PLANT SCIENCE TODAY
ISSN 2348-1900 (online)
Vol 12(2): 1-6
https://doi.org/10.14719/pst.7233

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RESEARCH ARTICLE

Impact of planting patterns and weed control treatments on weed dynamics, growth and yield of transplanted rice under unpuddled and puddled conditions

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OPEN ACCESS

ARTICLE HISTORY
Received: 16 January 2025
Accepted: 18 March 2025
Available online
Version 1.0 : 30 April 2025
Version 2.0 : 09 May 2025

Check for updates

Additional information
Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

CITE THIS ARTICLE
Chandra GS, Walia US, Singh R. Impact of planting patterns and weed control treatments on weed dynamics, growth and yield of transplanted rice under unpuddled and puddled conditions. Plant Science Today. 2025; 12(2): 1-6. https://doi.org/10.14719/pst.7233

Abstract

Rice cultivation faces a major biotic challenge from weeds, which compete aggressively with the crop, hampering its growth and yield potential. Puddling operations in transplanted rice helps to supress weeds. However, the physico-chemical properties of soil are deteriorated with this practice. A field study was conducted for two years in Punjab, India during the *kharif* seasons of 2023 and 2024 to evaluate the weed dynamics, growth and yield of unpuddled transplanted rice under varying planting patterns and weed control treatments. The research was carried out in split plot design comprising of four planting patterns *viz.* two rows/ridge, two rows/ridge and one in furrow, flat (unpuddled), flat (puddled) in main plots and four weed control treatments, *viz.* pendimethalin 0.75 kg ha^{-1} as pre-em. *fb* bispyribac sodium 10 SC at 25 g/ha as post-em., pendimethalin 0.75 kg ha^{-1} as pre-em. *fb* penoxsulam 240 SC at 24 g ha^{-1} as post-em., pendimethalin 0.75 kg ha^{-1} as pre-em. *fb* fenoxaprop 6.7 EC at 67 g ha^{-1} as post-em. and unweeded (control) in sub-plots, with four replicates. The findings revealed that transplanting two rows per ridge and one in furrow significantly increased the paddy yield, with significant reduction in weed density and biomass in comparison to other planting patterns. Meanwhile, yields from flat unpuddled and flat puddled transplanting were found to be statistically similar. Among weed control treatments, the application of pendimethalin 0.75 kg ha^{-1} as pre-em. *fb* bispyribac 10 SC at 25 g ha^{-1} as post-em. effectively suppressed the population and biomass of weeds including grasses, sedges and broad-leaved weeds, as compared to all other weed control treatments.

Keywords

paddy yield; planting patterns; unpuddled rice cultivation; weed control treatments; weed dynamics

Introduction

Rice (*Oryza sativa* L.) is a globally significant cereal crop that serves as the primary staple food for over half of the global community. It is cultivated extensively across the globe, especially in Asian countries which contribute 90 % of its production and consumption, playing a crucial role in food security, income generation and sustaining livelihoods. During 2022-2023, rice cultivation in Punjab spanned 31.68 lakh hectares, producing a total of 205.24 lakh tonnes of paddy (137.51 lakh tonnes of rice) with an average paddy yield of 64.79 quintals per hectare (1). In India, the traditional method of rice cultivation involves transplanting about 30 days old seedlings into puddled soil. This practice is widely adopted for decades due to its ability to enhance water retention, suppress weeds and ensure reliable crop establishment but it is challenging practice due to its labour-intensive, costly and time-consuming nature (2). Moreover, puddling disrupts the soil's natural structure by destroying aggregates and macropores, which results in compacted soil, poor permeability and the development of a hard plough pan in the sub-surface layer that may adversely affect subsequent rotational crops like wheat (3). Although Direct Seeded Rice (DSR) has the potential to enhance the performance of rotational crops, it faces several challenges in the production system, including severe weed infestations, nutrient imbalances such as zinc deficiency (4). Unpuddled transplanted rice stands out as sustainable alternative, addressing major production challenges while minimizing production expenses. This practice is immensely helpful for improving soil physical properties. Conservation agriculture practices associated with this method reduce water consumption, enhance productivity and improve soil physical properties compared to traditional puddling techniques (5).

