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Weed management and nitrogen in enhancing productivity of direct seeded rice: A review

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Abstract

Direct-seeded rice (*Oryza sativa* L.) is starting to become a popular sustainable alternative to the conventional puddled transplant rice, as it has the benefits of less reliance on labor, water, and energy, allows crop establishment on time, and allows mechanization. Although these advantages exist, direct-seeded rice (DSR) has serious issues that may reduce its yield, and they can be summarized into reduced efficiency in the use of nitrogen and the existence of weeds when the soils are aerobic. In rice, nitrogen is a very essential nutrient as it affects the production of tillers, panicles, fill the crescent, and the total yield. Under DSR systems, leaching, denitrification, and oxidation are likely to contribute to higher nitrogen losses, so any strategy to reduce them, including split or fractional treatment of nitrogen according to crop demand, is necessary. These practices enhance the absorption of nitrogen, biomass creation, and boost the grain harvest. Another important aspect of DSR is weed management because of the aerobic environment and the use of dry-tillage, the germination and growth of various weed flora is promoted. Weeds have the potential to reduce the yield of grains by 80 percent when controlled at an early stage. Conventional hand weeding is tedious, expensive, and in most cases, impractical, particularly at times of abundance of weeds. Thus, effective weed control via chemical means has turned out to be very crucial through the adoption of sequential or integrated control using pre and post-emergence herbicides. Combining appropriate nitrogen management and optimal weed management promotes the efficiency of nitrogen management, minimization of competition between crops and weeds, and performance of crops. The review highlights the need to integrate optimized nitrogen application regimes and effective weed management systems to get maximum productivity, profitability, and sustainability of direct-seeded rice systems. The knowledge of these combined management practices is essential in solving the resource limitations to guarantee food security in rice-based planting systems.

Keywords: Direct-seeded rice (DSR), weed control, herbicides, nitrogen management, nitrogen use efficiency, crop productivity, sustainable rice cultivation

Introduction

Direct-seeded rice (DSR) is gaining popularity worldwide as a viable alternative to traditional puddled transplanted rice due to its water, energy, and labour savings, and its greater sustainability. But the uptake of DSR is limited by two closely related management issues: the ubiquitous weed problem and efficient nitrogen (N) use. In DSR, rice and weeds germinate almost at the same time in dry conditions, as opposed to puddled transplanted rice, where rice gets a "head-start," and many weed species are controlled in the flooded environment (Sandhu *et al.*, 2021; Kumar *et al.*, 2021) ^[63, 28]. This change in planting practice leads to more complex weed communities (grasses, sedges, and broadleaf weeds in two or more flushes), which can inflict much greater losses in DSR than in puddled transplanted rice if not managed properly (Sandhu *et al.*, 2021; Kumar *et al.*, 2021) ^[63, 28]. On the other hand, DSR is being introduced in areas facing groundwater scarcity, increasing production costs, and environmental concerns associated with greenhouse gas emissions and nutrient losses, so DSR's success depends on the management of nitrogen and nitrogen use efficiency (NUE) (Little *et al.*, 2021; Govindasamy *et al.*, 2023) ^[34, 19]. Nitrogen is a vital nutrient for rice, but it is also the most susceptible to losses; low NUE not only affects profitability but can also cause water and air pollution, and can promote weed growth and competitiveness, further exacerbating the yield gap (Marzouk *et al.*,

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2023; Govindasamy *et al.*, 2023; Korres *et al.*, 2022) [40, 19, 27].

Experiences with rice-based systems demonstrate that resource-conserving technologies such as improved N management, retention of crop residues, alternate wetting and drying, and use of both organic and inorganic N sources can improve NUE, but their success is highly site-specific and also interacts with weed biology (Sandhu *et al.*, 2021; Little *et al.*, 2021; Alam *et al.*, 2023; Kumar *et al.*, 2021) [63, 19, 4, 28]. Furthermore, sub-optimal N scheduling or high N rates can selectively promote growth and competitiveness of aggressive weeds (including weedy rice) and eliminate yield responses to fertilization unless complemented with timely and diverse weed control measures (Alagbo *et al.*, 2022; Rodenburg *et al.*, 2022; Kumar *et al.*, 2021; Korres *et al.*, 2022) [2, 62, 28, 27]. The increasing cost of labor and scarcity of other farm inputs are driving farmers to rely on herbicides for weed control. But the continuous and excessive use of herbicides has resulted in changes in weed composition and the development of herbicide resistance. This situation demands the development and use of novel herbicide cocktails with different modes of action for sustainable and effective weed management (Das *et al.*, 2026) [17]. Therefore, to develop sustainable, productive DSR systems, it is important to understand the interactions between weed and nitrogen management and how it affects crop establishment, resource use efficiency, and productivity under varying ecologies. This review highlights the importance and interaction of weed management and nitrogen management in improving the productivity, profitability, and sustainability of direct-seeded rice systems, based on recent research on agronomy, breeding, and resource-conserving technologies, and identifies opportunities for future research and extension (Sandhu *et al.*,

2021; Alagbo *et al.*, 2022; Little *et al.*, 2021; Govindasamy *et al.*, 2023; Kumar *et al.*, 2021) [63, 2, 19, 28].

Weed Flora in Direct-Seeded Rice (DSR)

Several studies have investigated the composition and prevalence of weed flora in direct-seeded rice in different areas of India and beyond. Kalyanasundaram *et al.* have reported that *Echinochloa colonum*, *Leptochloa chinensis*, and *Cyperus difformis* were the predominant weeds in the Annamalai University in Tamil Nadu. The other species that were found there included *Bergia capensis*, *Eclipta alba*, and *Marsilea quadrifolia*. Similarly, Malik *et al.* observed that over 80 percent of the total population of weeds in Pantnagar were *Commelina benghalensis*, *Fimbristylis miliacea*, *Echinochloa crusgalli*, *Cyperus difformis*, and *Cyperus iria*, with others like *Caesulia axillaris*, *Physalis minima*, and *Phyllanthus niruri* also present. *Cynodon dactylon*, *Cyperus rotundus*, *Cyperus difformis*, *Fimbristylis miliacea*, *Sphenoclea zeylanica*, and *Ludwigia parviflora* were the dominating species at the Central Rice Research Institute in Cuttack. Subramanian and Martin (2005) discovered a composite flora of weeds in Coimbatore. It comprised broad-leaved weeds (*Eclipta alba*, *Ammannia baccifera*, *Ludwigia parviflora*, *Marsilea quadrifolia*, *Monochoria vaginalis*), sedges (*Cyperus difformis*, *C. rotundus*, and *C. iria*), and grasses (*Echinochloa colona*, *E. crusgalli*, and *Leptochloa chinensis*). On the same note, Rajkhowa and Barua (2007) [56] listed in Jorhat in Assam, broadleaved weeds such as *Alternanthera philoxeroides*, *Commelina diffusa*, and sedges such as *Cyperus iria*, as well as grasses such as *Axonopus compressus* and *Cynodon dactylon*.

