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RESEARCH ARTICLE

Efficacy of alternative herbicides for managing metsulfuron-methyl (ALS inhibitor) resistant *Rumex dentatus* L. in wheat (*Triticum aestivum* L.) under the north-western Indo-Gangetic Plains

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Abstract

Rumex dentatus L. (Toothed dock) is a dominating broadleaf weed of irrigated wheat in the rice-wheat cropping system of north-western India. For more than 15 years, metsulfuron-methyl (Group B/2 herbicides, ALS (acetolactate synthase) inhibitor) has been used for effective control of this weed. Recently, reports from farmers' fields indicated poor efficacy of metsulfuron-methyl against *R. dentatus* due to herbicide resistance, potentially causing significant yield losses in wheat. Therefore, a field study was conducted during the Rabi seasons of 2017-18 and 2018-19 at the research farm of Krishi Vigyan Kendra (KVK), Chaudhary Charan Singh (CCS) Haryana Agricultural University, Panipat, India to identify alternative herbicides against *R. dentatus* in a field with a known history of poor control with metsulfuron-methyl. The findings revealed that metsulfuron-methyl (4 g ha^{-1}), mesosulfuron + iodosulfuron (14.4 g ha^{-1}) and sulfosulfuron + metsulfuron (32 g ha^{-1}) showed poor performance in terms of percent control (16.5, 34.3 and 19.6 % respectively), density (54.1, 42.6 and 52.1 plants m^{-2} respectively) and dry matter accumulation (8.18, 6.31 and 9.11 gm^{-2} respectively) of *R. dentatus* along with significant reduction in yield attributes and yields of wheat. Among the pre-emergence herbicides, pendimethalin (1000 and 1500 g ha^{-1}) was found most effective in terms of percent control (95.7 and 98.0 % respectively), density (2.8 and 1.3 plants m^{-2} respectively) and dry matter accumulation (0.48 and 0.12 g m^{-2} respectively) of *R. dentatus* with higher yield attributes and grain yield (5822 and 5957 kg ha^{-1}) of wheat. Among the post-emergence herbicide, 2,4-D ester (400 and 600 g ha^{-1}), 2,4-D Na (1000 g ha^{-1}), carfentrazone + metsulfuron (25 g ha^{-1}), carfentrazone-ethyl (20 g ha^{-1}) and 2,4-D amine (750 g ha^{-1}) were found effective against metsulfuron-methyl resistant *R. dentatus.*

Keywords: ALS inhibitors; herbicide resistance; metsulfuron-methyl; *Rumex dentatus*; wheat

Introduction

Wheat (*Triticum aestivum* L.) is the world's foremost staple crop having an area, production and productivity of 220.43 million ha, 774.41 million tonnes and 3510 kg ha^{-1} respectively (1). In India, it is the second most important crop after rice with production of 107.86 million metric tonnes from an area of 31.36 million ha with average productivity of 3440 kg ha^{-1} (1), contributing around 33 % of the total food grain production. Thus, its continued high production is essential for India's food security.

However, accelerated development of herbicide resistance against wheat associated weeds is halting its potential productivity in India (2). Earlier, *Phalaris minor* was the first weed documented to develop resistance to urea-based herbicides such as isoproturon, metoxuron, mesosulfuron, iodosulfuron, sulfosulfuron and metsulfuron during the early 1990s in north-western India (3). Later, it developed cross-resistance against alternative herbicides (4). This has been reported as one of the most serious cases of herbicide resistance in the world, threatening the productivity of wheat crop in the most productive north-western Indo-Gangetic Plains of India (5). Since then, no major problem of resistance in any other weed came into notice for a long period in India. Defying action of metsulfuron-methyl against *Rumex dentatus* has been reported and confirmed recently under pot conditions (6-9).

Among the broadleaf weeds observed during the Rabi (winter) season, *R. dentatus* is the most dominant species. It poses serious problem in irrigated wheat, particularly in the rice-wheat cropping system of Haryana, Punjab and Western Uttar Pradesh, which are part of the north-western Indo-Gangetic Plains of India. It belongs to the shorter weeds group with a higher photosynthetic rate, specific leaf area, leaf nitrogen mass, chlorophyll content, photosynthetic nitrogen-use efficiency and leaf area ratio in comparison to taller weeds group (*Chenopodium album* and *P. minor*) and wheat crop (10). The wheat crop had a low specific leaf area later in the season whereas, the smaller weeds like *R. dentatus* had relatively high specific leaf area, which might be an adaptation to the shaded environment below the crop canopy (10). This weed is highly competitive and causes yield losses up to 55 % in wheat (8, 11).

Initially in 1988, metsulfuron-methyl, a sulfonylurea herbicide, was recommended for the control of *R. dentatus* in wheat in India. This herbicide provided effective control of *R. dentatus* as well as most other broadleaf weeds at a very low dose rate (2-4 g ha^{-1}). However, in recent years, this weed has evolved resistance to Group B/2 herbicides, classified as acetolactate synthase (ALS) inhibitors that act by inhibiting the enzyme acetohydroxy acid synthase (AHAS) (7). The reports have shown that these particular biotypes were found resistant to florasulam, pyroxsulam, metsulfuron -methyl, mesosulfuron-methyl and iodosulfuron-methyl-sodium. Moreover, these biotypes also exhibit cross-resistance to herbicide mixtures such as mesosulfuron + iodosulfuron, pyroxsulam and halauxifen + florasulam. However, the resistant biotypes of *R. dentatus* were found sensitive to 2, 4-D, carfentrazone-ethyl, metribuzin, pendimethalin and terbutryn (2, 6). This represents the second documented case of herbicide resistance in India and the first reported case among broadleaf weeds (12). The population of *R. dentatus* from KVK (Farm Science Centre) Panipat (Haryana), India has been found to be resistant against metsulfuron-methyl (ALS inhibitor), which had been recommended for its control in India since the 1990s (8, 9). However, there is a strong possibility that resistance to metsulfuron-methyl and even other herbicides may emerge in *R. dentatus* populations from other regions as well.

