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REVIEW ARTICLE

Weed wars: Strategies for thriving direct-seeded rice fields

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Abstract

Rice holds a vital place in Indian agriculture, serving as the staple food for millions and positioning India as the second-largest rice producer globally, contributing over 20 % to the world's total rice production. With half the world's population relying on rice as a primary nutritional source, its cultivation is essential. Among the various methods of rice cultivation, direct-seeded rice (DSR) is gaining prominence due to challenges such as labor shortages and rising wages, particularly during peak agricultural seasons. Traditionally, transplanting has been the preferred method; however, DSR offers a viable alternative by addressing these limitations. A major concern in DSR cultivation is weed competition, as weeds aggressively compete with crops for critical resources like light, moisture, nutrients and space, ultimately reducing yields. While manual weeding remains effective, its high labor requirements and associated costs have made it less feasible, especially in large-scale cultivation. Chemical weed management, on the other hand, provides an efficient and less labour-intensive solution for controlling weeds in DSR systems. Wet-seeding is an integral part of DSR, where sprouted seeds are sown into puddled fields. This method offers multiple advantages, including time savings, reduced labour demand, better early establishment and improved water-use efficiency. Wet-seeding can be categorized into aerobic and anaerobic systems. In aerobic wet-DSR, pregerminated seeds are sown on the soil surface, whereas anaerobic wet-DSR involves sowing seeds in puddled soil. This distinction influences the growth environment, with anaerobic systems promoting specific soil conditions. Both methods are notable for conserving labor, energy and time, making wet seeding a sustainable and practical option in modern rice farming.

Keywords: direct seeded rice; economics; herbicide; weed flora

Introduction

Rice (*Oryza sativa L.*) is a major cereal crop belonging to the family *Poaceae* and ranks second in global cultivation after wheat. It is one of the most important food crops in Southeast Asia. It is a semiaquatic, C_3 short day plant. In India, rice is cultivated in an area of 45.77 million hectares with a production of 124.37 million tonnes and productivity of 2717 kg ha^{-1} (1). In India, Uttar Pradesh ranks first in both area and production and Punjab ranks first in productivity. Compared to maize, wheat and potatoes, rice is a better source of carbohydrates, calcium, iron, thiamine, pantothenic acid, folate and vitamin E. Per 100 g, rice contains approximately 5.8-7.7 g of protein, 0.5-2.3 g of fat, 0.01-0.78 g of crude fiber, 0.12-1.22 g of crude ash and 76.80-86.56 g of carbohydrates (2). Rice is established under lowland conditions using either transplanting or direct seeding methods. Transplanting requires continuous stagnation of water throughout the cultivation and also requires nursery preparation for raising the seedling. It consumes more laborers and energy in terms of fuel and machinery. Now a days, due to the scarcity of labour rice establishment methods have shifted from transplanting to direct seeding. Compared to transplanting, direct seeding consumes less laborer and energy in terms of fuel and machinery. In direct seeding, rice cultivation is done by two methods viz., wet direct seeding and dry direct seeding. Direct seeding of rice has several advantages such as labour savings; faster, easier and timely planting; earlier maturity by 7-10 days; reduced water requirement; greater drought tolerance; higher yield; lower production cost; improved profitability; and reduced methane emissions (3). Weed infestation is one of the major challenges in DSR cultivation. Compared to the transplanted system, crop weed competition is high in direct seeded rice. Weeds compete with the rice crop for light, space, moisture and nutrients. Weeds reduce the crop yield and quality. If weeds are not managed properly, they will reduce yield up to 90 %. To manage the weeds in the direct seeded rice, hand weeding is the best option but due to labour scarcity it is not a feasible one. Compared to hand weeding the chemical method of weed control is the most suitable option for controlling the weed flora in direct seeded rice.

Dominant weed species in direct seeded rice systems

In India, total rice production losses due to pests are estimated at 33 %, of which weeds alone account for 12.5 %. Compared to summer transplanted rice, higher number of weed flora observed in *kharif* rice (4). There are 350 weed species in rice ecosystems (5). Among 350 species, very few are the most important weed species. Among them, grasses ranked first, followed by sedges and broadleaved weeds (6). Table 1 presents the common weed species associated with DSR.

