



REVIEW ARTICLE

Study of weed growth and its interaction with direct-seeded rice (DSR) under different herbicides and irrigation conditions

Dharani D P^{1*}, Suchismita T¹, Rabiratna D¹, M Ray², A K Sethy³, A C Dash¹, Prekshya D¹ & G Prameela¹

¹Department of Agronomy, College of Agriculture, Odisha University of Agriculture and Technology, Bhubaneswar, 751003, Odisha, India

²All India Coordinated Research Project on Linseed, Regional Research and Technology Transfer Station, Keonjhar 758 002, Odisha, India

³All India Coordinated Research Project on Groundnut, Odisha University of Agriculture and Technology, Bhubaneswar, 751003, Odisha, India

*Correspondence email - dpradhan027@gmail.com

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Abstract

Rice cultivation continuously remains important for food and livelihood security. The forecasts of increasing water shortage under a changing climate and rising labour scarcities in agriculture have brought a paradigm swing in rice cultivation from the transplanting method (flooded) to direct-seeded rice (DSR). Despite all these returns, the potential yield losses through enormous weed threats under DSR remain a challenge and may reduce yield by up to 50 %. Several Southeast Asian nations have seen a transition in long-term DSR agriculture towards dominating grassy weeds, including *Echinochloa crusgalli*, *Leptochloa chinensis* and *Ischaemum rugosum*. DSR favours the proliferation of grasses and sedges over broadleaf weeds due to the absence of flooding, which is a natural weed suppressant in TPR. Early flooding in TPR can effectively suppress weed emergence, whereas DSR offers limited scope for early flooding since most rice cultivars are intolerant to anaerobic conditions during the germination process. However, anaerobic germination-tolerant rice varieties may enable early flooding and better weed control in DSR. Soil moisture, tillage techniques and application time all have a significant impact on their control efficacy. Crop phytotoxicity and decreased herbicide efficacy might result from improper soil moisture at the time of application. Herbicides may be washed away by excessive irrigation after application, while absorption may be hampered by inadequate moisture. Studies advise using herbicides soon after irrigation when the soil is sufficiently saturated. The efficacy of herbicides is also affected by variations in seasonal rainfall. For DSR systems to maintain productivity and reduce weed-related losses, integrated weed management, which includes prudent herbicide usage and water management, is essential.

Keywords: direct seeded rice; herbicides, moisture and herbicides interactions; soil moisture; weed dynamics

Introduction

Moreover half of the world's population depends on rice as a staple food, making it one of the most significant crops. Global rice production reached about 537.7 MT in 2024/25 and continues to rise in recent estimates (1). Production in India is projected to reach around 152 MT in 2025/26, a record level (2). To meet global rice demand, it is projected that an additional 96 MT of milled rice will be needed by 2040 as compared to 2015 (3). The challenge is that this additional rice must be produced with a lower environmental footprint (less water, labour and agrochemicals) in changing climates to ensure both food security and environmental sustainability. The shift from anaerobic (flooded) to aerobic soil conditions substantially reduces the emission of methane, a potent greenhouse gas, positioning DSR as a key climate mitigation tool (4, 5). Recently, there has also been increased interest in shifting from puddled transplanted rice (PTR), the most dominant rice cultivation method in Asia, to direct-seeded rice (DSR) to address major drivers of agricultural change in the region. These drivers include labour and water scarcity, as well as rising costs of cultivation (6–8).

Direct-seeded rice can be established by three methods: dry-seeding (Dry-DSR), wet-seeding (wet-DSR) and the water-seeding method (6, 9). Rice seeds that have not germinated but can be primed are placed in non-puddled soil in dry-DSR, whereas pre-germinated (sprouted) seeds are sown in wet or puddled soil in wet-DSR. However, dry-DSR is more appropriate in regions where labour and water are becoming scarcer, like South Asia and the focus is on expansion and adaptation of dry-DSR (6, 9-12). In water seeding conditions, pre-germinated seeds are sown in standing water on puddled or non-puddled soil. The transplanted rice system, although effective, is more input-intensive, needing supplementary water, which raises sustainability concerns and contributes to methane emissions and excessive use of non-renewable energy. Dry-DSR in South Asia has shown potential to improve economic sustainability and reduce the environmental imprint of rice cultivation as it saves labour, water and energy and hence reduces the cost of cultivation, increases net income and reduces greenhouse gas (GHG) emissions as given in Fig. 1 (6, 7, 11–15). Because of the above-mentioned benefits, farmers are transitioning from puddled transplanted rice to direct-seeded rice in various parts of South Asian countries (12, 16–18).

