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RESEARCH ARTICLE

Efficacy of integrated weed management (IWM) practices on the weed dynamics, production and productivity of direct-seeded rice

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Abstract

This study assessed the efficacy of Integrated Weed Management (IWM) practices on weed dynamics, crop resistance, weed persistence and the production and productivity of direct-seeded rice during the *Kharif* seasons of 2021 and 2022 at the Agronomical Research Farm, BAU, Ranchi, on sandy loam soil. Twelve IWM treatments, incorporating varying herbicidal doses and inter-culture practices, were evaluated. The weed composition was predominantly grassy (37.59 %), sedge (41.24 %) and broad-leaved (21.16 %) species. The highest weed density and dry weight at 60 days after sowing (DAS) were recorded in the weedy check. Weed Management Efficacy was quantified using indices such as Weed Control Index (WCI), Weed Persistence Index (WPI) and Crop Resistance Index (CRI). The most effective treatments included three hand weedings and the combination of Pretilachlor (1.00 kg a.i./ha, pre-emergence) followed by Bispyribac Sodium (0.025 kg a.i./ha, post-emergence at 20 DAS). Both treatments resulted in significantly higher grain (41.70 q/ha) and straw yield (61.30 q/ha) compared to the weedy check. Economic analysis revealed that Pretilachlor + Bispyribac Sodium provided the highest net return (Rs. 67,064 per ha) and benefit-cost ratio (B: C ratio), followed by three hand weedings (Rs. 58741 per ha). The results indicated that IWM practices, particularly herbicide combinations, significantly improved weed control, crop resistance, yield and economic returns in direct-seeded rice systems.

Keywords: bispyribac sodium; crop resistance index; direct seeded rice; pretilachlor; weed dynamics; weed persistence index

Introduction

India's economy was driven by agriculture, which contributes significantly to the country's GDP. To keep in pace with the growing population, food grain output needed to expand by approximately 3 million tons annually. Rice, the world's major staple crop, faced several challenges under conventional transplanted systems, including declining water tables, reduced productivity, methane emissions, poor soil health and labor shortages during peak demand periods (1). Transplanting was the traditional system of rice cultivation and remained prevalent in many rice growing areas. However, this technique, which involved puddling and transplanting, consumed a large amount of water (2, 3) was an energy-intensive, had been shown to degrade soil systems, increase salinity, cause disruption leading to water scarcity and carbon emissions and negatively affected subsequent winter crops (4). The primary disadvantage of direct-seeded rice (DSR) was its higher weed infestation, even though its yields were comparable to those of transplanted crops. Therefore, effective weed control using all available methods was crucial to the success of DSR. Due to the simultaneous germination of crop and weed seeds, yield loss in DSR could reach 50 - 60 % (5). Despite its proven effectiveness, hand weedings was highly time consuming, laborious and costly. Additionally, the high demand for labor during peak periods and its limited supply necessitated alternative weed management strategies. Under DSR, chemical weed management with pre-emergence herbicides was recommended to overcome these constraints, as it was less labor-intensive and more economical (6). However, spraying pre-emergence herbicides alone was often insufficient to manage the diverse spectrum of weeds, as multiple weed flushes occurred at different growth stages. Therefore, integrating pre-emergence herbicides with hand weedings or applying pre- and post-emergence herbicides sequentially proved to be a more practical and effective approach to weed control in DSR. Considering this background, the present study was conducted to evaluate the impact of weed management techniques on direct-seeded rice in the upland region of Jharkhand.

Material and Methods

To determine the effectiveness of integrated weed management techniques for weed control in direct-seeded rice, a two-year field experiment was conducted at

Agronomical Research Farm Agricultural University Birsa, Ranchi, Jharkhand, during Kharif seasons of 2021 and 2022. The experimental field had a sandy loam texture and was medium in available phosphorus (18.92 kg/ha), medium in available nitrogen (228.12 kg/ha) and low in organic carbon (0.38 %). It also had a potash content of 154.30 kg/ha. The experiment comprises of 12 treatments: Pendimethalin (30 EC) @ 0.75 kg a.i. /ha PE (T_1), Pendimethalin (30 % EC) @ 0.75 kg a.i. /ha as PE followed by 1 hand weedings at 25 DAS (T_2), Pendimethalin (30 % EC) @ 0.75 kg a.i. /ha as PE followed by 2 hand weedings at 25 DAS and 40 DAS (T_3), Pendimethalin (30 % EC) @ 0.75 kg a.i. /ha PE followed by Sesbania incorporation at 25 DAS (T_4), Pendimethalin (30 % EC) @ 0.75 kg a.i. /ha as PE followed by Bispyribac Sodium (10 % SC) @ 0.025 kg a.i. /ha PoE (T_5), Pretilachlor (50 % EC) @ 1.00 kg a.i. /ha PE (T_6),Pretilachlor (50 % EC) @ 1.00kg a.i. /ha PE followed by 1 hand weedings 25 DAS (T_7), Pretilachlor (50 % EC) @ 1.00 kg a.i. /ha PE followed by 2 hand weedings at 25 DAS and 40 DAS (T_8), Pretilachlor (50 % EC) @ 1.00kg a.i. /ha followed by Sesbania incorporation at 25 DAS (T_9), Pretilachlor (50 % EC) @ 1 .00 kg a.i. /ha PE followed by Bispyribac Sodium (10 % SC) @ 0.025 kg a.i. /ha PoE (T_{10}), 3 Hand weedings at 25, 40 and 55 DAS (T_{11}) and Weedy check (T_{12}). These treatments were arranged in randomized block design and three replications.