Globally, herbicides are a major tool for management of weeds in wheat because of cost and time effectiveness. However, sole reliance on herbicides has led to the problem of herbicide resistance development in weeds. There are currently 530 unique cases (species × site of action) of herbicide resistant weeds globally, with 272 species (155 dicots and 117 monocots). Weeds have evolved resistance to 21 of the 31 known herbicide sites of action and to 168 different herbicides. Herbicide resistant weeds have been reported in 100 crops in 72 countries. In wheat alone, 367 cases of herbicide resistance have been reported (13). Research on herbicide resistance in *R. dentatus* is limited. Hence, there is a need to evaluate alternate herbicidal options for its management and strategies for checking its further spread. Therefore, present study was planned to account the herbicide resistance/poor efficacy of different herbicides against *R. dentatus* population with known history of having defying action of metsulfuron-methyl, during the Rabi seasons of 2017-18 and 2018-19.

Materials and Methods

Experimental site and weather condition

A field experiment was conducted to evaluate the bio-efficacy of different herbicides against *R. dentatus* during the Rabi seasons of 2017-18 and 2018-19 at Krishi Vigyan Kendra (KVK), Chaudhary Charan Singh (CCS) Haryana Agricultural University, Panipat (29° 36'20"N 77°01'90"E), Haryana, India. The field had a history of poor control of *R. dentatus* with metsulfuron-methyl. The soil of experimental site was sandy loam in texture, slightly alkaline in pH, low in organic carbon (0.38 %), low in available nitrogen (178 kg ha^{-1}), medium in available phosphorus (14 kg ha^{-1}) and high in available potassium (342 kg ha^{-1}). The field was under rice-wheat rotation for more than five years.

The weather data pertaining to the location during both the years of study are presented in Fig. 1 (Rabi 2017-18) and Fig. 2 (Rabi 2018-19). In Rabi 2017-18 the mean weekly maximum and minimum temperatures ranged from 17.7-37.9 °C and 3.9-20.3 ° C, whereas during 2018-19, it ranged from 16.7-39.2 °C and 5.6-21.2 °C respectively. A maximum temperature of 37.9 °C and minimum temperature of 3.9 °C was recorded in 17^{th} and 2^{nd} standard meteorological week (SMW) during the cropping season of 2017-18; whereas during the cropping season of 2018-19, it was 39.2 °C and 5.6 °C in 17^{th} and 1^{st} SMW respectively. The total rainfall throughout the crop season was 85.4 and 79.2 mm for the year 2017-18 and 2018-19 respectively. The maximum weekly rainfall of 34.2 mm and 28.4 mm was observed during 4^{th} SMW during both the years.

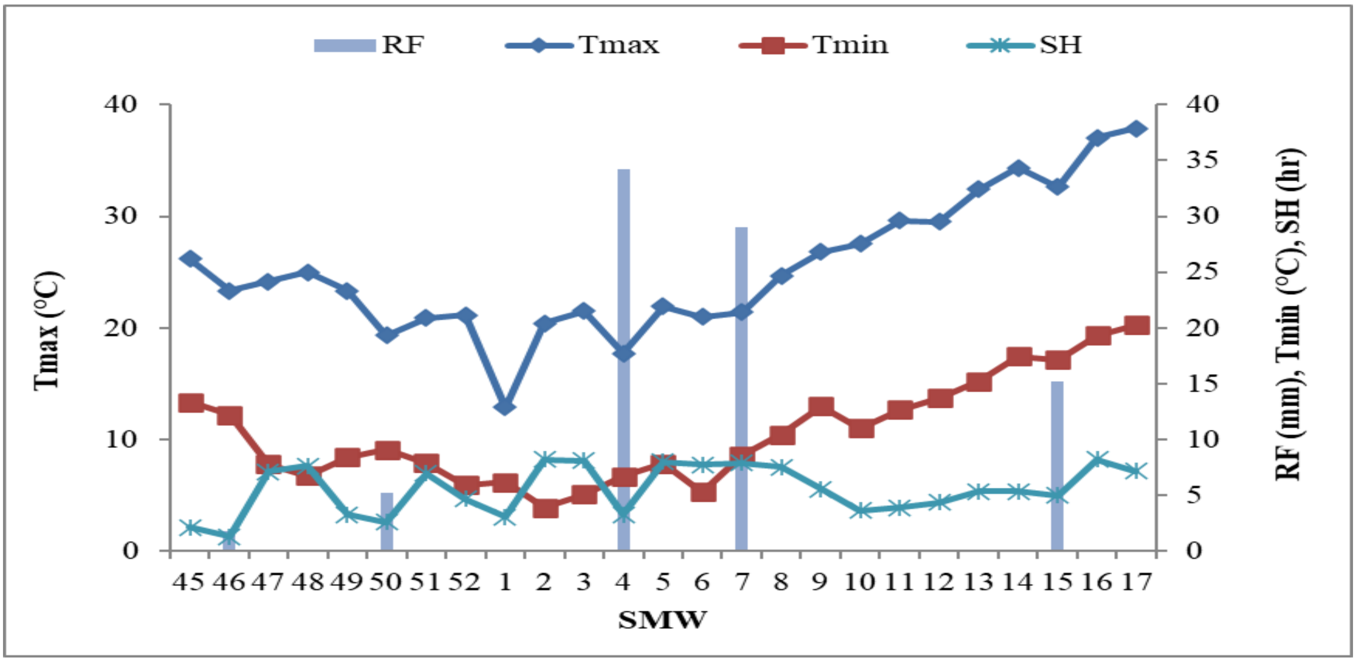

Fig. 1. Average weekly weather data during the cropping season (Rabi 2017-18).

Fig. 2. Average weekly weather data during the cropping season (Rabi 2018-19).

Crop management

Preceding rice crop of Kharif (summer) season was harvested manually and then field was prepared by conventional method i.e., pre-sowing irrigation followed by two times harrowing, once cultivator and planking. Wheat (cv. 'HD-2967') was sown on 14 November 2017 and 16 November 2018 using a seed-cum-fertilizer drill at 100 kg ha^{-1} with 20 cm row spacing. The experiment was laid out in randomized block design with three replications, keeping plot size 6 m × 2.2 m. Total six irrigations were applied as per the crop requirement during critical growth stages. The wheat crop was fertilized by using urea as a source of nitrogen at the rate of 150 kg N ha^{-1} in two splits with its application half as basal dose and remaining at the time of first irrigation. Phosphorous was applied at the rate of 60 kg P_2O_5 (phosphorus pentoxide) ha^{-1} through DAP (diammonium phosphate) as basal dose. The crop was managed according to the standard agronomic practices of the state university. The crop was harvested manually on 12 April 2018 and 16 April 2019.