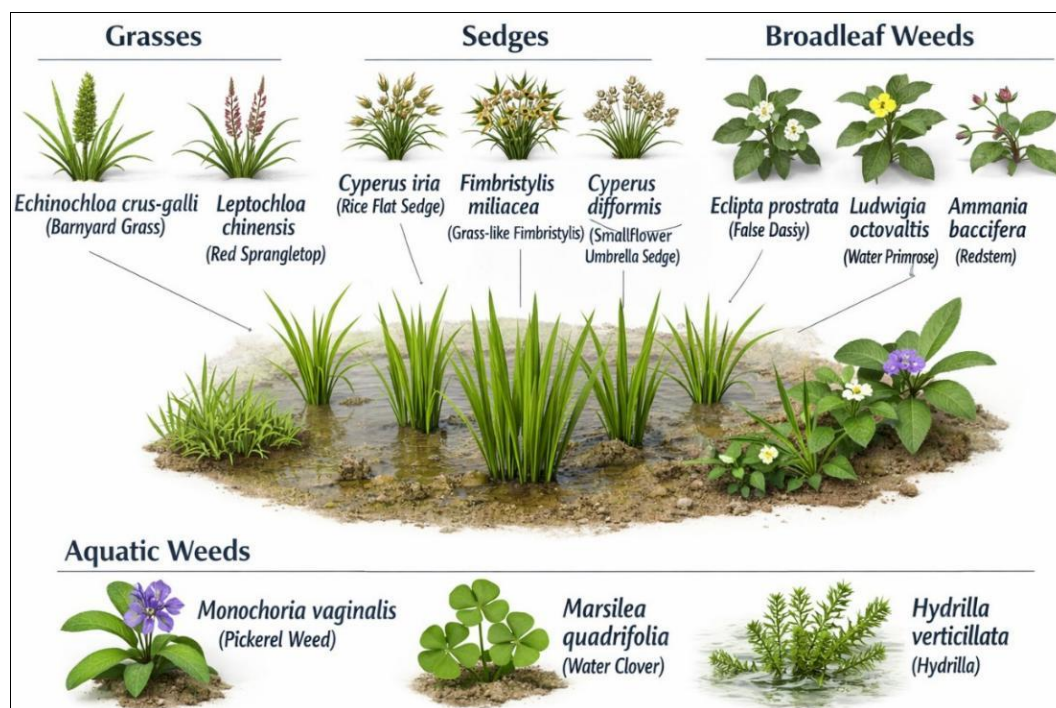


Fig 1: This diagram illustrates the major weed flora commonly found in direct-seeded rice (DSR), grouped into grasses, sedges, broadleaf weeds, and aquatic weeds. It highlights important weed species such as *Echinochloa crus-galli*, *Cyperus iria*, *Eclipta prostrata*, and *Monochoria vaginalis*, which compete with rice for nutrients, water, light, and space.

Sabour, Sharma *et al.*, (2007) [66] identified broad-leaved weeds (*Commelina benghalensis*, *Caesulia axillaris*, *Eclipta prostrata*, *Euphorbia hirta*, *Portulaca oleracea*, *Trianthema portulacastrum*, *Lindernia spp.*), sedges (*C. rotundus*, *C. iria*), and grasses (*Phyllanthus niruri*, *E. crusgalli*, *Lindernia viscosa*,

Amaranthus viridis) Mishra and Singh found them to be *Echinochloa colonum*, *Phyllanthus spp.*, *Commelina communis*, *Cyperus iria*, *Alternanthera sessilis*, *Dinebra retroflexa*, *Physalis minimum*, and *Caesulia axillaris* as the main weeds associated with dry direct-seeded rice (DSR) in Jabalpur,

Madhya Pradesh. Yadav *et al.* (2008) ^[75] identified *E. colonum*, *Cyperus rotundus*, *Cynodon dactylon*, *Commelina diffusa*, and *Ammania baccifera* as the most predominant species in Kumarganj (U.P.). Anwar *et al.* (2011) ^[5] conducted a study that found 20 species of weeds in 10 families at Universiti Putra in Malaysia. The *E. colonum*, *Physalis heterophylla*, *Cleome rutidosperma*, *C. iria*, and *C. rotundus* were the major weeds constituting 31% of the weed community, with the broad leaf weeds representing 49 percent of the total dry matter.

Losses Caused by Weeds in Rice

Naresh *et al.* (2011) ^[47] state that the weeds are uncontrolled and may lead to losses in production of 6592. Naseeruddin and Subramanyam (2013) ^[49] also identified broad-leaf weeds (*Eclipta alba* 6.5%), grasses (*E. colonum* 10.1%), and sedges (*Cyperus difformis* 40, *C. iria* 21.4, *C. rotundus* 12.22) as the predominant weeds in the loamy sands with the rice that has been sown with drum seeds. Raj *et al.* (2013) ^[55] showed that weeds in DSR that were not grass resulted in a 72 percent decrease in yield. Kaur and Singh (2015) ^[23-24] found the losses between 35 and 100 percent in resource conservation technologies (RCTs) systems, which have no weed management. According to Ramesh *et al.* (2015) ^[57], effective pesticide or hand-weeding treatments had a significant positive impact on yields by reducing the content of weeds, dry weight, and competition. Saravanane *et al.* (2016) ^[65] discovered that uncontrolled aerobic rice in coastal environments lost 86.3 percent of its output in Puducherry, India.

Critical Period of Crop-Weed Competition in Direct-Seeded Rice

Weed emergence interferes with yield loss patterns as Gibson *et al.* (2001) ^[18] demonstrated when they retarded the development of *Echinochloa phyllopogon* by 30 days after rice seeding. Some experiments have established CPWC of some rice establishment methods, such as upland DSR, the first 30 DAS (Ladu and Singh, 2006) ^[33]; dry-DSR, 15-45 DAS (Rao and Nagamani, 2007) ^[58-59]; wet-DSR, 15-60 DAS (Mukherjee *et al.*, 2011) ^[43]; and drilling DSR, up to 45 DAS (Naidu and B. Maintaining crop free of weeds during such periods is also critical in achieving yield outcomes that would be equal to the outcomes of the totally weed-free places. According to research, weed competition between 15 and 30 DAS has a significant impact on grain production, whereas it is found that weeds after the initial 15 DAS have minimal impact on the yield. Weed infestation of a season can cause an output hit by 93.6 percent (Ladu and Singh, 2006) ^[33]. Outsourcing in control weeds reduced output in wet and dry DSR 61 and 96 percent, respectively (Maity and Mukherjee, 2008) ^[39]. Recommended by Juraimi *et al.* (2010) ^[22] are the DSR weed-free situations of 2 to 71 DAS within saturated conditions and 15 to 73 DAS within flooded situations. Mubeena *et al.* (2014) ^[42] observed that paying attention to the weed control within 15-30 DAS reduces yield loss in DSR and effectively reduces the weed dry weight.