Planting patterns play a vital role in shaping weed dynamics, crop development and productivity. Adopting appropriate planting pattern helps can mitigate yield losses and keeps weed infestations under control. Ridge transplanting in rice cultivation can enhance yields and water use efficiency. Additionally, furrow-bed planting enhances soil aeration, minimizes lodging risks and limits soil crusting and cracking, ultimately aids in moisture retention by lowering evaporation losses (6). Weed management is a primary concern in unpuddled transplanting systems due to appearance of non-paddy and traditional paddy weeds, which can significantly reduce rice yields if left unchecked (7). Yield losses in rice caused by weed competition are estimated to range between 40 % and 60 %, potentially increasing to 94-96 % when weeds are left uncontrolled (8). The conventional approach of weed management in rice through manual methods like hoeing or hand weeding is becoming less feasible due to labour shortages and rising costs (9). Herbicides are now widely favoured for their efficiency, ease of application, selective targeting of weeds, labour reduction and cost-effectiveness. However, a comprehensive approach using pre- and post-emergence herbicides is crucial for sustained weed management and to avoid resistance or shifts toward more challenging weed species. Therefore, a study was conducted to evaluate the potential of sequential applications of various pre- and post-emergence herbicides, integrated with planting patterns, for effective weed control.

Materials and Methods

A field experiment was conducted for two consecutive years (*kharif* seasons of 2023 and 2024 respectively) at the research farm of Lovely Professional University, Phagwara (31° 14'43.8"N, 75°41'44.1"E), India. The experimental site is situated at an elevation of 252 meters above mean sea level in the central plain zone of the state's agro-climatic region and experiences a predominantly warm and hot climate and annual precipitation of 400-700 mm. Over the past five years, the experimental field was under rice-wheat crop rotation system. The soil at the experimental site was classified as clay loam, with a slightly alkaline pH of 7.6 and nutrient availability of 220.3 kg ha^{-1} nitrogen (N), 17.7 kg ha^{-1} phosphorus (P) and 196 kg ha^{-1} potassium (K). The experiment in each year was laid out in split plot design consisting of four planting patterns *viz.,* M_1- two rows per ridge, M_2- two rows per ridge and one in furrow, M_3- flat unpuddled and M_4- flat puddled in main plots and four weed control treatments *viz.,* T_1- pendimethalin @ 0.75 kg ha^{-1} as pre-em. *fb* bispyribac sodium @10 SC at 25 g ha^{-1} as post-em. (20-25 DAT) T_2- pendimethalin @ 0.75 kg ha^{-1} as pre-em. *fb* penoxsulam @ 240 SC at 24 g ha^{-1} as post em. (10-12 DAT) T_3- pendimethalin @ 0.75 kg ha^{-1} as pre-em. *fb* fenoxaprop @ 6.7 EC at 67 g ha^{-1} as post-em. (20-25 DAT) and T_4- control (unweeded) in sub-plots, executed with four replications.

During both years, field preparation was carried out by performing two passes with a disc harrow, cultivating the soil with a cultivator and levelling it using a tractor-mounted rotavator. Ridges were manually made with a 60 cm spacing in well prepared dry field. Before transplanting, a uniform basal application of 30 kg ha^{-1} P through SSP, 30 kg ha^{-1} K through MOP and 15 kg ha^{-1} zinc ($ZnSO_4$) was provided to all treatments. The rice nursery of variety PR 126 (30-day-old seedlings) was manually transplanted with a spacing of 20 cm × 15 cm across all treatments, except for the treatment with two rows per ridge, which had a spacing of 30 cm × 10 cm to ensure a uniform plant population across all planting patterns. Nitrogen was applied at a rate of 120 kg ha^{-1} using urea, in three evenly split doses. Pre-emergence application of pendimethalin, blended with 150 kg of sand per hectare, was uniformly broadcasted into standing water within two days after transplanting, adhering to the treatment specifications. A knapsack sprayer with a flat-fan nozzle was used to apply all post-emergence herbicides as per treatments, with water serving as the carrier at a rate of 375 litres per hectare.

