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Crop establishment and weed management effects on weed flora and yield of dry direct-seeded basmati rice (*Oryza sativa*) in the north-western Indo-Gangetic plains

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ABSTRACT

Despite the manifold advantages of dry direct-seeded rice (*Oryza sativa* L.), its adoption is constrained by severe weed infestation during the early stages of crop development. Therefore, a field experiment was conducted to evaluate the effect of crop establishment methods and weed management practices on weed dynamics, growth and yield of direct-seeded basmati rice during rainy (*kharif*) season of 2021 and 2022 at Punjab Agricultural University, Ludhiana, Punjab. The experiment was laid out in a split-plot design with four crop establishment methods in main plots (broadcasting, line sowing, raised bed sowing on 1 m and 0.67 m beds) and four weed management practices in sub-plots [manual weeding, pendimethalin @0.75 kg/ha (pre-emergence) + bispyribac sodium @0.25 kg/ha (post-emergence), pendimethalin @0.75 kg/ha (pre-emergence) + manual weeding, and mechanical weeding]. Line sowing significantly reduced sedge density while total weed dry matter was comparable under line sowing and bed sowing, which was significantly lower than broadcasting. Sequential application of pendimethalin followed by bispyribac sodium effectively reduced weed density and biomass was comparable with pendimethalin followed by one manual weeding. Line-sowing and 1 m raised bed sowing methods produced significantly higher grain yield than 0.67 m bed and broadcasting. The study concluded that line sowing or 1.0 m raised bed sowing combined with sequential herbicide application can be an effective and practical strategy for effective weed management and improving productivity of direct-seeded basmati rice under Punjab conditions.

Keywords: Bispyribac sodium, Integrated weed management, Pendimethalin, Sequential herbicide application

Rice (*Oryza sativa* L.) is one of the most important staple crops worldwide, sustaining billions of people. The method of crop establishment plays a decisive role in determining rice productivity, weed interference (Dhillon *et al.* 2025), water use efficiency (Deb *et al.* 2025) and overall sustainability of rice-based production systems (Kumar *et al.* 2020, Singh *et al.* 2022, Ahmed *et al.* 2025). Dry direct-seeded rice (DSR) has emerged as a viable alternative to conventional transplanting, particularly under conditions of labour and water scarcity. Dry DSR avoids puddling and continuous ponding, thereby conserving irrigation water, reducing labour and energy requirements, and enabling timely crop establishment (Kumar and Ladha 2011, Ramesh *et al.* 2023). Despite these advantages, the wider adoption of DSR has been constrained by severe and complex weed flora infestations, which remain the most critical yield-limiting factor under this system (Shekhawat *et al.* 2020, Nelapati *et al.* 2025). This could lead to substantial yield losses due to intense crop-weed competition during the early growth stages (Pradhan *et al.* 2023, Nagargade *et al.* 2024, Choudhary *et al.* 2025, Meena *et al.* 2025).

The success of dry DSR largely depends on efficient weed management strategies (Dhillon *et al.* 2021). Pre-emergence herbicides provide early weed suppression, while post-emergence herbicides help control later-emerging weed flushes (Mishra *et al.* 2024). Mechanical methods along with manual weeding, though labour-intensive, are effective tools for reducing weed pressure, particularly during critical growth periods. Recent studies under conservation agriculture-based DSR systems have highlighted weed management role in modifying weed dynamics and reducing overall weed pressure while improving crop productivity and soil health (Hazarika *et al.* 2024, Dash *et al.* 2025).

Crop establishment methods significantly influence weed dynamics and crop-weed competition in dry

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DSR systems. Broadcasting often leads to uneven plant distribution and delayed canopy closure, creating favourable conditions for weed emergence and growth (Singh *et al.* 2024). In contrast, line sowing ensures uniform plant spacing, promotes better crop stand establishment and improves resource use efficiency, thereby enhancing the competitive ability of rice against weeds (Yadav *et al.* 2008, Mir *et al.* 2024). Hence, the selection of an appropriate establishment method is crucial for suppressing early weed pressure and achieving higher productivity in DSR, particularly under the north-western Indo-Gangetic plains where weed infestation is a major constraint. Therefore, the present study was undertaken to identify effective weed management options under different crop establishment methods for improving weed control efficiency and grain yield of dry DSR in the Indo-Gangetic plains of India.