Nitrogen Management on Growth and Yield of Direct-Seeded Rice

Research conducted by Alagesan and Babu (2011) ^[3] and Chaudhary *et al.* (2011) ^[10] showed that four equal divisions at the seedling, active tillering, panicle initiation, and blooming stages performed better in developing growth, yield characteristics, and grain production compared to three-split plans. Mahajan *et al.* (2011) ^[37] have reported the highest output

of grain (7.55 to 7.76 t ha⁻¹) at 150 kg N ha⁻¹ applied in four applications with no baseline nitrogen. According to Yoseftabar (2013) ^[76], split nitrogen applications enhanced pre-anthesis dry matter, LAI, crop growth rate, the panicle-bearing tillers, kernels per panicle, 1000-grain weight, straw and grain yield, and harvest index, and maximized the spikelet fertility and reduced sterility. Kumawat *et al.* (2017) ^[32] also discovered that the highest combined grain production in DSR at IARI, New Delhi, was achieved when a quarter of the recommended amount of nitrogen was applied at baseline, week 2, week 5, and week 9 after planting.

Nitrogen Management on Weed Dynamics in Direct-Seeded Rice

The use of nitrogen has effects on the weed biomass and population, besides crop growth and production in direct-seeded rice (DSR). Nair *et al.* (2002) ^[45] examined the effects of different nitrogen treatments and methods of managing weeds on the dynamics of the weed in DSR (cv. Mahamaya). Besides six weed management methods, including mechanical weeding, manual weeding, submergence, anilofos, 2,4-D, and an unweeded control, the treatments included four schedules of N, namely 0:25:40:35, 25:0:40:35, 50:0:25:25, and 0:40:30:30 at 0, 20, 35, and 60 DAS. The results indicated that split nitrogen application had a capacity to influence the population of weeds, where the lowest population and dry matter of wheat was found in 0:25:40:35% N schedule at harvest.

Chaudhary *et al.* (2011) ^[10] found that four equivalent splits (¼ at early tillering, active tillering, panicle initiation, and blooming) lowered the growth of the weed. N-scheduling with ½ at sowing + ¼ at tillering + ¼ at panicle initiation raised weed density and dry weight. In directseeded rice, Kumar *et al.* (2015) ^[30] discovered that four splits of nitrogen treatments (¼ at 2 WS, 4 WS, 6 WS, and 8 WS) resulted in a single optimum total weed density and dry weight, highest weed control efficiency, least index of weed, and maximum crop growth and crop yield.

Nitrogen Management on Nutrient Uptake and Removal

Besides the crop development, the nutrient absorption and the competition with weeds in the direct-seeded rice (DSR) require nitrogen control. Sharma *et al.* (2007) ^[66] observed that the crop gained a greater amount of dry matter and more nitrogen when two-thirds of the nitrogen dose was administered at 20 DAS, followed by one-fourth and one-fourth at tillering and panicle initiation, respectively. These findings were comparable to the plots that were subjected to butachlor at 1.5kg/ha, followed by hand weed at 30 DAS. This implies that proper scheduling of N has the potential to improve nutrient uptake besides controlling weeds.

According to Raj *et al.* (2014) ^[54], the highest amounts of grain yield were recorded at 3752 and 3872 kg ha⁻¹ in the first and second year, respectively, when urea was divided into four equal doses between 5 -10 and 6065 DAE, which reduced the amount of nitrogen lost and maximized growth and production. Singh *et al.* (2015) ^[69] have found that 150 kg N ha in four splits (base, active tillering, panicle initiation, and flowering) at the N.E. increased nitrogen uptake (NPK) in DSR. Borlaug Crop Research Centre of Pantnagar. The effectiveness of N splits in DSR was also found by Rehman *et al.* (2016) ^[61], who also ensured that split application of 1/2 basal + 1/4 tillering + 1/4 anthesis and 1/3 basal + 1/3 tillering + 1/3 anthesis produced the highest overall nitrogen uptake, which was comparable to two-Split application.

Weed Management Practices on Crop and Weed

Even though it is impossible to kill the weeds completely, an effective weed management program must ensure that the levels of weeds remain below the economic level and prevent the weed flora from evolving into the more injurious species. Weed management has been one of the main inputs in rice production since weeding occupies a significant portion of labor in general.

The control of weeds has to be done within the initial 30 to 40 days of sowing, as the weeds pose the greatest threat to the production in the early stages of crop growth, as they compete the most in the initial stages. The management of weeds in rice may take three methods: chemical, mechanical, and cultural. Weed management is of particular concern to direct-seeded rice (DSR) because the soil is exposed at the initial stage of growth.

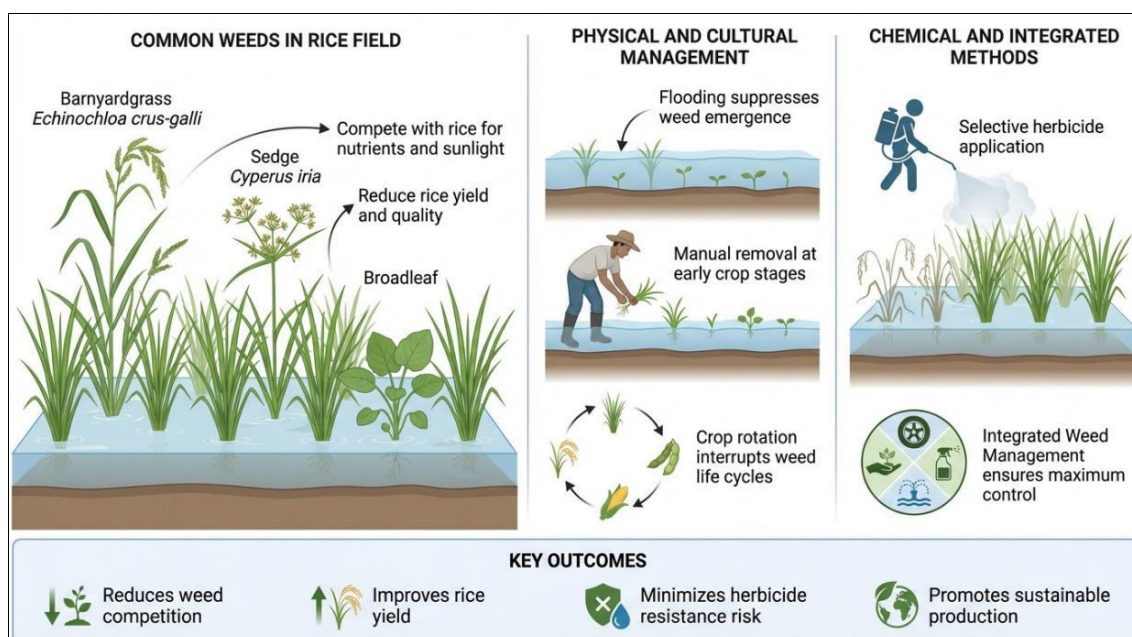


Fig 2: Weed Management Practices on Rice Crop and Weed

Table 1: Weed Management Practices in Rice Crop and Associated Weeds with Supporting References