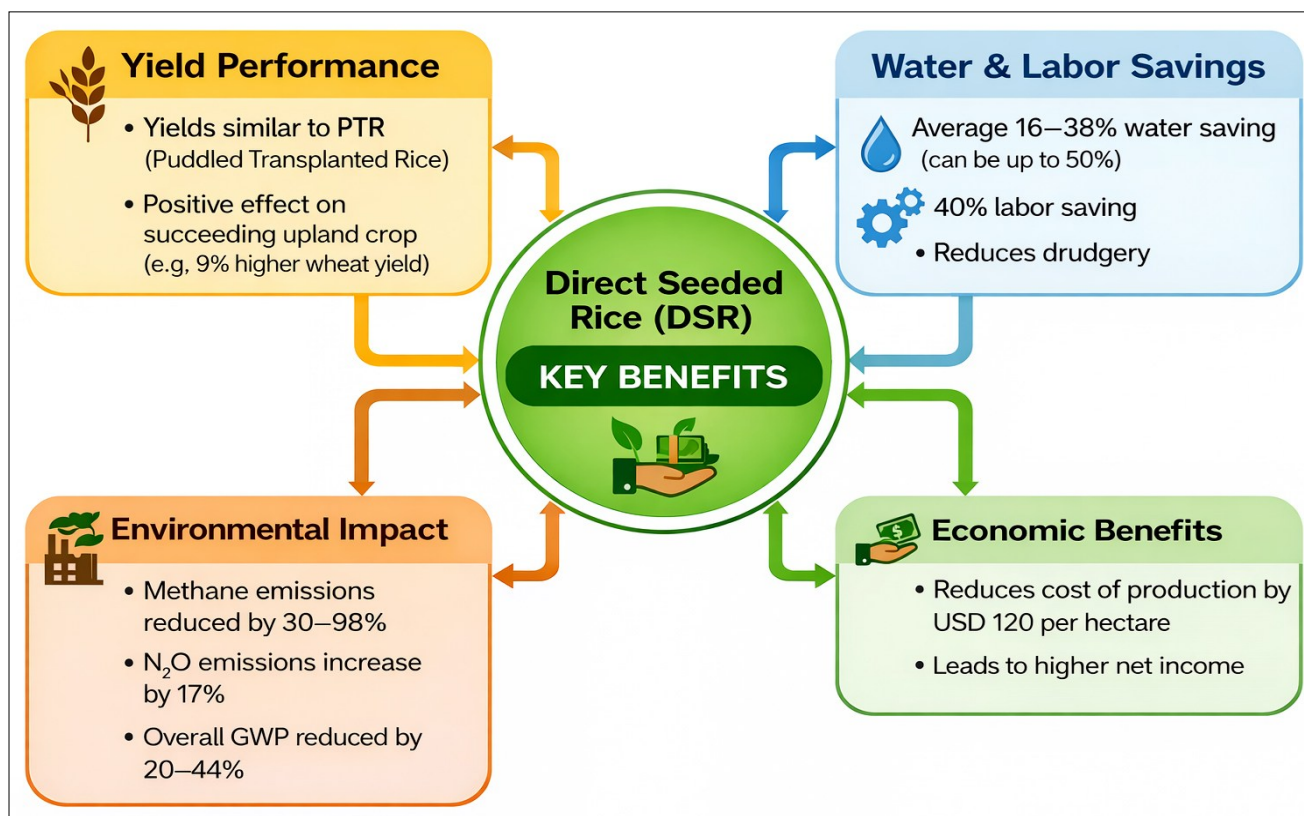


Fig. 1. Advantages of DSR System (6, 7).

Many farmers lack knowledge about the different kinds of herbicides and how to apply them correctly. The purpose of this review was to identify the dependence on herbicides and to present and discuss the patterns of herbicide use and weed control under varying rice moisture content. The information generated will help to formulate strategies to educate farmers to reduce herbicide dependency in DSR methods to ensure environmental safety.