The rice variety "Sahbhagi Dhan" was directly sown at a rate of 80 kg/ha in rows spaced 20 cm apart, following basal fertilizer treatment, on 22nd June 2021 and 25th June 2022, respectively. After rice sowing, Sesbania was also sworn at a seed rate of 40 kg/ha. The recommended fertilizer dose of 80 kg N + 40 kg P_2O_5 + 20 kg K_2O /ha was applied using urea, di-ammonium phosphate and muriate of potash. Half the nitrogen dose along with the full doses was applied as a basal application of potassium and phosphorus. The remaining half of the nitrogen was top-dressed in two splits-first at the peak tillering stage and the second at the onset of the panicle stage. Sesbania, swanned along with rice, was incorporated into soil five weeks after sowing using a spade. To prevent seed rotting, soil moisture was maintained slightly damp but not waterlogged from seeding to emergence. To avoid water stress during the three leaf phases, tillering, panicle initiation and grain filling stages, the field was irrigated, while excess water was drained off at anthesis to prevent spikelet sterility. At 60 days after crop sowing (DAS), a 25 × 25 cm quadrate measuring was placed randomly at two locations in each plot to record the dry weight (g/m^2) and weed density (number/ m^2). Weed control efficiency (WCE) was calculated based on dry matter production at 60 DAS. Prior to statistical analysis, the weed density and dry weight data were transformed using the square root transformation ($\sqrt{X + 0.5}$).

To assess the efficacy of weed management practices, several indices were used, including the Weed index (WI), Weed Control Efficiency (WCE), Weed Control Index (WCI), Herbicide Efficiency Index (HEI) and Weed Persistence Index (WPI). The growth and yield data were subjected to statistical analysis.

The weed control efficiency which was expressed in percentage to determine the basis of reduction in dry matter production in treated plot relative to the control plot.

$$\text{WCE (\%)} = \frac{\text{DWC-DWT}}{\text{DWC}} \times 100$$

where,

WCE = Weed control efficiency (%)

DWC = Weed dry weight in weedy check plot (g/m^2)

DWT = Weed dry weight in treated plot (g/m^2)

Weed index (%)

The amount of yield loss brought on by weeds compared to a plot free of weeds was known as the weed index (7) used the following formulas to obtain the weed index:

$$\text{WI (\%)} = \frac{\text{YMFC-YT}}{\text{YMFC}} \times 100$$

where,

WI = Weed index (%)

YWFC = Weight of grain yield in weed free check (kg/ha)

YT = Weight of grain yield in plot under treatment (kg/ha)

Weed Persistence Index (WPI)

The efficiency of the chosen herbicides and the resistance of weeds to the tested treatments are shown by this index, which was calculated using the following formula as recommended by (8):

$$\text{WPI} = \frac{\text{WT}}{\text{WC}} \times \frac{\text{WPC}}{\text{WPT}}$$

where,

WT = Weed dry weight in treated plot (g/ m^2)

WC= Weed dry weight in weedy check plot (g/ m^2)

WPC= Weed population in weedy check plot (No /m^2)

WPT= Weed population in treated plot (No / m^2)

Crop Resistance Index (CRI)

Using the crop resistance index, the relationship between crop and weed biomass was correlated, indicating an indirect proportionality between two. The index was computed using the formula provided below, which was provided by (8).

$$\text{CRI} = \frac{\text{WCT}}{\text{WCC}} \times \frac{\text{WC}}{\text{WT}}$$

where,

WT = Weed dry weight in treated plot (g/ m^2)

WC= Weed dry weight in weedy check plot (g/ m^2)

WCC=Dry matter accumulation by the crop in weedy check plot (g/ m^2)

WCT= Dry matter accumulation by the crop in treated plot (g/ m^2)

Herbicide Efficiency Index (HEI)

HEI index was calculated using the following formula, which shows the herbicides' potential to kill weeds and their phytotoxicity to the crop (9).

$$HEi = \frac{\frac{YT-YC}{YC}}{\frac{WT}{WC}}$$

where,

YT = Weight of grain yield in plot under treatment (kg/ha)

YC= Weight of grain yield in weedy check plot (kg/ha)

WT= Weed dry weight in treated plot (g/m^2)

WC= Weed dry weight in weedy check plot (g/m^2)

Economics analysis

The economics of each treatment were evaluated using a net return and benefit cost ratio.

Net return (Rs./ha)

The net profit from each treatment was calculated separately, by using the formula:

Net return = Gross return (Rs./ha) - Cost of cultivation (Rs./ha)

Benefit cost ratio

The benefit cost ratio was calculated using the formula:

$$\text{Benefit cost ratio} = \frac{\text{Net return (Rs./ha)}}{\text{Total cost of cultivation (Rs. /ha)}}$$

Statistical analysis

The ANOVA method, as described by (10) was used to statistically analyze data for various attributes, examining the relevance of comparisons. A 5 % probability of error was applied to calculate the value indicating significant difference and critical difference (CD) values were determined for comparisons among treatment means.

