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Herbicides for broad-leaved weeds management in wheat

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ABSTRACT

Field and pot studies were conducted to identify the effective broad-leaf herbicides for wheat crop. In field study, pre-mix combination (1:4 w/w) of metsulfuron-methyl + carfentrazone-ethyl (Ally-express 50 DF) 22.5 to 25 g/ha with 0.2% (v/v) non-ionic surfactant (NIS) was better than without NIS and sole application of metsulfuron (4 g/ha), carfentrazone (20 g/ha) and 2,4-D-amine (750 g/ha). Carfentrazone was poor in controlling *Lathyrus aphaca* (meadow peavine), whereas metsulfuron was ineffective against *Malva parviflora* (little mallow) and *Solanum nigrum* (black nightshade). Metsulfuron-methyl + carfentrazone-ethyl effectively controlled these weeds, leading to increased wheat yield than metsulfuron and carfentrazone. In pot studies, growth regulator herbicide, 2,4-D-E was ineffective against *S. nigrum* and *Physalis minima* (groundcherry) but controlled by another growth regulator herbicide, dicamba. Carfentrazone 20 g, isoproturon 1000 g, metribuzin 250 g, dicamba 360 g and topramezone 50 g/ha effectively controlled *S. nigrum* and *P. minima*. Additional herbicides, effective against *P. minima* were metsulfuron 4 g, mesosulfuron + iodosulfuron 12 + 2.4 g/ha, pyroxsulam 18 g and sulfosulfuron 25 g/ha. Auxin herbicide, halauxifen-methyl-ester in combination with florasulam 12.76 (6.51 + 6.25) g/ha was also poor against *S. nigrum* and *P. minima. Rumex dentatus* control with 2,4-D (ester, amine and sodium) was poor, whereas, halauxifen + florasulam 12.76 g, metsulfuron 4 g and metsulfuron + carfentrazone 4 + 20 g/ha provided complete control.

Key words: Broad-leaf weeds, Chemical control, Herbicide mixture, Surfactant, Wheat

Wheat (*Triticum aestivum* L. emend. Fiori and Paol) is an important staple food crop for billions people of the world and among cereals, it occupies maximum area (219.04 m/ha) globally (FAO 2014). For food security, its assured production and supply are necessary. Weed infestation is one of the major biotic factors limiting wheat production and productivity. The losses caused by weeds depend on their type, abundance and environmental factor (Chhokar *et al.* 2012). The estimated yield loss worldwide caused by weeds varied between 7.7 to 23.9% depending on the region (Oerke 2006, Kosina *et al.* 2007).

Wheat is infested with diverse weed flora, as it is grown in diverse agro-climatic conditions, under different cropping sequence, tillage and irrigation regimes (Chhokar *et al.* 2012). The crop rotations, tillage and herbicides have pronounced effect on the type of weed flora (Anderson and Beck 2007, Chhokar *et al.* 2007a). Reduced tillage or No-till (NT) wheat with higher moisture, in rice-wheat system favours the infestation of *Rumex dentatus* L. (toothed dock) and *Malva parviflora* L. (little mallow) (Chhokar *et al.* 2007a). Some parts of eastern and far eastern India have severe problem of *Solanum nigrum* L. (black nightshade) and *Physalis minima* (groundcherry) (Chhokar *et al.* 2012), where growers mostly depend on 2,4-D, which is not effective against these weeds.

Broad-leaf weeds are becoming a problem in area where grassy herbicides (clodinafop, fenoxaprop and pinoxaden) without supplementing with broad-leaf weed herbicides are used continuously. For control of broad-leaf weeds in wheat, three major herbicides used in India are metsulfuron 2,4-D and carfentrazone (Chhokar *et al.* 2007b). Generally, a herbicide is more effective against some of the weeds and less or not effective against others. Also, some of the post-emergent contact herbicides like carfentrazone-ethyl, are less effective on weeds having advanced stage, as well as, unable to control the subsequent weeds emerging after application due to its lack of residual activity (half life of carfentrazone is 2-5 days) in soil (Lyon *et al.* 2007, Willis *et al.* 2007). To broaden the spectrum of weed kill and to provide the long term residual weed control, the use of herbicide mixture/ combinations is advisable. Herbicide mixture besides providing control of complex weed flora will also help in managing and delaying the herbicide resistance problem.

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Further, the efficacy of herbicide and herbicide mixtures can be improved with the use of surfactant (Chhokar *et al*. 2011). Therefore, this study was planned with the objectives (1) to evaluate the efficacy of ready-mix combination of metsulfuron-methyl + carfentrazone-ethyl 40% (Ally Express 50 DF) with and without surfactant against important broad-leaf weeds in wheat crop (2) to determine the herbicide carry over effect on succeeding greengram (*Vigna radiata* L. Wilczek.) and maize (*Zea mays* L.) after wheat, and (3) to identify the effective herbicides against major problematic broad-leaf weeds of wheat namely *L. aphaca, M. denticulata, R. dentatus, P. minima*, and *S. nigrum*, so that weed specific herbicidal solutions can be recommended.

MATERIALS AND METHODS

Field and pot experiments were conducted at Resource Management Block, ICAR- Indian Institute of Wheat and Barley Research, Karnal, Haryana, India to evaluate the efficacy of pre-mix combination of metsulfuron + carfentrazone against broad-leaf weeds as well as to identify the additional effective herbicides for control of major broad-leaf weeds of wheat.

Field study: efficacy of pre-mix combination of metsulfuron + carfentrazone

An experiment involving 12 weed control treatments (Table 1) was conducted for two *Rabi* seasons of 2009-10 and 2010-11 keeping three replications in randomized block design. The soil of the experimental field was sandy clay loam with pH of 8.0 and organic carbon content 0.40%. Wheat CV. '*DBW-17*' was sown on 16^{th} November, 2009 and 12^{th} November 2010 during first and second year, respectively, at 20 cm row spacing using a seed rate of 100 kg/ha.