Establishment and advantages of DSR

Rice may be established in three ways: via transplanting, dry-DSR, or wet-DSR. These procedures differ from one another in terms of crop establishment (tillage) and ground preparation. In Asia, particularly in tropical areas, transplanting is the most common technique of rice crop establishment. This method entails ponding the ground and transplanting seedlings raised in nurseries. Direct seeding is the practice of putting seeds directly into the main field rather than transplanting rice seedlings. This can be done wet or dry. The first technique of planting rice is direct sowing, which was afterwards replaced by transplanting.

Dry-DSR

In Dry-DSR, rice crop is established using a variety of methods, such as broadcasting dry seeds on unpuddled soil after either zero tillage (ZT) or conventional tillage (CT), using the dibbling method in a field that has been well prepared and drilling seeds in rows after conventional tillage, minimum tillage using a power tiller operated seeder, zero tillage, or raised beds. In both conventional and zero tillage situations, a seed-cum-fertilizer drill is employed, which drills the seeds and applies fertiliser after preparing the ground or in ZT circumstances.

Wet-DSR

The wet-DSR practice is used to sow pre-germinated seeds (radicle 1–3 mm) into soil puddles. When pre-germinated seeds are sown on the surface of puddled soil, a seed environment known as aerobic

Wet-DSR is produced. To generate an anaerobic Wet-DSR environment, pre-germinated seeds are often sown or drilled into wet soil. Seeds can be spread or sown in line in wet-DSR in aerobic and anaerobic conditions using a drum seeder or an anaerobic seeder with a furrow opener and closure.

Advantages of the DSR system

The conventional approach to rice cultivation in most Asian countries involves rice transplantation, a high-energy, labour-intensive and water-intensive method. Additionally, this method has been found to negatively impact the soil's physico-chemical and biological properties. Therefore, the direct-seeded rice (DSR) is gaining popularity because it has a low ecological impact, also promotes soil properties, accumulation of organic carbon, improves infiltration and moisture content and reduces soil erosion (19, 20). In addition to savings on water, labour and energy, dry-DSR may provide several other potential benefits compared to PTR, which include higher net economic returns (due to lower costs), reductions in methane emissions and improvements in soil physical condition and yields of non-rice crops planted in rotation like wheat (6, 13–15).

Weed dynamics in DSR agro ecosystem

In South-East Asia, a weed flora shift in DSR has been reported towards more aggressive grasses and sedges. In long-term field trial observations in DSR, it was found that initially, the presence of weedy rice and *Leptochloa chinensis* (L.) remained very scanty, but they appeared after only two and four years, respectively. Broadleaf weeds remained dominant initially under DSR, but after a decade of DSR cultivation, grassy weeds like *Echinochloa crusgalli* (L.), *L. chinensis* and *Ischaemum rugosum* became dominant in Malaysia and Vietnam (21, 22). The most dominant grassy weed under Dry-DSR was *E. crusgalli* and the four most dominant sedges were *Fimbristylis miliacea* (L.), *Cyperus rotundus* L., *Cyperus iria* L. and *Cyperus difformis* L. in the Indian condition (23).

Based on practices with DSR in India and other Asian countries, the major grass weed species, including crowfoot grass (*Dactyloctenium aegyptium*), Chinese sprangletop (*Leptochloa chinensis*), love grass (*Eragrostis* spp.) and weedy rice (*Oryza sativa* L.), along with barnyardgrass and junglerice (*E. colona* L.), sedges such as globe fringe rush (*Fimbristylis miliacea* L.), purple nutsedge (*Cyperus rotundus* L.) and rice flatsedge (*Cyperus iria* L.) would dominate under DSR systems (6). Other important weeds of rice under zero-tillage in Rice-Wheat systems include broadleaves such as eclipta (*Eclipta prostrata* L.), red stem (*Ammannia* spp.), Caesulia (*Caesulia axillaris*), goose grass (*Sphenochloa zeylinica*), horsepurslane (*Trianthema portulacastrum* L.), niruri (*Phyllanthus niruri* L.) and *Digera arvensis*. and sedges such as small flower umbrella sedge (*Cyperus difformis* L.). The composition of weeds is dynamic and varies depending on location, time and management techniques. The infestation of certain weed flora is influenced by a variety of factors, including soil, climate, cropping system type and management techniques (24–26).

