) / WDC x100

Where, WDC= weed dry weight in weedy check; WDT= weed dry weight in a treatment.

*2.1.3. Carry over effects on succeeding sorghum crop:* After wheat harvest, sorghum was grown as rotational crop on the same plots to study the carryover effect of herbicides applied in wheat on the succeeding crop. Sorghum cultivar MY-999 was sown during last week of April during both the years after field preparation using Rotary-till machine followed by sowing at a row spacing of 20 cm. Need based irrigation and fertilizer applications were done. Observations on fresh biomass at about 45DAS were recorded.

*2.2. Effect of time of application and surfactant on pyroxsulam efficacy against grassy weeds:* Pyroxsulam at 9 and 18 $gha^{-1}$ was evaluated in pot studies with two surfactants @ 0.5% (Codacide and Polyglycol) at two stages (2 and 3-4 leaf stage) of *P. minor* and wild oat (Table 5 and 6). Pots having 4.5 kg soil capacity were filled with soil and FYM mixture 6:1 (v/v) after passing through a 2 mm sieve. Fifty seeds per pot of susceptible populations (DWR) of *P. minor* and 20 seeds of wild oat were sown and after germination, 10 and 15 plants per pot of wild oat and *P. minor*, respectively were uniformly maintained. Two weeks time difference was kept between sowing for two stages of weed growth so that the herbicide spraying for both the stages could be done simultaneously. Herbicides were applied 30 days after sowing using knap-sack sprayer in 350 $lit.ha^{-1}$ of spray solution. For both the growth stages, untreated controls were also kept. The experiment was conducted in two factor factorial CRD with three replications. The pots were harvested after three weeks of spray for fresh biomass recording. Due to differential sowing time, the fresh biomass was different in both the stages being higher in advanced stage of weed growth and therefore, for comparison, % biomass reduction compared to their respective control was worked out.

2.3. Response of *P. minor* populations to pyroxsulam

The response of ten *P. minor* populations {Chanarthal, Uchana-1, Uchana-2, Kachhawa, Sagga-1, Sagga-2, Nidana, Chaura, IPU-R and DWR (S)} having differential response to fop, sulfonylurea and phenylurea herbicides were evaluated against four herbicides in pot experimentation (Table 1). As mentioned in previous section, pots were filled and sown with various *P. minor* populations and finally 10 plants/pot were maintained. About 25-30 days old plants (3 leaf stage) were sprayed with graded doses of herbicides as mentioned in Table 1 using 350 litres of spray solution. Surfactant, Leader mix was used @ 0.35 % with sulfosulfuron while polyglycol was used @ 0.5% (v/v). with pyroxsulam, Three weeks after herbicide spray, fresh weight of *P. minor* was recorded and based on which the GR50 values were calculated using Probit Analysis.

**Table 1**. Herbicide rates for quantification of resistance in *P. minor*.

| Herbicide | Dose ($gha^{-1}$ ) |
|---|---|
| Isoproturon | 0, 250, 500, 1000, 2000 and 4000 |
| Clodinafop | 0, 15, 30, 60, 120 and 240 |
| Sulfosulfuron | 0, 3.125, 6.25, 12.5, 25, 50 and 100 |
| Pyroxsulam | 0, 9, 18, 36 and 72 |

*2.4. Pyroxsulam efficacy in comparison to standard herbicides against weeds*: Pyroxsulam efficacy against three major winter season weeds (*Malva parviflora*, *Medicago denticulata* and *Lathyrus aphaca*) was compared with other standard herbicides (Fig. 3, 4 and 5) in three pot experiments. The experiments were conducted in CRD with each treatment replicated 3- 4 times and for spraying herbicides, 7 plants of *Malva parviflora*, 8 plants of *Lathyrus aphaca* and 8 plants of *Medicago denticulata* per pot were kept in respective trial. One month after spraying, fresh weight was recorded and for statistical analysis, fresh biomass reduction in comparison to untreated control was calculated (Fig. 3, 4 and 5).

*2.5. Statistical analysis:* The data of both the field experiments were pooled over years (3 year pooled) since the results were similar over the years. The pooled data were subjected to analysis of variance (ANOVA) in block design using the Statistical Analysis System (SAS, version

9.2) software. The differences amongst the treatment means were compared using the Duncan's Multiple Range Test (DMRT) at 0.05 probability. Pot experiments were conducted in CRD. In field study, the weed dry weight data were square root transformed {$\sqrt{(x+1)}$} for statistical analysis, and based on this the interpretation of the results of the original data are given in the tables by mentioning the letters based on the transformed data analysis.

## 3. Results and discussion

*3.1 Evaluation of Pyroxsulam: P. minor, Avena ludoviciana* (wild oat), *Medicago denticulata* and *Rumex dentatus* were the main weeds in the experimental plots. Among these weeds, *P. minor* and *A. ludoviciana* were the dominant grass weeds.