Data of plant height (cm), panicle length (cm), total number of grains per panicle, number of fertile grains per panicle was obtained from five randomly selected rice plant clusters from each treatment at the time of harvest. The number of tillers and panicles were recorded from an area of one square meter from each treatment at the time of harvest. Two 30 cm × 30 cm quadrats were randomly positioned in each plot to measure weed density (count and dry matter) as well as rice biomass. The weeds were identified, categorized into grasses and broadleaved species, counted, weed biomass was oven-dried at 60 °C until a constant dry weight was achieved, after sun drying and their dry weight was recorded. Harvesting was done manually at full crop maturity from a net plot area of 4 m^2 area during both years and adjusted to 14 % moisture content before converting to q ha^{-1}. Weed Control Efficiency (WCE) was calculated by using weed dry weight recorded at harvest.

$$\text{WCE (\%)} = \frac{\text{Weed dry weight (control) - weed dry weight (treatment)}}{\text{Weed dry weight (control)}} \times 100$$

Analysis of variance (ANOVA) was performed using OPSTAT software to assess treatment differences, with means compared through the least significant difference (LSD) test at a 5 % level of significance. Data of weed density and biomass were subjected to square root transformation $(\sqrt{x+1})$ to address high variance before ANOVA, though non-transformed values are presented in parenthesis.

Results and Discussion

Weed dynamics

Data pertaining to weed dynamics of grassy weeds presented in Table 1 shows that adopting the planting pattern of two rows/ridge and one in furrow significantly reduced weed density/m^2 (6.99 and 7.39) and biomass (3.34 and 3.39 q ha^{-1} during 2023 and 2024, respectively) in comparison to other treatments, which can be attributed to early canopy closure that may have led to enhanced weed suppression by creating a smothering effect that inhibited weed growth (10). Conversely, flat unpuddled transplanting exhibited significantly higher weed density/m^2 (8.91and 9.12) and biomass (4.03 and 4.10 q ha^{-1}) of grassy weeds during both the years, respectively which can be attributed to the absence of puddling that may have allowed weeds to germinate and thrive more freely, resulting in increased weed density and biomass over time (11). Among the weed control treatments, it was observed that significantly lower weed density/m^2 (3.37 and 3.70) and biomass (1.43 and 1.65 q ha^{-1}) were recorded with the application of pendimethalin *fb* bispyribac sodium, whereas significantly higher weed density/m^2 (13.42 and 13.61) and biomass (5.60 and 5.69 q ha^{-1}) were observed in unweeded (control) which may be due to effective suppression of all weed types during the early crop growth stages by the pre-emergence application of pendimethalin and during the later stages by the post-emergence application of bispyribac sodium (12).

The assessment of data on broadleaf weeds presented in Table 2 reveals significantly higher weed density/m^2 (6.01 and 6.34) and biomass (2.31 and 2.41 q ha^{-1}) were observed in flat unpuddled transplanting, whereas significantly lower weed density/m^2 (4.18 and 4.61) and biomass (1.84 and 2.05 q ha^{-1}) were recorded in two rows/ridge and one in furrow. Amongst the weed control treatments, application of pendimethalin *fb* fenoxaprop has recorded substantially higher weed density/m^2 (6.58 and 6.96) and biomass (2.47 and 2.61 q ha^{-1}) of broadleaved weeds which was statistically at par with the unweeded (control), which may be due to the fenoxaprop's selective mode of action controlling certain grassy weeds, while having minimal impact on broadleaf weeds and sedges (13), whereas significantly lesser weed density/m^2 (2.54 and 3.15) and biomass (1.30 and 1.56 q ha^{-1}) were observed with the application of pendimethalin *fb* bispyribac sodium as compared to other treatments. This can be attributed to the broad-spectrum efficacy of bispyribac sodium targeting wide range of weed species including grasses and broadleaved weeds (12).

Data presented in Table 3 demonstrates the weed control efficiency during both the years, maximum weed control efficiency was observed in transplanting two rows per ridge and one in furrow (94.8 and 91.3 %) when compared to two rows/ridge (51.2 and 52.2 %), flat unpuddled (38.3 and 38.6 %) and flat puddled (46.2 and 43.4 %). Among the subplots, highest WCE was observed with the application of pendimethalin *fb* bispyribac sodium (94.8 and 91.3 %) which was followed by the treatment with application of pendimethalin *fb* penoxsulam (59.2 and 58.9 %) during both the years respectively.

Growth parameters

Data pertaining to growth parameters presented in Table 4 indicates that, over both years, planting patterns and weed control treatments had no significant effect on the establishment percentage of rice that was recorded at 20 DAT. Similarly, planting patterns had no significant effect on plant height. However, amongst the weed control treatments significantly higher plant height (80.6 and 80.7 cm) was recorded in pendimethalin *fb* bispyribac sodium when compared to other treatments, whereas significantly lower plant height was observed in unweeded (control) (67.7 and 66 cm) during both the years, respectively.

