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RESEARCH ARTICLE

Wheat growth and physiological response and management of herbicide resistant *Phalaris minor* Retz. as affected by selective herbicides

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ABSTRACT

Weeds are a major constraint of wheat productivity improvement in India. Among the major weeds, *Phalaris minor* Retz. is the most problematic weed that mimics wheat. Herbicides are mostly used by farmers to manage weeds in wheat and dependency on single herbicide or herbicides with same mode of action resulted in the development of multiple herbicide-resistance in *P. minor*. A field study was conducted at CCS Haryana Agricultural University, Hisar during 2016-17 and 2019-20 with an objective to study the growth and physiological response of wheat and management of herbicide-resistant *P. minor* with selective herbicides in wheat. The sequential application of tank-mix (TM) pre-emergence application (PE) of pendimethalin + pyroxasulfone (1500 + 102 g/ha) or pendimethalin + metribuzin (1000 + 175 g/ha) followed by post-emergence application (PoE) of pinoxaden 60 g/ha or mesosulfuron + iodosulfuron 14.4 g/ha resulted in complete control of herbicide- resistant *P. minor* and other broad-leaved weeds (BLW). The better control of weeds resulted in higher wheat leaf area index (LAI) and crop growth rate (CGR) with 43-46% higher wheat grain yield over the weedy check. However, 0-9% visual toxicity on the crop was observed in metribuzin-associated treatments, which was nullified with the advancement of crop stage. The maximum marginal benefit was observed in weed-free check (39,192 ₹/ha) closely followed by pendimethalin + pyroxasulfone (TM) PE *fb* mesosulfuron + iodosulfuron PoE, while marginal benefit-cost ratio (MBCR) was highest with mesosulfuron + iodosulfuron (17.8) PoE followed by pinoxaden + metribuzin (50+150 g/ha) PoE. It was concluded that sequential application of PE followed by PoE herbicide with a rotational application of herbicides having different mode of action is suitable for management of herbicide-resistant *P. minor* in wheat.

Keywords: Herbicide-resistance, *Phalaris minor*, Physiology, Weed management, Wheat

INTRODUCTION

Wheat (*Triticum aestivum* L.) is the second most important food grain crop after rice in India with an area of 31.4 Mha with production of 107.9 MT and average productivity of 3440 kg/ha (INDIASTAT 2022a). Haryana is one of the major wheat-growing states of India, comprising an 8% wheat area, 12.3% share in national wheat production having a productivity of 4687 kg/ha (INDIASTAT 2022b). The rice-wheat cropping system has possessed diverse weed flora, which if not managed during the critical crop growth period, results in wheat crop yield reduction of 15-40% or even higher (Soni *et al.* 2021). Among all weeds, *Phalaris minor* Retz. (littleseed canarygrass) is the most problematic annual grassy weed which mimics the wheat crop.

Herbicide-resistant *P. minor* was found susceptible to pre-emergence (PE) herbicides (Dhawan *et al.* 2012) but is not enough to control all weeds and their cohorts. One of the best ways to manage resistance in *P. minor* is the use of herbicides with different modes of action (MOAs) in a sequential application of pre-emergence (PE) herbicide followed by post-emergence (PoE) (Dhawan *et al.* 2012). However, some herbicides like metribuzin and their combinations were found phytotoxic to the wheat crop (Punia *et al.* 2017b) with crop recovery in time. Thus, an experiment was conducted to study growth and physiological response of wheat against selective herbicides while assessing their efficacy in managing herbicide-resistant *P. minor* in wheat.

MATERIALS AND METHODS

A field experiment was conducted at Agronomy Research Farm, CCS HAU, Hisar (29°8’56.62"N latitude and 75°41’4.24"E longitude) in *Rabi* (winter) season 2016-17 and 2019-20. This field has a history of poor control of *P. minor* with clodinafop. There