Results and Discussion

Effect of weed management practices on weed dynamics:

Table 1 and Plate 1 showed the primary weed flora germinated with the direct-seeded rice, as observed in the experimental field throughout both years (based on pooled data). Among grasses, *Eleusine indica* (L.) Gaerts, *Dactyloctenium aegyptium* (L.) and *Echinocloa crusgalli* (L.) P Beauv., *Cynodon dactylon* (L.) Pers., were the major weed species observed. In the broad-leaf group *Aeschynomene indica*, *Ageratum conyzoides* (L.), *Commelina nodifolia* (L.), *Alternanthra sessilis* (L.) and *Coronopus didymus* (L.) and among sedges *Cyperus rotundus* (L.) and *Cyperus iria* (L.) and *Fimbristylis miliacea* (L.) Vahl were identified as dominant weeds. The composition of grassy, broad-leaf and sedges weeds accounted for 37.59 %, 21.16 % and 41.24 % respectively. The relative weed density of major weed species was as follows: *Fimbristylis miliacea* (L.) Vahl- 19.02 %, *Eleusine indica* (L.) Gaerts -18.26 %, *Echinocloa crusgalli* (L.) P. Beauv -12.94 %, *Cyperus rotundus* (L.) -12.32 %, *Aeschynomene indica* (L.) -7.31 %, *Alternanthra sessilis* (L.) -6.01 %, *Commelina nodifolia* (L.) - 4.71 %, *Dactyloctenium aegyptium* (L.)- 4.5 %, *Ageratum conyzoides* (L.)- 3.04 %, *Cynodon dactylon* (L.) Pers.-1.82 % respectively of total weed flora infesting the experimental field. This might have

Table 1. Relative weed density (%) and dominant weed flora of the weedy check plot in the direct -seeded rice experimental field at 40 DAS. (Pooled data of 2021 and 2022)

Common name	Botanical name	Family	Number /m^2	Relative weed density (%)
		Grassy		
Banmadua (Goose grass)	*Eleusine indica* (L.) Gaerts.	Poaceae	120	18.26
Sawa (Barnyard grass)	*Echinocloa crusgalli* (L.) P. Beauv.	Poaceae	85	12.93
Makra (Crow foot grass)	*Dactyloctenium aegyptium* (L.)	Poaceae	30	4.56
Dub (Bermuda grass)	*Cynodon dactylon* (L.) Pers.	Poaceae	12	1.82
		Broad leaved		
Budda pea (Indian jointvetch)	*Aeschynomene indica* (L.)	Commelianaceae	48	7.30
Garundi (Wetland amaranth)	*Alternanthra sessilis* (L.)	Amaranthaceae	40	6.088
Kena (Common day flower)	*Commelina nodifolia* (L.)	Commelianaceae	31	4.71
Mahkua (Tropical ageratum)	*Ageratum conyzoides* (L.)	Asteraceae	20	3.04
		Sedges		
Choti bhui (Globe fringerwh)	*Fimbristylis miliacea* (L.) Vahl	Cyperaceae	152	23.14
Motha (nut grass)	*Cyperus rotundus* (L.)	Cyperaceae	81	12.32
Umbrella sedge (Rice foot sedge)	*Cyperus iria* (L.)	Cyperaceae	38	5.78
TOTAL			**657**	**100 %**

Echinocloa crusgalli

Dactyloctenium aegyptium

Eleusine indica

Cynodon dactylon

Grassy weeds

Broad leaved weeds

Commelina nodifolia

Ageratum conyzoides

Aeschynomene indica

Sedge weeds

Plate 1. Major grassy, broad leaved and sedge weeds of direct seeded rice.

been because *Eleusine indica* and *Echinocloa crusgalli* were the most serious weeds affecting direct-seeded rice. *Eleusine indica* tended to grow in direct-seeded rice fields due to a combination of environmental factors, seed bank dynamics and less intensive weed management techniques. *Aeschynomene indica* and *Ageratum conyzoides* were fast-growing species that competed with rice for nutrients, light and space. *Aeschynomene indica* thrived in disturbed or less compacted soil, while *Ageratum conyzoides* tolerated a range of soil types and conditions. Similarly, among sedges, *Cyperus rotundus* was a persistent weed that propagated through underground tubers, creating a recurring infestation. *Cyperus iria*, while less aggressive, produced large seeds and can germinate rapidly under direct-seeding conditions. It tolerated variable water levels and could overtake rice seedlings, reducing yields in direct-seeded systems. Both grew taller and competed for nutrients and water, making them problematic for rice cultivation. The results were in line with the previous research findings (11, 12).

Pooled data for total weed density in direct seeded rice were recorded as influenced by different weed management practices. The weed free plot (3 hand weedings at 25, 40 and 55 DAS) recorded significantly the lowest weed density at 60 DAS (234 / m^2) over weedy check (1194/ m^2), which was at par with herbicidal application of Pretilachlor @ 1.00 kg a.i /ha (PE) followed by Bispyribac Sodium @ 0.025 kg a.i / ha PoE 20 DAS (256 / m^2) (Table 2). The reduction in weed population in these treatments was mainly due to effective control of weeds during the critical crop-weed competition period (20 to 60 DAS). The lower weed density in this treatment might have been due to inherent ability to inhibit cell division and growth, thereby hampering weed germination. Emerging weeds were controlled by pre-emergence herbicides application and emerging weeds were controlled by post emergence application. These results were in conformity with previous reports (13, 14).

It was evident from pooled data (Table 2) that, among weed management practices, the weed free plot (3hHand weedings at 25, 40 and 55 DAS) significantly reduced the total dry weight of weeds (98.31 g/ m^2) at 60 DAS, which was at par with Pretilachlor @ 1.00 kg a.i /ha (PE) followed by Bispyribac Sodium @ 0.025 kg a.i/ha PoE 20 DAS (110.19 g/ m^2) and Pendimethalin @ 0.75 kg a.i / ha (PE) followed by Bispyribac Sodium @ 0.025 kg a.i/ ha PoE 20 DAS (151.86 g/ m^2). In contrast the significantly highest weed dry weight at 60 DAS (628.78 g/ m^2) was noted in weedy check. The critical period of crop weed competition in rice was identified to be around 20 to 60 DAS. Reduction in weed dry weight was attributed to effective control of grasses, sedges and broad-leaved weeds with Bispyribac in rice fields. This was also stated in earlier research reports (15, 16, 17, 18, 19).