Table 1. Weed species associated in direct seeded rice

S. No.	Weed species	Reference
1.	*Caesulia aris, Echinochloa colona, Panicum maximum, Cyperus iria* and *Ischaemum rugosum*	(7)
2.	*Trianthema portulacastrum L., Dactyloctenium aegyptium, Eleusine indica L.* and *Cyperus spp.*	(8)
3.	*Echinochloa colona, Echinochloa crussgalli, Leptochloa chinensis, Brachiaria deflexa, Chloris barbata, Digitaria sanguinalis, Dactyloctenium aegyptium, Cyperus rotundus, Cyperus iria, Eclipta alba, Cleome viscosa* and *Aeschynomene indicia*	(9)
4.	*Echinochloa crusgalli, Echinochloa colon*a, *Monochoria vaginalis,Lindernia ciliata, Ammania baccifera, Marsilea quadrifolia, Ludwigia parviflora, Spilanthes acmella, Cyperus difformis, Cyperus iria* and *Fimbristylis miliaceae*	(10)
5.	*Paspalum distichum, Echinochloa colona, Leptochloa chinensis, Echinichloa crus-galli, Digitaria setigera, Eleusine indica, Ischaemum rugosum, Cyperus difformis* and *Cyperus iria. Commelina benghalensis, Monochoria vaginalis, Eclipta prostrata, Sphenoclea zeylanica* and *Ludwigia adscendens*	(11)
6.	*Echinochloa crus-galli, Echinochloa colona, Cynodon dactylon*, *Cyperus rotundus*, *Cyperus iria, Eclipta alba* and *Caesulia axillaries*	(12)
7.	*Cyperus iria, Ludwigia parviflora* and *Fimbristylis miliacea*	(13)
8.	*Cynodon dactylon, Dactyloctenium aegyptium, Digitaria sanguinalis, Ischaemum rugosum, Echinochloa colona, Cyperus difformis, Cyperus iria, Fimbristylis miliacea, Abutilon indicum, Alternanthera sessilis, Cassia tora, Commelina diffusa, Cyanotis axillaris, Eclipta alba, Ludwigia parviflora, Phyllanthus niruri* and *Physalis minima*	(14)
9.	*Echinochloa colona, Alternanthera sessilis, Cyperus iria* and *Cynodon dactylon*	(15)
10.	*Echinochloa crus-galli, Echinochloa colona, Leptochloa chinensis, Cyperus iria*, *Cyperus difformis* and *Eclipta*	(16)
11.	*Echinochola colona (L.), Echinochloa crusgalli (L.), Cyperus difformis (L.), Cyperus rotundus (L.), Ammania, baccifera (L.), Bergia capensis (L.), Marsilia quadrifolia (L.)* and *Eclipta alba (L.).*	(17)

Identifying the critical window for crop-weed competition in direct seeded rice

The critical weed interference period is the period in which the weeds can be left with the crop without control. The critical weed free period is the period in which the crop would be maintained without weeds before the occurrence of yield loss caused by weeds (18). The period from 15 to 45 days after sowing (DAS) is considered the most critical for crop weed competition in both transplanted and direct seeded rice systems (19). Weed interference during the first 20 DAS adversely affects dry matter accumulation and hampers crop development (20). Under saturated conditions crop weed competition is up to 72 DAS and 2 to 98 DAS in flooded conditions is the critical period of crop weed competition (21).

Chemical strategies for effective weed control in direct seeded rice

Chemical weed control is considered the most cost effective and reliable strategy in DSR, as it manages diverse weed flora and reduces crop weed competition effectively (22). Table 2 presents the promising herbicides used in DSR cultivation (23).

Role of pre-emergence herbicides in early weed suppression

Compared to post emergence herbicides, pre-emergence herbicides are highly suitable and effective (24). Sequential use of pre-emergence herbicides followed by post-emergence applications plays a crucial role in managing the diverse weed population in DSR systems (25). Effective treatments included butachlor followed by almix (1.0 kg + 4 g ha^{-1}), their tank mix (4 g + 1.0 kg ha^{-1}) and standalone butachlor at 1.5 kg ha^{-1}, all of which controlled a broad spectrum of weed species (26). Pre-emergence application of pretilachlor @ 970 ml ha^{-1} at 5 DAT followed by one hand weeding at 40 days after transplanting was the best treatment for weed control at 30 and 60 days after transplanting (27). Pretilachlor applied at 500 g ha^{-1} (4 DAT), followed by hand weeding at 30 DAT, resulted in lower weed dry matter and weed density (28). Pretilachlor with safener @ 500 g ha^{-1} applied at 3 DAS along with one hand weeding at 35 DAS successfully controlled all the weeds (29). Application of pretilachlor at 0.75 kg ha^{-1} on the 4th DAT, combined with hand weeding on the 45th day, was effective in weed control while also enhancing yield and economic returns (30). Pre planting application of glyphosate and post planting application of