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were 16 treatments, *viz*. pendimethalin 1500 g/ha PE, metribuzin 210 g/ha PE, pendimethalin + metribuzin tank mix (TM) 1500 + 175 g/ha PE, pendimethalin + metribuzin (TM) 1000 + 175 g/ha PE followed by (*fb*) pinoxaden (60 g/ha) PoE, pendimethalin + metribuzin (TM) 1000 + 175 g/ha PE *fb* mesosulfuron + iodosulfuron ready mix (RM) 14.4 g/ha PoE, pendimethalin + pyroxasulfone (TM) 1500 + 102 g/ha PE, pendimethalin + pyroxasulfone TM 1500 + 102 g/ha PE *fb* pinoxaden 60 g/ha PoE, pendimethalin + pyroxasulfone (TM) 1500 + 102 g/ha PE *fb* mesosulfuron + iodosulfuron (RM) 14.4 g/ha PoE, pendimethalin + metribuzin (TM) 1500 + 175 g/ha pre-sowing application (PS) *fb* pinoxaden 60 g/ha PoE, pre-irrigation (PI) application of sulfosulfuron 25 g/ha PoE *fb* pinoxaden 60 g/ha PoE, pinoxaden 60 g/ha PoE, pinoxaden + metribuzin (TM) 50+120 g/ha PoE, pinoxaden + metribuzin (TM) 50+150 g/ha PoE, mesosulfuron + iodosulfuron (RM) 14.4 g/ha PoE, weed free and weedy check. A randomized block design (RBD) with three replications was used. Each plot size was 6 × 6 m. PE herbicides were sprayed just after sowing of wheat seeds, and PoE were applied at 35 days after sowing (DAS) of wheat and PI at 18 DAS. The hand weeding was done in weed-free whenever required in crop season and no weed management was done in weedy check.

The data on crop visual phytotoxicity of herbicides (%) was recorded at 15 and 45 DAS on a 0-100 scale (0 mean no mortality and 100 indicates complete crop failure). Leaf area index (LAI) was estimated at 90 and 120 DAS. Crop growth rate (CGR; g/m^2/day) was estimated at 30 days interval between 30-60, 60-90 and 90-120 DAS by using formula given below:

$$CGR = \frac{W_2 - W_1}{P\ (t_2 - t_1)}$$

Where, W_2 and W_1 are the dry weight of the crop at time t_2 and t_1, respectively and P is the ground area occupied by the plant in m^2.

The membrane injury to crop by herbicide and biotic stress measured as per cent proportion of ions leakage into an aqueous solution to total ions concentration of the stressed tissue as measured by electrical conductivity (EC) of the external medium. Sample of 200 mg of fresh leaf was kept in 20 ml test tube containing 10 ml distilled water for 5 hr at 27^{0}C. Then EC of this aqueous solution was measured by EC meter and represented as EC_1. Then same samples were kept in water bath at 100^{0}C for 50 min. After cooling, EC of solution was again measured and represented as EC_2. It was recorded at 60 and 90 DAS.

$$\text{Membrane injury index (MII) (\%)} = \frac{EC_1}{EC_2} \times 100$$

$$\text{Membrane stability index (MSI) (\%)} = \left(1 - \frac{EC_1}{EC_2}\right) \times 100$$

Total chlorophyll content (mg/g fresh weight) was estimated at 60 and 90 DAS. Sample of 50 mg of freshly harvested leaf tissue was placed in a test tube containing 5 ml of dimethyl sulfoxide (DMSO) at room temperature overnight till the tissue became colourless. The extracted chlorophyll in DMSO was assessed by recording its absorbance at the wavelength of 663 and 645 nm, respectively on Eppendorf BioSpectrometer® basic. DMSO was used as blank. It was calculated from the formula suggested by Hiscox and Israelstam 1979.

$$\text{Total Chlorophyll} = (20.2\ A_{645} + 8.02\ A_{663}) \times \text{dilution factor}$$

$$\text{Dilution factor} = \frac{V}{W \times 1000}$$

Where, V is volume of extract (ml) and W is fresh weight (FW) of sample (g)

Visual control of weeds (*P. minor* and broad-leaved weeds) was recorded 30, 90 and 120 DAS. It was evaluated on 0-100 per cent scale (0 means no control and 100 indicate complete control of weeds). The data of visual control from each treatment was estimated by comparing with the weedy check (control). Dry weight of weeds (biomass) was taken at 90 DAS from four randomly selected places from each plot using a quadrat. Individual weeds were first sundried followed by oven dried at 65±5 ^{0}C till a constant weight was achieved and finally biomass was expressed as g/m^2. The wheat grain yield (t/ha) was measured from net plot area using standard procedures. Marginal benefit-cost ratio (MBCR) was calculated by dividing marginal benefit to marginal cost incurred from different treatments over control (unweeded check).