Weed Control Efficiency at 60 DAS presented in Table 2 and in Fig. 1 was significantly highest in weed- free plot (3 hand weedings at 25, 40 and 55 DAS)- 84.39 %) followed by Pretilachlor @ 1.00 kg a.i /ha (PE) followed by Bispyribac Sodium @ 0.025 kg a.i/ha PoE 20 DAS (82.54 % on pooled basis). This was likely due to reduced weed dry matter compared to other treatments. Pretilachlor is a systemic herbicide absorbed by the roots and / or leaves and translocated to the meristems. Belonging to the Chloroacetamide group, it inhibited Very Long Chain Fatty Acid (VLCFA) synthesis, disrupting cell division and growth, thus leading to effective weed control. Bispyribac-sodium was an effective selective, systemic post-emergence herbicide used against grasses, sedges and broad-leaved weeds- particularly *Echinochloa* spp.- in direct-seeded rice. It inhibited the enzyme acetolactate synthase (ALS), disrupting amino acid biosynthesis, which halts cell division and resulted in plant growth cessation, chlorosis, necrosis and eventual plant death (20). The highest WCE with 3 hand weedings was also reported in earlier studies (21).

Weed index (WI) measures yield loss in percentage which was significantly influenced by weed control methods. Among the various herbicide combinations, Pretilachlor @ 1.00 kg a.i./ha (PE) followed by Bispyribac Sodium @ 0.025 kg a.i./ha PoE 20 DAS produced a significantly lower weed index (1.95 %). Based on pooled data (Table 2, Fig. 1) the highest WI value (83.09 %) was recorded under weedy check. This could have been due to the increased effectiveness of pre-emergence herbicide application combined with interculture action and broad-spectrum weed control, as described in earlier research (22, 23).

Table 2. Efficacy of integrated weed management on direct-seeded rice's weed index parameters, total weed density, weed dry weight and weed control efficiency at 60 DAS (Pooled data of 2021 and 2022)

Treatments	Total weed density (number / m^2)	Total weed dry weight (g/m^2)	Weed control efficiency (%)	Weed index (%)
	60 DAS			
T_1: Pendimethalin @ 0.75 kg a.i /ha (PE)	26.19 (689)	17.70 (315.45)	49.83	45.41
T_2: Pendimethalin @ 0.75 kg a.i /ha (PE) then 1hand weedings at 25 DAS	25.30 (650)	17.23 (300.32)	52.22	32.32
T_3: Pendimethalin @ 0.75 kg a.i /ha (PE) then 2 hand weedings at 25 and 40 DAS	24.74 (614)	16.23 (270.08)	57.20	23.55
T_4: Pendimethalin @ 0.75 kg a.i /ha (PE) then Sesbania incorporation at 25 DAS	24.10 (588)	15.63 (244.06)	61.12	17.89
T_5: Pendimethalin @ 0.75 kg a.i /ha (PE) then Bispyribac Sodium @ 0.025 kg a.i/ha (PoE) at 20 DAS	19.74 (397)	12.34 (151.86)	75.84	13.58
T_6: Pretilachlor @ 1.00 kg a.i /ha (PE)	25.75 (669)	17.39 (302.08)	51.93	38.61
T_7: Pretilachlor @ 1.00 kg a.i /ha (PE) then 1 hand weedings at 25 DAS	24.86 (620)	16.41 (278.52)	55.98	26.19
T_8: Pretilachlor @ 1.00 kg a.i /ha (PE) then 2 hand weedings at 25 and 40 DAS	24.42 (598)	16.05 (257.42)	58.98	20.98
T_9: Pretilachlor @ 1.00 kg a.i /ha (PE) then Sesbania incorporation at 25 DAS	22.09 (496)	14.89 (228.94)	63.39	16.45
T_{10}: Pretilachlor @ 1.00 kg a.i /ha (PE) then Bispyribac Sodium@ 0.025 kg a.i/ha (PoE) at 20 DAS	16.00 (256)	10.47 (110.19)	82.54	1.95
T_{11}: Three hand weedings at 25, 40 and 55 DAS (weed free plot)	15.29 (234)	9.91 (98.31)	84.39	0.00
T_{12}: Weedy Check	34.36 (1194)	25.08 (628.78)	0.00	83.09
SE m ±	1.25	1.19	6.01	2.41
CD (P = 0.05)	3.66	3.48	17.63	7.06
CV%	9.16	13.02	18.03	15.63