Sl. No.	Weed Management Practice	Category	Target Weed Group / Major Weeds	Stage / Time of Application	Purpose / Key Role in Rice	Supporting Reference(s)
1	Clean seed use	Preventive	Weedy rice, annual grasses, sedges, and broadleaf weeds	Before sowing	Prevents the introduction of weed seeds into the field	IRRI (n.d.); Chauhan (2012) ^[11]
2	Cleaning field bunds and irrigation channels	Preventive	<i>Echinochloa</i> spp., <i>Cyperus</i> spp., <i>Fimbristylis</i> spp.	Before sowing and during the crop season	Prevents the movement of weed seeds from field margins	IRRI (n.d.)
3	Use of weed-free FYM/compost	Preventive	General weed flora	Before sowing/transplanting	Reduces weed seed contamination through organic inputs	Rao <i>et al.</i> (2007) ^[58-59]
4	Stale seedbed technique	Cultural	<i>Echinochloa colona</i> , <i>E. crus-galli</i> , <i>Cyperus iria</i> , <i>Fimbristylis miliacea</i>	2–3 weeks before sowing	Allows the first weed flush to emerge and be destroyed before crop establishment	IRRI (n.d.); Chauhan (2012) ^[11] ; Kumar <i>et al.</i> (2020) ^[31]
5	Puddling	Cultural	Many upland grassy weeds and some sedges	Before transplanting	Reduces weed emergence under puddled lowland conditions	Rao <i>et al.</i> (2007) ^[58-59] ; IRRI (n.d.)
6	Proper land leveling	Cultural	Mixed weed flora	Before sowing/transplanting	Ensures uniform water distribution and better weed suppression	IRRI (n.d.)
7	Optimum seed rate	Cultural	General weed flora	At sowing	Increases crop competitiveness and suppresses weed growth	Kumar <i>et al.</i> (2020) ^[31]
8	Line sowing/row planting	Cultural / Mechanical	All weed groups	At sowing	Facilitates intercultural and mechanical weeding	IRRI (n.d.); Rao <i>et al.</i> (2007) ^[58-59]
9	Competitive rice cultivars	Cultural	<i>Echinochloa</i> spp., <i>Leptochloa chinensis</i> , sedges	Variety selection stage	Fast early growth and canopy development reduce weed competition	Chauhan (2012) ^[11] ; Kumar <i>et al.</i> (2020) ^[31]
10	Early canopy closure	Cultural	Annual grasses and broadleaf	20–40 DAS	Suppresses late weed emergence through shading	Chauhan (2012) ^[11]

			weeds			
11	Crop rotation	Cultural	Weedy rice, sedges, grassy weeds	Seasonal / yearly	Breaks the weed life cycle and reduces the weed seed bank	Rao <i>et al.</i> (2007) ^[58-59] ; Kumar <i>et al.</i> (2020) ^[31]
12	Brown manuring with <i>Sesbania</i>	Cultural / Biological	<i>Echinochloa spp.</i> , <i>Cyperus difformis</i> , broadleaf weeds	20–30 DAS in DSR	Smothering and allelopathic suppression of weeds	Kumar <i>et al.</i> (2020) ^[31] ; Chauhan (2012) ^[11]
13	Residue mulching	Cultural	Small-seeded annual weeds	After sowing	Suppresses weed germination by limiting light penetration	IRRI (n.d.); Kumar <i>et al.</i> (2020) ^[31]
14	Water management (continuous shallow flooding)	Cultural	<i>Echinochloa spp.</i> , <i>Cyperus spp.</i> , aquatic weeds	Early crop growth	Reduces the emergence and growth of many rice weeds	IRRI (n.d.); Rao <i>et al.</i> (2007) ^[58-59]
15	Alternate wetting and drying with monitoring	Cultural	Mixed weed flora	Throughout the crop season	Saves water while helping regulate weed flushes	Kumar <i>et al.</i> (2020) ^[31]
16	Manual hand weeding	Mechanical	All weeds, including escaped weeds	20–25 and 40–45 DAS/DAT	Effective removal of established weeds	IRRI (n.d.); Mir <i>et al.</i> (2024) ^[41]
17	Hoeing / cono weeding	Mechanical	Inter-row grasses, sedges, broadleaf weeds	15–30 DAS	Disturbs and buries weeds while improving aeration	IRRI (n.d.); Rao <i>et al.</i> (2007) ^[58-59]
18	Mechanical weeder/power weeder	Mechanical	Inter-row weeds	15–30 DAS	Saves labor and improves weed control in line-planted rice	IRRI (n.d.); Mir <i>et al.</i> (2024) ^[41]
19	Hand roguing of weedy rice	Mechanical / Preventive	Weedy rice (<i>Oryza sativa</i> f. <i>spontanea</i>)	Before flowering	Prevents seed set and spread of weedy rice	Kumar <i>et al.</i> (2020) ^[31] ; IRRI (2018) ^[21]
20	Pre-emergence herbicide: Butachlor	Chemical	Annual grasses and some sedges	0–3 DAT/DAS	Controls early germinating weeds in transplanted rice	IRRI (n.d.); Rao <i>et al.</i> (2007) ^[58-59]
21	Pre-emergence herbicide: Pretilachlor	Chemical	Grasses, sedges, and some broadleaf weeds	0–3 DAT/DAS	Effective early-season weed control in wet and transplanted rice	IRRI (n.d.); Rao <i>et al.</i> (2007) ^[58-59]
22	Pre-emergence herbicide: Pendimethalin	Chemical	Grasses and some broadleaf weeds	0–3 DAS	Controls weeds in direct-seeded rice	IRRI (n.d.); Kumar <i>et al.</i> (2020)
23	Pre-emergence herbicide: Oxadiargyl / Oxadiazon	Chemical	Broadleaf weeds and sedges	0–5 DAS	Useful in dry direct-seeded rice and puddled systems	IRRI (n.d.); Kumar <i>et al.</i> (2020) ^[31]
24	Pre-emergence herbicide: Pyrazosulfuron-ethyl	Chemical	Sedges and broadleaf weeds	0–5 DAS	Controls early-emerging sedges and BLWs	Rao <i>et al.</i> (2007) ^[58-59]
25	Early post-emergence herbicide: Bispyribac-sodium	Chemical	<i>Echinochloa spp.</i> , <i>Leptochloa chinensis</i> , sedges, some BLWs	15–25 DAS	Broad-spectrum weed control in DSR	IRRI (n.d.); Kumar <i>et al.</i> (2020)
26	Post-emergence herbicide: Cyhalofop-butyl	Chemical	Grassy weeds	15–25 DAS	Effective control of barnyardgrass and other grasses	Kumar <i>et al.</i> (2020) ^[31] ; Rao <i>et al.</i> (2007)
27	Post-emergence herbicide: Fenoxaprop-p-ethyl	Chemical	Grassy weeds	15–25 DAS	Selective control of annual grasses	IRRI (n.d.); Rao <i>et al.</i> (2007) ^[58-59]
28	Post-emergence herbicide: Penoxsulam	Chemical	Grasses, sedges, broadleaf weeds	15–25 DAS	Broad-spectrum weed management	IRRI (n.d.); Kumar <i>et al.</i> (2020) ^[31]
29	Post-emergence herbicide: Azimsulfuron	Chemical	Sedges and broadleaf weeds	15–25 DAS	Particularly useful for sedge-dominated flora	IRRI (n.d.); Rao <i>et al.</i> (2007) ^[58-59]
30	Post-emergence herbicide: 2,4-D	Chemical	Broadleaf weeds and some sedges	25–35 DAS	Controls broadleaf weed infestation in rice	IRRI (n.d.); Rao <i>et al.</i> (2007) ^[58-59]
31	Post-emergence herbicide: Metsulfuron + Chlorimuron	Chemical	Broadleaf weeds and sedges	20–30 DAS	Effective against BLWs and sedges in transplanted rice	IRRI (n.d.)
32	Herbicide mixtures	Chemical / IWM	Mixed weed flora	15–25 DAS	Improves the spectrum of control where multiple weed groups occur	IRRI (n.d.); Mir <i>et al.</i> (2024) ^[41]
33	Sequential herbicide application	Chemical / IWM	Early and late flushes of weeds	PRE followed by POST	Controls multiple flushes during the crop season	Kumar <i>et al.</i> (2020) ^[31] ; Mir <i>et al.</i> (2024) ^[41]
34	Herbicide rotation	Resistance management	Herbicide-resistant weeds and weedy rice	Across seasons	Prevents herbicide resistance build-up	Kumar <i>et al.</i> (2020) ^[31] ; IRRI (2018) ^[21]