Table 1. Impact of planting patterns and weed control treatments on weed dynamics of grassy weeds

Grassy weeds				
Treatments	**Weed density/m^2**		**Weed biomass (q/ha)**	
Main plots (Planting patterns)	**2023**	**2024**	**2023**	**2024**
Two rows/ridge	7.84 (73.9)	7.91 (73.6)	3.58 (14.3)	3.59 (14.0)
Two rows/ridge + One in furrow	6.99 (59.0)	7.39 (65.4)	3.34 (12.1)	3.39 (12.4)
Flat unpuddled	8.91 (93.9)	9.12 (96.0)	4.03 (17.5)	4.10 (18.0)
Flat puddled	8.28 (81.8)	8.51 (85.8)	3.74 (15.5)	3.94 (16.7)
Sem (±)	0.13	0.13	0.05	0.03
C.D. (5 %)	**0.41**	**0.42**	**0.14**	**0.10**
Sub plots (Weed control treatments)				
Pendi., pre-em *fb* bispyribac sodium	3.37 (10.7)	3.70 (13.1)	1.43 (1.1)	1.65 (1.8)
Pendi., pre-em *fb* penoxsulam	7.07 (50.2)	7.20 (51.9)	3.54 (11.6)	3.58 (11.9)
Pendi., pre-em *fb* fenoxaprop-p-ethyl	8.16 (67.7)	8.42 (70.9)	4.12 (16.1)	4.11 (16.0)
Control (unweeded)	13.42 (180.1)	13.61 (184.9)	5.60 (30.5)	5.69 (31.5)
Sem (±)	0.25	0.16	0.06	0.04
C. D. (5 %)	**0.70**	**0.46**	**0.17**	**0.13**
Interaction C.D (5 %) (A×B)	**NS**	**NS**	**NS**	**NS**

Table 2. Impact of planting patterns and weed control treatments on weed dynamics of broadleaved weeds

Broadleaved weeds				
Treatments	**Weed density/m²**		**Weed biomass (q/ha)**	
Main plots (Planting patterns)	**2023**	**2024**	**2023**	**2024**
Two rows/ridge	4.90 (26.3)	5.28 (29.2)	2.00 (3.3)	2.15 (3.9)
Two rows/ridge + One in furrow	4.18 (20.7)	4.61 (22.3)	1.84 (2.6)	2.05 (3.4)
Flat unpuddled	6.01 (38.5)	6.34 (41.9)	2.31 (4.7)	2.41 (5.0)
Flat puddled	5.46 (32.0)	5.67 (34.4)	2.17 (3.9)	2.29 (4.5)
Sem (±)	0.16	0.17	0.04	0.02
C. D. (5 %)	**0.50**	**0.49**	**0.13**	**0.07**
Sub plots (Weed control treatments)				
Pendi., pre-em *fb* bispyribac sodium	2.54 (6.2)	3.15 (9.3)	1.30 (0.7)	1.56 (1.5)
Pendi., pre-em *fb* Penoxsulam	4.75 (23.2)	5.06 (25.4)	2.01 (3.1)	2.11 (3.5)
Pendi., pre-em *fb* fenoxaprop-p-ethyl	6.58 (43.5)	6.96 (48.1)	2.47 (5.2)	2.61 (5.8)
Control (unweeded)	6.67 (44.7)	6.72 (45.0)	2.54 (5.5)	2.63 (5.9)
Sem (±)	0.26	0.16	0.04	0.02
C. D. (5 %)	**0.74**	**0.39**	**0.10**	**0.05**
Interaction C. D. (5 %) (A×B)	**NS**	**NS**	**NS**	**NS**

Table 3. Impact of planting patterns and weed control treatments on weed control efficiency (%)

Treatments	**Weed control efficiency (%)**	
Main plots (Planting patterns)	**2023**	**2024**
Two rows/ridge	51.2	52.2
Two rows/ridge + One in furrow	59.2	57.8
Flat unpuddled	38.3	38.6
Flat puddled	46.2	43.4
Sub plots (Weed control treatments)		
Pendi., pre-em *fb* bispyribac sodium	94.8	91.3
Pendi., pre-em *fb* penoxsulam	59.2	58.9
Pendi., pre-em *fb* fenoxaprop-p-ethyl	40.8	41.8
Control (unweeded)	-	-

Table 4. Impact of planting patterns on establishment percentage (%), plant height (cm) and tiller count (m^{-2}) of rice

