



RESEARCH ARTICLE

Impact of establishment methods and sequential herbicide application on weeds and productivity of rice

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Received: 22 January 2026 | Revised: 16 April 2026 | Accepted: 19 April 2026

ABSTRACT

Weed interference remains a major constraint to rice productivity under changing establishment methods and increasing labour and water scarcity. The objective of this study was to identify efficient rice establishment techniques and effective sequential herbicide application regimes to optimize weed control and improve rice productivity. The experiment was conducted in a split-plot design with three replications. The rice establishment methods, *viz.* conventional transplanting, direct dry-seeded rice, and wet-seeded rice were assigned to main plots and sequential herbicide application regimes along with weedy check and weed-free were allocated to subplots. Conventional transplanting of rice recorded the maximum rice grain yield recording a 16.5–18.5% yield increase over other establishment methods. Uncontrolled weed infestation caused severe yield losses of up to 42.3%. The pre-emergence application (PE) of pretilachlor 1000 g/ha at 3 days after transplanting (DAT)/seeding (DAS) followed by (*fb*) post-emergence application (PoE) of chlorimuron + metsulfuron 4 g/ha or bispyribac-sodium 25 g/ha at 30 DAS/DAT) were as effective as manual weeding and caused an increase in rice yield of about 69% over weedy check, while also curtailing weed seed production and thus gradually reducing the soil weed seed reserve.

Keywords: Dry-seeded rice, Sequential herbicides application, Transplanted rice, Wet-seeded rice, Weed management, Weed seed bank

INTRODUCTION

Rice remains vital for global food security, yet rice productivity faces increasing threats from weeds, labor scarcity and water deficits. The traditionally practiced puddled transplanted rice (PTR) suppresses weeds but was observed increasingly unsustainable (Manna 1991, Singh *et al.* 2005). Consequently, a strategic transition toward resource conservation technologies like dry direct-seeded rice (dry-DSR) and wet-seeded rice (WSR) is being opted by farmers (Rao *et al.* 2017). However, severe and diverse weed infestations remain the primary bottleneck for direct-seeded rice (DSR) (Rao *et al.* 2007). The magnitude of yield loss due to weeds varies with rice establishment method with yield reductions of 15–25% in TPR, 30–45% in wet-seeded rice (WSR) and 50–60% in DDSR (Rao *et al.* 2007, Rao *et al.* 2017a).

The sequential herbicide application has emerged as an alternative to manual weeding to manage weeds effectively and economically (Bhatt *et*

al. 2017, Rathika *et al.* 2020). as the sequentially applied herbicides manage the weeds during critical period of early vegetative stages when competition for nutrients and Photosynthetically Active Radiation (PAR) is most intense. Beyond immediate yield protection, sequential herbicides application approach disrupts the “seed rain” that replenishes soil seed banks, ensuring long-term ecological management (Joshi *et al.* 2015). Hence, there is a critical need to identify sequential herbicides application options for different rice establishment methods to maximize rice productivity under current labour and water constraints. Thus, the present study was undertaken to evaluate the different sequential herbicide options suited to diverse rice establishment methods for optimizing weed control efficiency and rice productivity.

MATERIALS AND METHODS

The field study was conducted over two consecutive summer cropping seasons: 2021–2022 and 2022–2023 at the College Farm, NMCA, Navsari Agricultural University (NAU), Navsari, Gujarat, India which is geographically situated in the South Gujarat Heavy Rainfall Zone (Agro-climatic Zone II).

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The experimental soil was characterized as a deep black clayey textured soil (*Vertisol*) with poor drainage and good water holding capacity. Initial soil sampling (0–20 cm depth) revealed a consistent slightly alkaline soil reaction with an average pH of 7.85 and normal electrical conductivity (EC) averaging 0.36 dS/m, confirming non-saline conditions. The soil exhibited an average organic carbon content of 0.425% (classified as low to medium status). The available nutrient profile indicated specific fertility levels: the soil tested low in available nitrogen (average of 221.5 kg/ha), medium in available phosphorus (average of 38.5 kg/ha P) and was classified as fairly rich in available potassium (average of 387 kg/ha K).

The experiment was laid out in a split-plot design with four replications. The main plots comprised three establishment methods, while the sub-plots included five management treatments (Table 1). Herbicides were applied using a knapsack sprayer with a flat-fan nozzle, calibrated at 330 L/ha (PE) and 375 L/ha (PoE). These sequential regimes were hypothesized to provide early grass control followed by broad-spectrum suppression of late-emerging sedges and broad-leaf weeds during critical growth stages.

