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Herbicide options for cost-effective weed control and sustainable rice production in direct-seeded rice

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ABSTRACT
Direct-seeded rice (DSR) is an emerging resource-saving rice production system alternative to puddled transplanted rice (TPR). However, yield variability due to severe weed infestations remains the major concern in DSR. Weeds outsmart the less competitive rice seedlings under direct seeding situation. Hence, initial weed control in DSR till canopy closure is indispensable for realizing a steady yield. Weed control using herbicides has become the most popular and practical way of managing weeds in time, particularly in large areas where manual laborer is scarce and wage rates are high. Selection of appropriate herbicides based on target weeds and stages of weeds/crop along with recommended rates and accurate application techniques can facilitate a viable way of controlling weeds in DSR that may help in promoting this system. This article attempts to provide an insight to specific herbicides available, their rates, application time, safe handlings, and correct application methods crucial for controlling weeds effectively in DSR.
Keywords: Calibration of sprayer, direct-seeded rice, herbicide mixture, post-emergence herbicides, sequential application.

Globally, rice (*Oryza sativa* L.) is one of the major food crops and a staple food for more than half of the world's population. About 90% of the world's rice is grown and produced in Asia, where it is usually grown by transplanting seedlings into puddled soil. This method is labour, water, and energy intensive. It is estimated that about 114 million tons of additional milled rice need to be produced by 2035 to keep pace with global rice demand (Kumar and Ladha, 2011). This additional rice has to come from increasing productivity instead of land expansion, and with less water and labour as these resources are becoming increasingly scarce and expensive. Moreover, puddling deteriorates soil physical condition that adversely affects the performance of succeeding crops, besides methane emissions. All these factors act as drivers of shift from water-guzzling TPR to direct seeding of rice, particularly in irrigated rice ecosystems. For instance (Table 1), in Punjab state of India, 77% and 95% of farmers reported water scarcity, and high wages and unavailability of labour as the driving forces for adoption of dry-seeded rice, respectively, in addition to sub-surface hard pan formation due to puddling that affects subsequent crop (97%). The DSR, particularly dry seeding (direct seeding under unpuddled condition), largely eliminates puddling and raising seedlings in the nursery, and hence needs 30% less water and saves up to 60% labour costs (Kumar and Ladha, 2011), thereby ensuring long-term sustainability.

Despite of these benefits, farmers are wary of adopting this technology. Yield instability has been a major concern in DSR limiting its large-scale adoption among farmers. Severe weed infestation remains the major limitation causing yield uncertainty in DSR. Dry tillage and alternate wetting-drying are conducive for weed growth and weeds severely contend with DSR. In absence of effective control, yield losses due to weeds are greater in DSR than in TPR. Unlike TPR, DSR crop lacks the initial head start over weeds and the initial flush of weeds which is not controlled by flooding, thereby making it vulnerable to weeds. Yield losses in DSR without effective weed control range from 50-90% (Rao *et al*., 2007; Kumar and Ladha, 2011; Sen *et al*., 2018). Even complete crop failure occurs under unchecked weed growth. Therefore, effective weed control is indispensable for sustainable production in DSR, particularly under dry seeded situation.

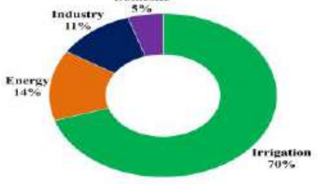

Fig. 1. Projected annual availability of water for different economic sectors by 2025

Table 1. Driving forces for adoption of dry-seeded rice in Punjab

Factors	Farmers reported (%)
Deep water table (>25 m)	77
Labor scarcity during transplanting and high wage	95
Puddling causing drudgery and wear and tear of machinery	60
Hard pan due to puddling affects subsequent crop	97
High cost of transplanting	25

Source: Adapted from Mahajan *et al*., (2013)

Major weed flora observed in DSR

A DSR crop is generally infested with a wide range of complex weed flora (grasses, broadleaves and sedges) in its life cycle. The 12 most troublesome weeds of rice in Asia, namely, *Cyperus iria*, *Cyperus difformis*, *Echinochloa colona*, *Echinochloa crus-galli*, *Eclipta prostrata*, *Fimbristylis miliacea*, *Ischaemum rugosum*, *Leptochloa chinensis*, *Ludwigia hyssopifolia*, *Oryza sativa f. spontanea*, *Schoenoplectus juncoides*, *Sphenoclea zeylanica*, also known as 'The dirty dozen', are observed in DSR fields, particularly in dry seeding (aerobic rice).