Based on the pooled data of three years, the weed control treatments significantly influenced ($p < .0001$) the weed dry weight (Table 2). Minimum weed dry weight (13.6 g m$^{-2}$) was observed in pyroxsulam 18 gha-1 with surfactant polyglycol (1000 ml ha$^{-1}$) and the maximum weed dry weight was observed in weedy check (452.3 g m$^{-2}$). There was significant reduction in the dry weight of *P. minor* and wild oat under various herbicide application treatments compared to weedy check except metsulfuron 4 gha$^{-1}$ as it was ineffective against grassy weeds.

The dry matter of grassy weeds reduced as the dose of pyroxsulam increased and minimum dry weight of grassy weeds was observed with sulfosulfuron 25 gha$^{-1}$ application. There was no significant difference among pyroxsulam rates applied at 12-18 gha$^{-1}$ for wild oat dry weight but were superior over sulfosulfuron 25 gha$^{-1}$ . Among the herbicide treatments, the maximum grassy weed dry weight was observed under metsulfuron, whereas the dry weight of broad-leaved weeds was maximum under weedy check treatment followed by sulfosulfuron 25 gha$^{-1}$ . The higher broad-leaved weeds dry weight in sulfosulfuron was due to the presence of *R. dentatus* as sulfosulfuron does not provide the effective control of this weed. The earlier results (Chhokar *et al.*, 2006, 2007a, 2007b) have also shown ineffectiveness of sulfosulfuron against *R. dentatus.* Pyroxsulam provided the effective broad-spectrum weed control and was superior to sulfosulfuron 25 gha$^{-1}$ due to better control of *R. dentatus* (Table 2). For control of *R. dentatus* all rates of pyroxsulam (12-18 gha$^{-1}$ ) and metsulfuron 4 gha$^{-1}$ were equally effective and were significantly superior to sulfosulfuron and untreated weedy check.

Pyroxsulam was effective in controlling *P. minor*, wild oat, Rumex and *Medicago denticulata* (Table 2). Pyroxsulam without surfactant was poor in controlling the *P. minor* compared to its application with surfactant (Polyglycol 1000 ml ha$^{-1}$). The dry weight of *P. minor* under pyroxsulam 18 gha$^{-1}$ with surfactant was statistically not different from sulfosulfuron. Pyroxsulam at 18 gha$^{-1}$ with surfactant had better control of weeds (WCE 97.0%) compared to lower

**Table 2**. Performance of Pyroxsulam against weeds in wheat (Pooled data of three years)

| Herbicides | Herbicide Dose (g a.i. ha$^{-1}$) | Surfactant Dose (ml ha$^{-1}$) | *Weed dry weight g/m$^{2}$ | | | | | | WCE** | Wheat grain yield q/ha |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | P. minor | Wild oat | Rumex | Medi-cago | Other | Total | | |
| Pyroxsulam | 12 | - | 86.7 $^{B}$ | 0.4 $^{B}$ | 0.2 $^{C}$ | 0.4 $^{B}$ | 1.0 $^{BC}$ | 88.7 $^{C}$ | 80.4 | 51.26 $^{D}$ |
| Pyroxsulam | 15 | - | 62.3 $^{C}$ | 0.2 $^{B}$ | 0.1 $^{C}$ | 0.2 $^{B}$ | 0.6$^{BCD}$ | 63.3$^{CD}$ | 86.0 | 52.60 $^{CD}$ |
| Pyroxsulam | 18 | - | 38.8 $^{D}$ | 0.0 $^{B}$ | 0.0 $^{C}$ | 0.1 $^{B}$ | 0.6$^{BCD}$ | 39.5 $^{DE}$ | 91.3 | 54.29 $^{BC}$ |
| Pyroxsulam + Surfactant Polyglycol 26-2 N | 12 | 1000 | 43.5 $^{CD}$ | 0.3 $^{B}$ | 0.1 $^{C}$ | 0.2 $^{B}$ | 1.2 $^{B}$ | 45.4 $^{DE}$ | 90.0 | 54.21 $^{BC}$ |
| Pyroxsulam + Surfactant Polyglycol 26-2 N | 15 | 1000 | 28.4 $^{D}$ | 0.0 $^{B}$ | 0.0 $^{C}$ | 0.1 $^{B}$ | 0.9 $^{BC}$ | 29.4 $^{EF}$ | 93.5 | 55.59 $^{AB}$ |
| Pyroxsulam + Surfactant Polyglycol 26-2 N | 18 | 1000 | 12.9 $^{E}$ | 0.0 $^{B}$ | 0.0 $^{C}$ | 0.1 $^{B}$ | 0.7$^{BCD}$ | 13.6 $^{F}$ | 97.0 | 57.33 $^{A}$ |
| Sulfosulfuron + Surfactant Leader Mix | 25 | 1250 | 5.6 $^{E}$ | 1.8 $^{B}$ | 68.6 $^{A}$ | 0.2 $^{B}$ | 4.1 $^{A}$ | 80.2 $^{C}$ | 82.3 | 53.93 $^{BC}$ |
| Metsulfuron methyl + NIS Dupont | 4 | 625 | 271.4 $^{A}$ | 98.7 $^{A}$ | 0.1 $^{C}$ | 0.0 $^{B}$ | 0.1 $^{D}$ | 370.3 $^{B}$ | 18.1 | 31.78 $^{E}$ |
| Untreated weedy check | - | - | 274.0 $^{A}$ | 115.7 $^{A}$ | 51.3 $^{B}$ | 11.0 $^{A}$ | 0.3 $^{CD}$ | 452.3 $^{A}$ | | 26.45 $^{F}$ |
| | p-Value | | <.0001 | <.0001 | <.0001 | <.0001 | <.0001 | <.0001 | | <.0001 |

