Indian Journal of Agronomy **70** (4): 409–415 (December 2025)
DOI: 10.59797/ija.v70.i4.5662

Research Paper

Efficacy of herbicide mixtures on weed control, yield and water productivity of direct-sown summer rice

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Received: March 2025; Revised accepted: December 2025

ABSTRACT

Rice is more susceptible to weed infestation than other food crops, necessitating the prioritization of effective weed management strategies. The potential for sustainable weed control through herbicide mixtures is a key consideration. A study was conducted at the ICAR-National Rice Research Institute, Cuttack, India, during the summer seasons of 2020 and 2021 to assess the efficacy of a new formulation of penoxsulam 1.02% + cyhalofop butyl 5.1% in comparison to the existing ready-mix formulation, penoxsulam 1.02% + cyhalofop butyl 5.1% (marketed as Vivaya). In terms of weed composition, grasses, sedges, and broadleaf weeds accounted for 45.0%, 27.2%, and 27.8%, respectively. Among these, *Echinochloa crus-galli* emerged as the dominant weed, constituting 23.2% of the total weed population. The application of penoxsulam 1.02% + cyhalofop butyl 5.1% at 135 g/ha demonstrated effective broad-spectrum weed control, particularly strong against sedges. In plots with crop-weed competition, the grain yield of rice was reduced by 37.5%. The new formulation and Vivaya showed comparable results in reducing weed density and biomass. Application of ready-mix penoxsulam 1.02% + cyhalofop butyl 5.1% at 135 g/ha as a post-emergence herbicide at 15 DAS resulted in a remarkable 45.9% increase in grain yield over the weedy check plots. Weed control with the new formulation of ready-mix penoxsulam 1.02% + cyhalofop butyl 5.1% at 135 g/ha recorded physical water productivity (0.44 kg/m³), economic water productivity (₹8.65/kg), and net return (₹57.00×10³/ha), which were comparable to Vivaya. Thus, new formulations of penoxsulam 1.02% + cyhalofop butyl 5.1% were found to be safe and effective for controlling weeds in wet direct-seeded rice at a dose of 135 g/ha.

***Key words*:** Economics, Herbicide mixtures, Water productivity, weed biomass, Wet direct-seeded rice

Direct-seeded rice has emerged as an environmentally sound alternative to traditional transplanting in rice cultivation (Bana *et al*., 2020). Among the two prevalent direct seeding systems in India, wet seeding stands out as a competitive approach, specifically in Eastern India. In wet seeding, pre-germinated seeds are sown in puddled soil, making it suitable for regions with abundant water resources. Generally, the crop's performance in terms of yield is comparable to that of transplanted rice (Biswakarma *et al*., 2021). Wet direct-seeded rice holds significant potential for adoption in the irrigated ecosystem of Odisha, especially during the summer season. Moreover, in flood-affected coastal lowland rice ecosystems, farmers have successfully established rice crops through direct wet seeding of pre-germinated seeds after the recession of flood waters (Saha *et al*., 2011).

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Rice is notably more susceptible to weed infestation when compared to other staple crops (Gharde *et al*., 2018). This vulnerability becomes particularly pronounced in direct-seeded rice (Bana *et al*., 2020). Allowing weeds to proliferate unchecked in rice fields can lead to a potential reduction in grain yield of up to 61% (Maity and Mukherjee, 2008). Traditional manual weeding methods are no longer cost-effective, which has led to the adoption of herbicidal weed control as an economically efficient alternative. Various pre-emergence and post-emergence herbicides have demonstrated promise in effectively managing diverse weed species in direct-seeded rice (Bana *et al*., 2020). However, due to the inherent biological adaptability of weeds and their ability to evolve over time, they maintain a survival advantage from one generation to the next. The repeated use of similar herbicides, often with the same mode of action, can lead to shifts in weed populations and, more significantly, the development and spread of herbicide resistance among weeds (Kumawat *et al*., 2018). Consequently, it is hypothesized that herbicide products formulated as mixtures with dissimilar modes of action may offer a potential solution to mitigate the development of herbicide resistance in weed populations.