Grassy weeds: These weeds grow concurrently with rice throughout the entire growth period as several cohorts of weeds emerge when conditions are favourable for germination. These are the most troublesome weeds in DSR causing significant yield losses. Major grassy weeds are: Jungle rice (*Echinochloa colona*), Barnyard grass (*E. crus-galli*), Saramollagrass/mararo (*Ischaemum rugosum*), weedy rice (*Oryza sativa f. spontanea*), Chinese sprangletop (*Leptochloa chinensis*), Large crab grass (*Digitaria sanguinalis*), Crowfoot grass (*Dactyloctenium aegyptium*), Torpedo grass (*Panicum repens*), Love grass (*Eragrostis japonica*), Goose grass (*Elusine indica*), *Dinebra retroflexa*, etc.

Broad-leaved weeds: These weeds emerge subsequently at later crop growth stages. These include: False daisy (*Eclipta alba*), Goose weed (*Sphenoclea zeylanica*), blistering ammannia (*Ammannia baccifera*), Alligator weed (*Alternanthera philoxeroides*), Sessile joyweed (*Alternanthera sessilis*), Primrose (*Ludwigia parviflora*), Dayflower (*Commelina* sp.), *Caesulia axillaris*, *Cynotis axillaris*, Goat weed (*Ageratum conyzoides*), etc.

Sedges: Purple nut sedge (*Cyperus rotundus*), Yellow nut sedge (*C. esculentus*), Flat sedge (*Cyperus iria*), Small flower Umbrella sedge (*Cyperus difformis*), Forked fringerush (*Fimbristylis miliacea*), Rock bulrush (*Schoenoplectus juncoides*; synonym, *Scirpus juncoides*), etc. Among sedges, perennial weeds like *C. rotundus* and *C. esculentus* appear during initial growth stages, while annual sedges such as *C. iria* and *C. difformis* emerge at later stages of crop growth.

Manual weeding being nonchemical way of controlling weeds is ecologically sound and effective where labour is available at low wages. However, considering the labour-intensiveness, higher cost, drudgery, stress on labour, resemblance of weeds with rice seedlings and higher dependence on soil conditions, manual weeding is very difficult and not convenient for large areas. Mechanical weed control could provide desirable control in row crops, but the intra-row escapes (weeds within the crop rows are not removed) pose higher competition to rice crops and comparatively higher labour needs (6-8 person-days/ha/weeding) lower its efficacy. Thus, weed management using herbicides has become the most economical and convenient way of timely weed control, particularly in areas where agricultural labour is scarce and wage rates are high. Weed control through herbicides facilitates various benefits over other methods, which typically include (1) requires less labour (0.5 person-day/ha/application), (2) less drudgery, (3) cost-effective, if adopted properly, (4)it can discriminate between rice and weeds, particularly grassy weeds even at seedling stage where it is very difficult to differentiate, and (5) weed control at early stages and/or critical period of weed competition as there is no need to wait for weeds to grow bigger as in hand weeding.

For effective weed control, herbicides should provide extended control of weeds until the canopy closes. Different types of herbicides are applied at specific stages of crop growth.

Pre-planting burn down: A weed-free field is desirable for good crop establishment and early vigour in DSR crop, especially in dry-seeded rice. Non-selective herbicides like paraquat, glufosinate, etc. are sprayed on existing vegetation to knockdown weeds before sowing, particularly under zero till sowing (chemical ploughing). Controlling weeds before planting or during land preparation suppresses subsequent in-field weed pressure and avoids yield losses to weeds.