*Original values for weed dry weight were square root transformed ($\sqrt{x}+1$) for statistical analysis and based on which the uppercase letters have been mentioned with original values for interpretation.; Means within column having at least one letter common are not significantly different according to Fisher's Least Significant Difference at 5% level of significance; Mean separations were performed using Fisher's Least Significant Difference at 5% level of significance

**Table 3**. Performance of Pyroxsulam 9%WDG + Sulfosulfuron 75%WG against weeds in wheat (Pooled data of three yeras)

| Herbicides | Herbicide Dose (g a.i. $ha^{-1}$) | Surfactant Dose (ml $ha^{-1}$) | *Weed dry weight $g/m^2$ | | | | | | WCE ** | WG yield q/ha |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | P. minor | Wild oat | Rumex | Medicago | Other | Total | | |
| Pyroxsulam +Sulfosulfuron | 12 +12 | - | $101.4^{B}$ | $0.6^{BC}$ | $0.2^{C}$ | $0.6^{B}$ | 0.6 | $103.2^{B}$ | 84.5 | $48.44^{F}$ |
| Pyroxsulam +Sulfosulfuron | 15 +15 | - | $68.8^{C}$ | $0.1^{C}$ | $0.0^{C}$ | $0.1^{B}$ | 0.4 | $69.4^{CD}$ | 89.6 | $50.33^{DEF}$ |
| Pyroxsulam +Sulfosulfuron | 18 +18 | - | $56.1^{C}$ | $0.1^{C}$ | $0.0^{C}$ | $0.1^{B}$ | 0.2 | $56.4^{D}$ | 91.5 | $51.85^{CDE}$ |
| Pyroxsulam +Sulfosulfuron+S* | 12 +12 +1000 | 1000 | $32.0^{D}$ | $0.3^{BC}$ | $0.0^{C}$ | $0.1^{B}$ | 0.3 | $32.7^{EF}$ | 95.1 | $52.91^{ABC}$ |
| Pyroxsulam +Sulfosulfuron+S | 15 +15 +1000 | 1000 | $20.2^{DE}$ | $0.1^{C}$ | $0.0^{C}$ | $0.0^{B}$ | 0.1 | $20.5^{EFG}$ | 96.9 | $53.74^{ABC}$ |
| Pyroxsulam +Sulfosulfuron+S | 18 +18 +1000 | 1000 | $7.8^{E}$ | $0.1^{C}$ | $0.0^{C}$ | $0.0^{B}$ | 0.1 | $8.0^{G}$ | 98.8 | $54.82^{A}$ |
| Pyroxsulam | 18 + 1000 | 1000 | $32.9^{DE}$ | $0.0^{C}$ | $0.0^{C}$ | $0.1^{B}$ | 0.1 | $33.1^{E}$ | 95.0 | $52.00^{BCD}$ |
| Sulfosulfuron+S (Poly) | 25 + 1000 | 1000 | $11.5^{E}$ | $3.4^{B}$ | $76.2^{A}$ | $0.1^{B}$ | 0.8 | $92.0^{BC}$ | 86.2 | $49.48^{EF}$ |
| Sulfosulfuron + S | 25 + 1250 | 1250 | $16.4^{DE}$ | $2.4^{BC}$ | $83.0^{A}$ | $0.1^{B}$ | 0.9 | $102.8^{B}$ | 84.6 | $49.72^{DEF}$ |
| Atlantis 3.6WG (Mesosulfuron 3% + Iodosulfuron 0.6%) + Surfactant | 12 + 2.4 | 625 | $14.7^{E}$ | $0.0^{C}$ | $0.0^{C}$ | $0.0^{B}$ | 0.5 | $15.2^{FG}$ | 97.7 | $54.34^{AB}$ |
| Weedy check | - | - | $544.6^{A}$ | $75.6^{A}$ | $28.6^{B}$ | $14.5^{A}$ | 2.5 | $665.9^{A}$ | | $19.74^{G}$ |
| | p-Value | | <.0001 | <.0001 | <.0001 | <.0001 | 0.2945 | <.0001 | | <.0001 |

*S=Surfactant; **Original values are square root ($\sqrt{x+1}$) transformed for statistical analysis and based on which the upper-case letters have been mentioned with original values for interpretation.; Means within a column with at least one letter common are not significantly different using ($P<0.05$); **WCE= Weed Control Efficiency

doses with surfactant and all its doses without surfactant (WCE 80.4 to 91.3%). The total weed dry weight under pyroxsulam 18 $gha^{-1}$ + surfactant was 13.6 $g/m^2$ and in sufosulfuron 25 $gha^{-1}$ was 80.2 $g/m^2$. Geier *et al.* (2011) also reported superiority of pyroxsulam to sulfosulfuron in controlling downy brome (*Bromus tectorum* L.)