MATERIALS AND METHODS

An experiment was conducted during rainy (*kharif*) seasons of 2021 and 2022 at the Research Farm, Punjab Agricultural University (PAU), Ludhiana (30°56' N, 75°52' E; at an elevation of 247 m amsl), Punjab. The soil was sandy loam with 265 kg N/ha, 24.2 kg P_2O_5/ ha, 233 kg K_2O/ha and 0.42% soil organic carbon. The climate of the experimental site can be described as subtropical and semi-arid, with an annual rainfall of 760 mm, 80% of which occurs between June and September. Meteorological data were collected from the agro-meteorological observatory of PAU, Ludhiana (Fig. 1).

The experiment was laid-out in split plot design with three replications. Main plot consisted of four crop establishment methods i.e. broadcasting of seeds (BC), manual line sowing of seeds (20 cm row spacing sown in solid row) (LS), raised bed sowing (Four rows on 1 m wide bed with 70 cm bed top i.e. 17.5 cm spaced rows), and raised bed sowing (Two rows on 67.5 cm wide bed with 37.5 cm bed top i.e. 18.75 cm spaced rows); whereas sub-plots comprised of four weed control treatments i.e. manual weeding, sequential application of pre-emergence herbicide (Pendimethalin @0.75 kg/ha) + post-emergence herbicide (bispyribac sodium @0.25 kg/ha), combination of pre-emergence herbicide + manual weeding, and mechanical weeding. The field was prepared well prior to sowing as per dry direct-seeded basmati rice protocols (PAU 2020). Basmati rice variety 'Pusa Basmati 1509' was used at a uniform seed rate of 20 kg/ha for sowing in all the crop establishment methods.

In case of broadcasting, seeds were uniformly broadcasted in well prepared leveled plots followed by raking to mix the seeds with shallow soil. Whereas in line sowing, seeds were drilled at 20 cm row spacing. Beds of 0.675 m and 1.0 m wide were prepared using tractor operated bed planter. Pendimethalin @0.75 kg/ha as pre-emergence herbicide was used within 48 h after irrigation (applied on the day of sowing) using 500 L of water/ha, whereas, bispyribac sodium @0.25 kg/ha as a post-emergence herbicide was sprayed using 375 L of water/ha at 28 days after sowing (DAS) with knapsack sprayer fitted with flat fan nozzle as per treatments. Manual and mechanical weeding were also done at 20 and 30 DAS. In manual weeding, weeds were removed manually and in mechanical weeding, *triphali* (Wheel hoe) was used to uproot the weeds. A recommended dose of fertilisers comprising nitrogen (150 kg/ha) and zinc sulphate ($ZnSO_4$, 21%) @25 kg/ha was applied. Nitrogen was supplied through urea in three equal splits at 21, 42 and 63 DAS while the entire dose of $ZnSO_4$ was applied as basal at the time of final land preparation. Phosphorus and potassium fertilisers were not applied due to their sufficient availability in the experimental soil. Irrigations were scheduled as per crop requirement to maintain optimum soil moisture conditions for dry direct-seeded basmati rice. All other production and plant protection practices were kept uniform across treatments as per the recommendations of PAU (2020).

Weed density was recorded at panicle initiation stage from two spots in each plot by randomly placing quadrate of 50 cm × 50 cm. Collected weeds were sorted as grasses, broadleaf and sedges. Counted weeds were weighed and placed in oven at 70°C for 72 h for estimation of their dry weight (Mir *et al.* 2024). Plant height was recorded at crop maturity by randomly selecting five plants in each experimental unit. Panicles were counted from one meter row length. Five panicles were randomly selected from each plot for panicle weight, number of filled and unfilled grains. Out of the bulk samples, 1000-grains were counted and weighed on electronic balance to obtain 1000-seed weight. For recording grain yield, the grains obtained after threshing net plots were sun dried, winnowed, cleaned and weighed on an electronic balance. Grain yield was adjusted at 14% moisture using digital moisture meter (Kett's RICETER J Handheld grain moisture meter) and