The herbicide treatments comprised of four doses of ready mix combination (1:4 w/w) of metsulfuron + carfentrazone at 17.5, 22.5, 25.0 and 30.0 g/ha with and without surfactant, carfentrazone 20 g, metsulfuron 4 g and 2,4-D amine 750 g/ha. Non-ionic surfactant (iso-octyl-phenoxy-polyxethanol 12.5%) was used as 0.2% of spray solution volume with metsulfuron and ready mix combination of metsulfuron + carfentrazone. The herbicides were sprayed at 31-35 DAS (days after sowing) with knapsack sprayer fitted with flat fan nozzles using 350 litres water/ha. To control the grassy weeds, a blanket application of clodinafop 60 g/ha was made 10 days after broad-leaf herbicide application. Fertilizer and irrigation applications were done according to recommended package of practice for wheat. Broad-leaf weed population count and dry weight were taken at around 60 and 115 DAS, respectively. Weeds enclosed in quadrat (0.25 m^2) were counted randomly from two places in each plot and species wise density was recorded as average no./m^2 at 60 DAS, whereas, at 115 DAS, the enclosed weeds were harvested for recording dry weight. The crop was manually harvested on 11 April 2010 in first year and 12 April 2011 during second. The observations were also recorded on yield and yield attributes of wheat crop.

After wheat harvest, greengram and maize were grown in the same fixed plots under no tillage conditions, to evaluate the herbicide residual effect, if any, on these crops. After applying pre-seeding irrigation, the sowing of greengram (cv '*SML 668*') and maize (cv. '*African Tall*') was done on 15 April 2010 and 20 April 2011, during first and second year, respectively. The row to row spacing was 40 cm for greengram and 20 cm for maize. Irrigation and fertilization were done as per the standard recommendations for these crops. Maize crop was harvested for fodder on 40 DAS, whereas, greengram was harvested for grain yield.

Data were analyzed by using the General Linear Model (GLM) procedure of Statistical Analysis System (SAS, version 9.2). Treatment means were compared by using the DMRT (Duncan's Multiple Range Test) and Fisher's protected LSD (least significant difference) test at P=0.05. Prior to analysis, weed density and dry weight data were square root transformed $(\sqrt{x+1})$ and based on the transformed data, the letters were assigned to original data using DMRT for comparison of weed data.

Pot studies

Pot experiments were conducted to determine the effect of surfactant in improving the efficacy of metsulfuron and its combination with carfentrazone against *M. denticulata* and *L. aphaca* as well as to identify the effective herbicides for control of *L. aphaca, S. nigrum* and *P. minima*.

Pot study 1: Effect of surfactant on efficacy of metsulfuron and its mixture with carfentrazone against *M. denticulata* and *L. aphaca:* The graded doses of metsulfuron (1, 2 and 4 g/ha) and its combination with carfentrazone (1:4 w/w) were evaluated with and without surfactant against *L. aphaca* and *M. denticulata* (Fig. 1 and 2). In two set of experiments *L. aphaca* and *M. denticulata* (40 seeds/pot) were sown separately and finally 10 plants/pot were maintained for herbicide spraying.

Non-ionic surfactant (iso-octyl-phenoxy-polyxethanol 12.5%) was used as 0.2% of spray solution volume.

Pot study 2: Identifying effective herbicides for control of *L. aphaca, R. dentatus, S. nigrum* and *P. minima*

Lathyrus aphaca: About 20 seeds of *L. aphaca* were sown in each pot and 10 plants/pot were maintained before herbicide spraying. Different herbicides evaluated were metsulfuron 4 g, carfentrazone 20 g, mesosulfuron-methyl 3% + iodosulfuron-methyl sodium 0.6% WDG at 12.0 + 2.4 g/ha, sulfosulfuron 25 g, dicamba 480 g, 2,4-D-E 500 g, pyroxsulam 18 g, isoproturon 1000 g, triasulfuron 20 g, topramezone 50 g and metribuzin 175 g/ha (Fig. 3). Surfactants, 1250 ml/ha, 625 ml/ha, polyglycol 26-2N (1000 ml/ha) and methylated seed Oil (1500 ml/ha) were used with sulfosulfuron, mesosulfuron-methyl + iodosulfuron-methyl sodium, pyroxsulam and topramezone, respectively. Non ionic surfactant (625 ml/ha) was used with metsulfuron, and triasulfuron. At the time of herbicide spraying, *L. aphaca* was of about 7 cm height.

Solanum nigrum* and *Physalis minima: *S. nigrum* and *P. minima* berries (5 berries/pot) were sown in pots of 4.5 kg soil capacity and after germination 7 plants/pot were maintained for spraying herbicides. The herbicides used were metsulfuron 4 g, carfentrazone 20 g, metsufuron + carfentrazone 4 + 20 g, mesosulfuron + iodosulfuron 12.0 + 2.4 g/ha, sulfosulfuron 25 g, pyroxsulam 18 g, isoproturon 1000 g, metribuzin 250 g, halauxifen-methyl ester 10.4% + florasulam 10% W/W -20.4 WG at 12.76 g, topramezone 50 g, dicamba 360 g, 2,4-D-E 500 g, 2,4-D-E + carfentrazone 500 + 20 g, 2,4-D-E + metsulfuron 500 + 4 g, dicamba + metsulfuron 360 + 4 g, and dicamba + carfentrazone 360 + 20 g/ha (Fig. 4 and 5). *S. nigrum* and *P. minima* were 3-4 leaf stages at the time of herbicide spraying. Surfactants as mentioned for *L. aphaca* were used with metsulfuron, mesosulfuron-methyl + iodosulfuron-methyl sodium, sulfosulfuron, pyroxsulam, triasulfuron and topramezone and with halauxifen + florasulam ready mixture, polyglycol was used at 500 ml/ha.