For a sustainable weed management strategy, there is a need to evaluate new herbicide molecules for effective weed control. The new formulation of penoxsulam (1.02%) + cyhalofop-butyl (5.1%) has been evaluated with the following objectives: to assess its efficacy for weed control in direct-seeded rice, to estimate the economics and water productivity of direct-sown rice under different weed control methods, and to study weed dynamics in direct wet-seeded rice.

MATERIALS AND METHODS

Field experiments were conducted at the research farm of ICAR-National Rice Research Institute, Cuttack (20.50°N, 86.0°E, and 23.5 m above mean sea level), Odisha, during the dry seasons of 2020 and 2021. The soil of the experimental field was sandy clay loam in texture, slightly acidic to neutral in reaction, with a *p*H of 6.7, total carbon of 0.78%, available nitrogen of 216 kg/ha, available phosphorus of 18.4 kg/ha, and available potassium of 121 kg/ha.

The experiment was laid out in a randomized complete block design with three replications. The treatments consisted of penoxsulam 1.02% + cyhalofop-butyl 5.1% (New source) at 120 g/ha at 15 DAS (T_1), penoxsulam 1.02% + cyhalofop-butyl 5.1% (New source) at 135 g/ha at 15 DAS (T_2), bispyribac sodium 10% SC at 25 g/ha at 15 DAS (T_3), penoxsulam 1.02% + cyhalofop-butyl 5.1% (Vivaya) at 120 g/ha at 15 DAS (T_4), penoxsulam 1.02% + cyhalofop-butyl 5.1% (Vivaya) at 135 g/ha at 15 DAS (T_5), hand weeding twice (T_6), and a weedy check (T_7).

Pre-germinated paddy seeds were sown in puddled soil by spot seeding at a 15 × 15 cm spacing in the second week of February for both years of the experiment. The recommended doses of fertilizers was applied at 80 kg N, 40 kg P_2O_5, and 40 kg K_2O per hectare in the form of urea, di-ammonium phosphate (DAP), and muriate of potash (MOP), respectively. Irrigations were applied at 7-day intervals to maintain 3–5 mm of water depending upon rainfall until the grain-filling stage of the crop. Weed control treatments were imposed as per the treatment schedule. All herbicides were applied at saturated soil moisture using a knapsack sprayer fitted with a flat-fan nozzle at a spray volume of 350 liters per hectare, following the protocol. All other recommended agronomic and plant protection measures were adopted to ensure uniform crop growth across all plots.

Weed density and biomass data were recorded at 45 days after sowing (DAS) and 60 DAS. Weed density was measured using a 0.5 m × 0.5 m quadrat, which was placed randomly at four spots in each plot. Weeds were removed and dried in the sun, followed by oven drying at 70°C for 48 hours. Thereafter, the dry weight was recorded. The absolute data on the number of weeds and biomass were statistically transformed using the square root method for accuracy in statistical analyses.

Weed control efficiency (WCE) was calculated by using the following formula and expressed in percentage (Mishra and Mishra, 1997).

Weed control efficiency (%) = $[(WDM_C - WDM_T)/WDM_C] \times 100$

Where, WCE = Weed control efficiency (%), WDM_C = Weed biomass in weedy check plot and WDM_T = Weed biomass in the treated plot.

Grain yield of rice, along with other yield components, was recorded at harvest. Sampling was done from an area of 1 m² in each plot to record yield attributes. Grain yield was determined from the net area of 24 m² in each plot, excluding border rows at harvest. The weed index (WI) was computed using the following formula, as suggested by Gill and Kumar (1969).