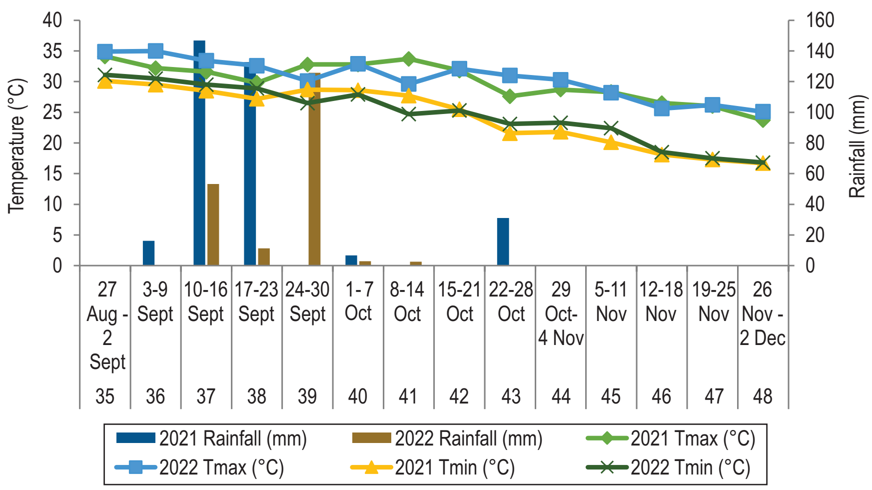

Fig. 1 Seasonal variation in rainfall and temperature during *kharif* 2021 and 2022.

expressed as t/ha. The weight of straw from each net plot was also recorded three days after harvest for estimation of straw yield. Weed index (WI) was calculated to quantify the yield loss due to weed competition under different crop establishment and weed management practices.

$$\text{WI (\%)} = \frac{Y_{max} - Y_t}{Y_{max}} \times 100$$

Where Y_{max}, Grain yield of the highest yielding treatment; Y_t, Grain yield of the treatment under consideration.

Statistical analysis: Data were subjected to analysis of variance (ANOVA) using SAS software version 9.3 (SAS Institute Inc., Cary, NC, USA). Treatment means were compared using Tukey's honestly significant difference (HSD) test at the 5% probability level ($p \leq 0.05$). Correlation analysis was performed using Pearson's correlation coefficients computed through the PROC CORR procedure in SAS and significance levels were determined at $p \leq 0.05$.

RESULTS AND DISCUSSION

Weed flora composition: A diverse and competitive weed flora comprising grasses, sedges and broad-leaved weeds was recorded during both years of experimentation. The dominant grassy weeds were *Echinochloa colona*, *E. crus-galli*, *Eleusine indica*, *Leptochloa chinensis*, *Digitaria sanguinalis*, *Cynodon dactylon* and *Dactyloctenium aegyptium*. Predominant sedges included *Cyperus difformis*, *C. iria*, *C. rotundus* and *Fimbristylis miliacea*, while *Ammania baccifera* was the major broad-leaved weed species.

The observed weed flora reflected that aerobic, well-drained conditions under dry DSR favoured competitive grasses and sedges. The consistent dominance of *E. colona* and *C. rotundus* indicated their strong adaptation to DSR ecosystems, attributable to traits such as rapid and staggered germination, high tillering ability, and prolonged seed viability. Similar shifts in weed flora from puddled transplanted rice to aerobic rice systems have been reported earlier from different rice-growing regions of India (Saravanane 2020, Shekhawat *et al.* 2020, Verma *et al.* 2023, Borah *et al.* 2024).