The rice cv. NAUR-1 was used that fertilized with 120 kg Nitrogen (N) and 30 kg Phosphorus (P)/ha. All phosphorus was applied as basal using single super phosphate. Nitrogen was applied as urea in three splits: 50% at planting, 25% at tillering, and 25% at panicle initiation. Water was kept at 2–3 cm during early growth, increased to 5 cm until the milking stage, and then kept at saturation until

harvest. To maintain these levels, irrigation was provided every 4–5 days, totalling 23 times for DSR and 21 times for PTR.

Weed data was collected using a standard square quadrat (0.25 m²) placed randomly within plots. As the data on grasses, sedges and broad-leaved weeds (BLW) occurring in the plots were recorded. Relative density (RD) was determined following Misra (1968) to assess the numerical strength of individual species relative to the total community. Weed dry biomass (kg/ha) was recorded at harvest. Weeds were oven-dried at 65 ± 2°C for 24 hours until reaching a constant weight and weed dry biomass data was noted. Weed control efficiency (WCE) was calculated (Kondap and Upadhyay 1985). The weed index (WI) was calculated to quantify the percentage yield reduction in treated plots relative to the weed-free baseline. The soil weed seed bank was evaluated using the germination method. Representative 0.5 kg soil samples were extracted from 0–10 and 10–20 cm depths, processed, and incubated in petri plates under optimal moisture conditions for 15 days; germinated seedlings were recorded at 20 days to determine the seed count per kilogram of soil.

Statistical analysis was performed using the Statistical Tool for Agricultural Research (STAR) from IRRI (2014). Data were subjected to Analysis of Variance (ANOVA) for a split-plot design, with mean separation determined by the Least Significant Difference (LSD) at $P=0.05$. Weed density and biomass were statistically analysed by square root transformation ($\sqrt{x+0.5}$) to ensure normality.

Table 1. The details of rice establishment methods and weed management regimes tested

Method / Regime	Technical specifications	Application details
<i>Main plot: rice establishment method (S)</i>		
Dry direct-seeded rice (Dry-DSR)	Aerobic seedbed; 60 kg/ha seed rate; 30 cm line spacing	Sown at 2–3 cm depth; light irrigation post-sowing
Conventional puddled transplanted (PTR)	25-day-old seedlings; 30 kg/ha seed rate for nursery	Manual transplanting at 20 cm × 15 cm; 5 cm standing water
Wet-Seeded rice - Line Sown (WSR)	Pre-germinated seeds (6h soak, 24h incubate)	30 cm rows on saturated puddled soil; gradual water increase
<i>Sub plot: weed management (W)</i>		
Weedy check (control)	Maximum competition	No weed control interventions
Hand weeding twice	Weed-free check	Two manual weeding at 20–25 and 40–45 days after seeding (DAS)/ days after transplanting (DAT)
Herbicides sequential application regime I	Pre-emergence application (PE) of pretilachlor + fenclorim followed by (<i>fb</i>) post-emergence application (PoE) bispyribac-sodium	1000 g/ha 3 DAS/DAT followed by (<i>fb</i>) 25 g/ha 30 DAS/DAT
Herbicides sequential application regime II	Pyrazosulfuron-ethyl PE <i>fb</i> bispyribac-sodium PoE	15 g/ha 3 DAS/DAT <i>fb</i> 25 g /ha 30 DAS/DAT
Herbicides sequential application regime III	Pretilachlor + fenclorim PE <i>fb</i> (Chlorimuron + Metsulfuron) PoE	1000 g/ha 3 DAS/DAT <i>fb</i> 4 g /ha 30 DAS/DAT