Pre-emergence herbicides: Immediately after sowing, weeds start to germinate before rice crop and quickly occupy the wide spaces. This necessitates application of pre-emergence herbicides that kill the germinating weeds. Pre-emergence herbicides (e.g., pendimethalin, oxadiazon, oxadiargyl, etc.) are applied onto a moist soil 1-3 days after sowing. In case of aerobic rice, where seed is sown on dry soil, field must be flush irrigated before spraying pre-emergence herbicide. However, these herbicides suffer from many limitations and should be used wisely. Being soil-active (directly applied to soil), efficacy of pre-emergence herbicides depends on adequate soil moisture (top 2 cm soil layer must be wet), and are ineffective in dry soils. In situation where rain is expected, herbicide spray should be delayed as it may trickle down in the soil with rain water to germinating crop seeds and cause severe injury, especially in light textured soils. Around 50-90% seedling mortality may occur when heavy rain follows herbicide application. Pre-emergence herbicides have narrow spectrum of weed control and also have narrow window of application. Subsequent flushes of weeds that emerge 3-4 weeks after sowing can't be controlled by pre-emergence herbicides.

Post-emergence herbicides: Weeds must be kept under control from planting until the crop canopy closes. In DSR, multiple flushes of weeds appear that can be controlled with new generation low-dose and high efficacy post-emergence herbicides. Grassy weeds contend heavily with rice crop and are the major weed problem in DSR, which necessitate application of early post-emergence herbicide (Table 2). Being foliage-active, a post-emergence herbicide should come in contact with weed leaves to be absorbed by the weeds. These herbicides have shown promising broad-spectrum control of diverse weeds during critical period of weed competition with an extended period of 30-40 days of crop establishment. However, response of post-emergence herbicides is often weed-specific and their efficacy depends on dosage, weather, and types of weeds, growth stages of rice and weeds, and time of application. Their dosage and time of application have been standardized for different rice ecosystems (Table 2). Identifying dominant weed types, selection of weed-specific herbicide(s) and proper time of application with recommended rate are crucial for effective and desirable weed control, and to avoid crop injury, residues in soil and crop, and to gain environmentally safe sustainable weed control.

Table 2. Herbicide options available for effective weed control in DSR

Herbicide formulation	Dose* (g a.i./ha)	Time of application	Target weeds	Limitations
		Knockdown/non-selective (before planting)		
Paraquat	500 (2000)	Pre-plant burndown (post-emergence)	Good control of most grasses, broadleaves and annual sedges	Non-selective to crops
Glufosinate-ammonium	375-450 (2500-3000)	Pre-plant burndown (post-emergence)	Mixed weed population (mainly used in tea and cotton with a spray shield to prevent drift on crops)	Non-selective to crops
		Pre-emergence		
Pendimethalin	1000 (3330)	1-3 DAS (has residual control)	Good control of most grasses, some broadleaves and annual sedges	Sufficient moisture is needed for its activity
Oxadiargyl	90 (112.5)	1-3 DAS (has residual control)	Broad-spectrum weed control of grasses, broadleaves, and annual sedges.	Sufficient moisture is needed for its activity
		Post-emergence		
Bispyribac-sodium	25 (250)	15-25 DAS (2-5 leaf stages of weeds)	Broad-spectrum control of grasses, broadleaves and annual sedges. Good control of *Echinochloa* sp.	Poor control of *L. chinensis*, *D. aegyptium*, *E. indica*, *Eragrostis* sp. No residual control.
Fenoxaprop-p-ethyl + safener	60-90 (870-1300)	15-20 DAS (3-5 leaf stages of weeds)	Good control of annual grassy weeds. Safe on rice at early stage.	Effective against grasses only
Cyhalofop-butyl	100 (1000)	12-15 DAS (2-4 leaf stages of weeds)	Grassy weeds	Effective against grasses only
Ethoxysulfuron	18 (120)	15-20 DAS (2-4 leaf stages of weeds)	Annual sedges and broadleaved weeds	Does not control grasses and poor on perennial sedges