Effect of establishment methods and weed management practices on weed dynamics: Crop establishment methods exerted a significant effect on weed density and biomass across years (Table 1, Fig. 2). Line sowing and bed sowing (1 m or 0.67 m) consistently demonstrated a reduction in total weed dry matter, registering 55.4–59.2 g/m² and 55.2–57.7 g/m² during 2021 and 2022, respectively, compared to broadcasting which recorded the highest weed dry matter (82.7 and 72.6 g/m², respectively). The reduced weed dry matter under LS and bed sowing can be ascribed to uniform spatial arrangement and enhanced crop competitiveness, facilitating quicker canopy closure and reduced resource availability for weeds. Likewise, BC also resulted significantly highest weed density, indicating higher crop-weed competition under non-uniform plant distribution. The absence of defined row spacing in BC

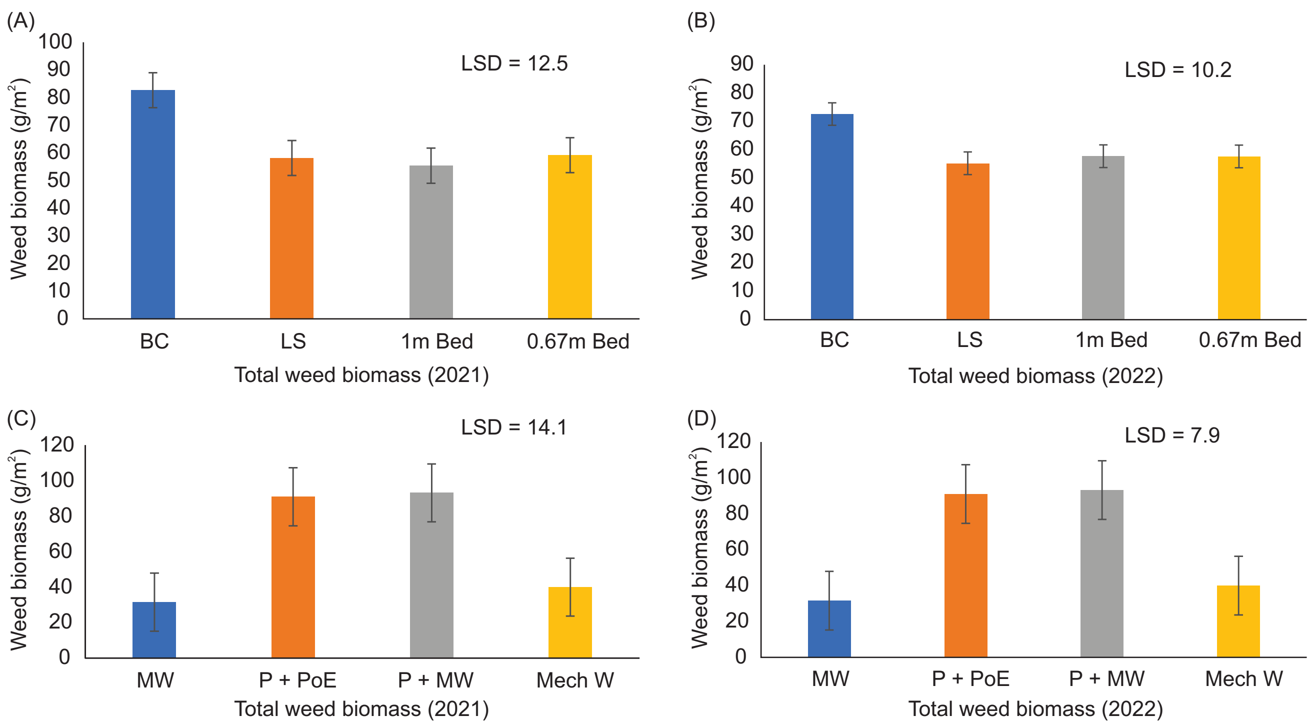

Fig. 2 Effect of crop establishment methods and weed control treatments on weed density in direct seeded rice.
BC, Broadcasting of seeds; LS, Line sowing of seeds in 20 cm apart rows; 1 m Bed, Raised bed sowing (Four rows on 1 m wide bed); 0.67 m Bed, Raised bed sowing (Two rows on 67.5 cm wide bed); P + PoE, Pre-emergence + post emergence herbicide; Mech W, Mechanical weeding; MW, Manual weeding; LSD, Least significance level.