Leptochloa chinensis (L.) emerged more dynamically when the soil moisture was below saturation, but *Echinochloa* sp. tended to dominate when the soil moisture was above saturation. The floral composition of weeds varied greatly and weed-related yield losses were more severe under saturated conditions (54 %) than in flooded conditions (35 %) (27). India has also recognised a rise in sedge dominance in response to DSR cultivation (28, 29). Broadleaved weeds dominated transplanted rice, whereas grasses and sedges were more extensively dispersed in direct-seeded rice (DSR). Weed seeds can be produced in large quantities during the fallow period following rice harvest. In Bihar, India, seeds of *Caesulia axillaris* Roxb. and other weed species that are undeveloped at the time of rice harvest can develop fast after the removal of the rice canopy, producing adult seeds (V. Kumar, personal observation).

Similarly, in Odisha, India and South Sumatra in Indonesia, where rice-fallow is the predominant cropping system, weeds grow and produce seeds and add to the seedbank during the fallow phase. In the rice-rice cropping systems of Southern Bangladesh, during the short fallow period between harvests of boro (dry) season and planting of succeeding Aman (wet) season rice, weeds such as *Echinochloa colona* (L.) can grow and produce many seeds and, hence, can contribute to the seedbank. *Striga hermonthica* (Delile) Benth of West Africa (30) and numerous other weeds continue to flourish after crop harvest, adding pointedly to total seed output. Annual weeds such as *F. miliacea* and *Echinochloa glabrescens* Munro ex Hook. F. produced an abundance of seeds in the field during the fallow period (31). Such seeds may survive in rotating crops, reducing yields or increasing weed control expenditures in DSR in later years.

Ecological interaction of irrigation and weeds in rice fields

Flooding can inhibit the growth of most of the rice weeds. Water management is critical for efficient weed control in transplanted rice. Rice production increase, particularly under monoculture systems, has caused substantial environmental and agronomic problems, such as changes in floristic composition and weed species proliferation. Weed emergence and growth are significantly influenced by flood duration, length and depth (32–34). Weed infestation was observed to be lower when using the PTR method of establishment and weeds such as *Dactyloctenium aegyptium*, *Eleusine indica*, *Trianthema monogyna*, *Digera arvensis* and *Cyperus rotundus* were not observed in the PTR. These weeds need aerobic

conditions, but stagnant water in transplanted fields create anaerobic conditions, slowing germination and development of these specific weed species. *Hydrilla verticillata* and *Cyperus difformis*, on the other hand, required submerged conditions to grow and were not found by the DSR method because of the aerobic conditions in the fields.

It was found that grasses such as *Leptochloa chinensis*, *Eragrostis* spp., *Dactyloctenium aegyptium* and *Eleusine indica*, along with sedges like *Cyperus rotundus*, which were only marginal weeds in puddled transplanted rice (PTR) in Northwestern India, became predominant under the direct-seeded rice (DSR) approach (35). Applying pre-sowing irrigation to achieve adequate but workable soil moisture was found to significantly reduce weed infestation in direct-seeded rice (DSR) fields. (36). Sowing in moist field conditions was also found to suppress and delay the emergence of weeds in direct-seeded rice (DSR) fields (35). In DSR systems, options to minimise weed emergence by flooding are limited since early flooding to suppress weeds would also inhibit rice emergence because current rice cultivars do not survive anaerobic conditions during the germination/emergence stage. Weed appearance and growth suppression in response to flooding are determined by the physical, chemical and biological potentials of flooded soil, which are heavily impacted by tillage types (37). Indirect indication from multiple studies shows that the seed development of many weed species in irrigation channels may lead to a weed problem in nearby DSR fields. The floating seeds of 26 weed species from 17 families were exposed from a lowland rice field in China, suggesting that these plants might easily move into rice fields by irrigation (38). Similarly, it was revealed that 74 weed species seeds in irrigation water, with half belonging to the Poaceae, Asteraceae and Polygonaceae families (39). Although the origin of these seeds is uncertain, their proliferation along irrigation canals can add to weed issues in irrigated DSR systems. Weed insurgency in Dry-DSR is accelerated by simultaneous crop and weed development, as well as the absence of stagnant water during the first crop establishment period (40). Weeds might be handled in these systems using hand weeding method (manual techniques), herbicides, or a mix of both.

