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Weed management in dry direct-seeded rice: Assessing the impacts on weeds and crop

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ABSTRACT

Weeds are the major biotic stress limiting productivity, profitability and sustainability of direct-seeded rice (DSR). Effective weed control determines the success of DSR. Therefore, a field study was undertaken to assess the impacts of potential pre- and post-emergence herbicides in sequence and integrated use of herbicides with other methods on weeds and DSR. Eleven weed control treatments comprising of six combinations of pre- and post-emergence herbicides, two brown manuring, one herbicide with manual weeding, and two control (weed-free check and unweeded control) were evaluated in a randomized complete block design with three replications. Results showed that grassy weeds were most dominant, constituting 66.0–91.8% of total weed dry weight across the treatments. Unit increase in weed density (per m^2) and weed dry weight (g/m^2) could reduce rice grain yield by 14.5 and 11 kg/ha, respectively. All weed control treatments impacted weed interference, crop growth and yield significantly. Sequential applications of pendimethalin (1.0 kg/ha) as pre-emergence and ready-mixture of penoxsulam + cyhalofop-butyl (130 g/ha) at 25 days after sowing (DAS) significantly reduced weed dry weight by 87.6% at harvest, and was superior to other treatments. This treatment increased rice grain yield (3.92 t/ha) by 378.9% over unweeded control, gross benefit: cost (2.30) by 31.4% over weed-free check, and gave highest overall impact index (1.27) with an economic threshold level of 9.0 weeds/m^2, and found to be the best weed control option in DSR. Likewise, brown manuring followed by application of metsulfuron-methyl 10% + chlorimuron-ethyl 10% (20 g/ha Almix) at 40 DAS led to 80.3% reduction in weed dry weight, causing significant improvements in crop growth and grain yield (3.67 t/ha) with 30.3% higher gross benefit: cost over weed-free check, and could become a profitable alternative weed control option in DSR.

Direct-seeded rice (DSR) is emerging as a profitable and sustainable rice production system to address the mounting scarcity of fresh water, labour and energy in agriculture sector. Dry seeding of rice avoids need for ponding water vis-à-vis transplanting, thus requires ~36% less water (Mohammad *et al.* 2018) and ~60% less labour (Kumar and Ladha 2011) compared to traditionally grown puddled transplanted rice (TPR), depending on season and types of DSR. However, unlike TPR, it lacks the initial 'head start' over weeds and is subjected to high weed pressure due to dry tillage and alternate wetting and drying conditions. In absence of effective weed control measures, yield losses are greater in DSR than in TPR, which vary from 50-91% (Rao *et al.* 2007, Sen *et al.* 2018). Effective weed management is therefore, key for sustainable rice production under dry-seeded situation. Currently, herbicide has become the most important weed management tool as it offers timely, effective, economical and practical way of weed control. However, sole applications of either pre- or post-emergence herbicides could not control diverse weeds effectively in DSR (Awan *et al.* 2015). Again, over-dependence on similar herbicide(s) may lead to weed shift and/or herbicide-resistant weeds. Fewer studies have highlighted the higher efficacy of sequential applications of pre- and post-emergence herbicides on weeds compared to their sole applications (Awan *et al.* 2015, Chauhan *et al.* 2015). Pre-emergence herbicides initially control germinating weeds and late-emerging weeds are controlled by selective post-emergence herbicides. Response of herbicides is location-specific, depends on climate, soil and types of weeds, and therefore, needs to be evaluated across locations. Further, brown manuring (co-culture of *Sesbania* with rice and subsequent killing with 2, 4-D) has been reported to smother weeds in DSR and enhance rice yield (Maity and Mukherjee 2011, Nawaz *et al*. 2017). In view of these facts, an experiment was formulated with a hypothesis that sequential applications of pre- and post-emergence herbicides and/or integration of herbicides with brown manuring may provide desirable weed control in DSR, leading to higher productivity and profitability.

