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RESEARCH ARTICLE

Impact of herbicide combinations on weed dynamics, crop productivity and economics in wet-direct seeded rice ecosystem

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Abstract

A field experiment was conducted during the summer of 2023 at Tamil Nadu Agricultural University, Coimbatore, to evaluate the effects of various pre- and post-emergence herbicide combinations on weed dynamics and productivity in wet direct-seeded rice. The experiment employed a randomized block design with ten treatments replicated three times. The study assessed various weed management practices, including pre-emergence herbicides followed by post-emergence herbicides, pre-emergence herbicides followed by hand weeding, post-emergence herbicides followed by hand weeding, and the farmer's practice of two hand weedings. Key observations included weed flora, density, dry weight and crop parameters such as plant height, leaf area index, total dry matter production and yield attributes. The study found that, *Echinochloa colona* and *Leptochloa chinensis* were the dominant grasses, *Cyperus difformis* was the dominant sedge and *Eclipta prostrata* was the prominent broad-leaved weed. The pre-emergence application of pretilachlor + pyrazosulfuron ethyl effectively controlled grasses, sedges and broadleaf weeds, particularly at 20 DAS. The ready-mix formulation of pendimethalin followed by triafamone + ethoxysulfuron was most effective at 40 DAS and harvest, significantly reducing weed density and improving yield parameters.

Keywords

crop productivity; herbicide combinations; weed dynamics; weed management practices; wet direct-seeded rice

Introduction

Rice (*Oryza sativa* L.), a staple for over half the world's population, is cultivated year-round in India depending on geographical conditions. In India, farmers predominantly practice the conventional method of rice transplanting over direct seeding of rice (DSR). DSR involves sowing pregerminated seed on a puddled soil surface (wet seeding), on shallow standing water (water seeding), or dry seeds on a prepared seedbed (dry seeding). It is labour-efficient, requires less seed and water and results in 10-12 days early maturity compared to transplanted rice (1). Hence, the shift in crop establishment methods from manual transplanting of seedlings to direct seeding is increasingly adopted in Asian countries (2). The primary challenge of DSR is effective weed management. Yield loss due to weeds depends on the type of weed flora, its intensity and the stage, nature and duration of crop weed competition. The magnitude of crop yield loss ranges from 40 to 60% due to weed competition in the wet seeding method of rice cultivation, and it can escalate to 94-96% in uncontrolled weed plots. The weed community changes significantly with the shift from transplanted to direct-seeded rice (3). Weeds can reduce the grain yield of direct-seeded (dry) rice by 75.8%, wet-seeded rice by 70.6% and transplanted rice by 62.6% due to their rapid growth (*Echinochloa* spp. and *Leptochloa chinensis*) and adaptability (4).

The critical period of weed control in dry direct-seeded rice is within the first 25-45 DAS to prevent yield loss. In wet-seeded rice, yield decreases by 64-66% due to weeds throughout the cropping season compared to a weed-free plot. Crop performance can be improved by weeding during the critical period i.e., 15-60 days after sowing, resulting in a yield reduction of only 0.4-3%, which is comparable to a weed-free plot (5).

In India, the predominant grass weeds include *Echinochloa colona, Echinochloa crus-galli, Eleusine indica, Leptochloa chinensis, Digitaria sanguinalis, Brachiaria ramose, Cynodon dactylon* and *Dactyloctium aegyptium*; Broad-leaf weeds such as *Alternanthera sessilis, Ammania baccifera, Caesulia axillaris, Cleome viscosa, Commelina benghalensis, Commelina communis, Cyanotis axillaris* and *Digera arvensis,* as well as sedges like *Fimbristylis miliacea, Cyperus difformis, Cyperus iria* and *Cyperus rotundus* are commonly found in rice fields (6). In wet-seeded rice field, weeds emerge simultaneously with the crop, increasing competition and necessitating herbicide application (7). Hence, to manage weed infestation, pre-emergence herbicides followed by post-emergence herbicides or pre-emergence herbicides followed by manual weeding can be practiced (1). Combining pre-emergence herbicides with manual weeding reduces chemical use but increases labour costs. Therefore, a single-shot application of ready-mix or tank-mix combinations of compatible herbicides at a reduced cost provides satisfactory results. The efficacy of various pre-mix herbicides can reduce the weeds to an acceptable level.

This study addresses a significant gap in current knowledge about the effectiveness of specific herbicide combinations in direct-seeded rice systems. While numerous studies have investigated individual herbicides or standard herbicide practices, data are lacking on the performance of combined herbicide treatments, such as pendimethalin with ALS inhibitors (e.g., triafamone, ethoxysulfuron) or bispyribac sodium, in direct-seeded rice (8). Specifically, the study aims to evaluate how these combinations influence weed control efficacy, crop growth and yield in systems where weeds emerge alongside the crop, a common challenge in direct-seeded rice fields.

Materials and Methods

Location

The experiment was conducted during the summer of 2023 (March to July) in field No. B2 of the wetland farm at Tamil Nadu Agricultural University, Coimbatore, located at 11°N latitude, 77°E longitude and an altitude of 426.7 m above mean sea level.