Penoxsulam	22.5-25 (93.75-104.17)	15-20 DAS (3-4 leaf stage of weeds)	Broad-spectrum weed control of grasses, broadleaves, and annual sedges.	Poor control of grasses like *L. chinensis*, *D. aegyptium*, *E. indica*, *Eragrostis* sp.
Azimsulfuron	17.5-35 (35-70)	15-20 DAS	Broad-spectrum control of grasses, broadleaves, and sedges. Good control of sedges, including *C. rotundus*.	Poor on *Echinochloa* sp.
Carfentrazone	20 (50)	15-20 DAS	Broadleaf weeds. Has no residual control	Does not control grasses.
2,4-D ethyl ester	500 (1250)	15-25 DAS	Broadleaves and annual sedges.	Has no residual control. Does not control grasses.

***figures in parentheses denote product (g/ha or mL/ha); a.i., active ingredient; DAS, days after sowing**

Herbicide mixture and sequential application

Repeated use of same herbicide(s) with similar mode of action for an extended period leads to shift in weed flora and/or herbicide-resistant weeds. Hence, herbicide rotation must be followed especially for sulfonyl urea herbicides against which highest numbers of resistant weed species exist. Several studies have highlighted the inadequacy of sole herbicide in controlling the diverse weeds cohort in DSR. Combination of two or more compatible but dissimilar herbicide (with different modes of action) may broaden the spectrum of weed control and reduce the chance of evolution of herbicide-resistant weeds. Herbicide mixture, either tank-mix or ready-mix can provide complete control of diverse weeds in DSR and often reduces doses of component herbicides compared to their sole applications. Component herbicides in a herbicide mixture (especially for tank-mix) should be selected keeping in mind their compatibility and synergistic interaction, such that each herbicide can kill the weeds missed by its partner.

Table 3. Herbicide mixtures available for effective weed control in DSR

Herbicide formulation	Dose* (g a.i./ha)	Time of application	Target weeds	Limitations
Ready-mix (commercial product)				
Penoxsulam + cyhalofop-butyl	135 (2250)	15-20 DAS (4-8 leaf stages of rice)	Broad spectrum control of grasses, broadleaves, and sedges.	-
Bensulfuron methyl + Pretilachlor	60+600	7 DAS	Mixed population of weeds	-
Metsulfuron methyl + chlorimuron ethyl	4 (20)	15-25 DAS (3-4 leaf stages of weeds)	Annual sedges and broadleaved weeds	Does not control grassy weeds and poor on *C. rotundus*.
Pyrazosulfuron ethyl + pretilachlor	1050 (3500)	15-20 DAS	Mixed population of weeds	-
Bispyribac-sodium + metamifop	70 (500)	15-20 DAS	Mixed population of weeds	-
Tank-mix (mixed at farmer level)				
Fenoxaprop-p-ethyl + ethoxysulfuron	60+18 (645 + 120)	15-25 DAS (3-4 leaf stages of weeds)	Mixed population of weeds. Good control of major grasses, including *L. chinensis* and *D. aegyptium*.	Poor on perennial sedges such as *C. rotundus*.
Bispyribac-sodium + azimsulfuron	25 + 17.5 (250 + 35)	15-25 DAS	Grasses, broadleaves, and sedges, including *C. rotundus*	Poor on grasses other than *Echinochloa* sp.
Bispyribac-sodium + pyrazosulfuron	25 + 25 (250 + 250)	15-20 DAS	Grasses, broadleaves, and sedges, including *C. rotundus*	Poor on grasses other than *Echinochloa* sp.
Bispyribac-sodium + fenoxaprop-p-ethyl	25 + 60 (250 + 645)	15-20 DAS	Mixed population of weeds. Good control of grasses, like *Echinochloa* sp., *L. chinensis*, etc.	-