Rumex dentatus: Fifty seeds of *R. dentatus* were sown in each pot and finally 10 plants/pot were maintained for herbicide spraying. The herbicide treatments (Fig. 6) assessed were 2,4-D Na (250 and 500 g/ha), 2,4-D-E (250 and 500 g/ha), 2,4-D-amine (250 and 500 g/ha), ready mixture of halauxifen-methyl ester + florasulam 12.76 (6.51 + 6.25) g/ha + surfactant polyglycol 26-2N 500 ml/ha, metsulfuron (2 and 4 g/ha) with NIS 625 ml/ha, carfentrazone (10 and 20 g/ha) and metsulfuron + carfentrazone 4 + 20 g with NIS 625 ml/ha. At the time of herbicide spraying weed was of 4 leaf stage.

In all the above pot experiments, herbicide spraying was done using knap-sack sprayer fitted with flat fan nozzles. Each treatment was replicated at least thrice and experiment was conducted in CRD and repeated to confirm the results. Fresh weight per pot was recorded 28-30 days after herbicide spraying. The results of repetition of the experiments were similar, so pooled analysis was performed. Differences among treatment means were determined using ANOVA and when the F test was significant means were compared with LSD test at 5% level of significance.

RESULTS AND DISCUSSION

Field study: Efficacy of pre-mix combination of metsulfuron + carfentrazone

Major weeds infesting the experimental plots were: *Rumex dentatus*, *Medicago denticulata*, *Coronopus didymus*, (lesser swinecress), *Lathyrus aphaca* and *Malva parviflora*. Among these, the most dominant weed species was *R. dentatus* and the dry matter accumulated by this weed in untreated control during first and second year was 362.2 and 262.1 g/m^2, respectively (Table 2 and 4). The maximum broad-leaf dry weight was recorded under weedy check (471.7 and 344.6 g/m^2). Compared to weedy check, all the herbicide treatments caused significant reduction in total density and dry weight of weeds (Table 1, 2, 3 and 4). Among different weeds, *R. dentatus* and *C. didymus* showed high sensitivity to various herbicides and their population and dry weight was drastically reduced with metsulfuron, carfentrazone, metsulfuron + carfentrazone and 2,4-D amine. Similarly, effectiveness of metsulfuron, carfentrazone and 2,4-D against *Rumex* spp. has already been reported by Balyan and Malik (2000) and Chhokar *et al.* (2007b).

The reduction in population and dry weight of *M. denticulata* was more with pre-mix combination of metsulfuron + carfentrazone applied with non ionic surfactant (NIS) than without NIS. The beneficial effect of surfactant was more clearly evident with density and dry weight of *L. aphaca*. Metsulfuron + carfentrazone at 25 and 30 g/ha with 0.2% NIS had significantly lower density of *L. aphaca* compared to sole application of metsulfuron or carfentrazone as well as without surfactant (d” 25 g/ha during first year and up to 30 g/ha during second year) application of ready mixture (Table 1, 2, 3 and 4). The improvement in efficacy of sulfonyl urea herbicide with surfactant has been reported earlier also (Singh *et al.* 2008, Chhokar *et al.* 2011).

Carfentrazone at 20 g/ha was significantly poor against *L. aphaca* and was significantly better in controlling *M. parviflora* compared to metsulfuron and 2, 4-D amine application, which failed to control *M. parviflora*. The densities of *L. aphaca* under carfentrazone application during first and second year were 14.0 and 26.0 plants/m^2 with the corresponding dry weight of 15.3 and 29.3 g/m^2. All treatments involving carfentrazone provided excellent control of *M. parviflora* (Table 1 to 4). Chhokar *et al.* (2007b) also reported effective control of *M. parviflora* with carfentrazone-ethyl. Carfentrazone alone and in combination had very fast action and toxicity symptoms appeared on the next day of herbicide application. Brosnan *et al.* (2012) also reported that carfentrazone accelerates ground ivy (*Glechoma hederacea* L.) and khaki weed (*Alternanthera pungens* Kunth) control with metsulfuron.

The ready-mix combination, metsulfuron + carfentrazone was better against the diverse weed flora compared to sole usage of metsulfuron, carfentrazone or 2,4-D amine. The total weed density and dry matter accumulation reduced as the dose of metsulfuron + carfentrazone (premix) increased. The total weed density was significantly less with metsulfuron + carfentrazone at 25 and 30 g/ha with 0.2% NIS compared to lower doses with and without surfactant as well as alone application of metsulfuron 4 g, carfentrazone 20 g or 2,4-D amine 750 g/ha.

The advantage of combination of metsulfuron and carfentrazone over metsulfuron or carfentrazone alone will be in situations having the diverse infestation of broad-leaved weeds particularly the *M. parviflora, S. nigrum and L. aphaca* (Table 1 to 4, Fig. 4). Metsulfuron and 2,4-D are not effective against *M. parviflora* and *S. nigrum*, whereas, carfentrazone is not effective against *L. aphaca*. The ready mix combination of metsulfuron + carfentrazone will provide the control of these weeds.

Similarly, Singh *et al.* (2011) reported better control of *R. spinosus* (92%) with metsulfuron + carfentrazone tank mixture compared to sole application of either metsulfuron (85%) or carfentrazone (78%). This mixture was better than 2,4-D formulations as none of the 2,4-D formulations was effective against *R. spinosus*. Although, carfentrazone causes temporary injury due to speckling on wheat leaves, which recover within 2-3 weeks without any reduction in yield (Howatt 2005) but its major advantage is its compatibility with grass herbicides.