$$MBCR = \frac{\text{Marginal benefit due to treatment over control (₹/ha)}}{\text{Marginal cost due to treatment over control (₹/ha)}}$$

The data were subjected to statistical analysis by Analysis of Variance (ANOVA) using OPSTAT software (Sheoran *et al*. 1998). The response of different treatments was similar during both the years and followed the homogeneity test; data were pooled for statistical analysis. The significance of the different treatment effects was tested with help of "F" (variance) test, least significant difference (LSD) was tested at 5% level of significance.

RESULTS AND DISCUSSION

Effect on wheat morpho-physiology

The metribuzin, as a component of herbicide combinations tested, caused visual phytotoxicity ranging from 5-9% at 15 DAS and 1.5-5.5% at 45 DAS (**Table 1**). Metribuzin PE caused higher visual phytotoxicity than TM combination with other herbicides and with the advancement of crop growth stage, visual symptoms on crop phytotoxicity got recovered as observed by Punia *et al*. (2017a). Significantly higher LAI of 5.03 and 3.12 at 90 and 120 DAS was recorded in weed-free check. This was at par with TM pendimethalin + pyroxasulfone PE *fb* mesosulfuron + iodosulfuron PoE in both the stages and it was statistically similar with most of the treatments except a few treatments including sole applied PE herbicides and its TM combinations. The effective weed control by sequentially applied herbicides resulted in the least crop weed competition producing more healthy leaves leading to higher LAI value (Sattar *et al*. 2010). CGR is the measure of dry matter accumulation by crop per unit leaf area per unit time. The CGR was low in the beginning, increased up to 90 DAS and decreased thereafter in all treatments. The significantly highest CGR value of 7.97, 24.73 and 15.46 g/m^2/day during 30-60, 60-90 and 90-120 DAS intervals, respectively was obtained in TM pendimethalin + pyroxasulfone (PE) *fb* mesosulfuron + iodosulfuron PoE, which were statistically similar to weed-free check. Lower CGR was observed in herbicides applied alone either as PE or PoE, when compared to their sequential application. The broad-spectrum weed control by sequentially applied herbicides helped in better crop growth, leading to higher dry matter accumulation and CGR. Similar findings were reported by Yadav and Choudhary (2015).

Ion's leakage from leaves was calculated as MII and MSI. Membrane injury index (MII) increased gradually from 60 to 90 DAS (**Table 1**). At 60 DAS, TM pendimethalin + pyroxasulfone PE *fb* pinoxaden PoE recorded significantly highest MII (66.8%). At 90 DAS, sulfosulfuron PI *fb* pinoxaden PoE recorded significantly higher MII (82.9%) that was statistically similar to almost all the treatments having pinoxaden and/or pyroxasulfone as a component herbicide. Whereas, significantly lowest MII was recorded in weed-free check (69.7%) at par with almost all PE treatments. The reverse was true for MSI. Stress caused by weed infestation and herbicide application with sequential application of higher dose of herbicides led to an increase in MII (Sairam *et al*. 2001). However, it declined with the advancement of crop age, while, stress-induced by weed infestation increased with an increase in weed density and dry biomass. The average increase in MII due to weeds infestation in weedy check was 21.1 and 13.5% higher than weed-free check at 60 and 90 DAS, respectively. Dhawan *et al.* (2010a) also stated that

Table 1. Effect of different treatments on physiological response of wheat crop at different growth stages (pooled data of two years)