The experiment was initiated at ICAR–Indian Agricultural Research Institute (IARI), New Delhi, India (28°38' N, 77°10' E and 228.6 m above mean sea-level) under natural weed infestations during the rainy season of 2016. Eleven weed control treatments (**Table 1**) were evaluated in a randomized complete block design with three replications. The field was dry-cultivated before sowing and rice cultivar '*Pusa Sugandh 5*' (125-130 days' duration) was directly sown using a seed drill with a seed rate of 25 kg/ha at 20-cm row spacing. Crop was managed uniformly throughout the growth period, except for weed control. Pre- (at 1 DAS) and post-emergence (at 25 DAS) herbicides were applied with a knapsack sprayer calibrated to deliver 500 litres water per ha through flat-fan nozzle. For brown manuring (BM), *Sesbania* seeds (25 kg/ha) were sown in between the rice rows and subsequently, knocked down with 2, 4-D (0.5 kg/ha) at 28 DAS. An area of 50 cm (along the rows) × 40 cm (across the rows) was randomly selected from two places in each plot and weed samples were collected at 60 DAS and harvest from that area, and categorized into grasses, broad-leaved weeds and sedges. Collected weed samples were first air-dried for 2 days and then oven-dried at 65±5°C until constant dry weight (~48 h), which is more reliable estimate for bio-efficacy evaluation of weed control treatments (Das 2001). Weed control index (WCI), that portrays per cent reduction in weed dry weight per unit area was determined as per Das (2008). Rice crop was harvested at physiological maturity and grain yield was recorded at 14% moisture content. Minimum support price (MSP) was used to calculate the economics. Analysis of data was performed through analysis of variance (ANOVA) using the F-test. Weed data with coefficient of variation (CV) >20% were transformed through square-root method $[(x+0.5)^{1/2}]$ prior to ANOVA to improve the homogeneity of variance (Das 1999). Multiple comparisons of treatment means were made using least significant difference (LSD) method at p=0.05 (Fisher 1960). The relationships between rice grain yield and weed density and dry weight were evaluated using regression analysis.

The economic threshold based on weed density at 60 DAS (end of critical period of weed competition) was worked out as per Uygur and Mennan (1995).

$$Y = [\{(100/He \times Hc) + Ac\}/(Gp \times Yg)] \times 100$$

Where, Y= yield reduction (%) at a weed density; He= herbicide/control efficiency; Hc= herbicide cost; Ac= application cost; Gp= grain price; Yg= weed-free yield

Different impact indices, *viz*. weed persistence index (WPI), weed management index (WMI), agronomic management index (AMI) and integrated weed management index (IWMI) were worked out as suggested by Mishra and Misra (1997) using the following formulae.

$$WPI = [WD_C \div WD_T] \times [WDM_T \div WDM_C]$$

$$WMI = [Y_T/Y_C] \div [(WDM_C - WDM_T) \div WDM_C]$$

$$AMI = (WMI - 1)$$

$$IWMI = (WMI + AMI) \div 2$$

Likewise, crop resistance index (CRI; Das 2008), treatments efficiency index (TEI; Krishnamurthy *et al.* 1975), weed intensity (WIn; Rana and Kumar 2014) and crop intensity (CIn; Rana and Kumar 2014) were calculated as per following formulae.

$$CRI = (CDM_T \div CDM_C) \times (WDM_C \div WDM_T)$$

$$TEI = [(Y_T - Y_C)/Y_T] \div (WDM_T / WDM_C)$$

$$WIn\ (\%) = [\text{weed density} \div (\text{weed + crop density})] \times 100$$

$$CIn\ (\%) = 100 - WIn$$

Where, Y_T and Y_C, yield in treated and unweeded control (UWC) plot, respectively; WD_T and WD_C, weed density (no./m^2) in treated and UWC plot, respectively; WDM_T and WDM_C, weed dry weight (g/m^2) in treated and UWC plot, respectively; CDM_T and CDM_C, crop dry matter (g/m^2) in treated and UWC plot, respectively.