WI (%) = $[(Y_{WFC}-Y_T)/Y_{WFC}] \times 100$

Where, WI = Weed index (%), Y_{WFC} = Yield of the crop in weed-free check, and Y_T = Yield of the crop in plot under weed control treatment

Physical water productivity was calculated by dividing grain yield by the total water used (rainfall + irrigation). Economic water productivity was determined by dividing the gross return by the total water used. The economics of rice cultivation was computed based on the local market price of various inputs used and the minimum support price for paddy. The cost of production per kg of grain yield (₹/kg) was calculated by dividing the cost of cultivation (₹/ha) by the grain yield (kg/ha). Statistical analysis was performed in MS Excel for a randomized block design (RBD), following standard calculation methods to obtain an Analysis of Variance (ANOVA). Treatment means were differentiated using the least significant difference (LSD) at a 5% probability level. As mentioned earlier, all weed-related data were transformed using the square root transformation before statistical analysis to normalize their distribution.

RESULTS AND DISCUSSIONS

Composition of weed flora, weed density, biomass and weed control efficiency

In our study, the weedy check plots were infested with 15 weed species belonging to 9 families in both years. Among the different categories of weeds, grasses were the most dominant (45.0%), followed by broad-leaved weeds (27.8%) and sedges (27.2%). The grassy weed *Echinochloa crus-galli* was the most dominant (23.2%), followed by *Cyperus difformis* (14.3%) and *Echinochloa glabrescens* (12.8%). Among the broad-leaved weeds, the average population of *Ludwigia adscendens* accounted for 8.7% of the total weed population, followed by *Eclipta alba* (7.9%).

Throughout the crop's growth period in the weedy check plots, there was substantial competition between the crop and weeds. We observed significantly higher weed density and weed biomass across all categories of weeds in these weedy check plots. In contrast, the competition was noticeably lower in the treated plots. Among the treatments, the manual weeding applied twice (T_6) resulted in the lowest weed density and weed biomass. Furthermore, treatments involving herbicide applications demonstrated a significant reduction in weed density and weed biomass for all three categories of weeds, including grasses, sedges, and broadleaf weeds, in comparison to the weedy check (Table 1). Specifically, the application of the ready-mix penoxsulam 1.02% + cyhalofop butyl 5.1% led to a substantial decrease in weed density and weed biomass compared to the weedy check. Both technical formulations, Vivaya and the new formulation of penoxsulam 1.02% + cyhalofop butyl 5.1%, performed equally well in terms of reducing total weed density and biomass at 45 and 60 days after sowing (DAS). The application of ready-mix penoxsulam 1.02% + cyhalofop butyl 5.1% at 135 g/ha was comparable to the standard herbicide bispyribac sodium in reducing weed population, biomass, and weed control efficiency. Similarly, ready-mix penoxsulam + cyhalofop-butyl was found to be effective in controlling a broad spectrum of weeds in transplanted rice (Radhamani, 2019).

The effectiveness of post-emergence herbicides in weed management in direct-seeded rice depends on the growth stage of the weeds, considering the differential absorption and metabolism of the herbicide. In our study, herbicides were applied at 15 DAS, when most weeds were at the 2- to 4-leaf stage, resulting in a significant reduction in weed population and biomass. Singh *et al*. (2019) reported that the post-emergence application of ready-mix penoxsulam + cyhalofop-butyl in puddled soil for direct-seeded rice also provided effective broad-spectrum weed control. The concentration of the herbicide and the stage of application were found to be critical factors in reducing weed pressure in rice. The application of penoxsulam + cyhalofop-butyl at 135 g/ha at the 2- to 4-leaf stage significantly increased plant height and the number of tillers while reducing nutrient uptake by weeds. However, at lower concentrations, its effectiveness was not as pronounced, particularly in the later stages of crop growth (Patil *et al*., 2016). Raj and

Table 1. Weed density, weed biomass and weed control efficiency (WCE) at 45 DAS as influenced by weed control methods (mean of 2 years; data processed with square root transformation)