Climate and weather

During the field experiment, the maximum and minimum temperatures ranged from 30.0°C to 37.0°C and 22.9°C to 24.9°C, respectively. The total rainfall received was 287.6 mm over 23 rainy days. Relative humidity during the forenoon and afternoon ranged from 92% to 74% and 67% to 28%, respectively. Solar radiation during the cropping period ranged from 400.2 to 253.0 cal cm^{-2} day^{-1}. Sunshine hours averaged 10 hours per day. Evaporation during the cropping period ranged from 4.4 to 8 mm and wind speed varied from 3.7 to 19.7 km hr^{-1}.

Soil characteristics

The soil of the experimental field is slightly alkaline in nature and the soil analysis revealed low available nitrogen (215 kg ha^{-1}), medium available phosphorus (17.1 kg ha^{-1}) and high available potassium (400 kg ha^{-1}) content. The initial properties of the soil are presented in Table 1.

Table 1. Soil properties of experimental field

A.	Physical properties	Value
1.	Clay (%) of soil	42.1
2.	Silt (%)	11.4
3.	Coarse sand (%)	19
4.	Fine sand (%)	27.5
5.	Texture	Clay loam
B.	**Chemical properties**	
1.	pH	8.3
2.	EC (dS m^{-1})	0.41
3.	Organic carbon (%)	0.62
4.	Available nitrogen (kg ha^{-1})	215
5.	Available phosphorous (kg ha^{-1}) (Olsen et al., 1954)	17.1
6.	Available potassium (kg ha^{-1})	400

Experiment details

The field experiment was conducted using a randomized block design (RBD) with three replications. The treatment and cropping details are provided in Table 2 and 3. These herbicides function through different mechanisms to target specific processes in weed growth, such as disrupting cell division (pendimethalin), inhibiting amino acid synthesis (ALS inhibitors like bispyribac sodium, ethoxysulfuron, triafamone and pyrazosulfuron ethyl) and interfering with fatty acid biosynthesis (cyhalofop butyl).

Agronomic management

The short-duration rice variety CO 55 was used for the field experiment conducted during the summer of 2023 (March to July). The experimental field was initially prepared using cage-wheel puddling with a tractor, followed by roto-puddling. The field was levelled with a wooden plank. A TNAU drum seeder was used for direct seeding (9). Fertilizers were applied at the recommended dose of 150:50:50 N: P: K kg ha^{-1} in the form of urea (46% N), single super phosphate (16% P_2O_5) and muriate of potash (60% K_2O). Twenty-five percent of the nitrogen, the full dose of phosphorous and 25% potassium were applied basally at sowing. The remaining 75% of nitrogen and potassium were top-dressed in three equal splits during the active tillering,

Table 2. Treatment details

T_1	Pendimethalin 1 kg ha^{-1} on 3 DAS followed by bispyribac sodium 25 g ha^{-1} + ethoxysulfuron 18 g ha^{-1} on 20 DAS (tank mix)
T_2	Pendimethalin 1 kg ha^{-1} on 3 DAS followed by penoxulam + cyhalofop butyl 135 g ha^{-1} on 20 DAS (ready mix)
T_3	Pendimethalin 1 kg ha^{-1} on 3 DAS followed by triafamone + ethoxysulfuron 66.5 g ha^{-1} on 20 DAS (ready mix)
T_4	Pretilachlor 600 g ha^{-1} + pyrazosulfuron ethyl 15 g ha^{-1} on 3 DAS (Tank mix) followed by HW on 40-45 DAS
T_5	Pendimethalin 1 kg ha^{-1} on 3 DAS followed by HW on 40-45 DAS
T_6	Pendimethalin 1 kg ha^{-1} on 3 DAS followed by Bispyribac sodium 25 g ha^{-1} on 25 DAS followed by HW on 45 DAS
T_7	Triafamone + ethoxysulfuron 66.5 g ha^{-1} on 20 DAS (ready mix) followed by HW on 40-45 DAS
T_8	HW twice (20 and 40 DAS)
T_9	Weed free control
T_{10}	Weedy check (unweeded control)

Table 3. Details of the experiment

1	Crop and variety	Rice (CO 55)
2	Design	RBD
3	Replication	Three
4	Date of sowing	30.03.2023
5	Herbicide application Pre-emergence Post-emergence	1.04.2023 19.04.2023
6	Date of harvest	27.07.2023

panicle initiation and heading stages of the rice crop. Irrigation and plant protection measures were carried out as recommended in TNAU crop production guide (9). Weed management practices were followed according to the treatment schedule. Irrigation was applied based on weather conditions and physical evaluation of the field. From each experimental plot, four border rows were harvested from the gross plot first, followed by the net plot. The grain from the net plot was threshed, cleaned and weighed. A moisture level of 14% was maintained to measure the grain weight. Straw weight was recorded after sun drying.

Observations

Observations for weed parameters were recorded at 20 DAS, 40 DAS and at harvest. Weed density was determined by placing a 0.25 m^2 quadrat in each plot. Weed control efficiency was calculated using the standard formula given below (10):

$$WCI (\%) = (DWc - DWt) / DWc$$

WCI – Weed control efficiency (%); DWc – Weed dry weight in control plot (g); DWt – Weed dry weight in treated plot (g)

At harvest, the number of tillers m^{-2}, the number of filled grains per panicle, panicle weight, test weight (g) and crop yields (t ha^{-1}) were recorded, along with computation of the harvest index. Economic analysis was performed by calculating the B:C ratio and working out the partial budgeting.