***figures in parentheses denote product (g/ha or mL/ha); a.i., active ingredient; DAS, days after sowing**

Several flushes of weeds come up in DSR during critical period of weed competition and sole applications of either pre- or post-emergence herbicides may not control diverse weeds effectively. Use of two or more herbicides with different modes of action, mainly involving pre- and post-emergence applications in sequence can broaden the spectrum of weed control including grassy, broadleaf, and sedge weeds. With sequential applications (e.g., pendimethalin followed by (~fb) penoxsulam + cyhalofop-butyl or bispyribac-Na), pre-emergence herbicide (pendimethalin) initially controls germinating weeds and late-emerging weeds are effectively controlled by selective and broad-spectrum post-emergence herbicide (e.g., penoxsulam + cyhalofop-butyl or bispyribac-Na). Then the crop itself is able to smother weeds through rapid canopy closure and hence, weed interference is reduced. Besides, early and late post-emergent herbicides can be used in sequence (e.g., bispyribac-Na fb bispyribac-Na or bispyribac-Na fb fenoxaprop-p-ethyl) for effective weed control. Use of dissimilar herbicides also lessens the build-up of herbicide resistance in weeds.

Table 4. Examples of few sequential application of herbicides for effective weed control in DSR

Herbicide formulation	Dose (g ai/ha)	Time of application	Target weeds
Pendimethalin (PE) fb Penoxsulam + cyhalofop-butyl (POST)	1000 fb 135	PE: 1-3 DAS; POST: 15-25 DAS	Broad spectrum control of several flushes of grasses, broadleaves, and sedges.
Pendimethalin (PE) fb bispyribac-sodium (POST)	1000 fb 20	PE: 1-3 DAS; POST: 15-25 DAS	Broad-spectrum control of weeds (several flushes)
Bispyribac sodium fb fenoxaprop-p-ethyl	30 fb 60	8-10 DAS and 25-30 DAS	Mixed population of weeds (in case of several flushes of grassy weeds)

a.i., active ingredient; PE, pre-emergence; POST, post-emergence; DAS, days after sowing

Brown manuring

Brown manuring is an integrated approach of weed management in DSR where Dhaincha (*Sesbania*) is sown in between rice rows and allowed to grow for a short period of 25-30 days and then, killed by applying post-emergence herbicides (2, 4-D or bispyribac-Na) selective to the crop. It initially smothers weeds by quickly occupying the inter-row spaces. After getting knocked down, it forms surface dead mulch that suppresses late-emerging weeds. Brown manuring can also be integrated with broad-spectrum post-emergence herbicides that would supplement weed control (for grassy weeds). It economizes herbicide use, improves profitability and reduces total herbicide loads into environment. Besides weed control, brown manuring incorporates organic matter in soil and improves soil conditions.

Calibration of sprayer and herbicide calculation (commercial product)

Calibration of sprayer is crucial for determining the water requirement for spraying a unit area which is a pre-requisite for efficient application of herbicides. The volume of water required (per hectare) depends on types of herbicides, sprayers, nozzles, spray pressure and speed of application. A sprayer must be calibrated before being used for spraying in the field.

First, a known area (in m^2) should be marked and the spray tank is to be filled with known quantity of clean water (litres). Then spraying should be carried out on that marked area at normal speed of the spray person/machine. The volume or quantity of water required is worked out with the following formula.

$$Q = \frac{(V_1 - V_2) \times A}{a}$$

where, Q, quantity of water (litres) required for a given area; V_1, quantity of water taken initially; V_2, quantity of water left are spraying; A, area to be sprayed in m^2 (10000 m^2 for 1 hectare, or 4050 m^2 for 1 acre); a, measured area sprayed (m^2)

Herbicide calculations

Hectare basis

$$\text{Commercial product} = \frac{100 \times R \times A}{P}$$

Where, commercial product in g or kg; R, recommended rate (g or kg a.i./ha); A, area in hectares (ha); P, percent active ingredient (a.i.) in commercial product

Acre basis

$$\text{Commercial product} = \frac{100 \times R \times A}{P \times 2.47}$$

Where, commercial product in g or kg; R, recommended rate (g or kg a.i./ha); A, area in acres; P, percent active ingredient (a.i.) in commercial product.