35	Spot spraying of weed patches	Precision / Chemical	Localized weed infestations	As needed	Reduces cost and prevents weed spread	Kumar <i>et al.</i> (2020) ^[31]
36	Ducks/fish in rice ecosystems	Biological	Young aquatic weeds and seedlings	Early crop stage in suitable systems	Grazing/trampling reduces weed emergence	Rao <i>et al.</i> (2007) ^[58-59]
37	Allelopathic rice genotypes	Biological / Cultural	Small-seeded annual weeds	Variety selection stage	Natural suppression of weeds by rice plants	Chauhan (2012) ^[11]
38	Integrated Weed Management (IWM)	Integrated	All major weed groups	Entire crop season	Combines cultural, mechanical, chemical, and preventive methods for sustainable control	Kumar <i>et al.</i> (2020) ^[31] ; Rao <i>et al.</i> (2007) ^[58-59] ; IRRI (n.d.)
39	Zero weed seed rain approach	Preventive / IWM	All seed-producing weeds	Before flowering and harvest	Prevents replenishment of the weed seed bank	Kumar <i>et al.</i> (2020) ^[31] ; Chauhan (2012) ^[11]
40	Monitoring and threshold-based weed control	Decision support	Site-specific weed flora	Throughout season	Enables rational, timely, and economical weed management	Mir <i>et al.</i> (2024) ^[41] ; Kumar <i>et al.</i> (2020) ^[31]

Table 2: Major Weeds Commonly Found in Rice and Relevant References

Sl. No.	Common Name	Scientific Name	Weed Group	Occurrence in Rice Ecosystem	Supporting Reference(s)
1	Barnyardgrass	<i>Echinochloa crus-galli</i>	Grass	DSR, wet-seeded and transplanted rice	Rao <i>et al.</i> (2007) ^[58-59] ; Kumar <i>et al.</i> (2020) ^[31]
2	Jungle rice	<i>Echinochloa colona</i>	Grass	DSR and upland rice	Rao <i>et al.</i> (2007) ^[58-59] ; Kumar <i>et al.</i> (2020) ^[31]
3	Chinese sprangletop	<i>Leptochloa chinensis</i>	Grass	Direct-seeded rice	Kumar <i>et al.</i> (2020) ^[31]
4	Bermuda grass	<i>Cynodon dactylon</i>	Grass	Upland rice and bunds	Rao <i>et al.</i> (2007) ^[58-59]
5	Goosegrass	<i>Eleusine indica</i>	Grass	Upland and aerobic rice	Rao <i>et al.</i> (2007) ^[58-59]
6	Rice flatsedge	<i>Cyperus iria</i>	Sedge	DSR and transplanted rice	Rao <i>et al.</i> (2007) ^[58-59] ; Kumar <i>et al.</i> (2020) ^[31]
7	Smallflower umbrella sedge	<i>Cyperus difformis</i>	Sedge	Wet lowland rice	Rao <i>et al.</i> (2007) ^[58-59]
8	Purple nutsedge	<i>Cyperus rotundus</i>	Sedge	Upland / aerobic rice	Rao <i>et al.</i> (2007) ^[58-59]
9	Globe fringerush	<i>Fimbristylis miliacea</i>	Sedge	Wet and direct-seeded rice	Rao <i>et al.</i> (2007) ^[58-59] ; Kumar <i>et al.</i> (2020) ^[31]
10	Monochoria	<i>Monochoria vaginalis</i>	Broadleaf / Aquatic	Lowland transplanted rice	Rao <i>et al.</i> (2007) ^[58-59] ; IRRI (n.d.)
11	False daisy	<i>Eclipta prostrata</i> (E. alba)	Broadleaf	Moist and puddled rice fields	Rao <i>et al.</i> (2007) ^[58-59]
12	Water primrose	<i>Ludwigia parviflora</i>	Broadleaf	Wet-seeded and transplanted rice	Rao <i>et al.</i> (2007) ^[58-59]
13	Dayflower	<i>Commelina benghalensis</i>	Broadleaf	Direct-seeded rice and moist fields	Rao <i>et al.</i> (2007) ^[58-59]
14	Slender ammania	<i>Ammannia baccifera</i>	Broadleaf	Wet rice ecosystems	Rao <i>et al.</i> (2007) ^[58-59]
15	Weedy rice / red rice	<i>Oryza sativa</i> f. spontanea	Special weed	Direct-seeded rice	Kumar <i>et al.</i> (2020) ^[31] ; IRRI (2018) ^[21]

Dry tillage, aerobic soil conditions, and methods such as alternating watering and drying promote the germination and growth of highly competitive weeds. In addition, herbicides, as well as all other weed management options, are not very effective in dry-seeded systems because of the limited water management. In the case of the puddled transplanted rice, manual weeding was the most popular in the past. Nevertheless, such a solution is not as viable and often unprofitable because of the high price of labor and the absence of personnel at the time of a vital wedding. It is under these circumstances that farmers are turning towards chemical weed management as an effective alternative in a bid to replace them in a prompt manner.