Statistical Analysis

Statistical analysis of the data was performed (11). The data collected during the study were analyzed using standard statistical procedures to ensure reliable interpretation of the results. Weed data, often exhibiting skewness or heteroscedasticity, were transformed using the square root scale $\sqrt{(X+0.5)}$, where X is the observed value, to stabilize variance and normalize the distribution. The + 0.5 adjustment addressed potential issues with zero values. The transformed data were subjected to analysis of variance (ANOVA) to identify significant differences among treatments. When significant differences were observed ($p < 0.05$), critical differences (CD) were calculated at a 5% probability level for pairwise comparisons. Results were reported as means with corresponding CDs to enhance reproducibility and interpretability (12).

Results

Weed flora in experimental field

The weeds commonly found in the experimental field included grasses, sedges and broad-leaved weeds (Table 4). They were observed in the unweeded check plot at flowering stage of the crop. The prominent grasses are *Echinocloa colona* (L.) and *Leptochloa chinensis* (L.); the major sedge was *Cyperus difformis (*L.) and the most common broad-leaved weed was *Eclipta alba* (L).

Total weed density

The total weed density was significantly influenced by different herbicide applications (Table 5). At 20 DAS, no weeds were observed in the weed-free control. This was followed closely by the treatment of pretilachlor at 600 g ha^{-1} + pyrazosulfuron-ethyl 15 g ha^{-1} applied on 3 DAS (tank mix) with hand weeding at 40-45 DAS (T_4), which recorded a weed density of 5.66 m^{-2}. By 40 DAS, the lowest weed density was noted in the treatment of pendimethalin 1 kg ha^{-1} on 3 DAS, followed by triafamone + ethoxysulfuron 66.5 g ha^{-1} on 20 DAS (ready mix) (T_3), with a weed density of 11.33 m^{-2}, which was on par with the weed-free control. This was followed by the treatment of pendimethalin 1 kg ha^{-1} on 3 DAS, followed by bispyribac-sodium 25 g ha^{-1} on 25 DAS with hand weeding on 45 DAS (T_6), which recorded a weed density of 16.67 m^{-2}. Similarly at harvest, the lowest weed density observed in the weed-free control, followed bypendimethalin 1 kg ha^{-1} on 3 DAS followed by triafamone + ethoxysulfuron 66.5 g ha^{-1} on 20 DAS (ready mix) (T_3), which recorded 7.33 m^{-2}.

Table 4. Details of the weed flora in experimental field

S.No.	Botanical name	Common name	Life form	Family
I.	**Grasses**			
1.	*Echinocloa colonum*	Jungle grass	Annual	Poaceae
2.	*Leptochloa chinensis*	Red sprangletop	Annual	Poaceae
II.	**Sedges**			
1.	*Cyperus difformis*	Umbrella plant	Annual	Cyperaceae
III.	**Broad leaved weeds**			
1.	*Eclipta prostrata*	False daisy	Annual	Asteraceae

Total weed dry weight

Table 5. Effect of herbicide combination on total weed density at 20 DAS, 40 DAS and harvest

	Treatments	Total weed density		
		20 DAS	40 DAS	Harvest
T_1	Pendimethalin 1 kg ha^{-1} on 3 DAS followed by bispyribac sodium 25 g ha^{-1} + ethoxysulfuron 18 g ha^{-1} on 20 DAS (tank mix)	5.52 (30.00)	4.22 (17.33)	4.67 (23.33)
T_2	Pendimethalin 1 kg ha^{-1} on 3 DAS followed by penoxulam + cyhalofop butyl 135g ha^{-1} on 20 DAS (ready mix)	5.33 (27.99)	5.67 (31.66)	5.21 (26.67)
T_3	Pendimethalin 1 kg ha^{-1} on 3 DAS followed by Triafamone + Ethoxysulfuron 66.5 g ha^{-1} on 20 DAS (ready mix)	5.40 (28.67)	3.43 (11.33)	2.79 (7.33)
T_4	Pretilachlor 600 g ha^{-1} + pyrazosulfuron ethyl 15 g ha^{-1} on 3 DAS (tank mix) + HW on 40-45 DAS	2.48 (5.66)	6.20 (38.00)	5.27 (27.33)
T_5	Pendimethalin 1 kg ha^{-1} on 3 DAS + HW on 40-45 DAS	5.36 (28.33)	9.47 (89.34)	6.62 (43.34)
T_6	Pendimethalin 1 kg ha^{-1} on 3 DAS followed by bispyribac sodium 25 g ha^{-1} on 25 DAS + HW on 45 DAS	5.58 (30.66)	4.14 (16.67)	3.34 (10.66)
T_7	Triafamone + ethoxysulfuron 66.5 g ha^{-1} on 20 DAS (Ready mix) + HW on 40-45 DAS	15.84 (250.67)	14.44 (208.10)	9.00 (80.66)
T_8	HW twice (20 and 40 DAS)	16.84 (283.33)	12.24 (149.43)	9.26 (85.33)
T_9	Weed free control	0.71 (0)	0.71 (0)	0.71 (0)
T_{10}	Weedy check (unweeded control)	14.42 (207.67)	17.95 (321.99)	17.98 (323.00)
	SE. d	0.32	0.37	0.18
	CD (P= 0.05)	0.97	1.05	0.73