Treatment	Weed density at 45 DAS (no/m²)				Weed biomass at 45 DAS (g/m²)				WCE (%)
	Grass	Sedge	BLW	Total	Grass	Sedge	BLW	Total	
T_1, Penoxsulam + Cyhalofop butyl (New Source) @ 120 g/ha at 15 DAS	5.1 (25.4)	2.3 (4.9)	5.5 (29.7)	7.8 (59.9)	4.92 (23.75)	1.68 (2.34)	5.02 (24.7)	7.16 (50.79)	69.5
T_2, Penoxsulam + Cyhalofop butyl (New Source) @ 135 g/ha at 15 DAS	4.9 (24.0)	1.8 (2.7)	5.1 (25.4)	7.2 (52.0)	4.47 (19.45)	1.27 (1.12)	4.79 (22.4)	6.59 (42.92)	74.2
T_3, Bispyribac sodium 10% SC @ 25 g/ha at 15 DAS	5.1 (25.9)	2.9 (7.7)	3.6 (12.5)	6.8 (46.1)	4.87 (23.20)	1.87 (3.00)	4.02 (15.65)	6.51 (41.85)	74.8
T_4, Penoxsulam + Cyhalofop butyl (Vivaya @ 120 g/ha at 15 DAS	5.0 (24.2)	2.5 (5.7)	4.9 (23.2)	7.3 (53.1)	4.97 (24.25)	1.78 (2.67)	4.52 (19.95)	6.88 (40.87)	75.4
T_5, Penoxsulam + Cyhalofop butyl (Vivaya) @ 135 g/ha at 15 DAS	4.4 (19.0)	2.0 (3.7)	4.5 (20.2)	6.6 (42.7)	4.38 (18.65)	1.38 (1.42)	4.01 (15.60)	6.01 (35.67)	78.6
T_6, Hand weeding twice at 20 and 40 DAS	4.1 (16.0)	1.7 (2.3)	3.0 (8.4)	5.2 (26.7)	3.80 (13.95)	1.17 (0.87)	2.29 (4.75)	4.48 (19.57)	88.2
T_7, Weedy check	8.9 (78.5)	7.0 (48.9)	7.1 (50.0)	13.3 (177.4)	8.47 (71.20)	6.50 (41.70)	7.35 (53.5)	12.92 (166.40)	0.0
SEm±	0.36	0.42	0.70	0.72	0.38	0.26	0.44	0.80	
CD (P=0.05)	1.02	1.32	2.06	2.18	1.12	0.81	1.36	2.46	

T_1, Penoxsulam 1.02% (w/w) + Cyhalofop butyl 5.1% (New Source) 120 g/ha at 15 DAS; T_2, Penoxsulam 1.02% (w/w) + Cyhalofop butyl 5.1% (New Source) @ 135 g/ha at 15 DAS, T_3, Bispyribac sodium 10% SC @ 25 g/ha at 15 DAS; T_4, Penoxsulam 1.02 % + Cyhalofop butyl 5.1% (Vivaya) @ 120 g/ha at 15 DAS; T_5, Penoxsulam 1.02 % + Cyhalofop butyl 5.1% (Vivaya) @ 135 g/ha at 15 DAS; T_6, hand weeding twice; T_7, Weedy check

Syriac (2018) reported significantly lower weed seed banks in plots treated with penoxsulam + cyhalofop-butyl in wet-seeded rice. Similarly, Singh *et al*. (2018) reported that the application of penoxsulam + cyhalofop-butyl at 135 g/ha did not match manual weeding applied twice in reducing weed biomass and increasing the grain yield of transplanted *kharif* rice.

Growth and growth attributes

In the weedy plots, crop-weed competition had a significant impact on plant height, as shown in Table 2. Notably, there were non-significant differences in plant height among the various weed control treatments, as they all effectively reduced weed density and biomass. However, the weedy check recorded significantly shorter plant heights due to intense competition from weeds. The synchronized flowering of the crop led to simultaneous harvesting in all treatments. Nevertheless, persistent weed presence throughout the crop's growth cycle in weedy plots resulted in significantly shorter panicle length. All herbicidal weed control practices performed equally well in terms of weed control, showing non-significant differences in panicle length. Herbicide treatments, on the other hand, effectively reduced weed populations, resulting in comparable spikelet counts per panicle across all treatments.