RESULTS AND DISCUSSION

Weed flora

The experimental field was infested with a diverse weed community consisting of 21 weed species belonging to 11 families (Table 2). There were grasses (8 species), broad-leaved weeds (9 species), and sedges (4 species). Grasses were the most predominant group across all three establishment methods. In dry-DSR, grass RD increased from 63.9% to 68.5%, while in WSR, it rose from 53.9% to 60.9%. The highest overall grass pressure was observed in PTR, where RD surged from 59.6% to 72.7% by 40 DAS. *Echinochloa colona* emerged as the most dominant species in both dry-DSR and PTR, nearly doubling its density in PTR to 25.1%. However, in WSR, *Echinochloa crus-galli* was the primary competitor, reaching 15.2% due to its superior adaptation to saturated soil. Broad-leaved weeds constituted the second major group, with WSR maintaining the highest relative density (32.1% at 20 DAS to 28.1% at 40 DAS). This sustained presence in WSR was driven by moisture loving

species such as *Marsilea quadrifolia* and *Alternanthera sessilis*. In contrast, the anaerobic puddled conditions of PTR effectively suppressed aerobic species like *Euphorbia hirta* and *Tridax procumbens*, leading to a significant decline in total BLW density to 20.4% by 40 DAS. Sedges maintained the lowest RD across all systems but showed distinct patterns by method. WSR recorded the highest initial sedge density at 14.0%, which gradually decreased to 11.0% by 40 DAS as grasses became more dominant. In dry-DSR, sedge RD remained relatively stable (moving from 10.0% to 9.4%), while it reached its minimum in PTR, dropping to 6.9%. While *Cyperus rotundus* persisted across all methods, moisture-loving sedges like *Cyperus iria* and *Fimbristylis miliacea* were significantly more prominent in the WSR system.

The grasses, *Echinochloa* spp. *B. ramose*; broad-leaved weeds, *A. sessilis* and *P. niruri* and sedges, *C. rotundus* and *C. difformis* were found to be the dominant weeds in puddled as well as unpuddled situations because they can tolerate and

Table 2. Weed flora and relative density (RD) of weeds in rice as influenced by establishment methods and sequential herbicide application (based on 2 years)

Scientific name	Common name	Family	Habitat	DSR - RD (%)						PTR-RD (%)	
				Dry-DSR	WSR	Mean*	Dry-DSR	WSR	Mean*	20	40
				20 DAS			40 DAS			DAPTR	DAPTR
Grasses											
<i>Echinochloa colona</i>	Wild rice	Poaceae	A, H, T, SU	12.1	9.1	10.6	17.9	14.5	16.2	13.1	25.1
<i>Echinochloa crus-galli</i>	Barnyard grass	Poaceae	A, H, T, SU	8.7	12.5	10.6	6.0	15.2	10.6	7.1	6.8
<i>Cynodon dactylon</i>	Bermuda grass	Poaceae	P, H, Cr, SU	5.2	1.9	3.6	6.5	4.1	5.3	6.1	11.0
<i>Eragrostis minor</i>	Love grass	Poaceae	A, H, T, SU	9.0	6.6	7.8	11.2	8.4	9.8	11.1	0.0
<i>Digitaria sanguinalis</i>	Hairy crabgrass	Poaceae	A, H, T, SU	6.2	3.8	5.0	3.1	0.9	2.0	3.0	6.8
<i>Dinebra retroflexa</i>	Viper grass	Poaceae	A, H, T, SU	5.5	3.1	4.3	6.0	4.6	5.3	10.1	9.9
<i>Brachiaria ramosa</i>	Signal grass	Poaceae	P, H, H, SU	11.8	9.4	10.6	13.6	10.0	11.8	9.1	7.9
<i>Dactyloctenium aegyptium</i>	Crow foot grass	Poaceae	A, H, T, SU	5.3	7.5	6.4	4.2	3.2	3.7	0.0	5.2
				63.8	53.9	58.9	68.5	60.9	64.7	59.6	72.7
Broad-leaved weeds											
<i>Alternanthera sessilis</i>	Alligator weed	Amaranthaceae	A/P, H, T, SU	4.5	6.9	5.7	10.8	9.6	10.2	5.1	2.6
<i>Marsilea quadrifolia</i>	Water clover	Marsileaceae	P, H, Cr, SU	0.8	3.6	2.2	1.2	6.2	3.7	5.1	3.7
<i>Phyllanthus niruri</i>	Gale of the wind	Phyllanthaceae	A, H, T, SU	6.8	4.6	5.7	1.8	0.6	1.2	7.1	5.2
<i>Euphorbia hirta</i>	Milk weed	Euphorbiaceae	A, H, T, SU	3.2	1.0	2.1	2.0	0.4	1.2	0.0	0.0
<i>Portulaca oleracea</i>	Common purslane	Portulacaceae	A, H, T, SU	3.5	2.1	2.8	2.4	1.6	2.0	7.1	2.1
<i>Commelina benghalensis</i>	Wandering jaw	Commelinaceae	P, H, Cr, SU	3.1	5.5	4.3	1.4	2.6	2.0	1.0	2.1
<i>Tridax procumbens</i>	Tridax daisy	Asteraceae	A/P, H, T, SU	3.2	2.4	2.8	1.1	1.3	1.2	0.0	0.0
<i>Physalis minima</i>	Ground cherry	Solanaceae	P, H, T, SU	0.4	2.4	1.4	0.6	1.8	1.2	2.0	1.6
<i>Digera arvensis</i>	Digera kondra	Amaranthaceae	A, H, T, SU	0.6	3.6	2.1	0.8	4.0	2.4	3.0	3.1
				26.1	32.1	29.1	22.1	28.1	25.1	30.4	20.4
(C) Sedges											
<i>Cyperus rotundus</i>	Purple nut sedge	Cyperaceae	A/P, H, T, SU	6.5	4.9	5.7	4.0	3.4	3.7	4.0	3.2
<i>Cyperus difformis</i>	Umbrella sedge	Cyperaceae	P, H, Cr, SU	0.4	1.0	0.7	4.0	3.4	3.7	1.0	0.5
<i>Cyperus iria</i>	Flat sedge	Cyperaceae	A, H, T, SU	1.8	5.2	3.5	0.4	2.0	1.2	2.0	1.6
<i>Fimbristylis miliacea</i>	Globefingerush	Cyperaceae	A, H, T, SU	1.4	2.9	2.2	1.0	2.2	1.6	3.0	1.6
				10.1	14.0	12.1	9.4	11.0	10.2	10.0	6.9