Treatment	Phytotoxicity (%)		LAI		CGR (g/m^2/day)			MII (%)		MSI (%)		Total chlorophyll (mg/g FW)	
	15 DAS	45 DAS	90 DAS	120 DAS	30-60 DAS	60-90 DAS	90-120 DAS	60 DAS	90 DAS	60 DAS	90 DAS	60 DAS	90 DAS
Pendimethalin 1500 g/ha PE	0	0	4.42	2.78	6.71	20.93	11.78	56.9	70.2	43.1	29.8	2.60	2.73
Metribuzin 210 g/ha PE	9	4	4.30	2.69	6.44	20.38	11.82	58.7	72.3	41.3	27.7	2.57	2.63
Pendimethalin + metribuzin 1500 + 175 g/ha PE	7	2	4.47	2.82	7.14	21.93	12.68	54.8	73.8	45.2	26.2	2.92	2.92
Pendimethalin + metribuzin 1000 + 175 g/ha PE *fb* pinoxaden 60 g/ha PoE	5	1.5	4.55	2.93	7.18	22.49	12.90	54.3	73.6	45.7	26.4	2.84	3.00
Pendimethalin + metribuzin 1000 + 175 g/ha PE *fb* mesosulfuron + iodosulfuron 14.4 g/ha PoE	5	1.5	4.79	3.11	6.74	23.54	13.99	51.6	80.1	48.4	19.9	3.13	3.42
Pendimethalin + pyroxasulfone 1500+102 g/ha	0	0	4.50	2.92	6.85	21.79	12.84	66.6	79.8	33.4	20.2	2.90	2.83
Pendimethalin + pyroxasulfone 1500+102 g/ha PE *fb* pinoxaden 60 g/ha PoE	0	0	4.85	2.96	7.58	23.23	12.97	66.8	79.6	33.2	20.4	3.04	3.14
Pendimethalin + pyroxasulfone 1500+102 g/ha PE *fb* mesosulfuron + iodosulfuron 14.4 g/ha PoE	0	0	4.97	3.11	7.97	24.73	15.40	56.1	77.3	43.9	22.7	2.93	3.03
Pendimethalin + metribuzin 1500 + 175 g/ha PS *fb* pinoxaden 60 g/ha PoE	8	4	4.62	2.91	6.79	22.40	12.91	62.3	78.0	37.7	22.0	2.64	2.63
Sulfosulfuron PI 25 g/ha *fb* pinoxaden 60 g/ha PoE	0	0	4.75	3.04	6.89	22.37	13.73	66.2	82.9	33.8	17.1	2.77	2.84
Pinoxaden 60 g/ha PoE	0	0	4.51	2.87	6.78	21.37	12.54	60.2	79.2	39.8	20.8	2.33	2.67
Pinoxaden + metribuzin 50+120 g/ha PoE	0	4.5	4.69	2.96	7.06	20.53	12.87	60.9	75.9	39.1	24.1	2.24	2.19
Pinoxaden + metribuzin 50+150 g/ha PoE	0	5.5	4.66	2.98	7.21	20.76	13.00	62.7	81.4	37.3	18.6	2.62	2.70
Mesosulfuron + iodosulfuron 14.4 g/ha PoE	0	0	4.79	3.05	7.14	21.07	13.20	54.7	78.1	45.3	21.9	2.76	2.97
Weed-free check	0	0	5.03	3.12	7.71	24.55	15.46	46.9	69.7	53.1	30.3	3.02	3.10
Weedy check	0	0	4.06	2.57	6.26	19.38	10.45	56.8	79.1	43.2	20.9	2.29	2.50
LSD (p=0.05)	-	-	0.37	0.21	1.02	2.03	2.57	9.1	5.9	9.1	5.9	0.61	NS

PE = pre-emergence, PoE = post-emergence, PS = prior to sowing and PI = prior to irrigation, TM = tank mixed, RM = ready mix, LAI = Leaf area index, CGR = Crop growth rate, MII = Membrane injury index, MSI = Membrane stability index ions leakage from leaves after herbicide spray was relatively higher than unsprayed leaves and higher in ACCase herbicides. None of the treatments tested had a significant effect on total chlorophyll content of wheat at 90 DAS. Higher chlorophyll values were recorded in weed-free check followed by herbicidal treatments, whereas, lower value was recorded in weedy check and pinoxaden + metribuzin PoE. In spite of selectivity of herbicides to wheat, some of the herbicides may reduce the chlorophyll and carotenoids of wheat (Agostinetto *et al.* 2016). The decrease in chlorophyll content by different herbicides in wheat for a limited time was reported (Dhawan *et al.* 2010b, Kaur *et al.* 2016, Prinsa *et al.* 2018).