Based on pooled analysis of two years data (Table 5), among various weed control treatments, the lowest yield (3.53 t/ha) was recorded in untreated weedy control. The presence of weeds throughout the crop season reduced the grain yield by 38.6%. Compared to weedy control, all the weed control treatments resulted in significant wheat grain yield improvement due to effective control of broad-leaf weeds. The yield in metsulfuron + carfentrazone at 25 g/ha without surfactant was inferior to its

Table 1. Effect of metsulfuron methyl + carfentrazone-ethyl and weed populatin on weed density at 60 DAS in wheat (2009-10)

Treatment	Dose (g/ha)	Weed population(no./m^2)						
		Rumex dentatus	*Coronopus didymus*	*Medicago denticulata*	*Malva parviflora*	*Lathyrus aphaca*	Others	Total weeds
Metsulfuron + carfentrazone	17.5 (3.5+14.0)	10.7^{C}	1.3^{B}	10.0^{B}	0.0^{C}	12.0^{BC}	0.7^{B}	34.7^{BC}
Metsulfuron + carfentrazone	22.5(4.5+18.0)	4.7^{DEF}	0.7^{B}	7.3^{BC}	0.0^{C}	10.0^{BC}	0.0^{B}	22.7^{D}
Metsulfuron + carfentrazone	25(5.0+20.0)	3.3^{EFG}	0.0^{B}	6.7^{BC}	0.0^{C}	8.0^{CDE}	0.0^{B}	18.0^{DE}
Metsulfuron + carfentrazone	30(6.0+24.0)	1.3^{FG}	0.0^{B}	2.7^{CD}	0.0^{C}	5.3^{EF}	0.0^{B}	9.3^{FG}
Metsulfuron + carfentrazone+NIS*	17.5(3.5+14.0)+0.2%	7.3^{CDE}	0.0^{B}	4.0^{CD}	0.0^{C}	6.0^{DE}	1.3^{B}	18.7^{D}
Metsulfuron + carfentrazone+NIS	22.5(4.5+18.0)+0.2%	4.0^{DEFG}	0.0^{B}	2.7^{CD}	0.0^{C}	4.7^{EF}	1.3^{B}	11.3^{EF}
Metsulfuron + carfentrazone+NIS	25(5.0+20.0)+0.2%	2.0^{FG}	0.0^{B}	0.7^{D}	0.0^{C}	2.7^{FG}	0.0^{B}	5.3^{GH}
Metsulfuron + carfentrazone+NIS	30(6.0+24.0)+0.2%	0.7^{G}	0.0^{B}	0.7^{D}	0.0^{C}	1.3^{G}	0.0^{B}	2.7^{H}
Metsulfuron + NIS	4+0.2%	6.7^{CDE}	0.0^{B}	6.0^{BC}	2.7^{A}	9.3^{CD}	0.7^{B}	25.3^{CD}
Carfentrazone	20	8.7^{CD}	8.7^{B}	7.3^{BC}	0.0^{C}	14.0^{B}	0.7^{B}	33.3^{BC}
2,4-D amine	750	22.7^{B}	0.0^{B}	12.7^{B}	1.3^{B}	5.3^{EF}	0.7^{B}	42.7^{B}
Untreated control	-	96.7^{A}	88.7^{A}	44.7^{A}	1.3^{B}	20.0^{A}	12.0^{A}	263.3^{A}
p-Value		<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

*NIS= Non ionic surfactant; **Original values were square root transformed $(\sqrt{x+1})$ for statistical analysis and based on which the upper-case letters have been mentioned with original values for interpretation. Means within column having at least one letter common are not significantly different according to DMRT (Duncan's Multiple range Test) at 5% level of significance

Table 2. Effect of metsulfuron-methyl + carfentrazone-ethyl and on weed dry weight in wheat (2009-10)

Treatment	Dose (g/ha)	Weed dry weight (g/m^2)					
		Rumex dentatus	*Medicago denticulata*	*Lathyrus aphaca*	*Malva parviflora*	Others	Total weeds
Metsulfuron + carfentrazone	17.5 (3.5+14.0)	8.0^{B}	4.0^{BC}	14.5^{AB}	0.4^{D}	3.5^{C}	30.4^{B}
Metsulfuron + carfentrazone	22.5(4.5+18.0)	0.7^{C}	0.7^{D}	11.4^{BC}	0.0^{D}	0.2^{D}	12.9^{CD}
Metsulfuron + carfentrazone	25(5.0+20.0)	0.0^{C}	0.3^{D}	7.9^{CD}	0.0^{D}	0.0^{D}	8.3^{D}
Metsulfuron + carfentrazone	30(6.0+24.0)	0.0^{C}	0.1^{D}	6.2^{DE}	0.0^{D}	0.0^{D}	6.3^{DEF}
Metsulfuron + carfentrazone + NIS*	17.5(3.5+14.0)+0.2%	0.1^{C}	1.3^{CD}	7.2^{CD}	0.0^{D}	0.0^{D}	8.6^{D}
Metsulfuron + carfentrazone + NIS	22.5(4.5+18.0)+0.2%	0.0^{C}	0.9^{CD}	5.3^{DE}	0.0^{D}	0.0^{D}	6.2^{DE}
Metsulfuron + carfentrazone + NIS	25(5.0+20.0)+0.2%	0.0^{C}	0.1^{D}	0.7^{F}	0.0^{D}	0.0^{D}	0.7^{EF}
Metsulfuron + carfentrazone + NIS	30(6.0+24.0)+0.2%	0.0^{C}	0.0^{D}	0.5^{F}	0.0^{D}	0.0^{D}	0.5^{F}
Metsulfuron + NIS	4+0.2%	0.1^{C}	0.7^{D}	5.1^{DE}	8.7^{A}	8.7^{A}	23.2^{BC}
Carfentrazone	20	2.9^{BC}	7.1^{B}	15.3^{AB}	0.0^{D}	0.2^{D}	25.4^{B}
2,4-D amine	750	9.7^{B}	0.7^{D}	2.3^{EF}	5.9^{B}	4.3^{C}	22.8^{BC}
Untreated control	-	362.2^{A}	79.4^{A}	21.4^{A}	2.0^{C}	6.3^{B}	471.7^{A}
p-Value		<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

Table 3. Effect of metsulfuron-methyl + carfentrazone-ethyl and weed populatin on weed density at 60 DAS in wheat (2010-11)