Table 1 Effect of crop establishment methods and weed control treatments on weed dynamics of under direct seeded rice

Treatment	Grasses (No./m²)*		Sedges (No./m²)		BLWs (No./m²)		Total (No./m²)		Total weed dry matter (g/m²)	
	2021	2022	2021	2022	2021	2021	2021	2022	2021	2022
Crop establishment method										
Broadcast	3.82 (15.7)	3.10 (9.3)	4.74 (25.1)	3.26 (10.7)	5.40 (30.3)	6.32 (41.2)	8.08 (71.0)	7.70 (61.2)	82.7	72.6
Line sowing	3.98 (18.0)	2.69 (7.0)	2.87 (7.9)	2.02 (3.8)	4.89 (24.3)	5.23 (29.5)	6.85 (50.2)	6.13 (40.3)	58.2	55.2
1 m Raised bed	3.83 (16.0)	3.25 (10.0)	3.24 (12.7)	3.41 (13.0)	4.63 (22.3)	5.76 (32.5)	6.87 (51.0)	7.50 (55.5)	55.4	57.7
0.67 m Raised bed	3.57 (13.7)	3.77 (13.8)	3.43 (13.3)	3.47 (13.3)	4.44 (19.7)	5.46 (29.3)	6.62 (46.7)	7.51 (56.5)	59.2	57.6
CD (p = 0.05)	NS	NS	0.79	0.87	0.37	0.38	0.83	0.54	12.5	10.2
SEM±	0.25	0.39	0.28	0.31	0.13	0.13	0.29	0.19	4.42	3.61
Weed control options										
Pre- + Post-emergence	1.99 (3.3)	3.02 (9.3)	1.46 (1.4)	1.44 (1.33)	3.41 (10.9)	4.97 (25.8)	4.05 (15.7)	6.34 (40.3)	31.5	50.2
Mechnical weeding	5.67 (31.7)	3.30 (10.8)	5.05 (26.5)	3.97 (15.3)	6.15 (38.2)	5.88 (34.8)	9.80 (96.3)	8.01 (63.8)	90.9	57.1
Manual weeding	4.53 (20.0)	3.22 (9.7)	4.32 (18.3)	3.49 (13.7)	5.42 (28.6)	6.61 (43.7)	7.83 (61.3)	7.78 (60.5)	93.1	88.2
Pre-emergence + Manual weeding	3.01 (8.3)	3.26 (10.3)	3.45 (12.8)	3.25 (10.5)	4.38 (18.8)	5.30 (28.2)	6.75 (45.5)	6.70 (48.8)	40.0	47.6
CD (p = 0.05)	0.59	NS	0.61	0.38	0.48	0.62	0.64	0.57	14.1	7.9
SEM±	0.21	0.18	0.22	0.13	0.17	0.22	0.23	0.20	4.99	2.79
Interaction	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

*Values after square root transformation; and values in parenthesis are original values. BLW, Broad-leaved weed; NS, Non-significant.

likely promoted heterogeneous crop stands, enabling greater light penetration and niche availability for weed growth. Although, weed dry matter during both the years and weed density during 2021 was similar under line sowing and bed sowing but during 2022, bed sowing registered higher weed density, which might be explained in light of the fact that the furrow spaces may act as microsites conducive for weed emergence, particularly under irrigated conditions. Among weed categories, sedges were significantly affected by establishment methods, whereas grasses and broad-leaved weeds (BLWs) remained statistically similar under different crop establishment methods. Line sowing registered the least sedge density, whereas BC had the highest and bed sowing remained in between. This suggests that hydro-ecological variations induced by establishment methods preferentially affect sedge proliferation, given their affinity for specific moisture regimes. These findings are in agreement with earlier reports highlighting the role of row-based crop geometry in suppressing weeds through improved light interception and resource use efficiency (Kumar *et al.* 2020, Saha *et al.* 2021, Sharma *et al.* 2025, Guru *et al.* 2025).