*A: Annual; P: Perennial; A/P: Annual/Perennial; H: Herb; T: Therophytes; Cr: Cryptophytes; Hc: Hemicryptophytes; SU: Summer; DSR: Direct seeded rice; WSR: Wet-Seeded rice; PTR: Transplanted rice; RD: Relative weed density, *Mean: Average of Dry DRS and WSR to compare PTR rice and DSR establishment methods.

flourish easily under submerged conditions as that of paddy. Similar weed flora was reported earlier under puddled conditions (Subbulakshmi and Pandian 2002), in transplanted rice and in direct-seeded rice (Rekha *et al.* 2002). Parameshwari and Srinivas (2014) also reported the dominance of grasses followed by BLWs and sedges. The habitat analysis indicated that the majority of these weeds are adapted to both aquatic and terrestrial environments, making them highly competitive in both DSR and PTR systems. Overall, DSR supports higher initial weed diversity, whereas the PTR system exerts selective pressure favoring grasses, specifically *Echinochloa* species.

Effect on weeds

The conventional transplanted rice significantly minimized grasses, BLWs and sedges at 20 and 40 DAS/DAT compared to dry-DSR and WSR systems (**Table 3**). Among herbicide treatments, pretilachlor PE *fb* bispyribac-sodium PoE recorded significantly lower weed density and biomass at 20 and 40 DAS/DAT, tailed significantly by pyrazosulfuron-ethyl PE *fb* bispyribac-sodium PoE and pretilachlor PE *fb* (chlorimuron-ethyl + metsulfuron-methyl) PoE. These sequential regimes proved superior to the weedy check. The sequential regime of pretilachlor PE *fb* bispyribac-sodium PoE emerged as the most effective treatment, in minimising the sedge density and biomass at 40 DAS/DAT and was proved statistically superior to the hand weeding twice intervention

The reduction in weed pressure (grasses, BLWs and sedges) under conventional transplanting is due to puddling which induced seed burial and the maintenance of an anaerobic environment. These conditions inhibit the germination of photoblastic and oxygen sensitive species (Singh *et al.* 2005, Mandal *et al.* 2013). Additionally, the initial vigour of young seedlings ensures early niche occupancy, providing a competitive advantage in light and nutrient sequestration that stifles weed development (Baloch *et al.* 2006, Subbaiah and Kumar 2011).

Sequential herbicide regimes provided an extended “protection window” (Kumar *et al.* 2017). Pretilachlor PE *fb* bispyribac-sodium PoE proved superior for grasses and sedges, while pyrazosulfuron-ethyl PE *fb* bispyribac-sodium PoE excelled against broad-leaved weeds. However, this efficacy was selective; while it neutralized aggressive species like *Echinochloa*, it did not offer universal control across all taxa. Dry DSR presented a greater challenge due to aerobic diversity, unlike PTR, where

puddling-induced seed burial and crop vigour provided a natural advantage that complemented the chemical barrier. Subsequent PoE applications neutralized escapes by inhibiting the ALS enzyme, disrupting the “seed rain” that replenishes the soil seed bank (Joshi *et al.* 2015, Shah and Negi 2024).