Treatments	**Establishment percentage (%)**		**Plant height (cm)**		**Tiller count (m^{-2})**	
Main plots (Planting patterns)	**2023**	**2024**	**2023**	**2024**	**2023**	**2024**
Two rows/ridge	88.1	90.0	75.4	73.8	351.9	347.5
Two rows/ridge + One in furrow	92.8	94.2	75.9	74.2	394.4	392.2
Flat unpuddled	86.0	90.8	75.1	74.3	332.8	323.8
Flat puddled	91.8	88.9	74.3	74.4	317.8	310.3
SEm(±)	2.0	1.4	0.5	0.5	5.6	3.6
C. D. (5 %)	**NS**	**NS**	**NS**	**NS**	**18.05**	**11.61**
Sub plots (Weed control treatments)						
Pendi., pre-em *fb* bispyribac sodium	91.2	90.4	80.6	80.7	409.5	406.3
Pendi., pre-em *fb* penoxsulam	90.6	91.1	77.0	76.0	383.5	372.3
Pendi., pre-em *fb* fenoxaprop-p-ethyl	90.3	93.6	75.3	74.0	342.0	333.7
Control (unweeded)	86.6	88.9	67.7	66.0	261.8	261.5
SEm(±)	1.5	1.9	0.5	0.5	7.2	4.9
C. D. (5 %)	**NS**	**NS**	**1.52**	**1.44**	**20.87**	**13.99**
Interaction C. D. (5 %) (A×B)	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**

The planting pattern with two rows per ridge and one in the furrow produced a greater number of tillers /m² (394.4 and 392.2) compared to other planting patterns. This could be attributed to the increased surface area available in comparison to that of a flat configuration (14). In sub-plot treatments, the sequential application of pendimethalin *fb* bispyribac sodium resulted in a significantly higher tiller count/m² (409.5 and 406.3) than all herbicide-treated plots. This may be due to effective suppression of weeds during the critical early growth phase of rice, allowing the crop to access essential resources such as water, nutrients and light, thereby fostering robust growth and development (15). Meanwhile, tiller count/m² (261.8 and 261.5) was observed to be significantly lower in the unweeded (control) plots across both the years of study.

Yield and yield attributes

Data presented in Table 5 reveals that yield attributes *viz.*, number of panicles/m², total number of grains/panicle, number of fertile grains/ panicle were significantly higher under the planting method of two rows per ridge and one in furrow when compared to other treatments, whereas the application of pendimethalin *fb* bispyribac sodium, recorded significantly better yield attributes relative to other weed control treatments which may be due to the effective control of weeds during the critical stages of growth crop facilitating optimal access to nutrients, ultimately boosting yield attributes (16).

Analysis of the crop yield data indicates that significantly higher biological yield (194.8 and 194.9 q ha^{-1}) was observed by implementing the planting pattern of two rows

Table 5. Impact of planting patterns and weed control treatments on no. of panicles/m², total no. of grains/ panicle, no. of fertile grains/panicles

Treatments	No. of panicles/m²		Total no. of grains/ panicle		No. of fertile grains/panicle	
Main plots (Planting patterns)	**2023**	**2024**	**2023**	**2024**	**2023**	**2024**
Two rows/ridge	333.3	331.7	217.3	225.0	202.0	208.8
Two rows/ridge + One in furrow	371.6	366.6	227.7	234.8	212.7	218.9
Flat unpuddled	312.8	310.6	208.7	215.5	189.9	197.2
Flat puddled	306.9	309.1	205.5	210.6	186.3	194.4
SEm(±)	6.9	4.8	2.3	2.5	3.0	1.8
C. D. (5 %)	**22.25**	**15.38**	**7.44**	**7.92**	**9.61**	**5.72**
Sub plots (Weed control treatments)						
Pendi., pre-em *fb* bispyribac sodium	390.5	392.4	237.5	247.7	223.5	232.2
Pendi., pre-em *fb* penoxsulam	365.2	359.6	228.3	234.1	211.6	217.7
Pendi., pre-em *fb* fenoxaprop-p-ethyl	327.1	322.5	215.4	221.7	198.4	206.9
Control (unweeded)	241.8	243.4	178.1	182.4	157.3	162.5
SEm(±)	5.3	5.5	2.8	2.2	2.8	2.0
C. D. (5 %)	**15.20**	**15.75**	**8.04**	**6.42**	**8.15**	**5.82**
Interaction C. D. (5 %) (A×B)	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**