Effect on weeds

Visual control of weed (*P. minor* and BLW) was recorded at 30, 90 and 120 DAS on a 0-100 scale (**Table 2**). Pendimethalin and metribuzin PE, applied alone caused <80% control of *P. minor* at 30 DAS while tank-mixed (TM) application of pendimethalin with metribuzin or pyroxasulfone PE resulted in increased *P. minor* control efficiency up to 91%. The efficacy of pendimethalin + pyroxasulfone TM PE was better than pendimethalin + metribuzin (TM) PE. At 90 and 120 DAS, pendimethalin + metribuzin (TM) PE resulted in <70% control while its sequential application with pinoxaden or mesosulfuron + iodosulfuron PoE resulted in 90-93 and 100% control of *P. minor*, respectively. Similarly, pendimethalin + pyroxasulfone (TM) PE recorded <85% and its sequential application with pinoxaden or mesosulfuron + iodosulfuron PoE resulted in nearly complete control of *P. minor*. At 30 DAS, visual control of BLW indicated that pendimethalin, metribuzin, TM pendimethalin + pyroxasulfone PE and sulfosulfuron PI recorded 68, 63, 65-68 and 56% control, respectively. Whereas, pendimethalin + metribuzin (TM) PE at different doses resulted in 82-85% control of BLW. At 90 and 120 DAS, pendimethalin + metribuzin (TM) (PE) *fb* mesosulfuron + iodosulfuron PoE and pendimethalin + pyroxasulfone (TM) (PE) *fb* mesosulfuron + iodosulfuron PoE caused complete control of BLW. Similarly, maximum reduction in *P. minor* biomass (complete control) was caused by pendimethalin + pyroxasulfone PE *fb* mesosulfuron + iodosulfuron or pinoxaden PoE. Concerning BLW, among herbicidal treatments significant reduction in biomass accumulation was recorded under pendimethalin + pyroxasulfone (TM) (PE) *fb* mesosulfuron + iodosulfuron PoE (96.6%). Yadav *et al.* (2016) reported that sequential application of pendimethalin with PoE herbicides could effectively control weeds. Pinoxaden provided 90-100% control of resistant *P.*

Table 2. Effect of different treatments on visual control of weeds at different stages and their dry matter production at 90 DAS (pooled data of two years)

Treatment	*P. minor* (%)			BLW (%)			*P. minor* biomass (g/m^2)	BLW biomass (g/m^2)
	30 DAS	90 DAS	120 DAS	30 DAS	90 DAS	120 DAS	90 DAS	90 DAS
Pendimethalin 1500 g/ha PE	77	55	55	68	70	70	5.1(24.6)	2.8(6.7)
Metribuzin 210 g/ha PE	65	43	40	63	52	50	5.8(32.4)	3.6(11.9)
Pendimethalin + metribuzin 1500 + 175 g/ha PE	85	68	68	85	77	75	4.0(15.0)	2.3(4.3)
Pendimethalin + metribuzin 1000 + 175 g/ha PE *fb* pinoxaden 60 g/ha PoE	80	93	90	82	70	75	2.0(2.9)	2.6(5.8)
Pendimethalin + metribuzin 1000 + 175 g/ha PE *fb* mesosulfuron + iodosulfuron 14.4 g/ha PoE	81	100	100	84	100	100	1.4(0.8)	1.3(0.6)
Pendimethalin + pyroxasulfone 1500+102 g/ha	91	85	83	68	70	77	2.6(5.9)	2.9(7.5)
Pendimethalin + pyroxasulfone 1500+102 g/ha PE *fb* pinoxaden 60 g/ha PoE	89	100	99	69	72	77	1.2(0.4)	2.7(6.4)
Pendimethalin + pyroxasulfone 1500+102 g/ha PE *fb* mesosulfuron + iodosulfuron 14.4 g/ha PoE	90	100	100	65	100	100	1.0(0.0)	1.2(0.5)
Pendimethalin + metribuzin 1500 + 175 g/ha PS *fb* pinoxaden 60 g/ha PoE	80	95	96	86	70	75	1.7(1.8)	2.8(7.2)
Sulfosulfuron PI 25 g/ha *fb* pinoxaden 60 g/ha PoE	46	88	94	56	81	86	1.4(0.9)	2.6(5.8)
Pinoxaden 60 g/ha PoE	0	77	72	0	22	25	1.9(2.7)	4.2(16.4)
Pinoxaden + metribuzin 50+120 g/ha PoE	0	83	80	0	83	89	2.0(3.0)	2.3(4.5)
Pinoxaden + metribuzin 50+150 g/ha PoE	0	86	83	0	90	93	1.9(2.5)	2.0(3.0)
Mesosulfuron + iodosulfuron 14.4 g/ha PoE	0	90	91	0	93	95	1.7(1.8)	1.8(2.4)
Weed-free check	100	100	100	100	100	100	1.0(0.0)	1.0(0.0)
Weedy check	0	0	0	0	0	0	6.8(45.5)	4.8(21.7)
LSD (p=0.05)							0.3	0.3