Treatment	Dose (g/ha)	Weed population (no./m^2)**						
		Rumex dentatus	*Coronopus didymus*	*Medicago denticulata*	*Malva parviflora*	*Lathyrus aphaca*	Others	Total weeds
Metsulfuron + carfentrazone	17.5 (3.5+14.0)	6.0^{BCD}	1.3^{CD}	4.0^{BC}	0.0^{C}	22.7^{B}	1.3	35.3^{BC}
Metsulfuron + carfentrazone	22.5(4.5+18.0)	3.3^{CDE}	0.0^{D}	3.3^{BC}	0.0^{C}	19.3^{BC}	0.7	26.7^{CD}
Metsulfuron + carfentrazone	25(5.0+20.0)	0.7^{EF}	0.0^{D}	2.0^{BCD}	0.0^{C}	13.3^{CD}	0.7	16.7^{EF}
Metsulfuron + carfentrazone	30(6.0+24.0)	0.7^{EF}	0.0^{D}	0.7^{CD}	0.0^{C}	11.3^{D}	0.0	12.7^{F}
Metsulfuron + carfentrazone + NIS*	17.5(3.5+14.0)+0.2%	2.0^{EF}	0.0^{D}	2.0^{BCD}	0.0^{C}	11.3^{D}	0.0	15.3^{EF}
Metsulfuron + carfentrazone + NIS	22.5(4.5+18.0)+0.2%	0.7^{EF}	0.0^{D}	1.3^{BCD}	0.0^{C}	9.3^{D}	0.0	11.3^{F}
Metsulfuron + carfentrazone + NIS	25(5.0+20.0) +0.2%	0.7^{EF}	0.0^{D}	0.7^{CD}	0.0^{C}	3.3^{E}	0.0	4.7^{G}
Metsulfuron + carfentrazone + NIS	30(6.0+24.0) +0.2%	0.0^{F}	0.0^{D}	0.0^{D}	0.0^{C}	2.0^{E}	0.0	2.0^{G}
Metsulfuron + NIS	4+ 0.2%	2.7^{DEF}	1.3^{CD}	5.3^{B}	3.3^{A}	8.0^{D}	0.0	20.7^{DE}
Carfentrazone	20	7.3^{BC}	3.3^{C}	4.7^{B}	0.0^{C}	26.0^{AB}	0.0	41.3^{B}
2,4-D amine 58% SL	750	12.0^{B}	10.7^{B}	5.3^{B}	2.0^{B}	10.7^{D}	0.0	40.7^{B}
Untreated control	-	72.0^{A}	74.0^{A}	24.0^{A}	1.3^{B}	34.7^{A}	5.3	211.3^{A}
p-Value		<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.1093	<0.0001

Table 4. Effect of metsulfuron-methyl + carfentrazone-ethyl on weed dry weight in wheat (2010-11)

Treatment	Dose (g/ha)	Weed dry weight (g/m^2)**				
		Rumex dentatus	*Medicago denticulata*	*Lathyrus aphaca*	Others	Total weeds
Metsulfuron + carfentrazone	17.5 (3.5+14.0)	10.8^{BC}	3.4^{BC}	22.0^{BC}	0.0^{C}	36.2^{BC}
Metsulfuron + carfentrazone	22.5(4.5+18.0)	5.9^{CDE}	0.6^{D}	17.3^{C}	0.0^{C}	23.8^{DE}
Metsulfuron + carfentrazone	25(5.0+20.0)	3.9^{DEF}	0.1^{D}	10.3^{D}	0.0^{C}	14.3^{F}
Metsulfuron + carfentrazone	30(6.0+24.0)	1.1^{FGH}	0.0^{D}	7.3^{DE}	0.0^{C}	8.5^{F}
Metsulfuron + carfentrazone + NIS*	17.5(3.5+14.0)+0.2%	6.0^{CDE}	1.1^{CD}	8.3^{DE}	0.0^{C}	15.5^{EF}
Metsulfuron + carfentrazone + NIS	22.5(4.5+18.0)+0.2%	2.7^{EFG}	0.5^{D}	6.0^{DE}	0.1^{C}	9.3^{F}
Metsulfuron + carfentrazone + NIS	25(5.0+20.0)+0.2%	0.1^{EFGH}	0.0^{D}	2.2^{F}	0.0^{C}	2.4^{G}
Metsulfuron + carfentrazone + NIS	30(6.0+24.0)+0.2%	0.0^{H}	0.0^{D}	2.0^{F}	0.0^{C}	2.0^{G}
Metsulfuron + NIS	4+0.2%	5.8^{CDE}	1.1^{CD}	5.6^{E}	0.1^{BC}	12.7^{F}
Carfentrazone	20	7.4^{CD}	6.0^{B}	29.3^{B}	1.1^{B}	43.8^{B}
2,4-D amine	750	15.3^{B}	0.6^{D}	8.7^{DE}	0.6^{BC}	25.2^{CD}
Untreated control	-	262.1^{A}	38.0^{A}	38.9^{A}	5.6^{A}	344.6^{A}
p-Value		<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

*NIS= Non ionic surfactant; **Original values were square root transformed $(\sqrt{x+1})$ for statistical analysis and based on which the upper-case letters have been mentioned with original values for interpretation. Means within column having at least one letter common are not significantly different according to DMRT (Duncan's Multiple range Test) at 5% level of significance application with surfactant. The ready mixture applied with surfactant had statistically similar yields. The application of ready mixture with NIS produced more grain yield compared to alone application of metsulfuron and carfentrazone as well as 2,4-D amine. The improvement in wheat grain yield under various weed control treatments was due to improvement in yield attributes (tillers and 1000 grain weight) as a result of effective weed control. The results show that for better efficacy of the ready-mix combination of metsulfuron- + carfentrazone, its application with a surfactant is a must. Similarly, Chhokar *et al.* (2011) also reported better weed control and wheat productivity when ready-mix combination of carfentrazone + sulfosulfuron was applied with surfactant than without surfactant application as well as alone application of either carfentrazone or sulfosulfuron. Similarly, the broad spectrum weed control and higher wheat yield were observed with combination of sulfosulfuron + metsulfuron over alone usage of either sulfosulfuron or metsulfuron (Chhokar *et al.* 2007a)

After wheat harvest, greengram and maize were grown to evaluate the herbicide carry over effect. No effect on germination (data not shown) and growth (Table 5) was observed indicating that carfentrazone, metsulfuron and premix combination of metsulfuron methyl + carfentrazone ethyl are safe for maize/greengram included in wheat based system.