Table 2. Promising herbicides used in direct seeded rice cultivation

Herbicides	Time of application (DAS)	Dose	Application	Targeted control
Pendimethalin	0-3	1000 g a.i ha^{-1}	Pre-emergence	Annual grasses and broadleaved weeds
Oxadiargyl	3-5	100 g a.i ha^{-1}	Pre-emergence	Annual grasses, sedges and some broadleaved weeds
Pyrazosulfuron	0-3	20 g a.i ha^{-1}	Pre-emergence	Broadleaved and sedges
Bispyribac sodium	10-14	25-30 g a.i ha^{-1}	Contact herbicide for early post emergence application	Broad spectrum of weed control except *Leptocholoa chinensis*
Chlorimuron + metsulfuron	0-3, 10-14	4 g a.i ha^{-1}	Pre-emergence and early post emergence	Broadleaved and sedges
Bensulfuron methyl	6-10	300-500 g a.i ha^{-1}	Pre-emergence and early post emergence under wet/standing water conditions	Effective against almost all annual and perennial broad- leaved weeds and some sedges during
Cyhalofop butyl	10-14	100 g a.i ha^{-1}	Early post emergence Herbicide Tank mixed with Sulfonyl urea gives wide spectrum of weed control	Effective against *E. crusgalli* and *L. chinensis* until four leaf stage.

bensulfuron methyl + pretilachlor gave lesser weed dry weight, lower weed density and more grain yield in rice (31). Application of pretilachlor 750 g ha^{-1} as pre-emergence followed by azimsulfuron 35 g ha^{-1} at 15 DAT was effectively controlled the density and dry matter of grasses in rice (32). In aerobic rice, higher productive tillers per hill, panicle weight, thousand grain weight were recorded in pre-emergence application of bensulfuron methyl at 60 g + pretilachlor at 600 g a.i ha^{-1} (33). Pre-emergence application of bensulfuron methyl at 60 g combined with pretilachlor at 600 g a.i. ha^{-1} effectively reduced weed density, lowered the weed index and resulted in higher crop yield (34). Sequential application of pendimethalin (1000 g ha^{-1}, pre-emergence), penoxsulam (22.5 g ha^{-1}, post-emergence) and hand weeding at 45 DAS reduced weed density and biomass and improved weed control efficiency and grain yield in DSR (35). Sequential application of pendimethalin at 1.0 kg a.i. ha^{-1} as a pre-emergence treatment followed by a ready-mix of penoxsulam + cyhalofop-butyl at 130 g a.i. ha^{-1} at 25 DAS provided effective weed control, leading to increased rice yield and profitability in DSR (36). Pre-emergence application of pretilachlor at 0.75 kg a.i. ha^{-1} followed by post-emergence application of bispyribac sodium at 20 g a.i. ha^{-1} at 20 DAS and hoeing at 35 DAS resulted in reduced weed population, lower weed biomass, higher weed control efficiency and improved grain yield (37). Pre-emergence application of bensulfuron-methyl 0.6 % + pretilachlor 6 % GR 10 kg ha^{-1} *fb* post-emergence application of bispyribac sodium 25 g ha^{-1} were most effective and economical in controlling the weeds in wet seeded rice (38). In direct seeded rice pre-emergence application bensulfuron methyl + pretilachlor @ 660 g a.i. ha^{-1} was effectively controlled the weed flora (39).