It was cleared that, weeds were present in the hand weeding treatment due to the strategic timing of data collection relative to field operations. At 20 DAS, the weed density was recorded immediately before the first scheduled weeding (20–25 DAS) to accurately quantify the initial weed pressure the crop faced since sowing, whereas at 40 DAS, the weed density captured the “second flush” of weeds— newly germinated seedlings that emerged after the first weeding, prior to the second scheduled intervention at 40–45 DAS.

At harvest, the lowest biomass and highest WCE (83.6%) was recorded with two hand weeding, closely followed by the sequential application of pretilachlor PE *fb* chlorimuron-ethyl + metsulfuron-methyl PoE. The sequential herbicidal approach (PE *fb* PoE) maintains long-term suppression by neutralizing staggered weed flushes. Initial application of pretilachlor or pyrazosulfuron-ethyl secures an early resource-dominant niche for the crop by eliminating the primary flush of weed competitors (Bhatt *et al.* 2017). Subsequent intervention with bispyribac-sodium or chlorimuron + metsulfuron arrested the development of late-emerging weeds. This overlapping control window prevents weeds from transitioning into significant vegetative stages, ensuring that vital nutrients and PAR (Photosynthetically Active Radiation) are partitioned toward grain yield rather than being sequestered in weed biomass (Pal *et al.* 2012, Sunil *et al.* 2010).

Pooled data indicated that pretilachlor 1000 g/ha PE *fb* chlorimuron-ethyl + metsulfuron-methyl 4 g/ha PoE recorded the lowest weed index (2.36%), indicating maximum yield shield (**Table 3**). This was closely followed by pretilachlor 1000 g/ha PE *fb* bispyribac-sodium 25 g/ha PoE with a WI of 2.88%. In contrast, the weedy check exhibited the highest crop-weed competition, resulting in a 42.29% grain yield losses. The minimal WI in sequential herbicidal treatments is attributed to significantly reduced weed biomass and superior weed control efficiency. By mitigating crop-weed competition during the critical growth stages, these regimes ensured optimal resource availability for grain filling and yield development (Bhambri and Kolhe 2006, Patel *et al.* 2018a). Conversely, the substantial yield attrition in the weedy check was a direct consequence of

unrestricted weed establishment, which intensified competition for solar radiation, nutrients, and moisture, thereby limiting the crop’s reproductive potential (Joseph *et al.* 2008, Ravisankar *et al.* 2008, Patel *et al.* 2018).

Effect on rice

Rice establishment methods significantly influenced rice productivity, and conventional transplanting produced significantly the highest grain yield with 18.5% and 16.5% increase over dry direct-seeded and WSR methods, respectively (Table 3). Unlike direct-seeded systems, where seedlings face immediate inter-specific competition and abiotic stress, transplanted seedlings benefit from a controlled nursery period. This “head start” facilitates a more robust root-to-shoot ratio, allowing for optimized PAR interception. superior Leaf Area Index (LAI) that promotes more efficient dry matter partitioning towards the panicles, maximizing the number of filled spikelets per unit area (Subramanian *et al.* 2006).

Weed management treatments significantly influenced grain productivity with the weedy check suffering the most substantial losses. In contrast, two hand weeding produced significantly higher grain yield. Among herbicide treatments, pretilachlor PE *fb* chlorimuron + metsulfuron PoE and pretilachlor PE *fb* bispyribac-sodium PoE were statistically at par with manual weeding. This lack of significant difference between sequential herbicides and hand weeding underscores the high technical efficiency of

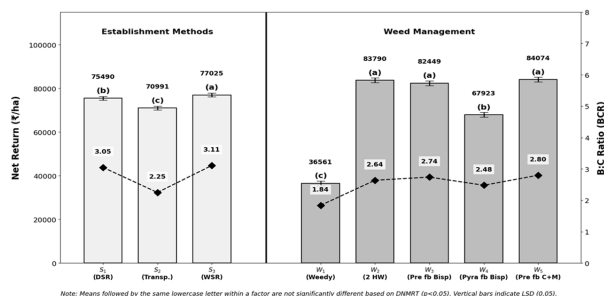


Figure 1. Impact of rice establishment methods and weed management on net returns and B:C ratio