Overall impact index (OII) was estimated in two steps (Rana *et al.* 2019). Firstly, by calculating the unit value of a parameter under a particular treatment and dividing it by the respective arithmetic mean of all treatments for that parameter. And, secondly, the OII of a treatment was determined as the mean of unit values of all the parameters under consideration.

$$Uij = Vij \div AMj$$

$$OII_i = \frac{1}{N}\sum_{i=1}^{N} U_{ij}$$

Where, Uij, unit value for ith treatment corresponding to jth parameter; Vij, actual value of jth parameter for ith treatment; AMj, arithmetic mean for j[th] parameter; OIIi, overall impact index for i[th] treatment; and N, total number of parameters under consideration.

Weed flora distribution

Weed flora under unweeded situation (~UWC) comprised of *Echinochloa crus-galli* (L.) Beauv., *Leptochloa chinensis* (L.) Nees. (grassy weeds); *Eclipta alba* L., *Digera arvensis* Forsk., *Trianthema portulacastrum* L. (broad-leaved weeds); and *Cyperus rotundus* L., and *C. iria* L. (sedges). Weed flora composition differed greatly across the treatments having herbicides with different site-specific modes of action. Grassy weeds were more dominant constituting about 66.0–91.8% of total weed dry weight across the treatments, followed by (~*fb*) broad-leaved weeds (5.1–15.3%) and sedges (2.8–19.0%).

Weed interference

Weed control treatments brought about 74.1-89.7% reduction in grassy weeds dry weight at 60 DAS and 57.7-87.6% reduction in total weed dry weight at harvest compared to UWC (**Table 1**). The sequential applications of pendimethalin (1.0 kg/ha) *fb* ready-mix of penoxsulam + cyhalofop-butyl (130 g/ha) led to lowest grassy weed dry weight at 60 DAS (30 g/m^2) and harvest (41.7 g/m^2) and had highest WCI (87.6%). Singh *et al.* (2016) reported similar higher efficacy of herbicide mixture penoxsulam + cyhalofop-butyl on complex weed flora in DSR. This might be attributed to broad-spectrum activity of sequential herbicides combination against weeds. Pre-emergence pendimethalin controlled initial flushes of weeds. Late-emerging weeds were effectively controlled by herbicides mixture, *i.e.,* penoxsulam + cyhalofop-butyl with two different modes of action. Penoxsulam (acetolactate/ acetohydroxy acid synthase inhibitor) is effective against broad-spectrum weeds and cyhalofop-butyl (acetyl-coenzyme A carboxylase inhibitor) effectively controls grassy weeds. Later, rice crop through vigorous/ rapid canopy formation also smothered late-emerging weeds and reduced weed interference. Thus, this combination found to be most effective against diverse weeds in DSR. Likewise, weed interference was lower in pendimethalin *fb* bispyribac-Na (65 g/m^2) and brown manuring *fb* metsulfuron-methyl 10% + chlorimuron-ethyl 10% 20 g/ha (Almix) (66 g/m^2) treated plots with 80.6% and 80.3% reductions (WCI) in weed dry weight over UWC, respectively (**Table 1**).

Pendimethalin *fb* bispyribac-Na although gave better weed control initially, the effect declined at later stages. This was due to lower persistence and activity of bispyribac-Na against weeds like *Dactyloctenium aegyptium*, *L. chinensis etc* (Awan *et al.* 2015). Integration of BM with herbicides (BM *fb* Almix) led to better weed suppression through smothering by live *Sesbania* mulch on initial weeds (Maity and Mukherjee 2011), and then by a combination of surface dead mulch and Almix applied at 40 DAS on late-emerging weeds. Again, BM was more effective against broad-leaved weeds and led to 79.4–83.5% reduction in their biomass compared to UWC (**Table 1**). Singh *et al.* (2007) reported similar results. However, the BM without the application of a grass-killer herbicide was unable to suppress grassy weeds initially resulting in significantly higher dry weight of grassy weeds at subsequent stages.