The weed competition, all over the crop season, in weedy check treatment resulted in the lowest grain yield (26.5 q.$ha^{-1}$) with a yield reduction of 53.9% compared to the best yielded treatment (57.33 $qha^{-1}$) of pyroxsulam 18 $gha^{-1}$ + surfactant (Table 2). All the herbicide treatment produced significantly more grain yield than weedy check. Among the herbicide treatments, metsulfuron 4 g $ha^{-1}$ had the lowest yield (31.8 q $ha^{-1}$) as it was ineffective against grassy weeds. The wheat grain yield under pyroxsulam with surfactant (54.21-57.33 q $ha^{-1}$) was better compared to its application without surfactant (51.26-54.29 q $ha^{-1}$) and sulfosulfuron (53.93 q $ha^{-1}$) application due to better control of complex weed flora. The magnitude of yield improvement was related to extent of weed control. Wells (2008) also found pyroxsulam effective against broad spectrum weeds with excellent wild oat control. DeBoer *et al.* (2011) also observed selective POST grass and broadleaf weed control in wheat with pyroxsulam.

This study clearly showed that pyroxsulam at 18 $gha^{-1}$ with surfactant (Polyglycol) 1000 ml/ha is effective against grassy (*P. minor* and wild oat) as well as broadleaf weeds and as a result of broad spectrum weed kill, this herbicide was superior over sulfosulfuron and metsulfuron.

*3.2 Evaluation of Pyroxsulam in combination with sulfosulfuron:* The major weeds which infested the experimental plots were *P. minor*, *A. ludoviciana*, *R. dentatus* and *M. denticulata.* The various weed control treatments significantly influenced ($p<0.001$) the weed dry matter accumulation (Table 3). Sulfosulfuron when applied alone failed to control the *R. dentatus.* When both the herbicides (Pyroxsulam + sulfosulfuron) were applied as tank-mix combination then broad-spectrum weed kill was achieved. However, the efficacy of pyroxsulam + sulfosulfuron mixture without external surfactant was poor on *P. minor* compared to their application along with surfactant and the total weed dry matter accumulation reduced by 68.3 to 85.8% with addition of surfactant as compared to without surfactant. The dry matter accumulation of weeds reduced as the dose of pyroxsulam + sulfosulfuron increased but the differences were not significant in case of *R. dentatus*, and *M. denticulata* and *A. ludoviciana.* The maximum dry weight of *R. dentatus* was observed under sulfosulfuron 25 $gha^{-1}$ (76.2-83.0 g $m^2$) followed by weedy check (28.6 g $m^2$). The lesser dry weight of *R. dentatus* in untreated control compared to sulfosulfuron were due to the strong competition from grass weeds. Pyroxsulam alone and in combination with sulfosulfuron and Atlantis (Mesosulfuron + Iodosulfuron) provided excellent control of *R. dentatus* (Table 3). The various herbicide treatments namely tank mix combination of pyroxsulam + sulfosulfuron at 12+12, 15+15 and 18+18 $gha^{-1}$ with surfactant, sulfosulfuron 25 $gha^{-1}$ and Atlantis 3.6WG (Mesosulfuron 3% + Iodosulfuron 0.6%) at 12+2.4 g a.i. $ha^{-1}$ provided effective control of *P. minor* and wild oat. The dry weight of grassy weeds under pyroxsulam + sulfosulfuron 18+18 gha$^{-1}$ with surfactant, sulfosulfuron 25 gha$^{-1}$ and Atlantis were not significantly different among themselves.

The total weed dry weight was significantly less under Atlantis (Mesosulfuron + Iodosulfuron) (15.2 g/m$^2$) and combination of pyroxsulam + sulfosulfuron at 15+15, 18+18 gha$^{-1}$ with 1000 ml/ha polyglycol (8.0-32.7 g/m$^2$) compared to all other weed control treatments. The total weed dry weight in Atlantis and pyroxsulam + sulfosulfuron @ 18+18 gha$^{-1}$ + surfactant 1000 ml/ha did not significantly differ (Table 3). Maximum weed control efficiency (WCE) based on weed dry weight was observed with the application of pyroxsulam + sulfosulfuron @ 18+18 gha$^{-1}$ with surfactant (98.8%) followed by Atlantis. The WCE of pyroxsulam and sulfosulfuron application alone was lower compared to their tank mix application.