Weed management practices exhibited a significant difference in weed dry weight at 20 DAS, 40 DAS and at harvest (Table 6). Significantly lower weed dry weight was observed in the treatment with pretilachlor at 600 g ha^{-1} + pyrazosulfuron-ethyl at 15 g ha^{-1} on 3 DAS (tank mix) (T_4), which recorded (0.38 g m^{-2}). At 40 DAS, the weed dry weight was further reduced in pendimethalin at 1 kg ha^{-1} on 3 DAS, followed by triafamone + ethoxysulfuron at 66.5 g ha^{-1} on 20 DAS (ready mix) (T_3), which recorded (4.60 m^{-2}). Similarly, at harvest pendimethalin 1 kg ha^{-1} on 3 DAS, followed by triafamone + ethoxysulfuron at 66.5 g ha^{-1} on 20 DAS (ready mix) (T_3), recorded a significantly lower weed dry weight (5.08 gm^{-2}) next to weed-free check.

Weed control efficiency

Weed control efficiency at 20 DAS, 40 DAS and at harvest is presented in Table 7. The treatment with pretilachlor at 600 g ha^{-1} + pyrazosulfuron-ethyl at 15 g ha^{-1} on 3 DAS (tank mix) (T_4) recorded higher weed control efficiency (98.1%) at 20 DAS. At 40 DAS, higher weed control efficiency was observed in the treatment with pendimethalin 1 kg ha^{-1} on 3 DAS, followed by triafamone + ethoxysulfuron at 66.5 g ha^{-1} on 20 DAS (ready mix) (T_3) (89.5%), after the weed free-check (T_9). Similarly, pendimethalin 1 kg ha^{-1} on 3 DAS followed by triafamone + ethoxysulfuron at 66.5 g ha^{-1} on 20 DAS (ready mix) (T_3), registered higher weed control efficiency even at harvest (88.6%), after the weed-free check (100%) followed by pendimethalin 1 kg ha^{-1} on 3 DAS, followed by bispyribac-sodium at 25 g ha^{-1} on 25 DAS + HW on 45 DAS (T_6) (83.5%) (Table 7).

Yield components

Yield components such as the number of tillers, productive tillers, panicle length, panicle weight, number of grains per panicle, number of unfilled grains panicle^{-1} and test weight are tabulated in Table 8.

There was a significant change in the number of tillers m^{-2} due to different weed management practices. The weed-free control treatment (565 tillers m^{-2}) was equivalent to pendimethalin 1 kg ha^{-1} on 3 DAS, followed by triafamone + ethoxysulfuron at 66.5 g ha^{-1} on 20 DAS (ready mix) (T_3) (552.3 tillers m^{-2}), pendimethalin at 1 kg ha^{-1} on 3 DAS, followed by bispyribac-sodium at 25 g ha^{-1} on 25 DAS + HW on 45 DAS (T_6) (546.7 tillers m^{-2}), pendimethalin at 1 kg ha^{-1} on 3 DAS, followed by bispyribac-sodium 25 g ha^{-1} + ethoxysulfuron at 18 g ha^{-1} on 20 DAS (tank mix) (T_1) (541.7 tillers m^{-2}) and pendimethalin at 1 kg ha^{-1} on 3 DAS, followed by penoxulam + cyhalofop butyl at 135 g ha^{-1} on 20 DAS (ready mix) (T_2) (535 tillers m^{-2}). The lowest number of tillers m^{-2} (379.3 tillers m^{-2}) was registered in the weedy check (T_{10}).

Table 6. Effect of herbicide combinations on total weed dry weight at 20 DAS, 40 DAS and harvest

	Treatments	Total weed dry weight		
		20 DAS	40 DAS	Harvest
T_1	Pendimethalin 1 kg ha^{-1} on 3 DAS followed by bispyribac sodium 25 g ha^{-1} + ethoxysulfuron 18 g ha^{-1} on 20 DAS (tank mix)	3.28 (10.30)	2.77 (7.19)	2.84 (7.60)
T_2	Pendimethalin 1 kg ha^{-1} on 3 DAS followed by penoxulam + cyhalofop butyl 135g ha^{-1} on 20 DAS (ready mix)	3.37 (10.90)	2.95 (8.23)	2.92 (8.05)
T_3	Pendimethalin 1 kg ha^{-1} on 3 DAS followed by triafamone + ethoxysulfuron 66.5 g ha^{-1} on 20 DAS (ready mix)	3.22 (9.93)	2.25 (4.60)	2.36 (5.08)
T_4	Pretilachlor 600 g ha^{-1} + pyrazosulfuron ethyl 15 g ha^{-1} on 3 DAS (tank mix) + HW on 40-45 DAS	0.93 (0.38)	3.72 (13.40)	3.50 (11.7)
T_5	pendimethalin 1 kg ha^{-1} on 3 DAS + HW on 40-45 DAS	3.34 (10.67)	4.11 (16.40)	3.58 (12.33)
T_6	Pendimethalin 1 kg ha^{-1} on 3 DAS followed by Bispyribac sodium 25 g ha^{-1} on 25 DAS + HW on 45 DAS	3.41 (11.12)	2.73 (6.99)	2.79 (7.33)
T_7	triafamone + ethoxysulfuron 66.5 g ha^{-1} on 20 DAS (ready mix) + HW on 40-45 DAS	4.28 (17.87)	3.32 (10.53)	5.44 (29.20)
T_8	HW twice (20 and 40 DAS)	3.88 (14.57)	3.05 (8.84)	5.14 (26.00)
T_9	Weed free control	0.71 (0)	0.71 (0)	0.71 (0)
T_{10}	Weedy check (unweeded control)	4.58 (20.53)	6.65 (43.83)	6.71 (44.60)
	SE. d	0.092	0.149	0.099
	CD (P=0.05)	0.195	0.315	0.209