PE: pre-emergence, PoE: post-emergence, PS: prior to sowing and PI : prior to irrigation, TM: tank mixed, RM: ready mix, BLW: Broad-leaved weeds; Data given in parentheses are original values, and outside are square-root transformed value *minor* population (Singh *et al*. 2010) and pyroxasulfone best suited against grassy weeds including resistant grassy weeds (Walsh *et al.* 2011). Punia *et al*. (2018) observed only <35% control of *P. minor* by pendimethalin or metribuzin PE, and their combination could not control second and further flushes of weeds.

Effect on wheat yield

The highest grain and biological yield were recorded in weed-free which was statistically at par with pendimethalin + pyroxasulfone (TM) PE *fb* mesosulfuron + iodosulfuron PoE, pendimethalin + metribuzin (TM) PE *fb* mesosulfuron + iodosulfuron PoE and mesosulfuron + iodosulfuron PoE and least in weedy check during both the years (**Table 3**). The beneficial effect of herbicide mixture and their sequential application for management of resistant *P. minor* and higher grain and biological yield comparable to weed-free have was reported by Yadav *et al*. (2016), Punia *et al*. (2020) and Soni *et al*. (2021).

Marginal benefit-cost ratio (MBCR)

The higher marginal benefit was recorded in weed-free (39,192 ₹/ha) which was closely followed by pendimethalin + pyroxasulfone (TM) PE *fb*

Table 3. Effect of different treatments on grain and biological yield

Treatment	Grain yield (t/ha)			Biological yield (t/ha)		
	2016-17	2019-20	Pooled	2016-17	2019-20	Pooled
Pendimethalin 1500 g/ha PE	4.98	4.47	4.72	10.60	9.67	10.13
Metribuzin 210 g/ha PE	4.58	4.27	4.43	10.15	9.39	9.77
Pendimethalin + metribuzin 1500 + 175 g/ha PE	5.28	4.74	5.01	11.30	10.28	10.79
Pendimethalin + metribuzin 1000 + 175 g/ha PE *fb* pinoxaden 60 g/ha PoE	5.56	4.93	5.25	11.89	10.57	11.23
Pendimethalin + metribuzin 1000 + 175 g/ha PE *fb* mesosulfuron + iodosulfuron 14.4 g/ha PoE	6.15	5.37	5.76	12.80	11.22	12.01
Pendimethalin + pyroxasulfone 1500+102 g/ha	5.09	4.58	4.84	10.78	9.70	10.24
Pendimethalin + pyroxasulfone 1500+102 g/ha PE *fb* pinoxaden 60 g/ha PoE	5.78	5.13	5.45	12.14	10.87	11.50
Pendimethalin + pyroxasulfone 1500+102 g/ha PE *fb* mesosulfuron + iodosulfuron 14.4 g/ha PoE	6.28	5.45	5.87	13.09	11.36	12.22
Pendimethalin + metribuzin 1500 + 175 g/ha PS *fb* pinoxaden 60 g/ha PoE	5.43	4.98	5.20	11.44	10.53	10.98
Sulfosulfuron PI 25 g/ha *fb* pinoxaden 60 g/ha PoE	5.76	5.01	5.39	12.07	10.59	11.33
Pinoxaden 60 g/ha PoE	5.31	4.64	4.97	11.29	9.96	10.63
Pinoxaden + metribuzin 50+120 g/ha PoE	5.63	4.91	5.27	12.13	10.80	11.60
Pinoxaden + metribuzin 50+150 g/ha PoE	5.71	5.16	5.44	12.26	11.14	11.70
Mesosulfuron + iodosulfuron 14.4 g/ha PoE	5.93	5.26	5.59	12.61	11.24	11.93
Weed-free check	6.32	5.57	5.95	13.13	11.58	12.36
Weedy check	4.14	3.91	4.02	9.26	8.76	9.01
LSD (p=0.05)	0.45	0.41	0.40	1.04	0.88	0.89