Yield and yield attributes

The grain filling percentage in wet direct-seeded rice decreased significantly in the weedy check compared to the weed control treatments. The reduced number of spikelets and filled grains per panicle in the weedy check ultimately led to lower panicle weight, highlighting the impact of weed infestation on rice yield. When it comes to yield and yield attributes, rice plants in herbicide-treated and weed-free plots produced a higher number of panicles compared to those in the manually weeded and weedy check plots. This can be attributed to reduced competition for nutrients, water, and light when weeds are effectively controlled. In rice cultivation, effective weed control during the early growth stages is crucial, especially considering the slow canopy growth of rice (Mahajan and Chauhan, 2013). Weed control treatments significantly influenced yield attributes such as panicles per square meter and grains per panicle (Saha *et al*., 2016; Satapathy *et al*., 2020).

The data in Table 2 clearly demonstrates the significant role of weed control in determining rice yield. Manual weeding applied twice resulted in the highest number of filled grains per panicle, panicles per square meter, and overall grain yield, primarily due to reduced crop-weed competition during the critical growth period of 20-45 days after sowing (DAS). Early post-emergence herbicide applications at 15 DAS, targeting the 2- to 4-leaf stage of weeds, also reduced crop-weed competition for moisture, nutrients, and sunlight, leading to increased crop growth and final grain yield. In our study, all herbicide treatments showed a significant increase in yield compared to the weedy check. These treatments effectively controlled a broad spectrum of weeds, as evident from data on weed

Table 2. Yield attributes, yield of rice and weed index as influenced by weed control methods (mean of 2 years)

Treatment	Plant height (cm)	Panicle length (cm)	Panicles/ m^2	Grains/ panicle	Test weight (g)	Grain yield (t/ha)	Straw yield (t/ha)	WI
T_1, Penoxsulam + Cyhalofop butyl (New Source) @ 120 g/ha at 15 DAS	105.5	23.4	324.5	127.0	22.7	4.99	5.79	12.0
T_2, Penoxsulam + Cyhalofop butyl (New Source) @ 135 g/ha at 15 DAS	105.5	23.5	328.5	128.0	22.8	5.20	5.76	8.3
T_3, Bispyribac sodium 10% SC @ 25 g/ha at 15 DAS	106.5	23.9	323.5	129.5	22.8	5.12	5.94	9.7
T_4, Penoxsulam + Cyhalofop butyl (Vivaya @ 120 g/ha at 15 DAS	105.5	23.2	324.0	128.0	23.0	5.13	5.86	9.7
T_5, Penoxsulam + Cyhalofop butyl (Vivaya) @ 135 g/ha at 15 DAS	105.5	23.7	341.5	130.0	23.1	5.39	5.98	5.0
T_6, Hand weeding twice at 20 and 40 DAS	106.5	24.1	361.0	132.0	23.3	5.68	6.28	0.0
T_7, Weedy check	91.5	20.5	252.0	104.0	20.9	3.70	4.88	37.5
SEm±	0.7	0.3	11.7	2.1	0.2	0.17	0.18	-
CD (P=0.05)	2.1	1.0	34.4	6.2	0.6	0.50	0.52	-