Crop growth and yield

Rice crop growth and grain yield differed significantly due to variable weed control efficiencies of the treatments. The BM *fb* Almix led to highest mean relative growth rate (RGR) of rice (60.77 mg/g/ day), which was 51.1% higher than that in UWC at 60 DAS (**Table 1**), and was closely followed by that in the pendimethalin *fb* penoxsulam + cyhalofop-butyl, mainly because of relatively lower weed interference. Highest grain yield (4.4 t/ha) and harvest index (40.02%) were recorded in weed-free check (WFC) with 430.1% increase in grain yield over UWC. Among the herbicide treatments, pendimethalin *fb* penoxsulam + cyhalofop-butyl gave highest grain yield (3.92 t/ha) and harvest index (38.0%) of rice (**Table 1**).

Rice grain yield in this treatment increased by 378.9% over UWC. Higher crop growth in this treatment might have led to greater accumulation of photosynthates in sources that translocated to sink at later growth stages, resulting in significant yield improvement. Pendimethalin *fb* bispyribac-Na (3.70 t/ha) and BM *fb* Almix (3.67 t/ha) were the next best treatments. Crop growth and yield are directly related to efficiency of a weed control practice. With highest WCI, pendimethalin *fb* penoxsulam + cyhalofop-butyl provided season-long weed control that facilitated better crop growth through more tillering and higher accumulation of photosynthates resulting in significant improvement in yield. The sequential applications of pre- and post-emergence herbicides having higher bio-efficacy against diverse weeds leading to better crop growth and yield has been highlighted earlier in DSR (Chauhan *et al.* 2015, Singh *et al.* 2016, Baghel *et al.* 2018, 2020), and in vegetable pea (Kaur *et al.* 2020). *Sesbania* BM also increased rice yield by 342.2% over UWC. The BM suppressed initial weed flushes through space capture, and late-emerging weeds through surface dead mulch after getting knocked down by 2, 4-D. Later, the application of Almix could supplement weed control in the BM treatment and led to lower weed interference, higher crop growth and yield (Maity and Mukherjee 2011). Improved soil condition in the BM was also responsible for higher yield (Nawaz *et al.* 2017).

Grain yield was negatively correlated with weed density (y = -14.543x + 3999.2; R^2 = 0.733) and dry weight (y = -10.855x + 3947.8; R^2 = 0.744) at 60 DAS (end of critical period of weed competition). This implied that grain yield decreased with corresponding increase in weed density and dry weight, and *vice-versa*. These linear equations could explain 73.3% and 74.4% of the variations in rice grain yield (y) due to weed density and dry weight (x) during the critical period of weed competition in DSR, respectively. With every unit increase in weed density (per m^2) or weed dry weight (g/m^2), rice grain yield is subjected to reduce by 14.5 kg/ha and 11 kg/ha, respectively. Economic threshold (*i.e.,* weed density at which cost of weed control equals the economic benefits accrued from that control measure, and justifies adoption of control measure) across the weed control options varied between 4.9-27.1 weeds/m^2 (**Table 2**) during critical period of weed competition in DSR. Economic threshold level increased with increasing cost of weed control as in the case of manual weeding (WFC), attributable to higher wages. Contrarily, weed control through herbicides incurred lower costs, resulting in lower economic threshold level. The economic threshold level at which controlling weeds became economically worthwhile at the most effective weed control option (pendimethalin *fb* penoxsulam + cyhalofop-butyl) was 9.0 weeds/m^2.