Weed control options significantly affected weed density, composition, and biomass in both the years (Table 1, Fig. 2). The sequential application of pre- and post-emergence herbicides proved to be the most effective strategy, resulting in the lowest weed density (15.7 and 40.3 No./m²) and weed dry matter accumulation (31.5 and 50.2 g/m²) during 2021 and 2022, respectively. The superior efficacy of sequential application of pendimethalin followed by bispyribac sodium might be attributed to the formation of an effective herbicidal barrier at the soil surface by pendimethalin, which suppresses early weed flushes, followed by effective control of later-emerging weeds by bispyribac sodium by way of its temporal complementarity, ensuring effective control of both early- and late-emerging weed cohorts, thereby minimising crop-weed competition throughout the critical growth period. In contrast, mechanical weeding recorded the highest weed density and biomass, indicating its limited ability to suppress successive weed flushes and intra-row weeds. Manual weeding alone, although more effective than mechanical weeding, remained inferior to herbicide-based approaches, likely due to incomplete removal of intra-row weeds. The integrated approach i.e. pre-emergence + manual weeding (P + MW) demonstrated improved weed control over standalone manual or mechanical methods, underscoring the advantage of integrating chemical and manual weeding. This treatment effectively reduced weed density by combining early-stage weed suppression through pre-emergence herbicide with subsequent manual removal of escaped weeds. Data further highlighted that across weed flora, chemical control exhibited broad-spectrum control, significantly reducing grasses, sedges, and BLWs, whereas non-chemical methods showed variable and often inadequate control across species. The interaction between crop establishment methods and weed control treatments was non-significant with respect to weed dynamics. Similar advantages of sequential herbicide programmes in DSR have been reported earlier (Godara *et al.* 2016, Meena *et al.* 2025).

The present findings further indicated variations in weed density and biomass in response to different crop establishment and weed management practices. Reduced soil disturbance and continuous herbicide use are known to favour specific weed groups, particularly sedges and broadleaf weeds, while suppressing grassy weeds. Recent evidence suggested an increasing prevalence of problematic weed species such as *Leptochloa chinensis*, *Ischaemum rugosum* and *Paspalum distichum* under changing management practices in rice systems (Rao and Chandrasena 2024). Sequential herbicide application, although effective in reducing total weed pressure, may further accelerate species shifts due to differential sensitivity among weed flora.

Growth, yield attributes and yield: Crop establishment methods did not significantly affect days to 50% flowering and 1000-grain weight, suggesting that these traits remained stable across establishment systems and was primarily governed by genotype and prevailing environmental conditions. However, significant variations were observed in yield attributes (Table 2). Line sowing recorded significantly highest panicle density which can be attributed to uniform plant geometry, reduced intra-specific competition, and improved resource-use efficiency, ultimately enhancing tiller survival and sink capacity. Similar improvements in crop competitiveness under optimised geometry have been widely reported in DSR systems, where increased plant density and spatial uniformity suppress weed growth and improve productivity (Sahani *et al.* 2025). Raised bed planting produced significantly heavier panicles, indicating that improved soil aeration and root growth under beds enhanced assimilate partitioning toward reproductive organs (Kaur *et al.* 2023, Kaur *et al.* 2024**)**. However, this advantage under 0.67 m bed sowing treatment did not translate into significantly higher grain yield than LS, possibly due to lesser panicle density (Table 2).

Grain yield was significantly influenced by establishment methods (Table 3), with LS producing the highest yield (4.02 and 3.87 t/ha), followed by 1 m bed sowing. The BC recorded least grain yield (3.39 and 3.38 t/ha in 2021 and 2022, respectively) and LS excelled in grain yield over BC by a significant margin of 18.6% and 14.5% in 2021 and 2022**,** respectively. The lowest grain yield under BC can be attributed primarily to higher weed infestation and reduced panicle density, leading to lower sink strength. Straw yield

Table 2 Effect of crop establishment methods and weed control treatments on growth and yield attributes direct seeded rice