Treatment details

The experiment had seventeen treatments (including weed free and weedy checks) and three replicates. The herbicidal treatments used are given in Table 1. The pre-emergence (PE) herbicides (pendimethalin and metribuzin) were applied as spray just after sowing (JAS) of wheat crop, while the post-emergence (PoE) herbicides were sprayed at 35 days after sowing (DAS) with knapsack sprayer fitted with flat-fan nozzle using water volume of 500 L ha^{-1}. In weed free treatment, *R. dentatus* was removed manually whenever it appeared in the season. All other weeds were manually removed to isolate the effects of treatments on *R. dentatus*.

Table 1. Treatment details including dose and time of application of herbicides

Treatment	Dose (g ha^{-1})	Time of application (DAS)
Metsulfuron-methyl	4	35
Carfentrazone-ethyl	20	35
2,4-D ester	400	35
2,4-D ester	600	35
2,4-D amine	500	35
2,4-D amine	750	35
2,4-D Na	700	35
2,4-D Na	1000	35
Carfentrazone + metsulfuron	25	35
Mesosulfuron + iodosulfuron	14.4	35
Sulfosulfuron + metsulfuron	32	35
Pendimethalin	1000	JAS
Pendimethalin	1500	JAS
Metribuzin	175	JAS
Metribuzin	210	JAS
Weed free	-	-
Weedy check	-	-

Observations

Density of *R. dentatus* was recorded at 30 and 60 DAS using quadrat of 50 cm × 50 cm randomly at two places in each plot. All the *R. dentatus* plants falling within the quadrat were cut close to the ground at 30 and 60 DAS. These were sun dried followed by drying in a hot air oven maintained at 65±5 °C till constant dry weight and then weighed. The biomass was expressed as g m^{-2}. The data related to growth, yield attributes and yield were recorded at maturity. The economics of various treatments were calculated by using following formulae:

Total cost of cultivation=

$$\text{Variable cost + Fixed cost + Transport cost} \quad \text{(Eqn. 1)}$$

$$\text{Net returns = Gross returns - Total cost of cultivation} \quad \text{(Eqn. 2)}$$

$$\text{Benefit-cost ratio} = \frac{\text{Gross returns}}{\text{Total cost of cultivation}} \quad \text{(Eqn. 3)}$$

Weed index (WI) (%) of different treatments was calculated on the basis of reduction in grain yield in treated plots (Wt) as compared to weed free plots (Wf). It was calculated using the following formula:

$$\text{WI (\%)} = \frac{\text{Grain yield in Wf - Grain yield in Wt}}{\text{Grain yield in Wf}} \times 100 \quad \text{(Eqn. 4)}$$

Weed control efficiency (WCE) of different treatments was calculated on the basis of reduction in weed biomass in treated plot (DMT) in comparison to weedy check (DMC) at 60 DAS and expressed as percentage. It was calculated by using the following formula:

$$\text{WCE (\%)} = \frac{\text{DMC - DMT}}{\text{DMC}} \times 100 \quad \text{(Eqn. 5)}$$

Statistical analysis

The statistical analysis was carried out using OPSTAT software of CCS HAU Hisar (14) with least significant difference (LSD) tested at 5 % level of significance. Bartlett's Chi-square test was employed to assess the homogeneity of variances among datasets. Interaction effect for year × treatment is not significant for crop growth and yield parameters, indicating that treatments behaved independently over season/years. Therefore pooled analysis of both years' data was done for drawing inferences. The data on different characters were analysed by using analysis of variance (ANOVA) technique for randomized block design. Standard error of mean difference at 5 % level of probability was calculated for significant effects. Weed population data were square-root transformed (√(x+1)) prior to analysis to stabilize variance.

Results

Studies on *R. dentatus*

Data on density and dry matter accumulation of *R. dentatus* along with WCE and WI of different treatments are presented in Table 2.

Density of *R. dentatus*

At 30 DAS, only the effects of PE herbicides, pendimethalin and metribuzin, were evident, as PoE herbicides had not yet been applied. Pendimethalin at 1500 g ha^{-1} was the most effective against *R. dentatus* and recorded lowest density (2.6 m^{-2}), followed by pendimethalin at 1000 g ha^{-1} with 8.4 m^{-2} of *R. dentatus* population (Table 2). Metribuzin (175 and 210 g ha^{-1}) was also found effective against *R. dentatus* (30.3 and 18.7 m^{-2} respectively) but showed comparatively poorer performance than pendimethalin.

The pooled data of two years at 60 DAS revealed that 2,4-D ester at 600 g ha^{-1} and 2,4-D Na at 1000 g ha^{-1} were found most effective against *R. dentatus* and achieved weed densities comparable to the weed-free treatment. The above treatments along with 2,4-D ester at 400 g ha^{-1} were statistically at par (1.0 p lants m^{-2}) with the weed free treatment. Carfentrazone-ethyl at 20 g ha^{-1}, 2,4-D amine at 500 g ha^{-1} and 750 g ha^{-1}, 2,4-D Na at 700 g ha^{-1}, carfentrazone + metsulfuron at 25 g ha^{-1} and pendimethalin at 1000 and 1500 g ha^{-1} were found effective and provided satisfactory control (89.4-98.0 %) of *R. dentatus* with lower density (1.3 -6.9 m^{-2}).

In contrast, the metsulfuron-methyl at 4g ha^{-1}, mesosulfuron + iodosulfuron at 14.4 g ha^{-1}, sulfosulfuron + metsulfuron at 32 g ha^{-1} and metribuzin at 175 g ha^{-1} exhibited poor efficacy, providing only 16.5, 34.3, 19.6 and 59.6 % control of *R. dentatus* respectively. However, metribuzin at 210 g ha^{-1} achieved moderate control (77.9 %) with a weed density of 14.3 plants m^{-2}.

Dry matter accumulation of *R. dentatus*

At 30 DAS, only the effects of PE herbicides, pendimethalin and metribuzin, were evident, as PoE herbicides had not yet been applied. Pendimethalin at 1500 g ha^{-1} was found most effective against *R. dentatus* in terms of lowest dry matter accumulation (0.14 g m^{-2}). It was statistically similar to pendimethalin at 1000 g ha^{-1} with *R. dentatus* dry matter accumulation of 0.33 g m^{-2}. Metribuzin (175 g ha^{-1} and 210 g ha^{-1}) was also found effective (1.39 g m^{-2} and 0.92 g m^{-2} respectively) but showed comparatively poorer performance than pendimethalin.