Among various weed control treatments, the lowest grain yield was observed in weedy control (19.74 q ha$^{-1}$) and compared to weedy control, all the herbicide treatments significantly improved the wheat grain yield. The presence of weeds through out the crop season decreased the grain yield by 64%. Pyroxsulam + sulfosulfuron without surfactant yielded less as compared to their application with surfactant. The tank mix combination of pyroxsulam + sulfosulfuron without surfactant as well as at its lower dose 12+12 and 15+15 gha$^{-1}$ with surfactant were significantly inferior to higher doses of 18+18 gha$^{-1}$ with surfactant and Atlantis (Mesosulfuron + Iodosulfuron) in producing the wheat grain yield.. The mean wheat grain yield with application of Atlantis and pyroxsulam + sulfosulfuron 18+18 gha$^{-1}$ with surfactant were 54.34 and 54.82 q ha$^{-1}$, respectively. The better yields under these treatments were due to their broad-spectrum weed control. Similar results that better weed control reflected in better yield have been reported by Chhokar *et al.* (2008) and Geier *et al.* (2011).

Based on this study it can be concluded that pyroxsulam 18 gha$^{-1}$ is effective against grassy (*P. minor* and wild oat) and broadleaved weeds. Pyroxsulam in combination with sulfosulfuron 18+18 g a.i.ha$^{-1}$ with surfactant polyglycol 1000 ml/ha provided the similar effective broad-spectrum weed kill and wheat yield as provided by Atlantis 3.6WG (Mesosulfuron 3% + Iodosulfuron 0.6%) at 12+2.4 g a.i.ha$^{-1}$.

*3.3. Herbicide carryover effect on succeeding sorghum crop after wheat:* In both the field experiments, immediately after wheat harvest, sorghum (cv. MY-999) was grown as rotational crop on the same plots to study the carry over effect of herbicide. In first study, pyroxsulam 18 gha$^{-1}$ applied in wheat produced the sorghum yield more or less similar to untreated control (Fig. 1). However, sorghum fodder yield was drastically reduced in treatments where sulfosulfuron was applied in wheat. Similar, results have been reported earlier (Chhokar *et al.*, 2006) that sulfosulfuron due to high persistency can injure the succeeding sensitive crops like sorghum and maize. Therefore, on the basis of carry over study, sorghum crop can be safely grown after harvesting wheat treated with pyroxsulam as no adverse effect of pyroxsulam applied in wheat was observed on succeeding sorghum crop. Carryover injury in sorghum (Geier and Stahlman, 2001), pea (*Pisum sativum*), barley (*Hordeum vulgare* L.) and oilseed rape (*Brassica napus* L.) (Shinn *et al.*, 1998) have also been reported after 1.0–1.25 years of sulfosulfuron application at 18–72 g ha$^{-1}$.

In another study (Fig 2), compared to untreated control, the pyroxsulam + sulfosulfuron 18+18 gha$^{-1}$ and sufosulfuron 25 gha$^{-1}$ applied in wheat had lower sorghum fresh biomass. Earlier results (Chhokar *et al.*, 2006) have also shown that application of sulfosulfuron 25 gha$^{-1}$ in wheat is not safe for the succeeding sorghum and maize crop. At 18+18 gha$^{-1}$ dose of sulfosulfuron + pyroxsulam, the reduction in sorghum biomass was 48.9 % compared to no herbicide treatment. It shows that if sorghum is to follow immediately after wheat, then pyroxsulam + sulfosulfuron use should be avoided in wheat.

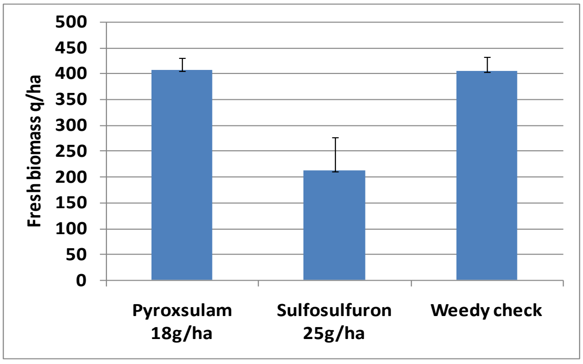

**Fig. 1.** The carry over effect of wheat herbicides on succeeding crop of sorghum. The vertical error bars above means represent the SEM.

*3.4 Effect of time of application on pyroxsulam efficacy:* Pyroxsulam applied at 2 leaf stage had significantly better *P. minor* control (Table 4) compared to its application at tillering (3-4 leaf stage) and the respective *P. minor* control was 98.9 and 95.9%. Geier *et al.* (2011) also observed poor downy brome (*Bromus tectorum* L.) control with pyroxsulam when application timing was delayed. However, wild oat control was similar when pyroxsulam 18 gha$^{-1}$ was applied either at 2 leaf or tillering stage of wild oat (Table 5) which mean that this weed species is

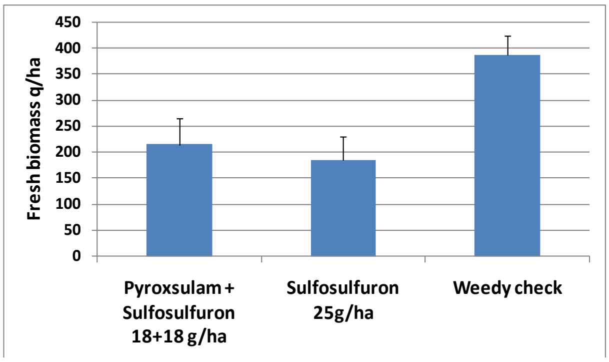

**Fig. 2.** The carry over effect of wheat herbicides on succeeding crop of sorghum. The vertical error bars above means represent the SEM.

highly sensitive to pyroxsulam. However, Hanson and Howatt (2007) reported poor control of wild oat (*Avena fatua* L.) when pyroxsulam was applied at the five leaf stage than at one- or three leaf stage. Similarly, poor control as a result of advanced growth stage of the weeds, due to delayed herbicide application, has also been reported earlier (Chhokar *et al.*, 2001; Chhokar *et al.*, 2006).