Pot study 1: Surfactant effect on efficacy of metsulfuron and its mixture with carfentrazone: The efficacy of metsulfuron and metsulfuron + carfentrazone against *Lathyrus aphaca* and *M. denticulata* was improved when applied with external NIS compared to without surfactant (Fig. 1 and 2). However, the magnitude of improvement was compartively less in *M. denticultata* to *L. aphaca*. The differential response is due to differential nature of weeds and herbicides. Hodgson (1973) reported differential 2,4-D sensitivity in quack grass due to wax coating on the cuticular surface and in different ecotypes of *Circium arvense* due to variation in the wax content and amount of leaf lipid. Malik *et al.* (1989) reported significant improvement in efficacy of urea herbicides with surfactant, Selwet at 0.1% against *Lathyrus aphaca* L. and *Vicia sativa* L.

The combination, metsulfuron + carfentrazone was better compared to alone application of carfentrazone or metsulfuron. Carfentrazone 20 g/ha was better than its lower doses (5 and 10 g/ha) as well as with surfactant application of metsulfuron 1 g/ha and metsulfuron + carfentrazone (1 + 4 g/ha) (Fig. 1). With NIS, the lowest dose of metsulfuron alone (1 g/ha) and in combination with carfentrazone (1+ 4 g/ha) were equally effective in reducing the fresh weight of *M. denticulata* as their respective 2 and 4 times doses without surfactant (Fig. 1). The improvement in herbicide efficacy with surfactant has been earlier reported by many research workers (Chhokar *et al.* 2011, Malik *et al.* 1989, Singh *et al.* 2008).

Table 5. Effect of metsulfuron + carfentrazone on wheat and succeeding maize and greengram (pooled data of two years)

Treatment	Dose (g/ha)	Wheat yield and yield attributes				Carry over effect on succeeding crops	
		Tillers/m²	Biomass (t/ha)	1000 grain wt (g)	Grain yield (t/ha)	Maize fresh biomass (fodder) (t/ha)	Greengram grain yield (t/ha)
Metsulfuron + carfentrazone	17.5 (3.5+14.0)	462 [B]	12.89 [B]	37.1 [A]	5.33 [C]	12.84	1.12
Metsulfuron + carfentrazone	22.5(4.5+18.0)	476 [AB]	13.53 [AB]	37.3 [A]	5.44 [BC]	12.28	1.10
Metsulfuron + carfentrazone	25(5.0+20.0)	478 [AB]	13.39 [AB]	36.9 [A]	5.55 [ABC]	13.03	1.10
Metsulfuron + carfentrazone	30(6.0+24.0)	486 [AB]	13.36 [AB]	37.1 [A]	5.65 [AB]	12.16	1.05
Metsulfuron + carfentrazone +NIS*	17.5(3.5+14.0)+0.2%	478 [AB]	13.44 [AB]	37.1 [A]	5.60 [ABC]	12.00	1.06
Metsulfuron + carfentrazone + NIS	22.5(4.5+18.0)+0.2%	488 [A]	13.85 [A]	37.1 [A]	5.75 [A]	12.63	1.09
Metsulfuron + carfentrazone + NIS	25(5.0+20.0)+0.2%	482 [AB]	13.59 [AB]	37.4 [A]	5.73 [AB]	12.47	1.16
Metsulfuron + carfentrazone + NIS	30(6.0+24.0)+0.2%	482 [AB]	13.77 [A]	37.7 [A]	5.72 [AB]	12.67	1.13
Metsulfuron + NIS	4+0.2%	478 [AB]	13.34 [AB]	37.0 [A]	5.58 [ABC]	12.07	1.09
Carfentrazone	20	488 [A]	13.20 [AB]	37.3 [A]	5.32 [C]	12.42	1.10
2,4-D amine	750	467 [AB]	12.87 [B]	36.9 [A]	5.45 [BC]	12.44	1.17
Untreated control	-	379 [C]	10.09 [C]	34.5 [B]	3.53 [D]	12.52	1.11
p-Value		<0.0001	<0.0001	0.0038	<0.0001	0.9921	0.9905
LSD (0.05)		25.6	0.81	1.22	0.29	NS	NS

*NIS= Non ionic surfactant; ** Means in column having at least one letter common are not significantly different using DMRT (Duncan's Multiple Range Test) at 5% level of significance

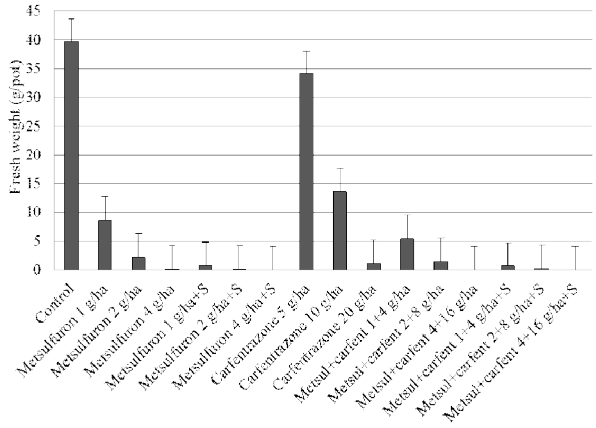

Fig. 1. ***Medicago denticulata*** **fresh weight as affected by herbicide and surfactant. Vertical bars represent LSD (P=0.05)**

Among, metsulfuron, carfentrazone and metsulfuron + carfentrazone treatments, carfentrazone had the least effect on *L. aphaca*. Carfentrazone 20 g/ha application reduced the *L. aphaca* fresh weight by 37.3% compared to untreated control (Fig. 2). The NIS significantly improved the efficacy of metsulfuron and metsulfuron + carfentrazone. The lowest dose of metsulfuron alone 1 g/ha and metsulfuron + carfentrazone 1 + 4 g/ha with NIS were equally effective to their respective highest doses 4 g/ha and 4 + 16 g/ha without NIS.