The pooled data of dry matter accumulation at 60 DAS revealed that 2, 4-D ester at 600 g ha^{-1} and 2, 4-D Na at 1000 g ha^{-1} resulted in complete control of *R. dentatus*. The treatments of 2,4 -D ester at 400 and 600 g ha^{-1}, 2,4-D amine at 500 and 750 g ha^{-1}, 2,4-D Na at 700 and 1000 g ha^{-1}, carfentrazone + metsulfuron at 25 g ha^{-1} and pendimethalin at 1000 and 1500 g ha^{-1} were statistically at par with the weed free treatment with lower dry matter accumulation of *R. dentatus* (0.12 - 0.90 g m^{-2}). Carfentrazone-ethyl (20 g ha^{-1}) and metribuzin (210 g ha^{-1}) were also found effective, with lower dry matter accumulation of *R. dentatus* (1.19 and 1.59 g m^{2} respectively) as compared to weedy check (11.36 g m^{2}). In contrast, metsulfuron-methyl at 4 g ha^{-1}, mesosulfuron + iodosulfuron at 14.4 g ha^{-1}, sulfosulfuron + metsulfuron at 32 g ha^{-1} and metribuzin at 175 g ha^{-1} showed poor performance against *R. dentatus* with higher dry matter accumulation (8.18, 6.31, 9.11 and 2.66 g m^{2} respectively) at 60 DAS.

Table 2. Effect of different herbicidal treatments on density, dry matter accumulation of *R. dentatus*, WCE and WI in wheat crop (pooled data of 2017-18 and 2018-19)

Treatments	Dose (g ha^{-1})	Density of *R. dentatus* (no. m^{-2}) 30 DAS	Density 60 DAS	Dry matter of *R. dentatus* (g m^{-2}) 30 DAS	Dry matter 60 DAS	WCE at 60 DAS (%)	WI (%)
Metsulfuron-methyl	4	7.9(62.6)	7.4(54.1)	3.64	8.18	21.7	29.7
Carfentrazone-ethyl	20	8.5(71.1)	2.5(5.7)	4.10	1.19	91.3	10.8
2,4-D ester	400	8.1(64.1)	1.4(1.0)	3.96	0.13	99.0	6.6
2,4-D ester	600	8.3(67.5)	1.0(0.0)	3.97	0.00	100.0	5.3
2,4-D amine	500	8.5(71.5)	2.8(6.9)	4.18	0.90	91.7	16.0
2,4-D amine	750	7.6(57.3)	2.2(3.8)	3.13	0.36	97.3	13.2
2,4-D Na	700	7.9(61.7)	1.6(1.7)	3.82	0.27	98.2	10.4
2,4-D Na	1000	7.6(57.6)	1.0(0.0)	2.99	0.00	100.0	5.8
Carfentrazone + metsulfuron	25	8.1(64.4)	2.1(3.2)	3.70	0.62	95.5	9.0
Mesosulfuron + iodosulfuron	14.4	7.7(58.8)	6.6(42.6)	3.26	6.31	41.5	24.4
Sulfosulfuron + metsulfuron	32	8.0(63.6)	7.3(52.1)	3.71	9.11	17.8	26.5
Pendimethalin	1000	3.1(8.4)	2.0(2.8)	0.33	0.48	96.7	3.1
Pendimethalin	1500	1.9(2.6)	1.5(1.3)	0.14	0.12	99.1	0.7
Metribuzin	175	5.6(30.3)	5.2(26.2)	1.39	2.66	74.6	19.2
Metribuzin	210	4.4(18.7)	3.9(14.3)	0.92	1.59	86.7	15.3
Weed free	-	1.0(0.0)	1.0(0.0)	0.00	0.00	100.0	0.0
Weedy check	-	8.4(69.3)	8.1(64.8)	4.02	11.36	0.0	32.9
CD (p=0.05)		0.4	0.4	0.69	0.98		5.2

Note: The original values in parenthesis were subjected to square root transformation (√x+1) before statistical analysis.

Weed control efficiency and weed index

The pooled data of WCE at 60 DAS revealed that 2,4-D ester at 600 g ha^{-1} and 2,4-D Na at 1000 g ha^{-1} provided 100 % WCE against the population of *R. dentatus*. Carfentrazone-ethyl at 20 g ha^{-1}, 2,4-D ester at 400 g ha^{-1}, 2,4-D amine at 500 and 750 g ha^{-1}, 2,4-D Na at 700 g ha^{-1}, carfentrazone + metsulfuron at 25 g ha^{-1} and pendimethalin at 1000 and 1500 g ha^{-1} were also found highly effective in terms of higher WCE (91.3 - 99.1 %). In contrast, comparatively lower WCEs were recorded for metribuzin at 175 g ha^{-1} (74.6 %) and 210 g ha^{-1} (86.7 %). The performance of metsulfuron-methyl at 4 g ha^{-1} (21.7 %), mesosulfuron + iodosulfuron at 14.4 g ha^{-1} (41.5 %) and sulfosulfuron + metsulfuron at 32 g ha^{-1} (17.8 %) was poor in terms of WCE.

All the treatments recorded significantly lower WI than weedy plot (32.9 %) except metsulfuron-methyl at 4 g ha^{-1} (29.7 %) which was statistically at par with weedy check. The lowest WI (0.7 %) was recorded by pendimethalin at 1500 g ha^{-1} followed by pendimethalin at 1000 g ha^{-1} (3.1 %), which were statistically similar to weed free treatment. On the other hand, the highest WI (29.7 %) was found in metsulfuron-methyl at 4 g ha^{-1}. However, 2,4 -D ester (400 g ha^{-1}), 2,4-D ester (600 g ha^{-1}) and 2,4-D Na (1000 g ha^{-1}) also had lower values of WI (6.6 , 5.3 and 5.8 % respectively).