Manual Weeding

Manual weeding is one of the most effective methods to deal with the weeds in direct-seeded rice (DSR). Subash and Solanki (2003) reported that a single-hand weeding enhanced the ear bearing tillers, but two-hand weeding enhanced the ear length, the number of grains per ear, the weight of grain, the test weight, the harvest index, and the straw yield. Comparative with

herbicides application at sequential stages: Two hand weeding of 20 40 DAS reduced the weed density and dry weight, enhanced the weed control efficiency, and yield and yield components, as found in the studies by Rao *et al.* (2008) ^[60], Sangeetha *et al.* (2009) ^[64], Brar and Buller (2012) ^[8], Murthy *et al.* (2012) ^[44], and Naseeruddin and Subramanyam (2013) ^[49].

Herbicide Application

Manual and cultural methods of weed control have been supplemented by herbicide-based chemical control as an important tool in rice agriculture. Herbicides can be used to overcome the shortage of labor, increased labor costs, and the inappropriate availability at the right time. Herbicides are also an effective, economical, and efficient control method of weeds, once the appropriate concentration and stage of crop development are used. Chemical weed control is particularly useful in intensive agricultural areas, where timely manual weeding is prohibited by shortages of manpower and financial constraints. Nonetheless, since it is dangerous when used incorrectly and leads to phytotoxicity and negative effects on the

development of crops, it is of utmost importance to pay close attention to the dose and time used.

Pendimethalin

Pendimethalin is a selective pre-emergence herbicide that is effective against most of the annual grassland weeds as well as some broad-leaf weed species. It operates by inhibiting microtubule formation, perturbing cell division, and disrupting microfibrils. It is, however, less productive in the resistance to sedges and is primarily effective against those weeds that are just emerging. Bahar and Singh (2004) [6] realized that 1.0 kg/ha at 2 DAS gave ideal control of *Echinochloa colonum*, *Setaria glauca*, and *Dactyloctenium aegyptium*, hence their maximum grain yield. In comparison, risking all the other combinations of herbicides and manual weeding, pendimethalin at 1.0 kg/ha, then hand weeding at 30 DAS decreased the growth of the weed plants and increased the production, as reported by Rao *et al.* (2008) [60].

Oxadiargyl

Gitsopoulos and Williams (2004) conducted glasshouse pot experiments to determine the selectivity of another recently developed herbicide, oxadiargyl, on direct-seeded rice under aerobic and anaerobic conditions. They found that wet-seeded (anaerobic) rice was more resistant to oxadiargyl compared to dry-seeded (aerobic) rice. The efficiency of the herbicide on *Echinochloa crusgalli* (L.) was also enhanced when anaerobic conditions were used. These findings imply that pre-sowing treatment, followed by subsequent flooding, would reduce the selectivity of oxadiargyl in wet-sown rice and that it is more active in flood conditions. Chauhan and Johnson (2011) [12-13] also concluded that when aerobic soils were subjected to herbicides, rice exhibited worse symptoms of phytotoxicity as compared to saturated soils.

Ramesh *et al.* (2015) [57] conducted an experiment in Bapatla, Agricultural College Farm, using direct-seeded rice, pyrazosulfuron-ethyl, and oxadiargyl as separate agents and in succession with azimsulfuron. When comparing the pyrazosulfuron-ethyl and penoxsulam, they discovered that the combination of oxadiargyl and penoxsulam gave the highest yield and the least density of the weed. The findings of Singh *et al.* (2016) [70] showed that one dose of preemergence (PRE) of oxadiargyl or one dose of post-emergence (POST) of bispyribac-sodium reduced the weed density by 27-61 percent and resulted in 16 and 11 broadleaf weeds per m², respectively, as compared to untreated plots. Comparatively, a greater reduction of 64-82 percent in the density of weeds was achieved through repeated PRE and POST treatments with herbicides.

Bispyribac

Qiang *et al.* (2000) [53] have indicated that bispyribac-sodium has moderate control activities on *Leptochloa chinensis*, and it has good control properties towards grasses (Poaceae), sedges, as well as broadleaf weeds such as *Echinochloa crusgalli*, *Paspalum distichum*, and *Alternanthera philoxeroides*. Bispyribac-sodium 0.04 kg ha⁻¹ inhibited a broad range of rice weeds when sprayed during the third or fourth unfolded leaf stage and at the tillering stage (Risi *et al.*, 2004). The herbicide raised the productivity, and it was not phytotoxic to rice. It has an excellent ecotoxicological physiology that qualifies it to be used in rice cultivation, which acts by inhibiting the formation of branched amino acids. Ranjit and Suwanketnikom (2005) found that the use of mechanical or physical weed management methods in combination with bispyribac-sodium or anilofos led

to promising grain production in dry direct-seeded rice.

Contrary to bispyribac-sodium alone, Damalas *et al.* (2008) [16] observed that it reduced its efficacy on *Echinochloa oryzoides* and *Echinochloa phylogopogo* with the use of carbaryl or dichlorvos, but increased its efficacy with diazinon. Bispyribac-sodium and ethoxysulfuron, respectively, according to Hussain *et al.* (2008) [20], give better control at 90.5 and 87.19 with the two weeds, respectively. Yadav *et al.* (2008) [75] found that application of bispyribac on the 15th or 25th day after transplanting (DAT) was more effective in managing grassy weeds; meanwhile, bispyribac application on 15 DAT was more effective in managing sedges and wider-leaf weeds. The increase in grain production of the 25 g ha⁻¹ applied at 15 or 25 DAT over weedy checks was 174-199% and 37-41% in 2006 and 2007, respectively. Wheat harvests did not have any phytotoxicity or lasting effects.

Mahajan and Timsina (2011) [37] performed a study to understand the nitrogen rates and the weed control methods, and found that either hand-weeding or using herbicides like pendimethalin + bispyribac-sodium enhanced the grain yield, water productivity, and profitability of the directseeding rice. When they managed the weeds so that the nitrogen levels went up to 150 kg/ha, then there was a great increase in yields. Like ethoxysulfuron ethyl and penoxsulam, bispyribac-sodium reduced the density of the weed by 75 percent (Khaliq *et al.*, 2013) [25]. The second-best weed control was bispyribac-sodium with an inhibition rate of 80%, and hand weeding reduced the weed biomass by nearly 90%.