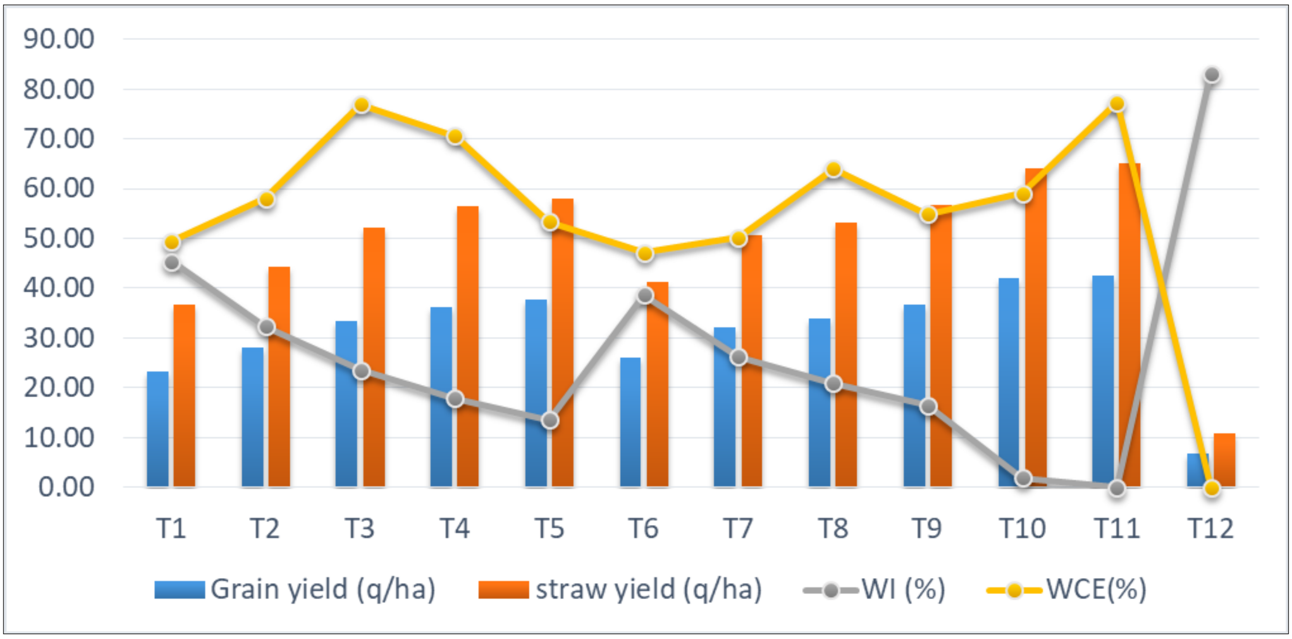


Fig. 1. Effect of integrated weed management (IWM) on grain yield (GY -q/ha), straw yield (SY-q/ha), weed index (WI -%) and weed control efficiency (WCE- %). This figure clearly showed that T_{11} recorded the highest grain and straw yield, along with the highest WCE and the lowest WI followed by T_{10}. (Pooled data of 2021 and 2022).

Assessment of the efficacy of weed management practices

Pooled data for WPI indicated the tolerance of weeds to different herbicide treatments as well as their efficacy to eradicating weeds in direct seeded rice. Table 2 indicated that the Pretilachlor @ 1.00 kg a.i /ha (PE) followed by Sesbania incorporation 25 DAS recorded the highest persistence index (0.92) next Pendimethalin @ 0.75 kg a.i / ha (PE) (0.91) indicating resistance of escaped weeds to control measures. Among other weed control treatments combination of different herbicides such as Pendimethalin @ 0.75 kg a.i /ha (PE) then 2 hand weedings at 25 and 40 DAS and Pretilachlor @ 1.00 kg a.i /ha (PE) followed by Bispyribac Sodium @ 0.025 kg a.i/ha PoE at 20 DAS recorded the lowest persistent index 0.80 at 20 DAS. This indicated broad- spectrum effect in controlling the weeds.

The HEI and reflected the crop's susceptibility to herbicide damage and its ability to control weeds effectively. The three hand weedings at 25, 40 and 55 DAS showed the highest crop resistance, subsequently by Pretilachlor @ 1.00 kg a.i /ha (PE) and then by by Bispyribac Sodium @ 0.025 kg a.i/ha PoE at 20 DAS which recorded a CRI of 29.60 at 60 DAS Table 3. This indicated that compared to other treatments, herbicides had a much less detrimental effect on crops. The weedy check had the most detrimental impact, as evidenced by its lowest CRI value (1.0), revealing that proper weed management significantly enhances crop vigor. The HEI, which exhibited the phytotoxicity and weed control ability of herbicide treatment (Pretilachlor @ 1.00 kg a.i /ha (PE) then *Bispyribac* Sodium @ 0.025 kg a.i/ha (PoE) ha measured the highest, 31.76 at 60 DAS, next the three hand weedings at 25, 40 and 55 DAS recorded 34.13. The weedy check recorded the lowest HEI grade of (0) indicating the greatest adverse impact on the crop.

Table 3. Effect of weed management practices on weed persistence, crop resistance and herbicide efficiency index of direct seeded rice at 60 DAS under upland condition (Pooled data of 2021 and 2022)