Application of early post-emergence herbicides for optimal weed control

Pyrazosulfuron-ethyl was found to be effective in managing diverse and complex weed flora in rice fields (40). Pre and early post-emergence application of oxadiargyl was effective in reducing weed density in rice cultivation (41). *Echinochloa colona* was effectively controlled by application of oxadiargyl at 80 g ha^{-1} (42). Pre-emergence application of oxadiargyl at 70 g ha^{-1} was effective in reducing the dry weight of *Echinochloa crus-galli* (43). Pre and early post-emergence application of oxadiargyl 75 g ha^{-1} effectively controls the weeds at early stages of crop growth followed by post-emergence application of bispyribac-sodium @ 30 g ha^{-1} which controls the late emerging weeds (44). Pyrazosulfuron-ethyl, an early post-emergence systemic herbicide, was found to effectively control a broad spectrum of weed species in rice cultivation (45). Application of pyrazosulfuron ethyl + pretilachlor 30 % (pre-mix) @ 3.50 kg ha^{-1} (commercial product) as post-emergence recorded the highest weed control efficiency, lesser weed count, high herbicide efficiency index and a low weed persistence index (4). Application of penoxsulam at 20 g a.i. ha^{-1} on the 20^{th} DAT significantly reduced the populations of *E. colona, L. hexandra, C. iria, L. parviflora* and *M. vaginalis* in rice (46).

Post-emergence herbicides: targeting weeds at later growth stages

Post-emergence application of bispyribac sodium effectively controlled the grasses, sedges and broadleaved weeds (47). In DSR, azimsulfuron applied post-emergence at 25-30 g ha^{-1} effectively controlled sedges and broad-leaved weeds (12). In direct seed rice eco system azimsulfuron was applied as a post-emergence and effectively suppressed the late emerging weeds (48). Application of bispyribac sodium at the fourth leaf stage effectively controlled early and late emerging grasses by up to 89 % and 84 %, respectively (49). Post-emergence application of bispyribac sodium @ 30 g ha^{-1} recorded a higher yield which was on par with pre-emergence application of pendimethalin @ 0.75 kg ha^{-1} followed by one hand weeding in direct seeded rice (50). Application of bispyribac sodium at 50 g a.i. ha^{-1} resulted in a weed control efficiency of 98.1 % (51). Early post-emergence application of bispyribac sodium @ 40 g a.i. ha^{-1} effectively controlled the weed density and lesser weed dry weight (52). Pre-emergence application of pretilachlor at 750 g ha^{-1} followed by post-emergence application of a chlorimuron ethyl and metsulfuron methyl mixture at 4 g ha^{-1} effectively controlled grasses, sedges and broad leaved weeds in rice, resulting in higher weed control efficiency compared to other treatments (53). Post-emergence application of bispyribac sodium at 40 g a.i. ha^{-1} was effective in controlling weed flora in DSR (39). Post-emergence application of bispyribac sodium at 25 g a.i. ha^{-1} significantly reduced weed density and dry biomass. Its performance was statistically comparable to that of fenoxaprop-p-ethyl + penoxsulam (60 + 26.7 g a.i. ha^{-1}) (15). A tank mix comprising Pretilachlor 50 % EC (625 g a.i. ha^{-1} at 3 DAS), Bispyribac sodium 10 % SC (20 g a.i. ha^{-1}) and Ethoxysulfuron 15 % WDG (15 g a.i. ha^{-1}) applied at 15 and 40 DAS resulted in lower weed density, higher weed control efficiency and improved yield in direct wet-seeded rice (16). In summary, post-emergence application of bispyribac sodium alone or in combination with other herbicides has proven highly effective in managing diverse weed flora in DSR, resulting in significantly reduced weed density and biomass, enhanced weed control efficiency and improved grain yield.

Cost-effectiveness of weed management in direct seeded rice systems

The combination of herbicides (pretilachlor + safener) application along with hand weeding at 20 and 40 days after sowing resulted in the highest net income (₹ 25208 ha^{-1}) in DSR (54). Application of pretilachlor at 0.45 kg ha^{-1} on 3 DAS followed by azimsulfuron at 35 g ha^{-1} on 20 DAS, along with one hand weeding at 45 DAS, resulted in the highest gross and net returns (48). Pre-emergence application of bensulfuron methyl + pretilachlor (0.06 + 0.60 kg a.i. ha^{-1}), combined with one inter-cultivation at 40 DAS, resulted in higher grain yield (4425 kg ha^{-1}), straw yield (5020 kg ha^{-1}), net returns and benefit-cost ratio (55). The highest net return (₹9459 ha^{-1}) and benefit-cost ratio (1.98) were achieved with the application of pretilachlor + safener at 0.5 kg ha^{-1} followed by butachlor at 1.5 kg ha^{-1}, along with one hand weeding at 25 DAS. In comparison, other treatments resulted in a lower net return of ₹7479 ha^{-1} and a benefit-cost ratio of 1.64 (56). The highest benefit-cost ratio (3.7) and net return were recorded with the application of pyrazosulfuron at 25 g ha^{-1} between 3-7 DAS and pretilachlor-S at 750 g ha^{-1} between 0-5 DAS (57). The highest net return (₹85653 ha^{-1}) was observed with drum seeding combined with hand weeding, followed by transplanting with hand weeding, which recorded ₹79751 ha^{-1} (58).Pendimethalin @ 125 kg ha^{-1} combined with pyrazosulfuron at @ 5 g ha^{-1} was found to be profitable, producing a higher rice grain yield of 6.65 t ha^{-1} and a benefit-cost ratio of 1:2.25 (59). Application of pre-emergence herbicide pendimethalin @ 1.0 kg ha^{-1}followed by penoxsulam + cyhalofop-butyl @ 130 g ha^{-1} at 25 DAS recorded a maximum gross return (₹65530 ha^{-1}), net return (₹45330 ha^{-1}) and benefit cost ratio of