**Table 4.** Fresh weight reduction (%) of Phalaris minor by pyroxsulam when applied at two weed growth stage

| Weed Stage | Herbicide | | | | |
|---|---|---|---|---|---|
| | Pyroxsulam 9gha$^{-1}$ + 0.5% Codacide | Pyroxsulam 18gha$^{-1}$ + 0.5% Codacide | Pyroxsulam 9gha$^{-1}$ + 0.5% Polyglycol | Pyroxsulam 18gha$^{-1}$ + 0.5% Polyglycol | Mean |
| 1-2 leaf | 95.9 | 100.0 | 99.9 | 99.9 | 98.9 |
| Tillering | 93.3 | 96.8 | 94.1 | 99.5 | 95.9 |
| Mean | 94.6 | 98.4 | 97.0 | 99.7 | |
| | CD (0.05) | Weed stage(A) =1.97 | Herbicide(B) =2.79 | AXB = NS | |

Similarly, Henbit (Lamium amplexicaule L.) control was greatly reduced (Reddy *et al.*, 2013) by delaying herbicide applications until spring compared to fall applications (49% vs. 80% control). Similarly, decreased blue mustard, henbit and downy brome control control with delayed ALS-inhibiting herbicide (sulfosulfuron) or propoxycarbazone-Na applications has been reported by Geier *et al.*, 1998, 2002 and 2011.

Also, no significant difference between the performance of surfactant, Codacide and Polyglycol, with regard to improvement in pyroxsulam efficacy against weeds was observed (Table 4 and 5).

*3.5 Response of P. minor populations to pyroxsulam:* The responses of ten *P. minor* populations to four herbicides (pyroxsulam, sulfosulfuron, clodinafop and isoproturon) are presented in Table-6. Pyroxsulam effectively controlled the susceptible population as well as the populations resistant to clodinafop and/or isoproturon but failed in controlling sulfosulfuron resistant populations (Sagga-1, Sagga-2, Nidana and Chaura). It means that sulfosulfuron resistant populations are cross-resistant to pyroxsulam.

**Table 5.** Fresh weight reduction (%) of wild oat by pyroxsulam when applied at two growth stages

| Weed Stage | Herbicide | | | | |
|---|---|---|---|---|---|
| | Pyroxsulam 9gha$^{-1}$ + 0.5% Codacide | Pyroxsulam 18gha$^{-1}$ + 0.5% Codacide | Pyroxsulam 9gha$^{-1}$ + 0.5% Polyglycol | Pyroxsulam 18gha$^{-1}$ + 0.5% Polyglycol | Mean |
| 1-2 leaf | 99.1 | 100.0 | 100.0 | 100.0 | 99.8 |
| Tillering | 99.9 | 99.7 | 99.9 | 99.9 | 99.8 |
| Mean | 99.5 | 99.9 | 99.9 | 99.9 | |
| | CD (0.05) | Weed stage(A)=NS | Herbicide(B) =NS | AXB = NS | |

The GR50 values for sulfosulfuron of Sagga-1, Sagga-2, Nidana and Chaura were 83.61, 70.65, 8.76 and 27.97 gha$^{-1}$, respectively, and the corresponding values for pyroxsulam were 38.46, 28.56, 11.24 and 25.95 gha$^{-1}$. The most resistant population (Sagga-1) against sulfosulfuron was having Resistance Index (RI) of 26.21 and this

**Table 6.** Herbicide resistance profile of P. minor populations

| Populations | GR50 (gha-1 ) | | | | Resistance Index=GR50 R / GR50 S | | | |
|---|---|---|---|---|---|---|---|---|
| | Pyroxsulam | Sulfosulfuron | Clodinafop | Isoproturon | Pyroxsulam | Sulfosulfuron | Clodinafop | Isoproturon |
| Chanarthal | 4.75 | 3.23 | >240 | 214.71 | 0.86 | 1.01 | >16.32 | 1.09 |
| Uchana-1 | 8.56 | 4.79 | 41.56 | 984.15 | 1.55 | 1.50 | 2.83 | 5.01 |
| Uchana-2 | 5.90 | 3.97 | 63.90 | 685.19 | 1.07 | 1.24 | 4.34 | 3.49 |
| Kachhawa | 5.93 | 5.08 | 79.74 | 821.58 | 1.08 | 1.59 | 5.42 | 4.19 |
| Sagga-1 | 38.46 | 83.61 | 34.17 | 623.94 | 6.98 | 26.21 | 2.32 | 3.18 |
| Sagga-2 | 28.56 | 70.65 | 32.95 | 853.08 | 5.18 | 22.15 | 2.24 | 4.35 |
| Nidana | 11.24 | 8.76 | 28.85 | 586.97 | 2.04 | 2.75 | 1.96 | 2.99 |
| Chaura | 25.95 | 27.97 | 21.11 | 571.62 | 4.71 | 8.77 | 1.44 | 2.91 |
| IPU-R | 6.34 | 3.17 | 15.56 | 834.69 | 1.15 | 0.99 | 1.06 | 4.25 |
| DWR (S) | 5.51 | 3.19 | 14.71 | 196.27 | 1.00 | 1.00 | 1.00 | 1.00 |