Kumar *et al.* (2013) [29] found that bispyribac-sodium (2030 g ha⁻¹) was effective in controlling *Echinochloa colona*. Cyclophop-butyl/butachlor deviating to metsulfuron-methyl was the same in causing control of *Cyperus benghalensis* as was bispyribac-sodium. The number of *Cyperus* species was also significantly reduced up to 60 DAT. Bispyribac-sodium reduced the number of weeds and biomass, which was statistically similar to that of treatments at 20 and 25 g ha⁻¹. Height of plant, length of panicle, and tillers and spikelets per panicle were positively associated with rice grain yield, whereas biomass and weed counts were negatively associated with it. It was expected that the production of grain would reduce by 15.3 kg ha⁻¹ divided by m² of the additional weeds before harvest. No phytotoxicity or any long-term effects on the frequent harvests of wheat were observed. Prakash *et al.* (2013) [51] found that all the treatments reduced the population of weeds significantly and improved yield in their analysis of new herbicides on transplanted rice. Despite being very expensive and time-consuming, manual hand weeding yielded the best control (6482%).

Maximum control of weeds (5875) was realized with the use of bispyribac-sodium at 50 g ha⁻¹, which was similar to the lower doses, 25 and 35 g ha⁻¹, at 1520 DAT. Veeraputhiran and Balasubramanian (2013) [72] evaluated bispyribac-sodium on rice transplants ASD 16 and ADT 37. They found that 25 g ha⁻¹ was equally effective in the inhibition of weeds and increasing the grain yield as compared to the higher doses (35 and 50 g ha⁻¹). In 2010 and 2011, the highest yields were 6.84 and 6.51 t ha⁻¹, respectively. These yields were much superior to butachlor sprays and were similar to increased dosages, hand weeding, and weed-free treatments.

Pyrazosulfuron

Yadav *et al.* (2011) [74] observed that the herbicides pyrazosulfuron, azimsulfuron, and ethoxysulfuron were more effective than the herbicides pendimethalin and oxadiargyl in direct-seeded rice. Ramesh *et al.* (2015) [57] conducted their

experiments with pyrazosulfuron-ethyl and oxadiargyl in the Agricultural College Farm in Bapatla, either separately or in combination with azimsulfuron. As in direct-seeded rice, where pyrazosulfuron-ethyl was used followed by penoxsulam, they found that oxadiargyl was used followed by penoxsulam, resulting in the highest yield and least weed density. Shukla *et al.* (2016) [67] found that the most effective treatment of pre-emergence was the application of pyrazosulfuron at a rate of 20 g ha⁻¹ with a single hand weeding of the crops at 40 DAT/DAS. This dramatically decreased the population of the grass weeds as compared to all other tank-mix herbicide treatments, even a mixture of fenoxaprop and ethoxysulfuron 18 DAT/DAS in direct-seeded rice.

Sequential Herbicide Application

A combination of herbicides and the consecutive application of pre- and post-emergent herbicides has been identified to effectively control weeds in dry direct-seeded rice (DSR), thereby enhancing production and giving economic benefits. Pre-emergence herbicides such as quinolac, benthocarb, and pendimethalin inhibit the growth of annual grasses and broadleaf weeds due to their persistent nature in the soil. These are followed by the use of post-emergence herbicides used to control weed flushes. The extent of grain production lost due to the lack of the post-emergence treatment may be 9% to 60% (Cauley *et al.*, 2005) [9].

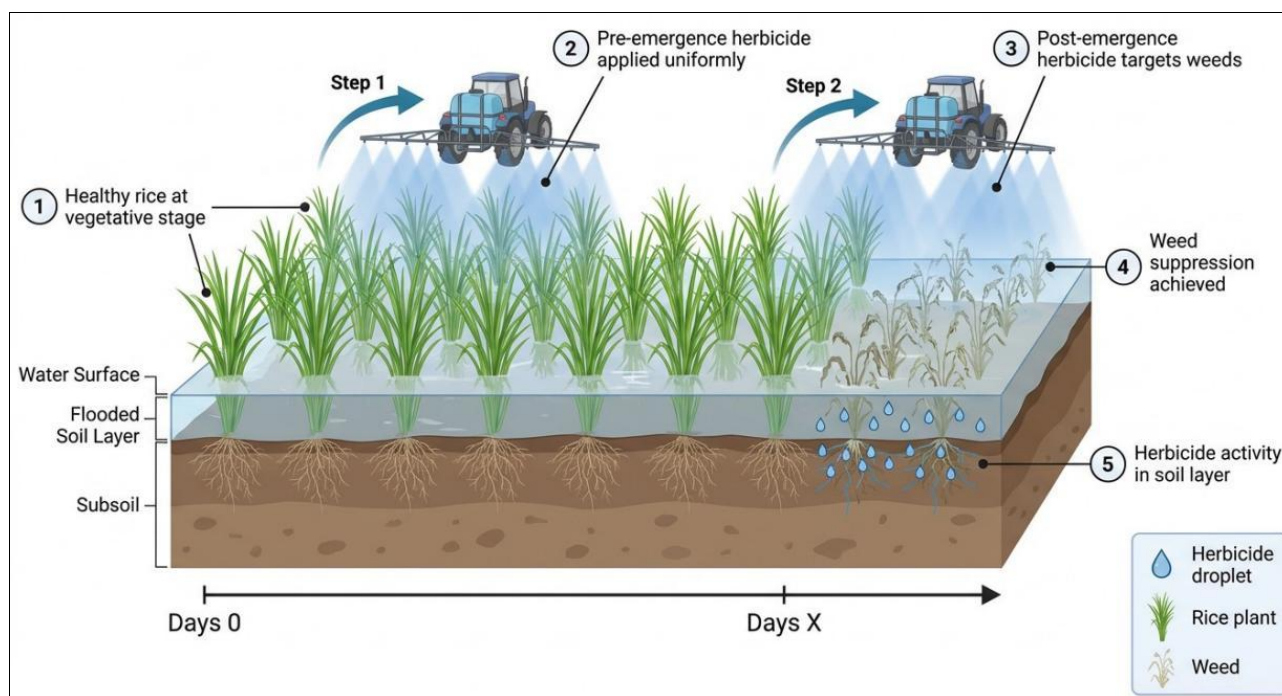


Fig 3: Sequential Herbicide Application

As an example, pre-emergence pendimethylan (0.75 kg ha⁻¹) and bispyribac sodium (0.025 kg ha⁻¹) at 20 DAS gave an equal effectiveness in weed control as the manual weeding (Anonymous, 2007). It is because of the enormous range of species of the weed present in DSR fields that single applications of a herbicide are ineffective and less cost-effective (Khaliq *et al.*, 2011) [26]. Since a majority of the herbicides attack grassy, sedges, or broadleaf weeds but not all of them, the action is rarely effective enough to provide a high level of control as it does in other upland cereals (Ahmed and Bhuiyan, 2010) [1]. Mahajan and Chauhan (2013) [36] confirmed that either pendimethylan-sulfuron then azimsulfuron or pendimethylan-sulfuron then bispyribac-sodium at 15 DAS effectively reduced the weed biomass in DSR.