Different herbicides used in rice plant and rice productivity

In Asia, 22 % of the acreage of total rice cultivation is under DSR and the region-specific integration of these weed management methods might decrease herbicide use in these areas by up to 50 % (41). Among different herbicides, pendimethalin and pretilachlor are the most used herbicides. Presently, the Pendimethalin ranks as the world's third-largest selective herbicide (42). Numerous studies have observed the impact of herbicides in DSR practices on nutrient dynamics and crop yield in rice agroecosystems (43, 44). A study was conducted to determine the role of pendimethalin and pretilachlor in reducing weed infestation in direct-seeded rice fields (45). In dry-seeded rice (DSR) production systems in particular, high weed density lowers the profitable returns and, in extreme cases, causes complete crop failure (46, 47). Previous studies have shown that if weeds are managed properly, the yield achieved under DSR systems could be comparable to that of transplanted rice (48, 49).

Herbicide interface under different soil moisture conditions

Differences in soil moisture, coleoptile and root growth in seeding systems may alter rice plant reaction to herbicide residue by changing herbicide concentration in soil solution and herbicide absorption (Table 1–2). Herbicide residue will be influenced by soil herbicide concentrations and crop susceptibilities. Herbicide

Table 1. Recommended Herbicide for direct-sown rice (Rainfed uplands and lowlands).

Sr. No.	Name	Mode of action	Target weeds	Time of application	Dose (g a.i. ha ⁻¹)
1.	Oxadiazon	Protoporphyrinogen oxidase (PPO) inhibitor	Early emerging weeds (Grassy, Broadleaf, Sedges)	0–3 DAS (Before/Just after sowing)	75
2.	Pendimethalin	Dinitroaniline inhibitor	Early emerging weeds (Grassy, some Broadleaf)	0–3 DAS (Before/Just after sowing)	1000
3.	Pretilachlor with Safener	Inhibition of cell division / very long chain fatty acid (VLCFA) inhibitor	Early emerging weeds (Grassy, Broadleaf, Sedges)	0–3 DAS (Before/Just after sowing)	400
4.	Bispyribac-Sodium (Nominee Gold)	Acetolactate synthase (ALS) inhibitor	Early emerging grassy weeds; some sedges	8–10 DAS (or) when weeds are at 2–3 leaf stage	30
5.	Fenoxaprop-p-ethyl (Rice Star)	Acetyl-CoA carboxylase (ACCase) inhibitor	Late-emerging grassy weeds	15–20 DAS (or) weeds at 3–5 leaf stage	60
6.	Cyhalofop-butyl (Clincher)	Acetyl-CoA carboxylase (ACCase) inhibitor	Grassy weeds	Around 15 DAS (or) weeds at 2–4 leaf stage	100
7.	Ethoxysulfuron (Sunrise)	Acetolactate synthase (ALS) inhibitor	Sedges and broad-leaved weeds	15 DAS (or) weeds at 2–4 leaf stage	20
8.	Fenoxaprop-p-ethyl + Ethoxysulfuron (Tank-mix)	ACCase Inhibitor + ALS inhibitor	Mixed weed flora	15–20 DAS (or) weeds at 3–4 leaf stage	50+15
9.	Bensulfuron methyl + Pretilachlor (Ready-mix-Eraze-Strong/Londax power)	Acetolactate synthase (ALS) Inhibitor + inhibition of cell division / VLCFA inhibitor	Mixed population of weeds	7 DAS	10
10.	Metsulfuron methyl + chlomuron ethyl (Ready-mix-Almix)	Acetolactate synthase (ALS) inhibitor	Sedges and broadleaved weeds	15–18 DAS (or) weeds at 3–4 leaf stage	4

(Adapted from: 50).

Table 2. Loss of grain yield in different methods of rice establishment in India (51).

Sr. No.	Method of rice establishment	Reduction in yield due to weeds (%)
1	Upland rice	97 % (Near total loss)
2	Upland dry-seeded rice	94 % (Almost complete loss)
3	Dry-seeded rice	17 % to 73 % (Highly variable, but significant loss)
4	Wet-seeded rice	85 % (Major loss)

absorption occurs predominantly through the dissolved herbicide in soil water (52, 53). The concentration of herbicide in soil solution is measured by herbicide solubility, soil sorptive capacity, soil moisture content and rate of dissipation (54). The most widely used and effective pre-emergence herbicides available now are oxadiazon, pendimethalin and pretilachlor with safener (55, 47). However, the effectiveness of pre-emergence herbicides in weed control is affected by a variety of parameters, including soil moisture, soil tilth, weed flora configuration, herbicide dosages and weather conditions (56). Soil moisture condition is the most vital component since it affects both herbicide efficiency and crop phytotoxicity by modifying herbicide absorption, transport, or metabolism (57, 58).