Studies on wheat crop

Yield attributes and yield

Data on yield attributes including number of effective tillers, grains spike^{-1}, spike length and 1000 grain weight along with yields are presented in Table 3. The highest numbers of effective tillers (94.8 tillers mrl^{-1}) were recorded with pendimethalin at 1500 g ha^{-1}. It was followed by the treatments of 2,4-D ester (400 and 600 g ha^{-1}), 2,4-D amine (500 g ha^{-1}), 2,4-D Na (1000 g ha^{-1}) and pendimethalin (1000 g ha^{-1}) which also resulted in significantly higher number of effective tillers (90.3-93.5 tillers mrl^{-1}) at par with weed free treatment (96 tillers mrl^{-1}). Except metsulfuron-methyl at 4 g ha^{-1}, mesosulfuron + iodosulfuron at 14.4 g ha^{-1} and metribuzin at 175 g ha^{-1}, all other treatments recorded significantly higher number of effective tillers than weedy plot. The highest numbers of grains spike^{-1} (52.8) was recorded under pendimethalin at 1500 g ha^{-1}. It was followed by treatments of carfentrazone-ethyl at 20 g ha^{-1}, 2,4-D ester at 400 and 600 g ha^{-1}, 2,4-D at Na 700 and 1000 g ha^{-1}, carfentrazone + metsulfuron at 25 g ha^{-1}, pendimethalin at 1000 g ha^{-1} and metribuzin at 210 g ha^{-1} with grains spike^{-1} (49.5-52.5). These were statistically at par with weed free check (53.8). While the lowest number of grains spike^{-1} (45.7) was recorded with metsulfuron-methyl (4 g ha^{-1}) which was statistically similar to weedy check (43.2). Spike length (10.4 - 11.3 cm) and 1000-grain weight (43.2- 47.3 g) were not affected by different treatments and non-significant differences were recorded among various treatments.

All the treatments provided significantly higher grain yield than weedy plot (4023 kg ha^{-1}) except metsulfuron-methyl at 4 g ha^{-1} (4220 kg ha^{-1}) which was at par with weedy check. Pendimethalin at 1500 g ha^{-1} recorded the highest grain yield (5957 kg ha^{-1}) followed by pendimethalin at 1000 g ha^{-1} (5822 kg ha^{-1}) which were statistically similar to weed free check (6004 kg ha^{-1}). Carfentrazone-ethyl at 20 g ha^{-1}, 2,4-D ester at 400 and 600 g ha^{-1}, 2,4-D amine at 500 and 750 g ha^{-1}, 2,4-D Na at 700 and 1000 g ha^{-1}, carfentrazone + metsulfuron at 25 g ha^{-1} and metribuzin at 210 g ha^{-1} also gave higher grain yields (5040 - 5682 kg ha^{-1}). However, these were lower than weed free treatment (6004 kg ha^{-1}) but higher than weedy check (4023 kg ha^{-1}).

All treatments were statistically at par with weed free treatment and provided significantly higher straw yield than weedy plot (4715 kg ha^{-1}) except metsulfuron-methyl at 4 g ha^{-1} (4922 kg ha^{-1}), mesosulfuron + iodosulfuron at 14.4 g ha^{-1} (4969 kg ha^{-1}) and sulfosulfuron + metsulfuron at 32 g ha^{-1} (5067 kg ha^{-1}) which were at par with weedy check. The highest straw yield (6263 kg ha^{-1}) was recorded with 2,4-D amine at 750 g ha^{-1}, while the lowest (4922 kg ha^{-1}) was obtained under metsulfuron-methyl at 4 g ha^{-1}. The highest biological yield (12155 kg ha^{-1}) was recorded with pendimethalin at 1500 g ha^{-1} followed by 2,4-D ester at 400 and 600 g ha^{-1} (11794 kg ha^{-1} and 11810 kg ha^{-1} respectively) and pendimethalin at 1000 g ha^{-1} (11993 kg ha^{-1}) which were at par with weed free check (12142 kg ha^{-1}). Moreover, the treatments of carfentrazone-ethyl at 20 g ha^{-1}, 2,4-D amine at 500 and 750 g ha^{-1}, 2,4-D Na at 700 and 1000 g ha^{-1} and carfentrazone + metsulfuron at 25 g ha^{-1} also provided higher biological yield (11176-11675 kg ha^{-1}). Trends in biological yield were in line with those of grain and straw yield.

Cost of cultivation

The weed free treatment recorded the highest gross returns; however, its total cost of production was also highest (₹100799 ha^{-1}), resulting in lower net returns (₹29150 ha^{-1}) and a benefit-cost ratio (1.29) compared to some more economically efficient

Table 3. Effect of different herbicidal treatments on yield attributes and yield of wheat crop (pooled data of 2017-18 and 2018-19)

Treatments	Dose (g ha^{-1})	Effective tillers (no. mrl^{-1})	No. of grains spike^{-1}	Spike length (cm)	1000-grain weight (g)	Grain yield (kg ha^{-1})	Straw yield (kg ha^{-1})	Biological yield (kg ha^{-1})
Metsulfuron-methyl	4	78.5	45.7	10.6	43.9	4220	4922	9142
Carfentrazone-ethyl	20	86.7	49.7	10.6	47.1	5363	6030	11393
2,4-D ester	400	90.3	52.0	10.4	46.5	5609	6185	11794
2,4-D ester	600	93.3	52.5	10.6	46.3	5682	6128	11810
2,4-D amine	500	91.2	47.7	10.5	46.8	5040	6136	11176
2,4-D amine	750	89.5	48.5	10.8	47.3	5213	6263	11475
2,4-D Na	700	88.8	50.2	10.7	46.0	5381	6034	11415
2,4-D Na	1000	90.3	51.2	10.9	46.4	5654	6020	11675
Carfentrazone + metsulfuron	25	88.7	50.0	10.5	44.7	5465	6151	11616
Mesosulfuron + iodosulfuron	14.4	79.8	47.8	11.0	43.8	4536	4969	9505
Sulfosulfuron + metsulfuron	32	83.2	46.8	10.8	44.5	4409	5067	9476
Pendimethalin	1000	93.5	52.3	11.0	45.3	5822	6171	11993
Pendimethalin	1500	94.8	52.8	11.1	45.6	5957	6198	12155
Metribuzin	175	81.7	48.7	11.2	45.9	4850	5848	10698
Metribuzin	210	85.2	49.5	11.3	46.0	5082	5663	10745
Weed free	-	96.0	53.8	10.7	46.1	6004	6138	12142
Weedy check	-	76.2	43.2	10.8	43.2	4023	4715	8738
CD (p=0.05)		6.1	4.3	NS	NS	313	366	398