R= Resistant; S= Susceptible

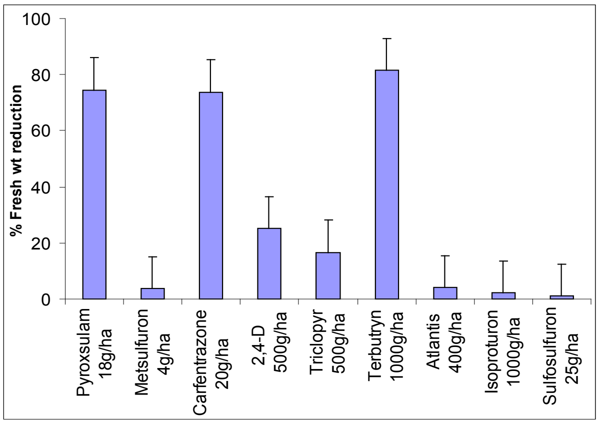

**Fig. 3.** Fresh weight reduction of Malva parviflra in comparison to control. The vertical error bars above means represent the LSD at the 0.05 probability level.

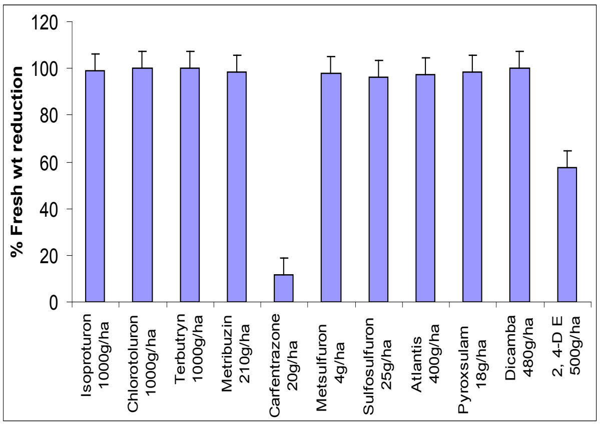

**Fig. 4.** Fresh weight reduction of Lathyrus aphaca compared to control. The vertical error bars above means represent the LSD (P=0.05).

population had RI of 6.98 for pyroxsulam. This shows that pyroxsulam is not effective against *P. minor* population resistant to sulfosulfuron. Pyroxsulam cross-resistance in sulfosulfuron resistant population is due to similar mode of action (ALS inhibition) of triazolopyrimidine sulfonamide as that of the sulfonylurea (sulfosulfuron) group of herbicides. In earlier studies, Chhokar and Sharma, 2008 have shown that sulfosulfuron resistant population of *P. minor* to be cross resistant to Atlantis (Mesosulfuron + iodosulfuron). Similarly, Salas *et al.* (2013), reported all mesosulfuron-resistant *Lolium perenne ssp. multiflorum* (Italian ryegrass) populations tested were cross-resistant to imazamox and pyroxsulam. Resistance to mesosulfuron was reported in Arkansas one year before its commercialization (Kuk and Burgos, 2007), and shortly after, also in Texas (Ellis *et al.*, 2008). Such populations were presumed to have been preselected for resistance to ALS inhibitors by other ALS herbicides that have been historically used preplant (PPL) or preemergence (PRE) in wheat such as chlorsulfuron and metsulfuron. Thus, in the present study, the selection pressure from sulfonylurea herbicides (sulfosulfuron/mesosulfuron) has predisposed *P. minor* populations to pyroxsulam resistance.

Resistance to both ACCase- and ALS inhibitors in *P. minor* populations is a serious problem to wheat growers in India. Multiple herbicide resistance has restricted herbicide choices for *P. minor* control in wheat and has laid stress on the need for devising integrated weed management approaches (crop rotation, tillage, timing of sowing etc.) to reduce the dependence on herbicides thereby extending the life of available herbicide options as well as delay the onset of the evolution of herbicide-resistantce.