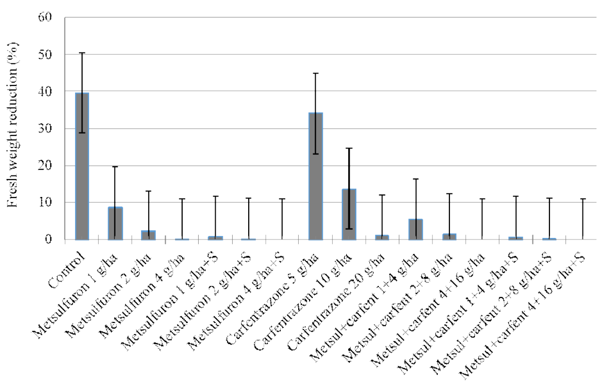

Fig. 2. ***Lathyrus aphaca*** **fresh weight reduction as affected by herbicide and surfactant. Vertical bars represent ± LSD (P=0.05)**

Pot study 2: Herbicides for control of ***L. aphaca, Rumex dentatus, S. nigrum*** **and** ***P. minima***

L. aphaca **control**: In another pot experiment, carfentrazone 20 g/ha was ineffective against *L. aphaca*, as the fresh weight accumulated by *L. aphaca* in carfentrazone and control was 22.9 and 19.9 g/pot, respectively. Dicamba 480 g/ha and topramezone 50 g/ha were the most effective treatments providing complete control of *L. aphaca*.

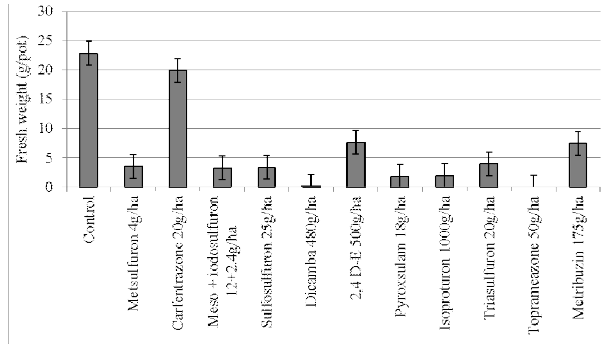

Fig. 3. Effect of herbicides on ***Lathyrus aphaca*****. Vertical bars represent ±LSD (P=0.05)**

Metribuzin 175 g and 2,4-D-E 500 g/ha were inferior to metsulfuron, Atlantis, sulfosulfuron, pyroxsulam, isoproturon and triasulfuron (Fig. 3).

S. nigrum **control:** All the herbicide treatments reduced the fresh weight of *S. nigrum* (Fig. 4) compared to control (100%). Metsulfuron 4 g/ha was least effective in controlling *S. nigrum* followed by halauxifen methyl + florasulam 12.76 g/ha and sulfosulfuron 25 g with respective reduction in *S. nigrum* fresh weight of 22.0, 29.2 and 39.8%. Application of 2,4-D-E 500 g/ha alone provided 58.8% control of *S. nigrum*. However, another growth regulator herbicide *i.e.* dicamba 360 g/ha was highly effective (99.2%) in controlling *S. nigrum*. The most effective control of *S. nigrum* was with isoproturon 1000 g/ha (100.0%), topramezone 50 g/ha (100.0%), dicamba 360 g/ha, and tank mix application of carfentrazone (20 g/ha) with metsulfuron (4 g/ha), 2,4-D-E (500 g/ha) and dicamba (360 g/ha).

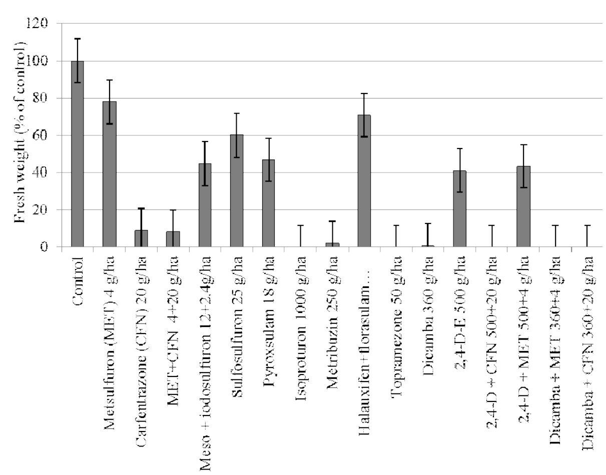

Fig. 4. ***Solanum nigrum*** **fresh weight as affected by herbicide. Vertical bars represent ±LSD (P=0.05)**

***P. minima* control:** The fresh weight of *P. minima* was significantly reduced with various herbicides. Among different herbicides, 2,4-D-E 500 g/ha was least effective in controlling *P. minima* followed by halauxifen methyl + florasulam 12.76 g/ha (Fig 5). Metsulfuron 4 g, carfentrazone 20 g, metsulfuron + carfentrazone (4+20 g/ha), pyroxsulam 18 g, isoproturon 1000 g, metribuzin 210 g, dicamba 360 g, topramezone 50 g, 2,-4-D-E+carfentrazone 500 + 20 g, 2,4-D-E+ metsulfuron 500 + 4 g/ha were quite effective in controlling *P. minima* and the fresh weight reduction by these herbicide was 98.4 to 100.0%. However, the genotype/crop selectivity to metribuzin and topramezone should be examined before use as differential crop tolerance to these herbicides can occur.