Treatments	Weed persistence index	Crop resistance index	Herbicide efficiency index
		60 DAS	
T_1: Pendimethalin @ 0.75 kg a.i /ha (PE)	0.91	5.82	4.89
T_2: Pendimethalin @ 0.75 kg a.i /ha (PE) then 1Hand weedings at 25 DAS	0.88	8.26	7.19
T_3: Pendimethalin @ 0.75 kg a.i /ha (PE) then 2 Hand weedings at 25 and 40 DAS	0.80	10.10	9.79
T_4: Pendimethalin @ 0.75 kg a.i /ha (PE) then Sesbania incorporation at 25 DAS	0.81	10.67	11.11
T_5: Pendimethalin @ 0.75 kg a.i /ha (PE) then Bispyribac Sodium @ 0.025 kg a.i/ha (PoE) at 20 DAS	0.81	17.64	18.95
T_6: Pretilachlor @ 1.00 kg a.i /ha (PE)	0.86	6.72	5.89
T_7: Pretilachlor @ 1.00 kg a.i /ha (PE) then 1hand weedings at 25 DAS	0.87	9.82	9.69
T_8: Pretilachlor @ 1.00 kg a.i /ha (PE) then 2 hand weedings at 25 and 40 DAS	0.81	9.85	9.79
T_9: Pretilachlor @ 1.00 kg a.i /ha (PE) then Sesbania incorporation at 25 DAS	0.92	12.75	13.60
T_{10}: Pretilachlor @ 1.00 kg a.i /ha (PE) then Bispyribac Sodium @ 0.025 kg a.i/ha (PoE) at 20 DAS	0.80	29.60	31.76
T_{11}: Three hand weedings at 25, 40 and 55 DAS	0.78	32.83	34.13
T_{12}: Weedy Check	1.00	1.00	0.00
SE m ±	0.11	3.13	2.86
CD (P = 0.05)	0.33	9.18	8.38
CV%	22.63	41.98	37.87

Impact of IWM practices on yield and productivity

Three hand weedings at 25, 40 and 55 DAS resulted in significantly higher grain and straw yield (44.36 q/ha and 63.96 q/ha, respectively), than the weedy check (Fig. 1 and Plate 2). However, this was statistically comparable to Pretilachlor @ 0.75 kg a.i /ha (PE) next Bispyribac Sodium @ 0.025 kg a.i/ha PoE at 20 DAS in terms of straw yield and Pretilachlor @ 1.00 kg a.i /ha (PE) then by Bispyribac Sodium @ 0.025 kg a.i/ha PoE at 20 DAS in terms of grain yield (Table 4-pooled based dataThe lower grain and straw yield under the weedy check attributed to maximum weed density and weed dry matter, which led to fewer tillers, lower plant dry matter and reduced plant height. Higher grain yield under effective treatment was attributed to enhanced remobilization of stem reserved towards the grain formation. Before flowering, certain carbohydrates are stored in culms and leaf sheaths were later translocated to the grain. The findings aligned with earlier research (24, 25, 26). Pretilachlor @ 1.00 kg a.i /ha (PE) followed by Bispyribac Sodium @ 0.025 kg a.i/ha (PoE) at 20 DAS yielded the highest net return (Rs. 67,064 per ha) and B : C ratio (3: 18), compared to Pendimethalin @ 0.75 kg a.i /ha (PE) followed by Bispyribac Sodium @ 0.025 kg a.i/ha (PoE) at 20 DAS. In contrast, the weed check exhibited significantly lower B: C ratios (0:16) and net returns (Rs 2550 per ha). The higher net return under herbicide-based treatment was due to lower labour and interculture cost compared to three manual weedings, not the higher yield. These findings were consistent with those from previous studies (27, 28).

Crop-Weed Interaction

The pattern of crop yield and the weed data clearly demonstrated that crop yield increases with a decrease in the weed population and the total weed dry weight. Treatment with the maximum WCE and the lowest WI recorded the highest yield. Three hand weedings at 25, 40 and 55 DAS was the best as compared to other treatments. 3 hand weedings produced the lowest weed number, weed dry matter, weed persistence index and WI, while also achieving the highest WCE, HEI and crop yield providing it to be most effective strategy. The interaction between crop and weed data can be more clearly explained with the help of correlation analysis:

Correlation analysis

Correlation analysis among weed and yield parameters revealed that the WI (%) was significant and negative correlated with WCE (%) at 60 DAS ($r = -0.855$; $p = 0.01$) and GY ($r = -0.998$; $p = 0.01$) (Fig. 2 A, B). Alternatively, it showed a positive correlation with total weed density ($r = 0.939$; $p = 0.01$) and total dry matter ($r= 0.965$; $p = 0.01$) at 60 DAS (Fig 2, C, D). WCE also exhibited that a significant negative correlation with WPI ($r = -0.858$; $p = 0.01$) and significant positive correlation with HEI ($r= 0.53006$; $p= 0.01$) at 60 DAS (Fig. 2 E, F). This analysis indicated that for every unit increase in WI, rice grain yield and WCE decreases, while weed density and dry matter increased. Furthermore, improvement in WCE led to a decrease in WPI and an increase in HEI. Linear regression explained 73.04 % and 99.7 % of the variation in WCE and GY (y-axis) respectively, as caused by WI (x-axis). Similarly, WI accounts for 81.2 % and 93 % of the change in total weed density and dry matter. Furthermore, 73 % and 28 % of the variation in WPI and WCE are explained by WCE and HEI respectively.

Table 4. Effect of integrated weed control practices on the profitability of direct-seeded rice as well as grain and straw yield characteristics (Pooled data of 2021 and 2022)