Table 4. Effect of different herbicidal treatments on economics of wheat crop

Treatment	Dose (g ha^{-1})	Total cost of cultivation (₹ ha^{-1})	Net returns (₹ ha^{-1})	Benifit-cost ratio
Metsulfuron-methyl	4	89149	4428	1.05
Carfentrazone-ethyl	20	89424	28611	1.32
2,4-D ester	400	89303	33703	1.38
2,4-D ester	600	89555	34552	1.39
2,4-D amine	500	89339	23433	1.26
2,4-D amine	750	89759	26618	1.30
2,4-D Na	700	89237	29163	1.33
2,4-D Na	1000	89424	33774	1.38
Carfentrazone + metsulfuron	25	89674	30649	1.34
Mesosulfuron + iodosulfuron	14.4	90699	8725	1.10
Sulfosulfuron + metsulfuron	32	89799	7731	1.09
Pendimethalin	1000	90132	36663	1.41
Pendimethalin	1500	90799	38547	1.43
Metribuzin	175	88879	19430	1.22
Metribuzin	210	88895	22880	1.26
Weed free	-	100799	29150	1.29
Weedy check	-	88799	553	1.01

treatments. All treatments recorded higher net returns and benefit-cost ratio than weedy check (Table 4).

Pendimethalin at 1500 g ha^{-1} recorded the highest net returns (₹38547 ha^{-1}) and benefit-cost ratio (1.43) followed by pendimethalin at 1000 g ha^{-1} (₹36663, 1.41), 2,4-D ester at 600 g ha^{-1} (₹34552, 1.39), 2,4-D Na at 1000 g ha^{-1} (₹33774, 1.38), 2,4-D ester at 400 g ha^{-1} (₹33703, 1.38) and carfentrazone + metsulfuron at 25 g ha^{-1} (₹30649, 1.34). In contrast, the lowest net-return and B:C ratio was observed in metsulfuron-methyl at 4 g ha^{-1} (₹4428, 1.05) followed by sulfosulfuron + metsulfuron at 32 g ha^{-1} (₹7731, 1.09) and mesosulfuron + iodosulfuron at 14.4 g ha^{-1} (₹8725, 1.10).

Correlation study between *R. dentatus* and wheat crop

The correlation between the number of effective tillers of wheat crop and the density of *R. dentatus* was worked out, which were negatively correlated with each other having determination factor of 0.728 and 0.803 for the years 2017-18 and 2018-19 respectively (Fig. 3 A & B).

Similarly, the mathematical relationship between the grain yield of wheat crop and the dry matter accumulation of *R. dentatus* (Fig. 4A & B) revealed that grain yield was strongly and negatively correlated with the dry matter accumulation of *R. dentatus* having determination factor of 0.818 and 0.810 during 2017-18 and 2018-19 respectively.

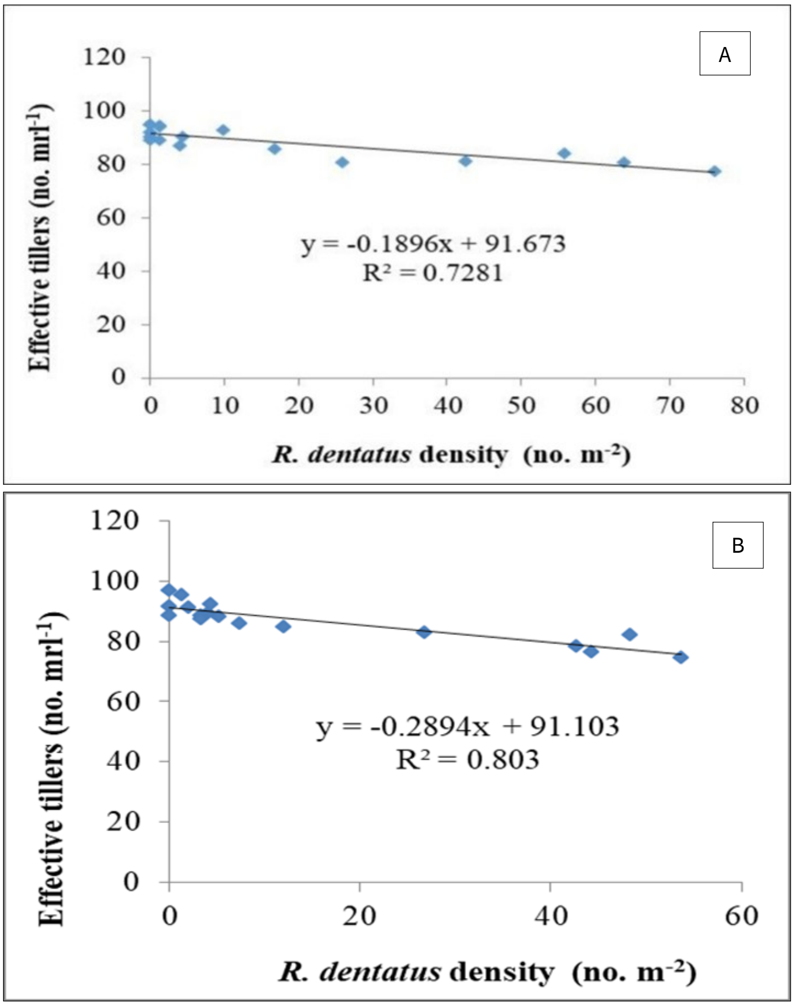

Fig. 3. Relationship between effective tillers of wheat crop and the *R. dentatus* density; (A) 2017-18, (B) 2018-19.