(Bars represent net return (Rs/ha) on the primary axis; the line with markers represents the Benefit-Cost (B:C) ratio on the secondary axis. S₁: direct seeded rice, S₂: conventional transplanting, S₃: sprouted seed line sowing. W₁: weedy check, W₂: two hand weedings, W₃: pretilachlor *fb* bispyribac-sodium, W₄: pyrazosulfuron-ethyl *fb* bispyribac-sodium, W₅: pretilachlor *fb* chlorimuron + metsulfuron-methyl).

these herbicides in keeping a negligible weed-to-crop competition during the critical period and preventing the sequestration of essential mobile nutrients (N, P, K) by weed biomass (Chopra and Angiras 2008). The early-season suppression provided by pretilachlor, followed by post-emergence follow-up applications prevents competition for light and nutrients that led to a 42.29% yield loss in the weedy check by limiting panicle length and grain filling (Khare *et al.* 2014).

Economics

Among the evaluated treatments, line sown wet-seeded rice (WSR) was the most economically efficient, achieving a significantly superior net return with B:C ratio of 3.11. While dry direct-seeded rice (dry-DSR) followed closely in net return with a B:C

Table 3. Weed density, biomass, rice grain yield and weed indices in rice as influenced by establishment methods and sequential herbicide regimes (pooled data)

Treatment	Weed density (no./m ²)						Weed dry biomass (kg/ha)	WCI (%)	WI (%)	Grain yield (t/ha)
	20 DAS/DAT			40 DAS/DAT						
	Grasses	BLWs	Sedges	Grasses	BLWs	Sedges				
<i>Main plot: methods of establishment</i>										
Dry direct-seeded rice	4.63(23.9)	3.03(10.7)	2.36(5.3)	4.03(22.5)	2.90(10.0)	2.39(5.8)	19.40(461)	62.5	15.63	4.37
Conventional transplanted rice	3.98(16.8)	2.56(7.1)	1.96(3.5)	3.57(18.7)	2.60(7.5)	1.96(3.5)	17.15(334)	72.8	--	5.18
Wet-seeded rice (line sown)	4.47(21.8)	2.90(9.6)	2.30(5.0)	3.99(22.3)	2.87(9.7)	2.38(5.7)	19.14(448)	63.5	14.14	4.45
LSD (p=0.05)	0.26	0.20	0.14	0.21	0.15	0.18	0.96	--	--	0.21
<i>Sub plot: weed management</i>										
Weedy check	6.19(38.2)	4.40(19.1)	2.70(7.0)	8.93(79.4)	5.36(28.5)	3.22(10.3)	34.80(1228)	0.0	42.29	3.08
Hand weeding	6.04(36.4)	4.27(18.0)	2.44(5.6)	3.43(11.4)	2.39(5.3)	2.37(5.3)	14.22(202)	83.5	---	5.34
Pretilachlor PE <i>fb</i> bispyribac-sodium PoE	3.08(9.1)	1.82(2.9)	1.90(3.2)	2.14(4.3)	2.15(4.2)	1.80(2.8)	14.57(213)	82.6	2.88	5.18
Pyrazosulfuron PE <i>fb</i> bispyribac-sodium PoE	3.31(10.6)	1.76(2.7)	2.02(3.6)	2.33(5.1)	1.97(3.5)	1.99(3.6)	14.74(219)	82.2	15.17	4.53
Pretilachlor PE <i>fb</i> (chlorimuron + metsulfuron) PoE	3.19(9.8)	1.87(3.1)	1.98(3.5)	2.49(5.7)	2.08(3.9)	1.86(3.0)	14.49(210)	82.9	2.36	5.21
LSD (p=0.05)	0.32	0.13	0.21	0.34	0.18	0.22	0.82	---	---	0.18

Note: *data in parentheses are original values; those outside are ($\sqrt{x+0.5}$) transformed values. **BLW:** broad-leaved weeds; **DAS/T:** days after sowing/transplanting; **fb:** followed by; **WCI:** weed control index; **WI:** weed index; **PE =** pre-emergence application; **PoE =** post-emergence application

Table 4. Percent reduction/increase in weed seed bank influenced by rice establishment and sequential herbicidal regimes (pooled data)