Treatments	Grain yield (q/ha)	Straw yield (q/ha)	Net return (Rs/ha)	B:C ratio
T_1: Pendimethalin @ 0.75 kg a.i /ha (PE)	25.74	39.35	34277	1.84
T_2: Pendimethalin @ 0.75 kg a.i /ha (PE) then 1 hand weedings at 25 DAS	30.63	46.88	37993	1.52
T_3: Pendimethalin @ 0.75 kg a.i /ha (PE) then 2 hand weedings at 25 and 40 DAS	34.79	52.73	41343	1.37
T_4: Pendimethalin @ 0.75 kg a.i /ha (PE) then Sesbania incorporation at 25 DAS	36.73	55.01	48349	1.79
T_5: Pendimethalin (PE) then Bispyribac Sodium @ 0.025 kg a.i/ha (PoE) at 20 DAS	38.33	55.68	56718	2.64
T_6: Pretilachlor @ 1.00 kg a.i /ha (PE)	28.37	43.45	40132	2.20
T_7: Pretilachlor @ 1.00 kg a.i /ha (PE) then 1hand weedings at 25 DAS	33.56	51.29	44421	1.81
T_8: Pretilachlor @ 1.00 kg a.i /ha (PE) then 2 hand weedings at 25 and 40 DAS	35.67	53.50	43462	1.47
T_9: Pretilachlor @ 1.00 kg a.i /ha (PE) then Sesbania incorporation at 25 DAS	37.55	55.33	51541	2.04
T_{10}: Pretilachlor @ 1.00 kg a.i/ha (PE) then Bispyribac Sodium@ 0.025 kg a.i/ha (PoE) at 20 DAS	43.19	62.76	67064	3.18
T_{11}: Three hand weedings at 25, 40 and 55 DAS	44.36	63.96	58741	1.85
T_{12}: Weedy Check	9.34	13.17	2550	0.16
SE m ±	1.85	2.92	3648	0.15
CD (P = 0.05)	5.43	8.57	10699	0.43
CV%	9.67	10.24	14.40	13.78

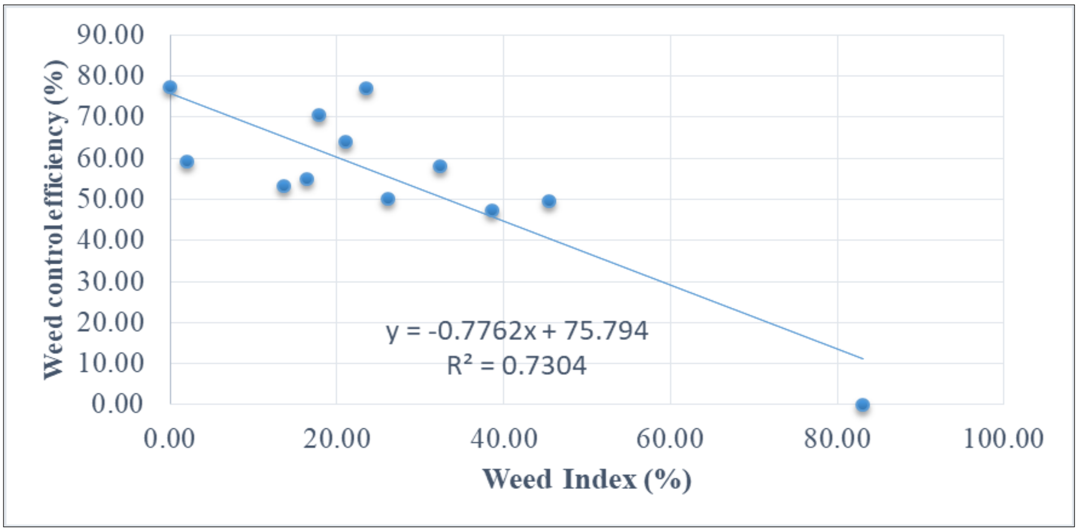
Weedy Check (T_{12})

Pretilachlor @ 1.00 kg a.i /ha (PE) followed by Bispyribac Sodium @ 0.025 kg a.i/ha (PoE) at 20 DAS (T_{10})

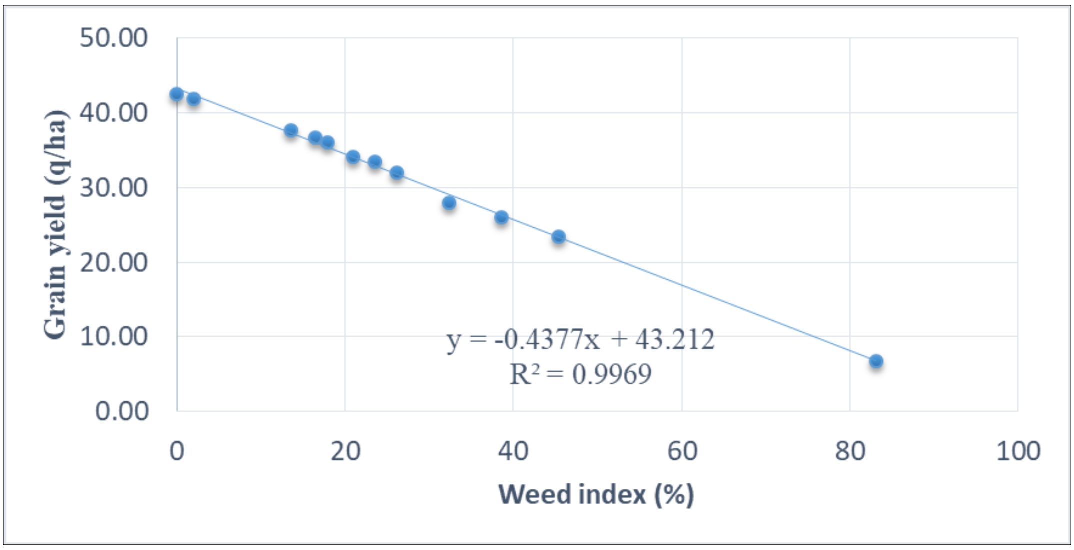
Pendimethalin @ 0.75kg a.i/ha (PE) followed by Bispyribac Sodium @ 0.025 kg a.i/ha (PoE) at 20 DAS (T_5)

Three hand weedings at 25, 40 and 55 DAS (T_{11})

Plate 2. Picture-Photographs of experimental plots.