Tank Mixture Herbicide Application

Direct-seeded rice (DSR) weed control requires simultaneous application of herbicides with multiple modes of action to get a broad-spectrum weed control and avoid herbicide resistance. In order to manage the various weed flora, there is a need to identify cost-effective and efficient herbicide combinations, which a small number of researchers have examined this approach in DSR. Single pre or post-emergence herbicides are difficult to use to manage weeds in DSR due to complex weed flora (Mahajan *et al.*, 2011) [37]. In comparison to using a single

herbicide, tank mixing, or concurrent application of herbicides, or sequential application, which is the combination of herbicides, does tend to improve the weed control (Mahajan and Timsina, 2011).

Mahajan and Chauhan (2013) [36] also supported the effectiveness of consecutive pre- and postemergence herbicide application as compared to individual herbicide application. Bispyribacsodium + azimsulfuron is an effective tank mixture that can be used in cases of co-existence of broadleaf and grassy types of weeds. Azimsulfuron enhances control spectrum by inducing bispyribac, which alone is unable to control sedges and broadleaf weeds (Walia *et al.*, 2008) [73]. In fact, the weed biomass was decreased at 45 DAS by 82-91 when the weed was treated with pendimethalin as a pre-emergence herbicide and bispyribac sodium and azimsulfuron as postemergence treatments.

Weed Management Practices on Nitrogen Removal by Weeds and Nitrogen Uptake by Crops

It has been demonstrated in the literature that effective weed management strategies are necessary to reduce the loss of nutrients by the weeds and enhance the uptake of the nutrients by the crop, which boosts productivity in direct-seeded rice in general. Brar and Bhullar (2013) [8] report that pendimethalin and bispyribac eliminated significantly more nitrogen,

phosphorus, and potassium when sprayed compared to when three-hand weedings were done. Weed biomass accumulation, on the other hand, was related to the nutrient removal by the weed, but crop dry matter accumulation and crop grain yield were directly related to crop nutrient uptake. Amazingly, the crop took up greater nitrogen in the three-hand herbicide treatment in comparison with the sequential application of herbicides. Narolia *et al.* (2014) ^[48] found that the use of pre-emergence pendimethylan (1.0 kg/ha) and bispyribac sodium (35 g/ha) yielded the most suitable growth and yield properties, enhanced weed control efficacy, and reduced weed uptake of NPK at 45 DAS and harvest.

Economics of Weed Management in Direct-Seeded Rice

One of the greatest contributors to the actual use of the methods of weed management is the economic feasibility of the method. Though hand weeding is an excellent method of minimizing the competition of weeds and achieving higher yields, it is impractical in the case of many rice farmers because of the high price of labor and shortage of manpower during the peak season of agricultural activities. When direct sown upland rice, pyrazosulfuron ethyl at 30 g a.i/ha gave the less expensive weed control cost (2,950/ha) compared to two instances of manual weeding (3,550/ha) (Anon., 2003). Transplanted rice was found to give the highest net return (34,223/ha) and benefit-cost (B: C) ratio of 1.90 when being treated with pyrazosulfuron ethyl at a pre-emergence rate of 10 g a.i. /ha (Nandi *et al.*, 2006) ^[46]. Meena (2010) discovered that application of nitrogen in three splits (40:40:40) resulted in higher net returns which were comparable with the other schedules and significantly higher than the two-split applications; Upasani *et al.* (2010) ^[71] found that untreated plots produced negative net returns in direct seeded rice under weed competition (when compared to other schedules), and Chaudhary *et al.* (2011) ^[10] found that untreated plots produced the maximum net returns (16, 145/ha) Bhurer *et al.*, (2013) ^[7] demonstrated that economic losses in direct-seeded rice, and they estimated that the lowest net returns per rupee invested are in untreated plots (0.70 in 2010 and 0.05 in 2011). Naseeruddin and Subramanyam (2013) ^[49] identified the preemergence application of oxadiargyl and azimsulfuron as the most beneficial-cost ratio of 3.30, which is far better than other weed management methods in the drum-seeded rice fields. Kaur and Singh (2015) ^[23-24] found that the untreated plots and the treatments of single applications of herbicides were found to give negative returns, whereas pendimethalin and bispyribac were found to give the highest net returns and B: C ratio when applied sequentially. Mahajan and Chauhan (2015) ^[35] established that tank mix application of azimsulfuron plus bispyribac plus fenoxaprop yielded the greatest incremental net profit and B: C ratio when compared to sequential or single herbicide treatment. The lowest profits were made in one application of herbicide. Pinjari *et al.* (2016) ^[50] concluded that because competition with weeds caused negative changes in crop development and yields over the course of the season, untreated plots were characterized by the lowest B: C ratio and negative net returns. Rehman *et al.* (2016) ^[61] found that certain nitrogen treatment regimes, including ½ basal + 1/4 tillering + 1/4 anthesis and 1/3 basal + 1/3 tillering + 1/3 anthesis, were the most practical as they yielded the highest net returns and B: C ratios due to higher grain yields. Saravanane *et al.* (2016) ^[65] found in directseeded rice that the B: C ratio (0.40) and net return (- 11,180/ha) were lowest in untreated plots compared to herbicide treatments. Singh *et al.* (2016) ^[70] found that pendimethalin, bispyribac

sodium, and azimsulfuron were most effective as the successive tank mix application in terms of net returns and B: C ratio, in direct-seeded rice at IRRI and Haryana. These were preceded by a succession of pendimethalin application and bispyribac sodium application.

Conclusion

The management of nitrogen and weeds is significant to improve the productivity of directseeded rice (*Oryza sativa* L.). When applied properly, nitrogen enhances proper nutrition of the crop, thus leading to healthy growth, tillering, and filling of the grain. Nevertheless, the competition between weeds usually compromises the efficiency of nitrogen use by depleting the available nutrients, decreasing the light interception, and making crops develop unproductively. Combined weed management techniques, such as the application of pre and post-emergence herbicides coupled with manual or mechanical weeding, hugely decrease the weed density and biomass and, as such, reduce nutrient losses. Balanced, timely, and proper application of nitrogen fertilization and weed management enhances nutrient uptake in crops, growth of dry matter, and eventually yields. Additionally, nutrient management can be done on a site-specific basis based on factors of soil fertility, water availability, and the crop stage to enhance the efficiency of nitrogen use without posing too much environmental risk that comes with over-fertilization. The use of these combined ways would not only increase yield but also help in the sustainable and resource-efficient production of rice. In conclusion, nitrogen and weed control are an essential part of direct-seeded rice farming, and their joint application is a major factor in the higher yield and food security.

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