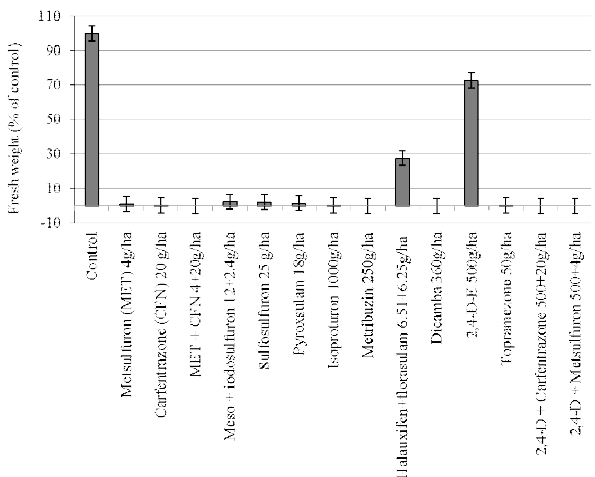

Fig. 5. *Physalis minima* fresh weight as affected by herbicide. Vertical bars represent ± LSD (P=0.05)

***Rumex dentatus* control:** Its control was poor with all the 2,4-D formulations (Fig. 6). The effectiveness of three formulations was in order 2,4-D-Amine, 2,4-D-E and 2,4-D-Na. Singh *et al.* 2011 also reported ineffectiveness of 2,4-D formulations for *Rumex spinosus* control. Metsulfuron, carfentrazone, metsulfuron + carfentrazone and halauxifen methyl + florasulam were effective in controlling the *Rumex dentatus*. Metsulfuron 2 to 4 g/ha and halauxifen methyl +florasulam 12.76 g/ha provided 100% control.

In the present study, herbicide combinations, 2,4-D E + carfentrazone 500 + 20 g/ha and dicamba 360 g + carfentrazone 20 g/ha effectively controlled the *P. minima* and *S. nigrum* and no antagonistic effect was observed. Lyon *et al.* (2007) also reported that carfentrazone at 18 g/ha tank mixed with 2,4-D amine or dicamba improved *Salsola iberica, Kochia scoparia* and *Helianthus annuus* control without

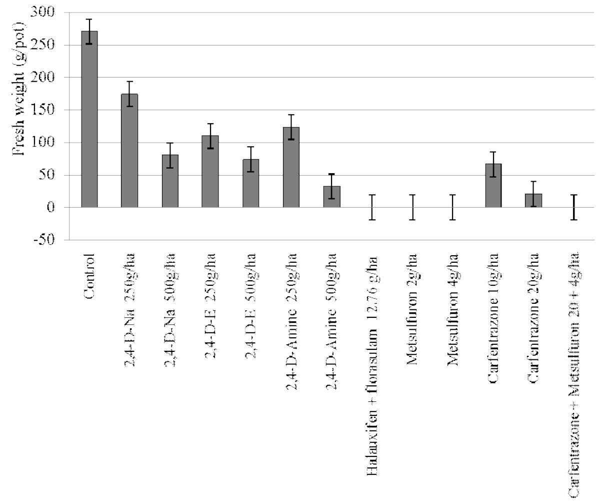

Fig. 6. *Rumex dentatus* fresh weight as affected by herbicide. Vertical bars represent ± LSD (P=0.05)

injury on proso millet (*Panicum miliaceum* L.) and foxtail millet (*Setaria italica* L.) in Nebraska. Contrary to it, Singh *et al.* (2008) reported tank mix application of carfentrazone with 2,4-D as antagonistic against some broad-leaf weeds, but not with tribenuron. However, care has to be taken while using 2,4-D and should be used at right dose and time. Its application at sensitive stages (seedling, spike initiation/flowering stage) as well as on sensitive cultivars and at higher rates can lead to yield reduction due to earhead malformation (Pinthus and Natowitz 1967). In addition, 2,4-D butyl ester application often results in injury to adjacent sensitive broad-leaf crops, due to its volatilization and solution drifting (Li *et al.* 2002, Zhang *et al.* 2005).

The control of broad-leaf weeds is easy as compared to grassy weeds in wheat crop. However, due to more diversity of broad-leaf weeds, still many broad-leaf weeds escape control with usage of single herbicide. Also, continuous use of herbicides having the same mechanism of action can result in the wide spread evolution of herbicide resistance in weeds and build up of tolerant weeds (Powles and Yu 2010). Repeated application of tribenuron in China has resulted in serious sulfonylurea resistance in main weed species *Descurainia sophia* (Cui *et al.* 2008). *L. aphaca, F. parviflora* and *Rumex spinosus* are becoming major weeds in light soils of North Western India. Whereas, *Malva parviflora, Solanum nigrum* and *Rumex dentatus* are increasing in abundance in no-till wheat fields of rice-wheat system. The increasing abundance of a particular weed is as a result of ineffectiveness of particular herbicide used. Metsulfuron and 2,4-D are ineffective against some of the weeds like *Malva parviflora* and *S. nigrum*.

2,4-D is also not effective against *R. spinosus* and carfentrazone is poor against *Lathyrus aphaca*. Combination of metsulfuron or 2,4-D with other herbicides like carfentrazone can provide control of diverse weed spectrum as observed here in field and pot studies. Herbicide mixture will also lower the selection pressure being imposed by the repeated use of same herbicide. Therefore, for broad spectrum weed kill, two or three herbicides combinations need to be tried. Although, wheat growers prefer herbicide over other method of weed control yet there is need to integrate the non-chemical methods with chemical for efficient weed management and sustainable crop production.

Present study suggests that fields having diverse infestation of weeds require herbicides combination. Metsulfuron-methyl + carfentrazone (premix) at 25 g/ha + 0.2% NIS was effective against diverse broad-leaf weeds in wheat. A combination of two or more herbicides, besides broadening the weed control also helped in reducing the cost of weed control. Therefore, future studies need to be directed towards evaluating the compatibility/suitability between different broad-leaved herbicides and broad-leaf and grass herbicides. The effectiveness of grass herbicides was generally reduced when mixed with broad-leaf herbicides (Damlas 2004).

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