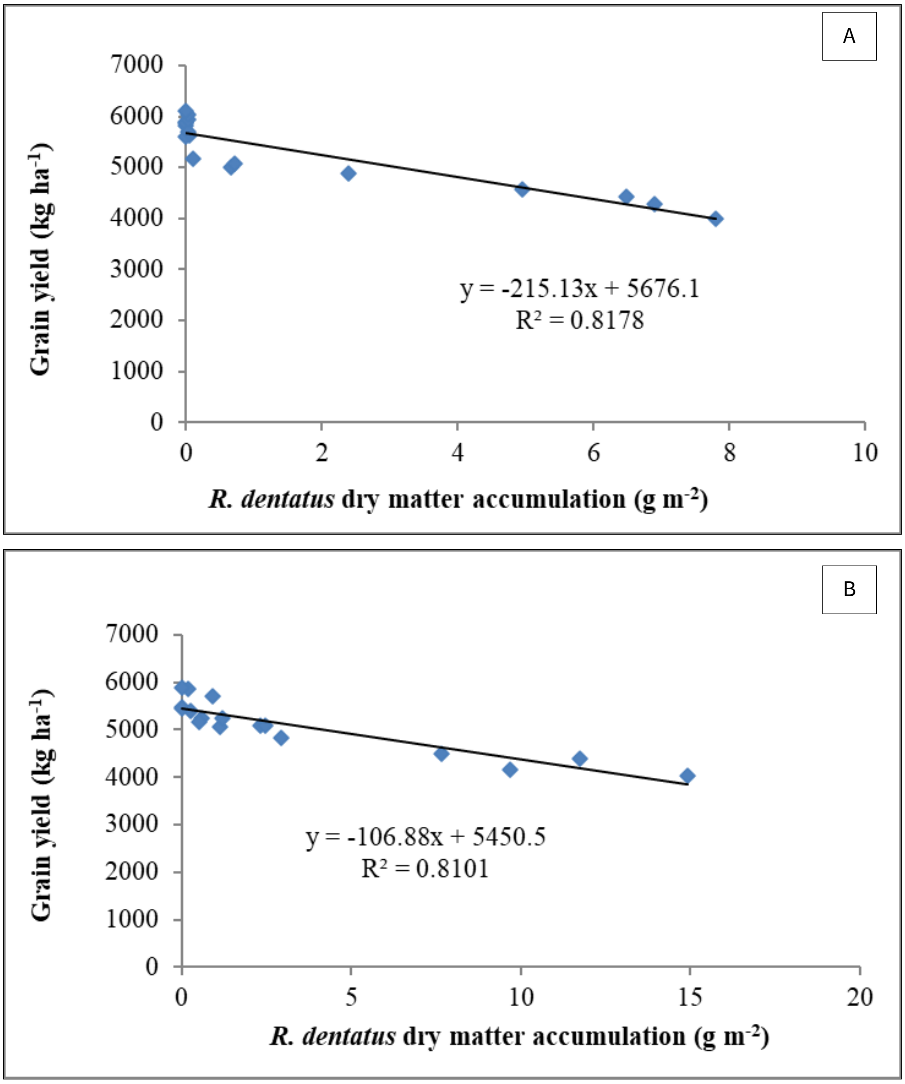

Fig. 4. Relationship between the grain yield of wheat crop and the *R. dentatus* dry matter accumulation during; (A) 2017-18, (B) 2018-19.

Discussion

In India, the rice-wheat system accounts for 26 % of total cereal production and 60 % of total calorie intake (15). However, sustainability issues such as declining factor productivity, crop residue burning and weed flora shift in wheat are halting its potential productivity. Besides these, evolutions of herbicide resistance against weeds like *P. minor* and *R. dentatus* in wheat are the factors governing its potential productivity (2, 16). Wheat is infested with diverse weed flora including *P. minor*, *R. dentatus, C. album* and *Avena ludoviciana* as it is cultivated under varied agro-climatic conditions (17). The types of tillage, rotation of crops, irrigation regimes and herbicides have significant effect on the weed flora type, species and severity of infestation (18).

The sole reliance on herbicides leads to development of herbicide resistance in weeds, irrespective of management regimes (19). In wheat, metsulfuron-methyl was highly effective against *R. dentatus* almost for the last 15 years in north-western India. But recently, resistance action of *R. dentatus* against metsulfuron-methyl (Group B/2 herbicides ALS inhibitors) has been reported in the Haryana and Punjab states of India (6, 8, 9, 19). It is second case of herbicide resistance in India and first among broadleaf weeds (12). The population of *R. dentatus* from KVK Panipat (Haryana), India has been found to be resistant against metsulfuron-methyl (ALS inhibitors), which had been recommended for its control in India in 1990s (8, 9). Therefore, the present study was conducted to account the herbicide resistance/poor efficacy of different herbicides against *R. dentatus* with known history of having defying action of metsulfuron-methyl against its biotype at KVK Panipat (Haryana), India during the Rabi seasons 2017-18 and 2018-19.

Current results showed that, pendimethalin (1000 and 1500 g ha^{-1}), carfentrazone + metsulfuron (25 g ha^{-1}), 2,4-D ester (400 and 600 g ha^{-1}), 2,4-D Na (700 and 1000 g ha^{-1}), 2,4-D amine (500 and 750 g ha^{-1}) and carfentrazone-ethyl (20 g ha^{-1}) provided effective control of *R. dentatus* with density (0.0-6.9 m^{-2}), dry weight (0.0 - 1.19 g m^{-2}) and WCE (91.3 - 100 %) at 60 DAS. While higher values for *R. dentatus* density (26.2-54.1 m^{-2}) were recorded with metribuzin (175 g ha^{-1}), mesosulfuron + iodosulfuron (14.4 g ha^{-1}), sulfosulfuron + metsulfuron (32 g ha^{-1}) and metsulfuron-methyl (4 g ha^{-1}). Similarly, higher dry matter (2.7 -9.11 g m^{-2}) and lower WCE (17.8 - 74.6 %) were recorded for metribuzin (175 g ha^{-1}), mesosulfuron + iodosulfuron (14.4 g ha^{-1}), sulfosulfuron + metsulfuron (32 g ha^{-1}) and metsulfuron-methyl (4 g ha^{-1}).