Treatment	0-10 cm	0-10 cm	vs. control (%)	10-20 cm	10-20 cm	vs. control (%)
	Initial	Final		Initial	Final	
<i>Main plot: methods of establishment (S)</i>						
Dry direct-seeded rice	46.59	47.05	+11.36	26.51	26.61	+12.47
Conventional transplanted rice	46.77	42.25	--	26.62	23.66	--
Wet-seeded rice (line sown)	45.04	45.30	+7.22	25.51	25.76	+8.88
LSD (p=0.05)	NS	1.61		NS	1.00	
<i>Sub plot: weed management (W)</i>						
Weedy check	44.76	51.68	--	25.33	29.47	--
Hand weeding	47.47	41.25	-20.18	27.08	23.14	-21.48
Pretilachlor PE <i>fb</i> bispyribac-sodium PoE	45.39	43.07	-16.16	25.74	24.26	-17.68
Pyrazosulfuron PE <i>fb</i> bispyribac-sodium PoE	46.36	46.55	-9.93	26.36	26.30	-10.17
Pretilachlor PE <i>fb</i> (chlorimuron + metsulfuron) PoE	46.67	41.76	-19.20	26.56	23.56	-20.05
LSD (p=0.05)	NS	1.85		NS	2.14	

Note: Initial and Final data represent weed seed bank (seeds/kg of soil) before sowing and after harvest, respectively (pooled data). **vs. Control (%)**: Percent difference calculated using Conventional Transplanted Rice as the control for main plots and Weedy Check as the control for sub-plots; (+) values indicate a higher seed bank than the control, while (-) values indicate a lower seed bank than the control. **PE** = pre-emergence application; **PoE** = post-emergence application, **fb**: followed by; **NS**: Non-significant

ratio of 3.05. In contrast, conventional transplanting recorded the lowest net return and B:C ratio (2.25); despite producing the highest grain yield, the excessive labour and input costs associated with the transplanting process drastically reduced the final profit margin compared to both wet-seeding and dry direct-seeding of rice.

Significantly higher net return and B:C ratio (2.80) were recorded with the sequential application of pretilachlor PE *fb* chlorimuron-ethyl + metsulfuron-methyl PoE, whoever remained statistically at par with hand weeding twice and pretilachlor *fb* bispyribac-sodium PoE. Moreover, herbicide-based sequences demonstrated a significantly higher B:C ratio than manual weeding, which was hampered by high labour costs (2.64). Further, sequential application of pyrazosulfuron-ethyl PE *fb* bispyribac-sodium recorded a relatively lower net return. Contrary to this, weedy check recorded the lowest B:C ratio (1.84), highlighting the shocking economic impact of uncontrolled weed competition on final rice profitability.

Weed seed bank

Initial weed seed bank density (**Table 4**) was uniform across depths. Post-harvest, the weedy check showed a 15.46% increase in weed seed, whereas the lowest final seed banks were recorded with hand weeding and sequential herbicide application. Approximately 63-65% of seeds were concentrated in the surface layer (0-10cm), a distribution typical of rice systems with minimal soil inversion (Misra 1968, Rao *et al.* 2017).

Establishment via conventional transplanting and sequential application of pretilachlor PE *fb*

chlorimuron + metsulfuron PoE effectively depleted the seed bank by 9.66% and 19.20% (vs. their respective controls). The superiority of transplanting (PTR) is attributed to the puddling process, which buries seeds deeper and induces anaerobic decay or fatal germination (Mandal *et al.* 2013, Singh *et al.* 2005). Conversely, the aerobic environment in dry direct-seeded rice favoured seed bank replenishment (Chauhan 2012). The efficacy of sequential herbicide resulted from “overlapping” control by pre- and post-emergence herbicides, which eliminated late-season weed flushes and prevented “seed rain” into the soil reservoir (Joshi *et al.* 2015, Shah and Negi 2024). This suppression of the active seed bank is essential for reducing the long-term weed pressure in non-puddled intensification systems (Rathika *et al.* 2020).

Conclusion

Sequential application of pretilachlor PE followed by chlorimuron + metsulfuron PoE or bispyribac-sodium PoE proved statistically comparable to manual weeding twice, in managing weeds and achieving substantial yield gains while minimizing weed seed rain and progressively depleting the soil weed seed bank. This suppression of seed bank replenishment is central to long-term sustainability and the successful intensification of direct-seeded rice systems.

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