T_1, Penoxsulam 1.02 % (w/w) + Cyhalofop butyl 5.1% (New Source) 120 g/ha at 15 DAS; T_2, Penoxsulam 1.02% (w/w) + Cyhalofop butyl 5.1% (New Source) @ 135 g/ha at 15 DAS, T_3, Bispyribac sodium 10% SC @ 25 g/ha at 15 DAS; T_4, Penoxsulam 1.02 % + Cyhalofop butyl 5.1% (Vivaya) @ 120 g/ha at 15 DAS; T_5, Penoxsulam 1.02 % + Cyhalofop butyl 5.1% (Vivaya) @ 135 g/ha at 15 DAS; T_6, hand weeding twice; T_7, Weedy check density, weed biomass, and weed control efficiency. The use of herbicides effectively managed the competition between rice and weeds, reducing it from the early stages of crop growth until maturity. Proper herbicide use facilitated higher nutrient and water uptake, enhanced photosynthetic activity, and provided optimal space for improved crop growth, ultimately resulting in higher dry matter accumulation and better allocation of dry matter towards grain formation.

Penoxsulam, a broad-spectrum triazolopyrimidine herbicide that acts as an acetolactate synthase (ALS) inhibitor, and cyhalofop-butyl, which inhibits acetyl coenzyme A carboxylase, were found to be more effective when applied as a mixture than individually in direct-seeded rice (Raj and Syriac, 2018). This herbicide combination demonstrated effective control of grass weeds, broadleaf weeds, and sedge weeds in direct-seeded paddy fields. In our study, both formulations of the ready-mix penoxsulam + cyhalofop-butyl, applied at 15 DAS (2- to 4-leaf stage of weeds), significantly reduced weed biomass across all three categories of weeds and increased grain and straw yield compared to the weedy check. The performance of penoxsulam + cyhalofop-butyl was comparable to the existing Vivaya formulation and the standard rice herbicide bispyribac sodium in terms of weed control efficiency and yield increase. Early weed control through the early post-emergence application of the ready-mix penoxsulam + cyhalofop-butyl at 15 DAS resulted in higher grain and straw yield due to improved nutrient availability and uptake in wet direct-seeded rice (Singh *et al.,* 2015). Application of penoxsulam + cyhalofop-butyl at lower dose was not comparable to manual weeding applied twice in terms of weed control and yield increase in transplanted rice (Singh *et al*., 2018). This difference can be attributed to the poor control of well-established broadleaf weeds (6- to 8-leaf stage) like *Ludwigia adscendens* and *Ludwigia octovalvis* at the time of herbicide application. Menon *et al*. (2016) also reported limited efficacy of this herbicide combination against *Ludwigia parviflora* in transplanted rice.

The extent of yield loss due to crop-weed competition can be assessed through the calculation of the weed index. The data in Table 2 show that the weed index varied with weed control practices. Without weed control, grain yield losses reached 37.5%. Among the herbicidal treatments, penoxsulam 1.02% + cyhalofop-butyl 5.1% (Vivaya) applied at 135 g/ha at 15 DAS resulted in the lowest weed index of 5.0% and was comparable to the standard herbicide bispyribac sodium. This minimal loss in grain yield can be attributed to the effective control of grasses, sedges, and broadleaf weeds.

Water productivity

Effective weed control not only enhances yield but also improves resource use efficiency, including water use. The physical and economic water productivity varied significantly among the weed control treatments (Table 3). The highest water productivity was recorded under T_6 (hand weeding twice), which was statistically on par with T_5

Table 3. Economics and water productivity of direct wet sown of summer rice as influenced by weed control methods (mean of 2 years)