per ridge and one in furrow outperforming other treatments. This is because the crop plants exhibit plasticity by growing toward areas with optimal resources when weeds are absent, reducing intra-crop competition and efficiently using resources between rows resulting in enhanced weed suppression and increased yield (17). The biological yield of flat unpuddled (173 and 177.2 q ha^{-1}) and flat puddled (168.4 and 174.3 q ha^{-1}) were statistically at par with each other (Table 6). This is in accordance with the previous findings. This study confirms that unpuddled transplanted rice, under fully irrigated conditions, can yield as much as or better than puddled transplanted rice (18). Amongst the weed control treatments, significantly superior biological yield was observed with the sequential application of pendimethalin *fb* bispyribac sodium (223.8 and 222.1 q ha^{-1}) when compared to other herbicidal treatments as pendimethalin ensured effective weed control in the early growth stages, while bispyribac suppressed weeds during tillering, reducing competition and improving rice biomass and yield potential (19), whereas significant reduction in biological yield was observed in the unweeded control. Similarly, highest paddy yield was recorded in two rows/ridge and one in furrow (67.6 and 67.5 q ha^{-1}), while the flat unpuddled (60.2 and 61.4 q ha^{-1}) and puddled (58.9 and 60.6 q ha^{-1}) were statistically at par, whereas the sequential application of pendimethalin *fb* bispyribac sodium significantly increased the paddy yield (77.9 and 76.9 q ha^{-1}), in comparison to other weed control treatments. Conversely, unweeded control recorded significantly lowest paddy yield (31.5 and 33.4 q ha^{-1}) which can be attributed to intense competition from weeds for water, light and nutrients, which hindered crop growth and ultimately led to reduction in yield (20, 21).

Conclusion

The findings of our study indicate that unpuddled rice cultivation has the capacity to equal or exceed the yield potential of puddled transplanted rice by employing a synergistic approach. This involves adopting the appropriate planting pattern with two rows per ridge and one in furrow and implementing a sequential herbicide program comprising both pendimethalin as pre-emergence *fb* bispyribac sodium as post-emergence which proves highly effective in suppressing both grassy and broadleaf weeds across different growth phases. By integrating these practices, farmers can effectively manage weeds and achieve consistent yield outcomes. Planting two rows per ridge and one in furrow increased paddy yield by 8.8 % compared to recommended practices of flat puddled transplanted rice, whereas application of pendimethalin *fb* bispyribac sodium increased the paddy yield by 138.5 % when compared to unweeded (control).

Table 6. Impact of planting pattern and weed control treatment on biological yield (q ha^{-1}) and paddy yield (q ha^{-1}) of rice

Treatments	Biological yield (q ha^{-1})		Paddy yield (q ha^{-1})	
Main plots (Planting patterns)	**2023**	**2024**	**2023**	**2024**
Two rows/ridge	183.9	185.1	63.6	64.7
Two rows/ridge + One in furrow	194.8	194.9	67.6	67.5
Flat unpuddled	173.0	177.2	60.2	61.4
Flat puddled	168.4	174.3	58.9	60.6
SEm(±)	2.7	1.4	0.6	0.4
C. D. (5 %)	**8.67**	**4.33**	**1.92**	**1.34**
Sub plots (Weed control treatments)				
Pendi., pre-em *fb* bispyribac sodium	223.8	222.1	77.9	76.9
Pendi., pre-em *fb* penoxsulam	205.0	210.0	72.7	74.1
Pendi., pre-em *fb* fenoxaprop-p-ethyl	192.3	196.8	68.3	69.8
Control (unweeded)	98.9	102.5	31.5	33.4
SEm(±)	3.1	2.2	0.7	0.6
C. D. (5 %)	**8.81**	**6.39**	**2.04**	**1.74**
Interaction C. D. (5 %) (A×B)	**NS**	**NS**	**NS**	**NS**

Acknowledgements

The authors acknowledge the Department of Agronomy, School of Agriculture at Lovely Professional University for providing the necessary research area and laboratory facilities.

Authors' contributions

The research work and field trials were conducted by GSC with valuable guidance from USW, who also handled manuscript editing, corrections and formatting. RS contributed significantly to data collection, analysis and formatting. All authors collectively reviewed and validated the final manuscript version.

Compliance with ethical standards

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

Ethical issues: None

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