*3.6 Efficacy of pyroxsulam against broad-leaved weeds:* Among the various herbicides tested for *Malva parviflora* control, pyroxsulam 18g, carfentrazone 20g and terbutryn 1000 gha$^{-1}$ were found significantly better compared to metsulfuron 4g, 2,4-D-E 500 g, triclopyr 500g, Atlantis (mesosulfuron + iodosulfuron) 400 (12+2.2g.a.i.) gha-1, Isoproturon 1000g and sulfosulfuron 25gha$^{-1}$ (Fig. 3). Sulfonylurea herbicides namely metsulfuron, sulfosulfuron and Atlantis (mesosulfuron + iodosulfuron) failed to control *Malva parviflora.* Triclopyr and 2,4-D were also having poor efficacy against *Malva parviflora.* It means that pyroxsulam can be used as partner with other herbicide like sulfosulfuron to broaden the spectrum of weed kill.

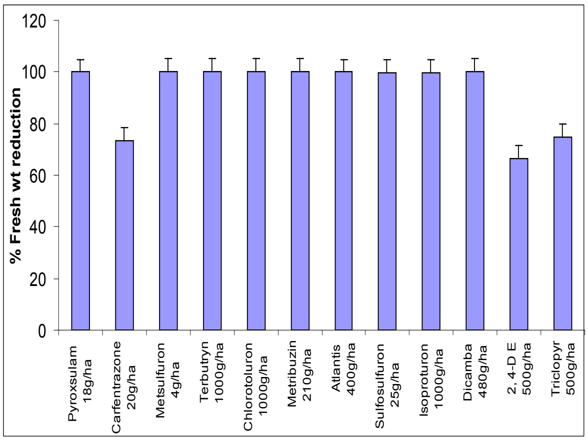

**Fig. 5**. Fresh weight reduction of Medicago denticulata compared to control. The vertical error bars above means denote the LSD (P=0.05).

Earlier studies (Chhokar *et al.*, 2007a; Chhokar *et al.*, 2015) also reported ineffectiveness of metsulfuron and 2,4-D against *Malva parviflora*

Among various herbicide treatments evaluated for control of *Lathyrus aphaca* (Fig 4), carfentrazone 20gha$^{-1}$ and 2, 4-D-E 500gha$^{-1}$ were significantly inferior. Carfentrazone provided only 11.5% fresh weight reduction in comparison to control pots. Whereas, L. aphaca fresh weight reduction with pyroxsulam was 98.5%. Isoproturon 1000g, chlorotoluron 1000g, terbutryn 1000 g, metribuzin 210g, metsulfuron 4 g, sulfosulfuron 25 g, Atlantis (Mesosulfuron + iodosulfuron) 12+ 2.4g a.i./ha, pyroxsulam 18 g and dicamba 480gha$^{-1}$ were quite effective in controlling L. aphaca and the fresh weight reduction by these herbicide was 98.4 to 100.0%. Similarly, early studies (Chhokar *et al*., 2015) have also shown the poor control of L. aphaca with carfentrazone and effective control with dicamba, Atlantis (Mesosulfuron + iodosulfuron) and isoproturon.

The reduction in fresh weight of *Medicago denticulata* with application of various herbicides was >66.5% (Fig. 5). Application of pyroxsulam 18 gha-1 caused 100% *Medicago denticulata* fresh biomass reduction. Carfentrazone 20g, 2,4-D-E 500g and triclopyr 500gha$^{-1}$ were inferior to rest of the herbicide treatments. The herbicide treatments namely metsulfuron 4 g, terbutryn 1000g, chlorotoluron 1000g, metribuzin 210g, Atlantis (Mesosulfuron + iodosulfuron) 12+ 2.4ga.i.ha$^{-1}$, sulfosulfuron 25 g, isoproturon 1000 g and dicamba 480 gha$^{-1}$ provided the statistically similar control as with pyroxsulam.

The present studies indicated that tank mix application of pyroxsulam + sulfosulfuron at 18 + 18 gha$^{-1}$ with surfactant polyglycol 1000 ml/ha provided effective broad spectrum (grassy and broadleaf) weed kill in wheat. The field and pot studies showed that for better efficacy of pyroxsulam and sulfosulfuron + pyroxsulam against grass weeds (*P. minor* and *A. ludoviciana*), surfactant is needed. The herbicide mixtures provided better wheat grain yield as a result of broad spectrum weed kill compared to sulfosulfuron alone application but performed similar to already recommended herbicide mixture i.e. Atlantis (Mesosulfuron + Iodosulfuron) 14.4(12+2.4)ga.i./ha. However, while using persistent herbicides, wheat growers should be cautious in selecting succeeding crops, as sulfosulfuron alone or in combination with pyroxsulam can harm the sensitive crops like sorghum. Sulfosulfuron resistant populations of *P. minor* showed cross resistance to pyroxsulam. Pyroxsulam was superior to metsulfuron (for control of *Malva parviflora*), carfentrazone (for control of *Lathyrus aphaca*) and 2,4-D (For control of M. parviflora and *Medicago denticulata*). This means that pyroxsulam can also be an alternative for broad-leaved weed control in wheat.

The results of the present studies recommend that in order to obtain optimum wheat yield, growers can tank mix sulfosulfuron + pyroxsulam at 18+18 g along with 1000 ml/ha surfactant for diverse spectrum of weed control.

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