Treatment	Days to 50% flowering		Plant height (cm)		Panicle density (No./m^2)		Panicle weight (g)		1000-grain weight (g)		Sterility (%)	
	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022
Crop establishment methods												
Broadcast	82.4	81.3	91.2	92.6	339	358	1.73	2.11	27.2	28.6	27.7	16.6
Line sowing	81.6	81.4	90.4	93.9	427	394	1.96	2.24	27.2	29.1	26.6	15.5
1 m Raised bed	81.3	80.1	90.9	92.3	387	381	1.98	2.23	27.3	29.9	24.0	16.1
0.67 m Raised bed	81.5	81.8	93.7	90.1	367	354	2.01	2.19	27.4	28.6	23.9	16.4
CD (p=0.05)	NS	NS	NS	2.0	34	29	0.14	0.09	NS	NS	2.4	NS
SEM±	0.57	0.62	0.88	0.71	12.02	10.26	0.05	0.03	0.07	0.12	0.85	0.53
Weed control options												
Pre- + Post-emergence	80.9	80.0	92.9	93.7	412	388	2.13	2.23	27.3	29.2	23.5	16.2
Mechanical weeding	82.2	81.3	90.2	91.3	348	353	1.74	2.19	27.2	28.6	29.2	16.9
Manual weeding	82.7	81.3	91.4	91.7	376	364	1.81	2.10	27.2	29.3	25.0	16.1
Pre-emergence + Manual weeding	81.1	81.0	92.3	92.9	383	382	2.00	2.14	27.3	29.1	24.4	15.5
CD (p=0.05)	1.0	NS	NS	2.0	32.6	17	0.09	NS	NS	NS	2.2	NS
SEM±	0.35	0.42	0.64	0.71	11.53	6.01	0.03	0.06	0.08	0.7	0.78	0.56
Interaction	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

NS, Non-significant.

Table 3 Effect of crop establishment methods and weed control treatments on grain and straw yield of direct seeded rice

Treatment	Grain yield (t/ha)		Straw yield (t/ha)		Weed index (%)	
	2021	2022	2021	2022	2021	2022
Crop establishment methods						
Broadcast	3.39	3.38	5.58	5.62	15.7	12.7
Line sowing	4.02	3.87	5.38	6.05	-	-
1 m Raised bed	3.94	3.79	4.26	6.04	2.0	2.0
0.67 m Raised bed	3.68	3.44	3.77	5.34	8.5	11.1
CD (p=0.05)	0.36	0.24	0.93	0.24	0.8	1.2
SEM$\pm$	0.13	0.08	0.33	0.08	0.28	0.42
Weed control options						
Pre- + Post-emergence	4.51	3.95	5.75	6.12	-	-
Mechanical weeding	3.01	3.24	3.91	5.40	33.3	18.0
Manual weeding	3.43	3.52	4.64	5.68	23.9	10.9
Pre-emergence + Manual weeding	4.07	3.73	4.70	5.85	9.8	5.6
CD (p=0.05)	0.25	0.18	0.58	0.26	0.9	1.2
SEM$\pm$	0.09	0.06	0.21	0.09	0.32	0.42
Interaction	NS	NS	NS	NS	NS	NS

NS, Non-significant.

followed a similar trend with line sowing producing 5.38 t/ha in 2021 and 6.05 t/ha in 2022, reflecting improved crop growth and biomass accumulation under uniform row planting. Narrower beds (0.67 m) recorded intermediate yields, with relatively lower performance in 2022, likely due to differences in moisture availability and aeration. Variability in the performance of bed planting across years may be attributed to differences in rainfall distribution and soil moisture dynamics. Wider beds (1 m) performed better under high rainfall conditions due to improved root development and drainage, whereas narrower beds occasionally restricted root growth, as also reported by Kumar *et al.* (2020) and Kaur *et al.* (2024). Weed index (WI) varied significantly among treatments and aligned closely with the yield trends (Table 3). Among crop establishment methods, broadcasting recorded the highest WI (15.7% in 2021 and 12.7% in 2022), whereas bed planting had intermediate values (2.0–11.1%). These findings are consistent with recent research highlighting that crop establishment method is a critical determinant of crop-weed competition dynamics (Dhillon *et al.* 2021, Choudhary *et al.* 2025, Meena *et al.* 2025, Nagargade *et al.* 2025).