Flushing, a predominant technique in DSR, is the use of irrigation water after rice sowing in a dry field to assist germination and seedling appearance (59, 60). When sprayed in dry soil, pre-emergence herbicides are absorbed by soil colloids, lowering their availability for absorption as the chemical barrier thins and becomes inadequate to prevent weeds from emerging. Moisture in the soil is critical for enhancing the efficiency of pre-herbicides because it increases herbicide transport in the soil, lowering herbicide losses from the soil surface and increasing herbicide absorption by emerging seedlings as given in Fig. 2 (61). Research found that using pendimethalin as a pre-herbicide during the Aman (June–November) season reduced rice plant population by 14–22 % because heavy rains fell quickly after herbicide spraying. Crop plant population is unaffected during the boro (December–May) season,

when there is no precipitation soon following herbicide spraying. Research indicates that rice plant stand was lower when heavy rains fell shortly after the application of oxadiazon compared to non-treated areas (62). It was observed that the effectiveness of pre-emergence herbicides depends on soil moisture, making butachlor suitable for drier soils and pendimethalin preferable for moist soil conditions (63).

Post-emergence herbicides (e.g., Bispyribac-sodium, Penoxsulam, Fenoxaprop, 2,4-D) are generally foliar-applied herbicides and their efficacy is dependent on absorption through the leaf surface and subsequent transport to the site of action. In post-emergence (PoE) (e.g., Bispyribac-sodium) and subsequent stress, the weed population remains high and the rice crop is stressed. If the field stays dry after the PoE treatment, resulting in low post-emergence effectiveness owing to decreased absorption. This causes the most total weed pressure and severe yield loss. However, certain soil-applied herbicides are relatively water-soluble and can transport through the soil with water. As a result, excessive watering may transfer the herbicide across the germination zone, resulting in ineffective weed control (64). In contrast, insufficient irrigation or rainfall may cause the herbicide to remain on the soil surface, where it is susceptible to environmental degradation. The field statistics indicate that there is a larger likelihood of requiring moisture below the 0 to 1-inch depth. Thus, there may be an advantage to first incorporating certain herbicides in moister soil to improve absorption (61). The critical takeaway, supported by evolving research, is that precise soil moisture management during and immediately after PRE application is the linchpin for maximising DSR productivity in lowland ecosystems, necessitating herbicide selection tailored to prevailing soil conditions (63). Herbicides that are easily translocated in the xylem and active in leaves (photosynthesis and pigment inhibitors) may suppress established weeds or harm the crop quickly after rainfall events because herbicides are released into solution and can be absorbed by plants.