Table 7. Effect of pre- and post-emergence herbicides on weed control efficiency at 20 DAS, 40 DAS and harvest

	Treatment	Weed control efficiency (%)		
		20 DAS	40 DAS	Harvest
T_1	Pendimethalin 1 kg ha^{-1} on 3 DAS followed by bispyribac sodium 25 g ha^{-1} + ethoxysulfuron 18 g ha^{-1} on 20 DAS (tank mix)	49.8	83.5	82.9
T_2	Pendimethalin 1 kg ha^{-1} on 3 DAS followed by penoxulam + cyhalofop butyl 135g ha^{-1} on 20 DAS (ready mix)	44.1	81.2	81.9
T_3	Pendimethalin 1 kg ha^{-1} on 3 DAS followed by Triafamone + Ethoxysulfuron 66.5 g ha^{-1} on 20 DAS (Ready mix)	51.6	89.5	88.6
T_4	Pretilachlor 600 g ha^{-1} + pyrazosulfuron ethyl 15 g ha^{-1} on 3 DAS (tank mix) + HW on 40-45 DAS	98.1	69.4	73.7
T_5	Pendimethalin 1 kg ha^{-1} on 3 DAS + HW on 40-45 DAS	48.0	62.5	72.3
T_6	Pendimethalin 1 kg ha^{-1} on 3 DAS followed by Bispyribac sodium 25 g ha^{-1} on 25 DAS + HW on 45 DAS	48.0	84.1	83.5
T_7	Triafamone + ethoxysulfuron 66.5 g ha^{-1} on 20 DAS (ready mix) + HW on 40-45 DAS	12.9	75.9	34.5
T_8	HW twice (20 and 40 DAS)	29.0	79.8	41.7
T_9	Weed free control	100	100	100
T_{10}	Weedy check (unweeded control)	0	0	0

Table 8. Effect of pre- and post-emergence herbicides on yield components

S. No	No. of productive tillers (m^{-2})	Panicle length (cm)	Panicle weight (g)	Filled grains panicle^{-1}	Unfilled grains panicle^{-1}	Test weight (g)
T_1	339.7	18.60	2.34	84.3	15.3	17.43
T_2	328.7	17.80	2.40	74.3	14.7	17.36
T_3	356.0	20.73	2.35	89.7	11.5	17.65
T_4	324.0	17.40	2.36	71.3	16.0	17.33
T_5	299.0	16.70	2.39	70.3	16.7	17.31
T_6	342.7	20.33	2.35	87.7	12.3	17.60
T_7	282.0	16.13	2.32	65.0	20.7	17.18
T_8	316.3	17.80	2.38	73.0	15.0	17.20
T_9	366.7	21.37	2.38	94.7	9.3	17.73
T_{10}	262.3	15.67	2.34	65.3	24.0	17.16
SE. d	12.9	0.309	0.04	3.6	1.0	0.391
CD (P=0.05)	27.3	0.654	NS	7.5	2.0	NS

Similarly, the number of productive tillers was highest in the weed-free control (366.7 no. m^{-2}) and it was on par with pendimethalin at 1 kg ha^{-1} on 3 DAS, followed by triafamone + ethoxysulfuron at 66.5 g ha^{-1} on 20 DAS (ready mix) (T_3) (356 tillers m^{-2}), pendimethalin at 1 kg ha^{-1} on 3 DAS, followed by bispyribac-sodium at 25 g ha^{-1} on 25 DAS + HW on 45 DAS (T_6) (342.7 tillers m^{-2}), pendimethalin at 1 kg ha^{-1} on 3 DAS, followed by bispyribac-sodium at 25 g ha^{-1} + ethoxysulfuron 18 g ha^{-1} on 20 DAS (tank mix) (T_1) (339.7 tillers m^{-2}). The weedy check recorded the lowest number of productive tillers (262.3 tillers m^{-2}).