Protocols for effective use of herbicides

- Appropriate herbicides should be selected based on type of target weeds and stage of weeds/crop.
- Ensure that field conditions are suitable for herbicide activity (e.g. soil must be moist for pre-emergence herbicides) and avoid irrigation immediately after spraying.
- Apply herbicides at recommended doses with proper quantity of water at appropriate time. For this, always read and follow the instructions on the product label.
- Always use clean water for dilution of herbicides before use. Avoid using muddy water as this reduces efficacy of herbicides.
- Calibrate the sprayer and use appropriate spray equipment for specific purpose. Usually knapsack sprayer with flat-fan nozzle is opted for smaller areas (1 ha/day).
- Ensure spray nozzles are functioning properly and providing uniform output before spraying in field. Usually a flat fan nozzle is used for post-emergence herbicides; however, both flat fan and flood jet nozzles may be used for spraying pre-plant and pre-emergence herbicides. Recently, multiple nozzle boom fitted with flat-fan nozzle is recommended for better delivery and higher efficacy of post-emergence herbicides.
- Spray on a sunny day and mix surfactants/adjuvants with herbicides and properly mix before spraying for achieving greater efficacy.
- Apply herbicides uniformly by maintaining a steady spray pressure; walking speed, application rate and sufficient swath overlap. The spray person/machine, nozzle and sprayer used for calibration should remain unchanged while spraying in field.
- Spray herbicides from a height of ~50 cm above the target. Direction of spray should be perpendicular to wind, so that spray solution is blown away from the applicator.
- Prevent spray drift onto other crops, grazing or other areas not under treatment. Avoid spraying during strong winds to prevent drift losses and non-target toxicity, and during rainy/cloudy day to limit water run-off from fields.
- With too much reliance on one type of herbicide(s), weeds can develop herbicide resistance. So, rotate herbicides with dissimilar ones to reduce weed shift and likelihood of herbicide-resistant weeds

Safety considerations before and after spraying

- Herbicides are toxic substances, which if used unwisely/incorrectly can cause health and environmental hazards. Thus, applicators need skills in application and calibration.
- Wear proper protective clothing viz., gloves, breathing mask, goggles, long sleeved shirts, long pants and covered footwear while spraying.
- Clean blocked nozzles using a non-abrasive implement. Never clean nozzles by blowing on them with the mouth.
- Do not mix herbicides together unless recommended. Wear protective clothing; especially face protection while mixing the product.
- Do not inhale vapours or spray mist. Avoid contact of herbicides with skin and wash contaminated parts of the body immediately with soap and water. On contact with eyes, immediately wash thoroughly with plenty of water (seek medical attention, if situation exacerbates).
- Wash/clean spray accessories properly after every use.
- Never eat, drink or smoke whilst mixing or spraying or before washing hands and face and changing clothes.
- At the end of spray, change clothes and thoroughly wash hands and face. Wash contaminated cloths separately from other household clothes.
- Empty containers/packages shall not be reused. Dispose of empty containers/packages, surplus materials, washing from the sprayer tank, etc. safely either in deep pits or in waste land away from human inhabitation to prevent environmental or water pollution and contamination of animal feeds.

Conclusions

Effective weed control may help in achieving steady yield in DSR comparable to TPR. Herbicides facilitate easier, timely, economical and convenient control of weeds in rice considering the higher cost, drudgery and lower efficacy of other weed control options. Herbicides, if applied properly at recommended rates can facilitate weed control with greater efficacy and without the unintended environmental and health impacts, crop phytotoxicity, residues in plant-soil systems, and non-target toxicity. Prior knowledge of various herbicides specific to weed species, their rates, time of application and safe handling, and correct application methods is essential. Thus, weed control using safest and recommended rates of low-dose high efficacy new generation herbicides, applied solely or in compatible mixtures or as sequential applications could be the most viable way to manage weeds in DSR fields. It may play a crucial role in enabling the adoption of DSR system widely. Like crop rotation; herbicides should be rotated too, instead of relying on similar type of herbicide(s) to avoid weed shift and herbicide-resistant weeds. However, integration of herbicides with ecological options such as brown manuring, zero-tillage with residue retention, and use of crop competition through optimum seed rate, spacing, and adjusting time and method of sowing is more desirable instead of depending on a single option for long-term sustainable weed control.

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