2.30 (36). Pendimethalin followed by bispyribac-sodium and manual weeding resulted in the highest grain yield (3.86 t ha^{-1}), gross return (₹77520 ha^{-1}), net return (₹47780 ha^{-1}) and benefit-cost ratio (1.60) (23). Pre-plant application of butachlor at 1.5 kg a.i. ha^{-1} followed by brown manuring and post-emergence application of 2,4-D at 0.50 kg a.i. ha^{-1} at 40 DAS resulted in higher grain yield, net returns and benefit-cost ratio (60). The highest gross return (₹81211 ha^{-1}), net return (₹48707 ha^{-1}) and benefit-cost ratio (2.51) were recorded with oxadiargyl applied at 70 g ha^{-1} between 7-11 DAS, followed by one hand weeding at 30-35 DAS (61).The highest net return (₹60118 ha^{-1}) and benefit-cost ratio (2.79) were achieved with pretilachlor 50 % EC at 625 g a.i. ha^{-1} on 3 DAS followed by a tank mix of bispyribac-sodium 10 % SC at 20 g a.i. ha^{-1} and ethoxysulfuron 15 % WDG at 15 g a.i. ha^{-1} applied on 15 and 40 DAS (16). It highlights that integrated weed management strategies involving pre- and post-emergence herbicides, combined with hand weeding, consistently enhance both yield and economic returns in DSR systems.

Conclusion

Traditionally, rice is cultivated through transplanting raising seedlings in nurseries and later planting them in the main field. While this method has been effective for centuries, modern challenges like labor shortages and water scarcity are shifting attention toward DSR. DSR offers several benefits, including reduced water use, shorter crop duration and lower labor input. However, it also introduces new challenges, the most significant of which is weed infestation, due to the absence of waterlogged conditions that typically suppress weed emergence. Weeds compete aggressively with rice plants for light, nutrients and moisture, significantly reducing yield. Thus, effective weed management is critical to the success of DSR systems. The primary goals are to control weeds before flowering and to prevent the build-up of a soil seed bank. Manual weeding is precise and effective, especially where selective removal is required. However, it is increasingly impractical on a large scale due to rising labor costs, physical demands and rural-to-urban migration, which has led to a shrinking agricultural workforce. In response, chemical weed control using herbicides has gained popularity for its efficiency and scalability. When applied correctly, herbicides can suppress weeds and reduce competition for resources. Integrating chemical control with other agronomic practices, such as timely sowing and proper water management, can enhance its effectiveness. Nevertheless, excessive herbicide uses poses risks, including resistance development, environmental harm and health concerns. To address these issues, Integrated Weed Management (IWM) is recommended. IWM combines various strategies crop rotation, cover cropping, mechanical control and judicious herbicide use for sustainable weed control. Additionally, proper land preparation, optimized plant density and sequential herbicide applications (pre and post-emergence) have proven effective in reducing weed pressure and increasing yields. In conclusion, while the shift from transplanting to DSR addresses labour and water constraints, it necessitates a more integrated and strategic weed management approach. By combining manual, chemical and cultural methods, farmers can manage weeds effectively and ensure sustainable productivity in DSR systems.

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Authors' contributions

SM wrote the manuscript draft and MV revised it. Authors RM, ASG, GC and SKKG contributed to the discussion. All authors read and approved the final manuscript.

Compliance with ethical standards

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