Panicle length was on par with weed free (T_9) (21.37 cm) and pendimethalin at 1 kg ha^{-1} on 3 DAS, followed by triafamone + ethoxysulfuron at 66.5 g ha^{-1} on 20 DAS (ready mix) (T_3) (20.73 cm). Lower panicle length (15.67 cm) was obtained in weedy check (T_{10}). Panicle weight was non-significant in all the treatments and ranged from 2.34 g to 2.38 g. There was a significant difference in the number of filled grains per panicle due to different weed management practices. Filled grains were more in the weed-free control (T_9) (94.7), followed by pendimethalin at 1 kg ha^{-1} on 3 DAS, followed by triafamone + ethoxysulfuron at 66.5 g ha^{-1} on 20 DAS (ready mix) (T_3) (89.7). The lowest number of filled grains per panicle was obtained in the weedy check (65.3). The maximum number of unfilled grains per panicle was observed in weedy check (24), while the minimum number of unfilled grains per panicle was observed in weed-free plot (9.3). It was followed by pendimethalin at 1 kg ha^{-1} on 3 DAS, followed by triafamone + ethoxysulfuron at 66.5 g ha^{-1} on 20 DAS (ready mix) (T_3) (11.5) and pendimethalin at 1 kg ha^{-1} on 3 DAS, followed by bispyribac-sodium at 25 g ha^{-1} on 25 DAS + HW on 45 DAS (T_6) (12.3), which were on par with each other. Test weight (thousand grain weight) was non-significant in all the weed management practices and the highest value was observed in weed free (17.73 g), while the weedy check recorded a lower test weight (17.16 g).

Yield

Grain yield and straw yield differed significantly among the treatments (Table 9). Weed-free control (T_9) recorded grain yield of 5,953 kg ha^{-1}. It was 54.9% higher than the weedy check and 30.8 % greater than the farmers practice of hand weeding twice (T_8) at 20 and 40 DAS. Weed free control (T_9) was on par with pendimethalin 1 kg ha^{-1} on 3 DAS, followed by triafamone + ethoxysulfuron at 66.5 g ha^{-1} on 20 DAS (ready mix) (T_3) (5,697 kg ha^{-1}), pendimethalin at 1 kg ha^{-1} on 3 DAS followed by bispyribac-sodium 25 g ha^{-1} on 25 DAS + HW on 45 DAS (T_6) (5,597 kg ha^{-1}).

Similar to grain yield, higher straw yield was recorded under weed free control (T_9) (8,719 kg ha^{-1}) and it was equivalent to pendimethalin at 1 kg ha^{-1} on 3 DAS, followed by triafamone + ethoxysulfuron at 66.5 g ha^{-1} on 20 DAS (ready mix) (T_3) (8,456 kg ha^{-1}), pendimethalin at 1 kg ha^{-1} on 3 DAS, followed by bispyribac-sodium 25 g ha^{-1} on 25 DAS + HW on 45 DAS (T_6) (8,128 kg ha^{-1}).

Harvest index was nonsignificant in across treatments. The maximum harvest index was observed in weed free control (T_9) (0.40), with values ranging between 0.40 to 0.35.

Table 9. Effect of herbicide combinations on economic yield and harvest index

S. No	Treatments	Grain yield (kg ha^{-1})	Straw yield (kg ha^{-1})	Harvest index
T_1	Pendimethalin 1 kg ha^{-1} on 3 DAS followed by bispyribac sodium 25 g ha^{-1} + ethoxysulfuron 18 g ha^{-1} on 20 DAS (tank mix)	4,806	7,173	0.394
T_2	Pendimethalin 1 kg ha^{-1} on 3 DAS followed by penoxulam + cyhalofop butyl 135g ha^{-1} on 20 DAS (ready mix)	4,617	6,698	0.399
T_3	Pendimethalin 1 kg ha^{-1} on 3 DAS followed by triafamone + ethoxysulfuron 66.5 g ha^{-1} on 20 DAS (ready mix)	5,697	8,456	0.397
T_4	Pretilachlor 600 g ha^{-1} + pyrazosulfuron ethyl 15 g ha^{-1} on 3 DAS (tank mix) + HW on 40-45 DAS	4,289	6,442	0.392
T_5	Pendimethalin 1 kg ha^{-1} on 3 DAS + HW on 40-45 DAS	3,903	5,525	0.405
T_6	Pendimethalin 1 kg ha^{-1} on 3 DAS followed by bispyribac sodium 25 g ha^{-1} on 25 DAS + HW on 45 DAS	5,597	8,128	0.401
T_7	Triafamone + Ethoxysulfuron 66.5 g ha^{-1} on 20 DAS (ready mix) + HW on 40-45 DAS	3,666	5,172	0.403
T_8	HW twice (20 and 40 DAS)	4,117	6,105	0.393
T_9	Weed free control	5,953	8,719	0.401
T_{10}	Weedy check (unweeded control)	2,684	4,560	0.359
	SE. d	338	654	0.036
	CD (P=0.05)	716	1,374	NS

Economics

The use of different weed control practices showed significant variations in gross returns, net returns, partial budgeting, and the B:C ratio (Table 10). The treatment with pendimethalin at 1 kg ha^{-1} applied on 3 DAS followed by triafamone + ethoxysulfuron at 66.5 g ha^{-1} on 20 DAS (ready mix) (T3) generated a gross income of ₹1,39,308 ha^{-1}, second only to the weed-free control which produced ₹1,45,217 ha^{-1}. This T_3 also resulted in a net return of ₹82,440.22 ha^{-1} and a B:C ratio of 2.45 (Fig. 1)