A



B

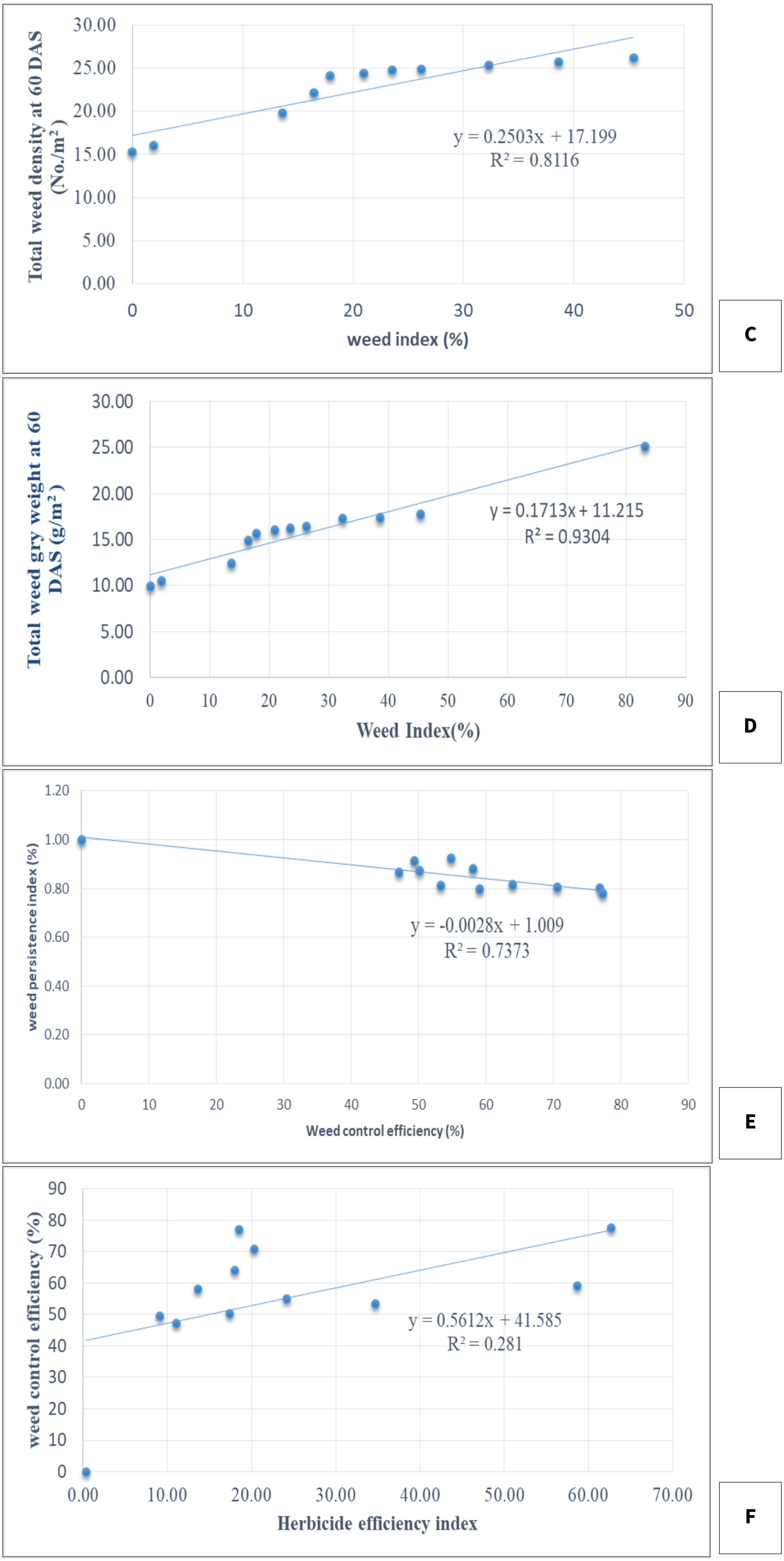


Fig. 2. (A, B, C, D, E, F) Correlation between various weed indices (WI) and yield parameters using pooled mean data from two years (2021 ad 2022). For total weed density and total weed dry weight transformed data values ($\sqrt{X} + 0.5$) were used prior to analysis. Also, present correlation was significant at $p = 0.01$.

Conclusion

Effective weed management was identified as a critical factor in achieving sustainable agricultural productivity, particularly in Jharkhand, where weed pressure posed a serious constraint to crop growth and yield. Among the strategies evaluated, the application of Pretilachlor (50 % EC) at 1.00 kg a.i./ha (PE) followed by Bispyribac sodium (10 % SC) at 0.025 kg a.i./ha (PoE) at 20 DAS provided the most effective weed suppression. This combination demonstrated superior herbicide efficacy and significantly enhanced WCE by minimizing weed competition during critical growth stages. It is therefore recommended as an optimal strategy for weed management in direct -seeded rice. Moreover, integrating this strategy with mechanical and cultural practices could further enhance its effectiveness leading to more sustainable and holistic weed management solutions in the region.

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Authors' contributions

RPM contributed to conceptualization, investigation, funding acquisition, methodology writing -original draft writing-review and editing. MK contributed to conceptualization, investigation methodology, writing-review and editing. SKP contributed to designing methodology, formal analysis, writing review and editing. All authors read and approved the manuscript.

Compliance with ethical standards

Conflict of interest: The authors declare no conflict of interest.

Ethical issues: None

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