Among pre-emergence herbicides, pendimethalin (1000 and 1500 g ha^{-1}) provided excellent control of *R. dentatus*. Pendimethalin provided effective control of *R. dentatus* by inhibiting its germination at early stage in wheat (2, 20). Higher WCE of pendimethalin (0.75 and 1.0 kg ha^{-1}) and metribuzin (0.175 and 0.21 kg ha^{-1}) against *R. dentatus*, ranging from 98-100 % and 68 -92 % respectively, at 30 DAS in wheat, has been reported previously (21). However, in this study, comparatively lower bio-efficacy was recorded with metribuzin at 175 g ha^{-1} as compared to pendimethalin. Further, among post emergence herbicides, the efficacy of metsulfuron-methyl was very poor in terms of per cent control, dry matter reduction and WCE against *R. dentatus* as compared to 2,4-D ester/sodium salt, carfentrazone-ethyl and carfentrazone + metsulfuron. This might be due to the development of resistance in the *R. dentatus* population against metsulfuron-methyl, as well as the differential modes of action of the above-mentioned herbicides-synthetic auxins (growth regulators), protoporphyrinogen oxidase (PPO) inhibitors (involved in the chlorophyll biosynthesis pathway) and those with multiple modes of action (PPO and ALS inhibitors) respectively Similarly, lower bio-efficacy of metsulfuron-methyl was also reported at KVK, Panipat and at farmer's field in Kheri Raiwali (Kaithal) as the resistant biotypes were not controlled by its recommended dose or by the ready mixtures of sulfosulfuron + metsulfuron and mesosulfuron + iodosulfuron (8). However, the ready-mix of metsulfuron + carfentrazone was found effective against these resistant biotypes. Further, a high level of resistance was observed previously in pot bioassay study against metsulfuron-methyl even up to 4X dose (16 g ha^{-1}), which controlled only 30 % of *R. dentatus* population from KVK, Panipat. Whereas 2,4-D (600 g ha^{-1}) and carfentrazone-ethyl (20 g ha^{-1}) improved control to the tune of >87 % as compared to X dose of metsulfuron-methyl (4 g ha^{-1}) (9). Similarly, higher control (75 -100 %) of *R. dentatus* with 2,4-D ester (250 and 500 g ha^{-1}), carfentrazone-ethyl (20 g ha^{-1}) and carfentrazone + metsulfuron (20 + 4 g ha^{-1}) was recorded previously in a pot experiment (22).

During the present study, effective control of *R. dentatus* with pendimethalin (1000 and 1500 g ha^{-1}), carfentrazone + metsulfuron (25 g ha^{-1}), 2,4-D ester (400 and 600 g ha^{-1}), 2,4-D Na (700 and 1000 g ha^{-1}), 2,4-D amine (500 and 750 g ha^{-1}) and carfentrazone-ethyl (20 g ha^{-1}) lead to improved yield attributes i.e., effective tillers mrl^{-1} (86 -95), grains $spike^{-1}$ (48-53) and grain yield (5040 -5957 kg ha^{-1}) of wheat. While, lower values of yield attributes i.e., effective tillers mrl^{-1} (78.5, 79.8, 83.2, 81.7), grains $spike^{-1}$ (45.7, 47.8, 46.8, 48.7) and grain yields (4220, 4536, 4409, 4850 kg ha^{-1}) of wheat were recorded under metsulfuron-methyl at 4 g ha^{-1}, mesosulfuron + iodosulfuron at 14.4 g ha^{-1}, sulfosulfuron+metsulfuron at 32 g ha^{-1} and metribuzin at 175 g ha^{-1}.

The improvement in yield attributes (effective tillers, grains $spike^{-1}$), yields and economics of wheat crop for the treatments pendimethalin, carfentrazone-ethyl, 2,4-D ester/Na/amine salt and carfentrazone + metsulfuron might be attributed to higher mortality, lower density and dry matter accumulation of *R. dentatus* in these treatments and vice versa in case of metsulfuron-methyl, mesosulfuron + iodosulfuron and sulfosulfuron + metsulfuron. The decreasing trend in grains $spike^{-1}$ (from 55.0 to 23.0) with incremental increase in population of *R. dentatus* (from 0 to 30 *R. dentatus* plants m^{-2}) was also reported previously (11). Additionally, the loss in grain yield of wheat increased from 1.3 - 69.8 % with increasing *R. dentatus* density from 5 - 30 plants m^{-2}. This negative correlation between *R. dentatus* dry matter accumulation and grain yield of wheat crops was also observed in this study.

Similarly, metsulfuron-methyl provided very poor control (10-14 %) of resistant biotypes of *R. dentatus* with lower numbers of effective tillers (364 -398 tillers m^{-2}) and lower grain yield (4.27 - 4.67 t ha^{-1}) of wheat crop (23). In contrast, metsulfuron-methyl + carfentrazone-ethyl (5+20 g ha^{-1}), carfentrazone-ethyl (20 g ha^{-1}), 2,4-D Na (500 g ha^{-1}) and 2,4-D ester (750 g ha^{-1}) were found effective against these resistant biotypes and improved the toothed dock control to the tune of 85-100 % with significantly higher numbers of effective tillers (427-484 tillers m^{-2}) and higher grain yield (5.19 -5.67 t ha^{-1}) of wheat crop (23).

Conclusion

Metsulfuron-methyl (4 g ha^{-1}), mesosulfuron + iodosulfuron (14.4 g ha^{-1}) and sulfosulfuron + metsulfuron (32 g ha^{-1}) were ineffective against the Panipat biotype of *R. dentatus,* showing poor performance in terms of percent control, density, dry matter accumulation of *R. dentatus*, WCE, yield attributes, yield and economics returns of wheat. In contrast, pendimethalin (1000 and 1500 g ha^{-1}) as pre emergence herbicide and 2,4-D ester (400 and 600 g ha^{-1}), 2,4-D Na (1000 g ha^{-1}), carfentrazone + metsulfuron (25 g ha^{-1}), carfentrazone-ethyl (20 g ha^{-1}) as post emergence herbicides effectively controlled ALS resistant biotype of *R. dentatus*. These alternative herbicide options identified in this study can help delay the development of cross- or multiple-herbicide resistance in *R. dentatus*. However, integrated weed management approach based upon herbicide rotation with different modes of action, crop sanitation measures, weed seed harvest to prevent weed seed bank enrichment and proper spray techniques should be adopted to delay herbicide resistance and restrict its spread. Further, farmer field surveys and field demonstrations should also be conducted for knowing real field situation and creating awareness among farmers about application of recommended dose of herbicides, with right spray nozzle, at right time with rotation of herbicides on yearly basis.

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Authors' contributions

The study was conceptualized and designed by DBY, SD[1] and AC. Material preparation, data collection and analysis were performed by SD[1], DBY, AC, RG, MS and SS. The original draft of the manuscript was written by SD[1] and AC. Validation, review and final editing were carried out by AC, DBY, RG and SD[2]. All authors read and approved the final manuscript. (SD[1] stands for Seema Dahiya and SD[2] for Sachin Dhanda)

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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