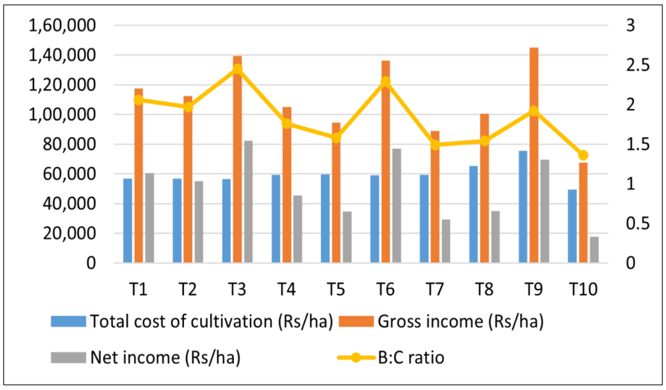

Fig. 1. Details of different cost of cultivation of pre and post emergence herbicide application in rice.

Partial budgeting

The feasibility of various weed control treatments was evaluated through partial budgeting against a weed-free scenario (Table 10). T_3 (pendimethalin 1 kg ha^{-1} on 3 DAS followed by triafamone + ethoxysulfuron 66.5 g ha^{-1} on 20 DAS) recorded as the most profitable option with a net return of ₹12,886. The highest loss was observed in the weedy check (T_{10}) with ₹51,901. These results highlight the economic importance of selecting effective weed control strategies, T_3 showed the best balance between cost and benefit.

Discussion

Direct seeding of rice involves sowing seeds directly into the field rather than transplanting seedlings from a nursery. Hence, it reduces the need for labour-intensive transplanting, which can be a significant advantage in areas with labour shortages or high labour costs. The risk of seedling loss due to transplant shock is eliminated. Lower labour costs and reduced need for nursery preparation can lead to overall cost savings for farmers. Reduced tillage associated with direct seeding can help maintain soil structure and health, enhancing soil moisture retention and reducing erosion. In some cases, direct seeding can improve water management practices by allowing for better control of irrigation. The shift from traditional transplanting to direct seeding in rice cultivation has become increasingly common as a strategy to reduce labour costs. While direct seeding offers economic advantages, it also introduces new challenges, particularly in weed management. Weed seeds, often remnants from previous crops, tend to have a longer viability and a faster germination rate compared to rice seeds. This creates competition and the weeds establish themselves more quickly, potentially dominating the field if not managed

Table 10. Estimation of feasibility of various treatments over weed free by partial budgeting

S. No.	Gain (Rs)			Loss (Rs)			Net gain (Rs)
	Added revenues	Reduced cost	Benefit	Added cost	Reduced revenues	Cost	
T_1	1,17,639	25,956	1,43,595	7,277	1,45,217	1,52,494	-8,899
T_2	1,12,434	25,956	1,38,390	7,426	1,45,217	1,52,643	-14,253
T_3	1,39,308	25,956	1,65,264	7,160	1,45,217	1,52,377	12,886
T_4	1,05,106	25,956	1,31,062	9,867	1,45,217	1,55,084	-24,022
T_5	94,635	25,956	1,20,591	10,269	1,45,217	1,55,486	-34,895
T_6	1,36,324	25,956	1,62,280	9,706	1,45,217	1,54,923	7,357
T_7	88,836	25,956	1,14,792	9,869	1,45,217	1,55,086	-40,294
T_8	1,00,655	25,956	1,26,611	15,862	1,45,217	1,61,079	-34,468
T_{10}	67,360	25,956	93,316	0	1,45,217	1,45,217	-51,901

effectively. The critical growth period for rice refers to the phase in the crop's growth cycle when it is most sensitive to competition from weeds. The presence of these weeds during the critical growth period of rice can significantly affect the crop growth, leading to reduced yields. Therefore, effective weed management is crucial for maximizing crop yield, with chemical methods playing a key role. This study investigates the impact of using pre- and post-emergence herbicides on weed density, control efficiency, and crop growth and productivity.

The higher weed control efficiency observed in the treatments can be attributed to the effective suppression of weed growth and reduction in weed dry weight. The treatment involving pendimethalin 1 kg ha^{-1} on 3 DAS followed by triafamone + ethoxysulfuron 66.5 g ha^{-1} on 20 DAS (T_3) also exhibited high weed control efficiency at 40 DAS due to the lower weed dry weight. Sequential application of herbicides, which effectively managed both early and later emerging weeds (*Echinochloa crus-galli, E. colona, E. oryzicola, Paspalum distichum, Isachne globosa*), preventing them from establishing and competing with the rice crop. This approach resulted in a consistently low weed population, which minimized competition with the rice plants, thereby enhancing crop growth and productivity.