Treatment	Gross Return (×10^3 ₹/ha)	COC (×10^3 ₹/ha)	Net Return (×10^3 ₹/ha)	B:C ratio	COP (₹/kg)	PWP (kg/m3)	EWP (₹/m^3)
T_1, Penoxsulam + Cyhalofop butyl (New Source) @ 120 g/ha at 15 DAS	97.7	44.3	53.4	2.21	8.89	0.42	8.32
T_2, Penoxsulam + Cyhalofop butyl (New Source) @ 135 g/ha at 15 DAS	101.5	44.5	57.0	2.28	8.57	0.44	8.65
T_3, Bispyribac sodium 10% SC @ 25 g/ha at 15 DAS	100.3	44.9	55.4	2.23	8.77	0.44	8.54
T_4, Penoxsulam + Cyhalofop butyl (Vivaya @ 120 g/ha at 15 DAS	100.3	44.3	56.0	2.26	8.65	0.44	8.54
T_5, Penoxsulam + Cyhalofop butyl (Vivaya) @ 135 g/ha at 15 DAS	105.3	44.5	60.8	2.37	8.26	0.46	8.96
T_6, Hand weeding twice at 20 and 40 DAS	110.9	47.6	63.3	2.32	8.38	0.48	9.44
T_7, Weedy check	73.1	39.2	33.5	1.85	10.69	0.32	6.22
SEm±	2.10	-	2.10	0.15	0.19	0.01	0.26
CD (P=0.05)	6.48	-	6.48	0.05	0.58	0.04	0.80

T_1, Penoxsulam 1.02 % (w/w) + Cyhalofop butyl 5.1% (New Source) 120 g/ha at 15 DAS; T_2, Penoxsulam 1.02% (w/w) + Cyhalofop butyl 5.1% (New Source) @ 135 g/ha at 15 DAS, T_3, Bispyribac sodium 10% SC @ 25 g/ha at 15 DAS; T_4, Penoxsulam 1.02 % + Cyhalofop butyl 5.1% (Vivaya) @ 120 g/ha at 15 DAS; T_5, Penoxsulam 1.02 % + Cyhalofop butyl 5.1% (Vivaya) @ 135 g/ha at 15 DAS; T_6, hand weeding twice; T_7, Weedy check

(Penoxsulam 1.02% + cyhalofop-butyl 5.1% (Vivaya) applied at 135 g/ha at 15 DAS) and T_2: Penoxsulam 1.02 % (w/w) + Cyhalofop butyl 5.1% (New Source) @135 g/ha at 15 DAS. However, the lowest water productivity was observed in the weedy check (T_7). The effects of other treatments on water productivity were intermediate. The superior performance of T_2, T_5 and T_6 can be attributed to effective weed control, which minimized competition for nutrients and reduced water loss through transpiration by weeds. This not only led to higher yields but also conserved significant soil moisture. The combined effect of increased yield and reduced soil moisture loss resulted in enhanced water productivity (Sen *et al*., 2021; Raj *et al*., 2017).

Economics

Hand weeding twice resulted in a higher net return (63.3×10^3/ha), but it was at par with T_5 (Penoxsulam 1.02% + cyhalofop-butyl 5.1% (Vivaya) applied at 135 g/ ha at 15 DAS) and T_2 (Penoxsulam 1.02% (w/w) + cyhalofop-butyl 5.1% (New Source) applied at 135 g/ha at 15 DAS). Weed control measures significantly contributed to the reduction in the cost of production. The application of herbicide penoxsulam 1.02% + cyhalofop-butyl 5.1% (Vivaya) at 135 g/ha at 15 DAS recorded the lowest cost of production (8.26/kg), which was at par with T_2 (Penoxsulam 1.02% (w/w) + cyhalofop-butyl 5.1% (New Source) applied at 135 g/ha at 15 DAS). The weedy check reflected a significantly higher cost of production (10.69/ kg). The reduced crop-weed competition and better resource use efficiency resulted in significantly higher grain yield in weed control plots compared to the weedy check (Satapathy *et al*., 2020).

The present study suggested that the application of both the old and new formulations of penoxsulam + cyhalofop (ready-mix) at 135 g/ha at 15 DAS could serve as an effective and cost-efficient method for controlling a broad spectrum of weeds and enhancing yield, net return, and water productivity in wet direct-seeded rice. The early post-emergence application of the ready-mix penoxsulam + cyhalofop at 135 g/ha was found to be safe for wet direct-seeded summer rice and can be recommended as an alternative to costly manual weeding for weed management in wet-seeded rice under the lowland rice ecosystem.

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