Table 1. Weed interference, crop growth and grain yield in direct-seeded rice

Treatment	Weed dry weight (g/m²) at 60 DAS			Weed dry weight (g/m²) at harvest	WCI (%)	Mean RGR (mg/g/day)	Grain yield (t/ha)	Harvest index (%)
	Grasses	BLWs	Sedges					
Pendimethalin 1.0 kg/ha *fb* bispyribac-Na 20 g/ha at 25 DAS	41.0	4.5	10.0	65.0	80.6	54.96	3.70	36.83
Pendimethalin 1.0 kg/ha *fb* penoxsulam (1%) + cyhalofop-butyl (5%) 130 g/ha at 25 DAS	30.0	5.0	7.0	41.7	87.6	58.45	3.92	38.00
Pendimethalin 1.0 kg/ha *fb* fenoxaprop-p-ethyl 75 g/ha at 25 DAS	59.2	13.5	17.0	116.7	65.2	56.52	2.67	32.25
Pendimethalin 1.0 kg/ha *fb* Almix (metsulfuron-methyl 10% + chlorimuron-ethyl 10%) 20 g/ha at 25 DAS	54.0	5.0	6.0	76.0	77.3	54.69	3.10	35.08
Pretilachlor 0.75 kg/ha *fb* cyhalofop-butyl 80 g/ha at 25 DAS	58.8	13.3	15.2	106.2	68.3	55.28	2.70	32.55
Pretilachlor 0.75 kg/ha *fb* ethoxysulfuron 15 g/ha at 25 DAS	75.2	4.2	4.2	142.0	57.7	49.59	1.88	30.50
Pendimethalin 1.0 kg/ha *fb* one hand weeding at 25 DAS	50.0	4.9	10.2	75.0	77.6	55.84	3.50	36.10
Brown manuring (BM)	56.0	3.5	4.0	81.0	75.8	57.59	3.07	34.93
BM *fb* Almix 20 g/ha at 40 DAS	45.0	2.8	5.0	66.0	80.3	60.77	3.67	36.82
Weed-free check	0	0	0	0	100.0	54.16	4.40	40.02
Unweeded control	290.0	17.0	9.0	335.3	0	40.22	0.83	25.13
LSD (p=0.05)	12.21	1.52	2.59	17.91	-	8.12	0.35	1.26

BLWs: Broad-leaved weeds; WCI: Weed control index; RGR: Relative growth rate

Table 2. Economics of weed control treatments

Treatment	Gross returns (x10³ ₹/ha)	GR_{UWC} (x10³ ₹/ha)	NR_{UWC} (x10³ ₹/ha)	Gross benefit: cost	ET (weeds/m²)
Pendimethalin 1.0 kg/ha *fb* bispyribac-Na 20 g/ha at 25 DAS	62.21	47.16	42.73	2.23	8.1
Pendimethalin 1.0 kg/ha *fb* penoxsulam (1%) + cyhalofop-butyl (5%) 130 g/ha at 25 DAS	65.53	50.48	45.33	2.30	9.0
Pendimethalin 1.0 kg/ha *fb* fenoxaprop-p-ethyl 75 g/ha at 25 DAS	45.86	30.81	26.26	1.64	9.4
Pendimethalin 1.0 kg/ha *fb* Almix (metsulfuron-methyl 10% + chlorimuron-ethyl 10%) 20 g/ha at 25 DAS	52.54	37.49	34.65	2.00	5.0
Pretilachlor 0.75 kg/ha *fb* cyhalofop-butyl 80 g/ha at 25 DAS	46.35	31.31	27.44	1.70	7.7
Pretilachlor 0.75 kg/ha *fb* ethoxysulfuron 15 g/ha at 25 DAS	32.73	17.68	15.04	1.26	4.9
Pendimethalin 1.0 kg/ha *fb* one hand weeding at 25 DAS	59.05	44.00	37.20	1.96	10.8
Brown manuring (BM)	52.02	36.97	33.98	1.98	5.3
BM *fb* Almix 20 g/ha at 40 DAS	61.66	46.61	42.94	2.28	6.2
Weed-free check	73.03	57.98	39.98	1.75	27.1
Unweeded control	15.05	0	0	0.64	0
LSD (p=0.05)	5.74	-	-	0.21	-

GR_{UWC}, Gross returns over UWC; NR_{UWC}, Net return over UWC; ET, Economic threshold density