Sequential application of pre- and post-emergence herbicides (P + PoE) resulted in superior performance in terms of panicle density, panicle weight, and grain yield (Tables 2 and 3). The higher productivity under P + PoE can be attributed to effective season-long weed suppression, which minimises competition during critical crop growth stages. Recent studies have demonstrated that sequential herbicide applications provide broad-spectrum and prolonged weed control, significantly improving rice productivity conditions (Dhillon *et al.* 2021, Kaur *et al.* 2024, Choudhary *et al.* 2025). The highest grain yield under P + PoE was closely associated with improved yield attributes, indicating that sink development (panicle density and weight) is highly responsive to weed-free conditions. This aligns with findings that effective weed management enhances resource availability, leading to improved growth and yield components. Mechanical weeding recorded the lowest yield indicating its limited efficiency in controlling successive weed flushes and intra-row weeds, especially under high weed pressure. Manual weeding, although relatively better, was still inferior to herbicide-based treatments due to operational inefficiencies. The integrated approach (P + MW) performed better than mechanical weeding and manual weeding, demonstrating that integration of chemical and manual methods enhances weed control efficiency while reducing reliance on herbicides alone. Importantly, the performance of P + MW highlights the potential of integrated weed management approaches in achieving high productivity with reduced chemical dependency with further research in integration with other variables. Sterility and 1000-grain weight remained largely unaffected across treatments, suggesting that yield improvements were primarily driven by enhanced sink size rather than grain filling efficiency. For weed management practices, WI was worked out over P + PoE treatment owing to its superiority in suppressing weeds. Pendimethalin followed by one manual weeding showed moderate WI (9.76% in 2021 and 5.57% in 2022), while mechanical weeding alone recorded the highest WI (33.26%

Table 4 Pearson correlation matrix of total weed density, weed biomass, effective tillers, panicle weight, grain yield and straw yield of direct seeded rice

Pearson correlation matrix						
	Total weed biomass (g/m^2)	Total weeds ($No./m^2$)	Effective tillers ($No./m^2$)	Panicle weight (g)	Grain yield (q/ha)	Straw yield (q/ha)
Total weed biomass (g/m^2)	1	0.330^{NS}	-0.469^{NS}	-0.018^{NS}	-0.556*	0.421^{NS}
Total weeds ($No./m^2$)	0.330^{NS}	1	-0.499*	-0.861**	-0.906**	-0.380^{NS}
Effective tillers ($No./m^2$)	-0.469^{NS}	-0.499*	1	0.504*	0.705**	0.138^{NS}
Panicle weight (g)	-0.018^{NS}	-0.861**	0.504*	1	0.732**	0.406^{NS}
Grain yield (q/ha)	-0.556*	-0.906**	0.705**	0.732**	1	0.273^{NS}
Straw yield (q/ha)	0.421^{NS}	-0.380^{NS}	0.138^{NS}	0.406^{NS}	0.273^{NS}	1

*,** denotes significance level at 1% and 5%, respectively; NS, Non-significant.

and 17.97%, respectively), indicating substantial yield losses due to inadequate control of competitive weed species. These results highlighted that uniform crop establishment combined with effective chemical or integrated weed management is essential for minimising weed-induced yield losses in direct-seeded basmati rice. The non-significant interaction between crop establishment methods and weed control treatments indicated that weed control strategies performed consistently across establishment systems, enhancing the robustness and wider applicability of the findings. Earlier studies in direct-seeded basmati rice have shown that integrated weed management significantly affects weed density, nutrient uptake, and crop performance (Anuradha *et al.* 2025). Therefore, a diversified approach combining crop establishment methods with herbicide rotation or mixtures of different modes of action is essential to prevent weed dominance and delay resistance.

Correlation analysis: Total weed density and total weed biomass showed significant and negative correlations with grain yield, whereas panicle density and panicle weight were significantly and positively correlated with grain yield (Table 4). Correlations between straw yield and grain yield were non-significant. The significant negative association between weed density and biomass with grain yield further emphasises the importance of effective season-long weed control for enhancing productive tiller formation and panicle development.

Overall, the study demonstrated that line sowing or 1 m raised bed sowing combined with sequential herbicide application (pendimethalin followed by bispyribac sodium) offers a robust, resource-efficient and sustainable strategy for effective weed management and higher productivity of direct-seeded basmati rice under Punjab conditions. These approaches ensure effective season-long weed suppression, improved yield attributes and higher productivity while reducing labour dependence.

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