The application of herbicide combination like triafamone + ethoxysulfuron at 66.5 g ha^{-1} on 20 DAS proves to be highly effective for weed control due to the distinct modes of action of its active ingredients. Triafamone inhibits acetolactate synthase (ALS), an enzyme essential for the synthesis of branched-chain amino acids in plants, while ethoxysulfuron targets a different enzyme, impacting various physiological processes in weeds. The combination of triafamone and ethoxysulfuron is highly effective due to their complementary ALS inhibition, disrupting amino acid synthesis in weeds. This dual action provides broad-spectrum control over grasses, sedges, and broadleaf weeds. The finding was in conformity with the previous studies (13). This dual mode of action allows the herbicide combination to effectively manage a wide range of weed species, including those that may have developed resistance to single-mode herbicides. Combined application of tank-mix or ready-mix more effective than single herbicides. These findings were in align with previous studies (13). By interfering with multiple biochemical pathways, this combination minimizes the chances of weed survival and resistance development, resulting in a more comprehensive and durable weed control approach. The findings align with previous studies reported the improved weed control efficiency with similar herbicide combinations (14).

The prominent factors behind rice grain yield are number of productive tillers m^{-2} and number of filled grains per panicle^{-1}. Among the treatments, the combination of pendimethalin 1 kg ha^{-1} applied on 3 DAS followed by triafamone + ethoxysulfuron 66.5 g ha^{-1} on 20 DAS (ready mix) (T_3) resulted in a higher number of productive tillers per square meter, which reflect on grain yield. Hence showing an 11.1% increase compared to the recommended practice of hand weeding twice at 20 and 40 DAS (T_8). Additionally, this treatment produced 18.6% more filled grains per panicle compared to hand weeding twice at 20 and 40 DAS (T_8). Pendimethalin applied as a pre-emergence herbicide minimize the early weed competition (6) allowing the rice seedlings to establish more robustly. The subsequent application of triafamone + ethoxysulfuron targeted later-emerging weeds, ensuring that the rice plants experienced minimal competition throughout critical growth stages (15-17). This favours the growth leads to development of more productive tillers and a higher number of filled grains per panicle directly contributing to the higher grain yield.

The partial budgeting analysis of various weed control treatments revealed that T_3, consisting of pendimethalin 1 kg ha^{-1} on 3 DAS followed by triafamone + ethoxysulfuron 66.5 g ha^{-1} on 20 DAS, was the most profitable, with a net return of ₹12,886. In contrast, the weedy check (T_{10}) resulted in a significant loss of ₹51,901. These results emphasize the importance of selecting cost-effective and efficient weed control strategies. T_3 demonstrated the best balance between input costs and output benefits, making it a favourable choice. This highlights the potential for improving profitability by optimizing herbicide combinations and application timing.

Pendimethalin 1 kg ha^{-1} applied on 3 DAS followed by triafamone + ethoxysulfuron 66.5 g ha^{-1} on 20 DAS achieved the highest B:C ratio of 2.45. This high B:C ratio indicates that this herbicide combination provided the best economic balance between the cost of weed management and the resultant returns. Although the weed-free control achieved higher gross income due to superior weed suppression, the total cost of cultivation was elevated because of the increased labour expenses associated with repeated hand weeding, which ultimately decreased the B:C ratio. In contrast, the T_3 treatment, despite yielding slightly lower gross income compared to the weed-free control due to reduced labour costs due to the effectiveness of the herbicide. This relationship between yield and economic performance is consistent with the previous findings (18-22).

In comparison, treatments involving single herbicide applications or delayed weed control interventions showed lower weed control efficiency, which corresponded to reduced yields due to persistent weed competition during critical growth stages. While some alternative treatments may have involved lower upfront costs, their reduced efficacy in weed suppression often translated into lower economic returns due to decreased grain yield and potentially higher labour requirements for supplementary weed control. The integration of a sequential herbicide strategy, as seen in this treatment, strikes a balance by optimizing weed control and yield while offering cost savings through reduced labour requirements. These findings suggested the importance of selecting herbicide strategies that align with both agronomic goals and economic viability, highlighting the trade-offs between input costs, weed control efficiency and overall profitability.

Conclusion

The application of pendimethalin at 1 kg ha^{-1} on 3 DAS followed by triafamone + ethoxysulfuron at 66.5 g ha^{-1} on 20 DAS demonstrated superior weed control efficiency, leading to increased grain yield and improved economic returns. The ready-mix herbicide effectively targeted weeds with different modes of action, reducing competition and enhancing crop growth, resulting in higher numbers of productive tillers and filled grains per panicle leads to higher grain yield. The reduced labour costs contributed to the higher B:C ratio. These findings highlight the economic and agronomic benefits of using a ready-mix herbicide strategy in rice cultivation. Future research should focus on evaluating the performance of pendimethalin and triafamone + ethoxysulfuron across varying agro-climatic conditions and rice cultivation systems, considering factors like temperature, soil type and irrigation methods. Such studies will help optimize their use for sustainable weed control and rice productivity

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Authors' Contributions

The study conceptualization by GP, with methodology developed by GP, ATM and SM and investigation carried out by GP and ATM. The original draft was prepared by KN, ATM and GP, while KN and GP contributed to the review and editing. Visualization was handled by KN and supervision was provided by GP, SM, BRPV, GM, VM, KT, PP. All authors have read and agreed to the published version of the manuscript.

Compliance with Ethical Standards

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

Ethical issues: None

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