Table 3. Impact assessment indices of weed control treatments

Treatment	TEI	WPI	CRI	WMI	AMI	IWMI	WIn	CIn	OII
Pendimethalin 1.0 kg/ha *fb* bispyribac-Na 20 g/ha at 25 DAS	4.47	0.88	15.29	5.48	4.48	4.98	12.65	87.35	1.16
Pendimethalin 1.0 kg/ha *fb* penoxsulam (1%) + cyhalofop-butyl (5%) 130 g/ha at 25 DAS	6.00	0.86	20.79	5.52	4.52	5.02	9.89	90.11	1.27
Pendimethalin 1.0 kg/ha *fb* fenoxaprop-p-ethyl 75 g/ha at 25 DAS	2.42	0.89	7.51	4.55	3.55	4.05	21.50	78.50	0.84
Pendimethalin 1.0 kg/ha *fb* Almix (metsulfuron-methyl 10% + chlorimuron-ethyl 10%) 20 g/ha at 25 DAS	3.66	0.98	11.58	4.76	3.76	4.26	14.44	85.56	1.00
Pretilachlor 0.75 kg/ha *fb* cyhalofop-butyl 80 g/ha at 25 DAS	2.50	0.90	7.75	4.56	3.56	4.06	20.91	79.09	0.86
Pretilachlor 0.75 kg/ha *fb* ethoxysulfuron 15 g/ha at 25 DAS	2.17	1.05	6.28	3.14	2.14	2.64	21.39	78.61	0.66
Pendimethalin 1.0 kg/ha *fb* one hand weeding at 25 DAS	3.76	0.89	12.34	5.38	4.38	4.88	15.00	85.00	1.08
Brown manuring (BM)	3.65	0.94	11.31	4.71	3.71	4.21	15.01	84.99	0.99
BM *fb* Almix 20 g/ha at 40 DAS	4.67	0.97	15.22	5.38	4.38	4.88	11.46	88.54	1.16

TEI, Treatment efficiency index; WPI, Weed persistence index; CRI, Crop resistance index; WMI, Weed management index; AMI, Agronomic management index; IWMI, Integrated weed management index; WIn, Weed intensity; CIn, Crop intensity; OII, Overall impact index

Economics

The weed-free situation (WFC) fetched highest gross returns owing to highest grain and straw yields, followed by the pendimethalin *fb* penoxsulam + cyhalofop-butyl (**Table 2**). Despite lower gross returns (by 7501.5 ₹/ha or 10.3%), the latter herbicide treatment (*i.e.,* pendimethalin *fb* penoxsulam + cyhalofop-butyl) gave 13.4% and 31.4% higher net returns over UWC (NR_{UWC}) and gross benefit: cost over WFC, respectively, because of higher grain yield and relatively lower cost of weed control in this treatment. Brown manuring *fb* Almix although had relatively lower grain yield and gross returns, led to 7.4% and 30.3% higher NR_{UWC} and gross benefit: cost over WFC, respectively, and found to be the next best weed control option in DSR in terms of profitability. Reduction in cost of herbicide and comparatively higher grain yield resulted in better profitability in this treatment. In contrast, Nawaz *et al*. (2017) and Paliwal *et al*. (2017) reported higher profitability of BM than herbicidal weed control.

Impact assessment

Among the weed control options, the sequential applications of pendimethalin *fb* penoxsulam + cyhalofop-butyl resulted in highest treatment efficiency index (6.0) followed by BM *fb* Almix (**Table 3**). It also led to highest crop resistance index (20.79), weed management index (5.52), agronomic management index (4.52), integrated weed management index (5.02), and crop intensity (90.11), indicating higher efficacy of this treatment on weeds. Lowest weed persistence index (0.86) and weed intensity (9.89) were also obtained from it, highest being in pretilachlor *fb* ethoxysulfuron. Overall impact index indicated higher bio-efficacy of sequential applications of pendimethalin *fb* penoxsulam + cyhalofop-butyl and BM *fb* Almix in controlling diverse weed flora in DSR (**Table 3**).

This study showed that the sequential applications of pendimethalin (1.0 kg/ha) as pre-emergence *fb* ready-mixture of penoxsulam + cyhalofop-butyl (130 g/ha) at 25 DAS resulted in better control of diverse weeds, resulting in higher rice growth, productivity and profitability. It may be adopted for effective weed control in DSR in the Indo-Gangetic Plains and in other areas with similar agro-ecologies. Furthermore, integration of *Sesbania* brown manuring with herbicide Almix 20 g/ha applied at 40 DAS can also be a profitable alternative for effective weed management in DSR.

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