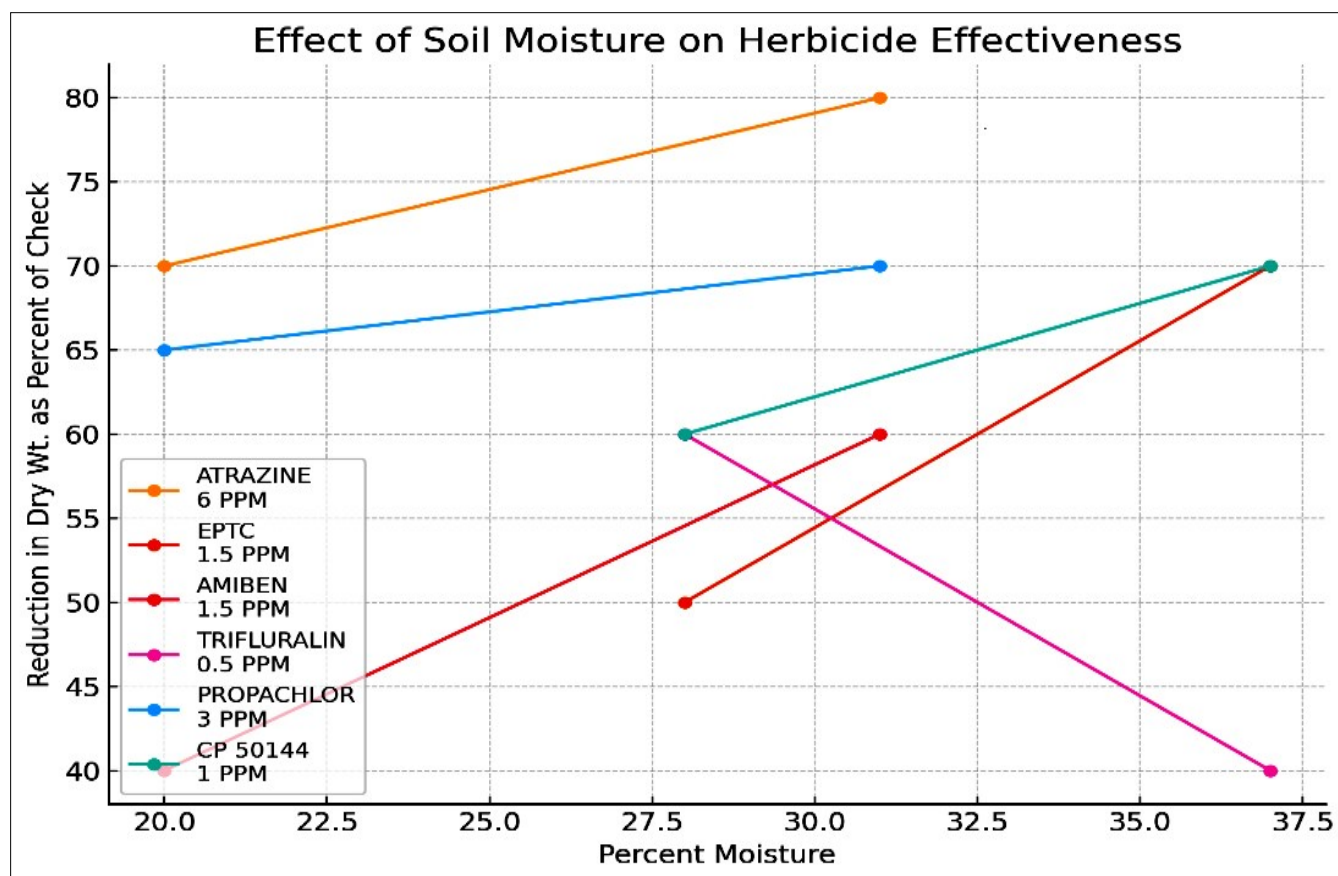


Fig. 2. Effect of soil moisture on herbicide effectiveness (61).

Future research direction

To improve weed control techniques in direct-seeded rice (DSR) systems through preventative methods, this review identifies several crucial knowledge gaps that need to be filled. Designing ecologically sustainable weed management tactics requires a knowledge of how crop rotation affects weed population dynamics over time. Investigating how alternating tillage and crop establishment techniques affect the suppression of difficult-to-control weeds unique to DSR, which frequently flourish in reduced tillage settings, is equally crucial. The unintentional facilitation of weed seed distribution by irrigation water and organic additives like compost and manure is another important but often ignored factor. Quantifying these consequences and creating strategies to prevent inadvertent weed spread are urgently needed. Additionally, using anaerobic conditions to suppress weed emergence might be revolutionised by optimising water management, specifically the time, length and depth of flooding, especially when combined with rice types that are tolerant of anaerobic germination. DSR systems that are more robust and resource-efficient may result from the comprehensive integration of various preventative techniques. To develop a strong, preventative weed management approach that promotes long-term production and sustainability in DSR, future research should give priority to these areas.

Conclusion

The effectiveness of these herbicides is critically dependent on soil moisture. Optimal results require saturated soil for proper herbicide movement into the germination zone, whereas dry soil leads to failure and excessive moisture causes leaching and crop injury. There is a greater reliance on herbicides for weed control in DSR systems since weed management is more challenging and the

potential yield losses from weeds are significantly larger than in transplanted rice. This calls for an integrated approach to weed control that comprises selective herbicide treatment, anaerobic germination-tolerant rice types and water management. Pendimethalin and pretilachlor are examples of pre-emergence herbicides that can be successful, although their effectiveness is mostly reliant on the right soil moisture content and environmental factors. Crop phytotoxicity or decreased effectiveness might be the outcome of poor management. Moreover, the weed problem is made worse by the input of weed seeds from irrigation channels and fallow times. Consequently, to manage weeds sustainably and guarantee production in DSR systems, a site-specific and season-sensitive approach that combines agronomic methods with chemical management is essential.

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Authors' contributions

DDP, ST, RD, MR, AKS, ACD, PD and GP conducted a thorough analysis of the data gathered. aided with the literature study, provided input on how the information was organised and made insightful recommendations that improved the article. All authors read and approved the final manuscript.

Compliance with ethical standards

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

Ethical issues: None.

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