PE: pre-emergence, PoE: post-emergence, PS: prior to sowing and PI: prior to irrigation, TM: tank mixed, RM: ready mix, BLWs: Broad-leaved weeds; Data given in parentheses are original values, and outside are square-root transformed value

Table 4. Effect of different weed control treatments on marginal-benefit, cost and marginal BC ratio of wheat (pooled data of two years)

Treatment	Marginal benefit (₹/ha)	Marginal cost (₹/ha)	Marginal benefit-cost ratio
Pendimethalin 1500 g/ha PE	13,861	1,900	7.4
Metribuzin 210 g/ha PE	8,462	1,063	8.0
Pendimethalin + metribuzin 1500 + 175 g/ha PE	20,402	2,494	8.2
Pendimethalin + metribuzin 1000 + 175 g/ha PE *fb* pinoxaden 60 g/ha PoE	25,231	4,312	5.9
Pendimethalin + metribuzin 1000 + 175 g/ha PE *fb* mesosulfuron + iodosulfuron 14.4 g/ha PoE	35,272	3,839	9.3
Pendimethalin + pyroxasulfone 1500+102 g/ha	15,802	3,900	4.1
Pendimethalin + pyroxasulfone 1500+102 g/ha PE *fb* pinoxaden 60 g/ha PoE	29,185	6,035	4.9
Pendimethalin + pyroxasulfone 1500+102 g/ha PE *fb* mesosulfuron + iodosulfuron 14.4 g/ha PoE	37,478	5,562	6.8
Pendimethalin + metribuzin 1500 + 175 g/ha PS *fb* pinoxaden 60 g/ha PoE	23,902	4,829	5.0
Sulfosulfuron PI 25 g/ha *fb* pinoxaden 60 g/ha PoE	27,474	3,302	8.4
Pinoxaden 60 g/ha PoE	19,058	2,335	8.2
Pinoxaden + metribuzin 50+120 g/ha PoE	26,484	2,412	11.1
Pinoxaden + metribuzin 50+150 g/ha PoE	29,841	2,513	11.9
Mesosulfuron + iodosulfuron 14.4 g/ha PoE	32,767	1,862	17.8
Weed-free check	39,192	22,750	1.8
Weedy check	-	-	-

PE: pre-emergence, PoE: post-emergence, PS: prior to sowing and PI: prior to irrigation, TM: tank mixed, RM: ready mix mesosulfuron + iodosulfuron PoE and pendimethalin + metribuzin (TM) PE *fb* mesosulfuron + iodosulfuron PoE (**Table 4**). While, higher marginal cost was with weed-free check (22,750 ₹/ha) followed by TM pendimethalin + pyroxasulfone PE *fb* pinoxaden PoE. MBCR was observed higher in mesosulfuron + iodosulfuron PoE (17.8) followed by pinoxaden + metribuzin PoE (50+150 g/ha). Whereas, the lowest MBCR was obtained in weedy free (1.8). Increase in MBCR due to sequential application of pre- and post-emergence herbicide has been reported by Khatri *et al*. (2020).

It was concluded that sequential application of tank-mixed pendimethalin + pyroxasulfone PE (or) pendimethalin + metribuzin PE *fb* pinoxaden (or) mesosulfuron + iodosulfuron PoE results in complete control of herbicide-resistant *P. minor* and BLW (except in pinoxaden) at all the wheat growth stages. It is advised to follow the rotation of herbicides of different mode of action, along with their sequential application for sustainable management of herbicide-resistant *P. minor* in wheat.

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