PERSPECTIVE

Recent Developments in Rice Weed Management in India

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Abstract

Rice is one of the major staple foods of India. India needs to produce 84 million tons more food grains than it currently produces (315.6 million tons) to meet the demands of 1.65 billion people by 2050. Weeds are among the most severe constraints in resource use efficiency in direct-seeded rice (DSR) than traditionally practiced puddled transplanted rice (TPR). The needed increase in rice production is possible with increased productivity of rice. However, it requires major interventions and system improvements to alleviate the pressure from weeds. In this mini-review, we studied the recent developments in weed management research in rice in India, especially herbicide combinations that might significantly improve the future outlook. Several well-known rice weeds, including *Leptochloa chinensis*, *Ischaemum rugosum*, *Paspalum distichum*, weedy rice and algal blooms, have increased in abundance in rice in some Indian states.

A novel method of direct seeding called 'Tar-wattar DSR' was introduced and successfully popularised in Punjab. In Jammu also, the Tar-wattar technology resulted in higher returns, but in Haryana, it did not perform well. Two RobiNOweed Basmati rice varieties, Pusa Basmati 1979 and Pusa Basmati 1985, the first non-GM (genetically modified) Basmati rice varieties tolerant to herbicide imazethapyr, have been released recently for commercial cultivation in India. A cautious approach is suggested for their popularisation amongst Indian farmers as non-adoption of stewardship guidelines leads to herbicide-tolerant weedy rice evolution, as has occurred in other countries.

Herbicide mixtures and sequential application of herbicides have been found to effectively manage many problematic weeds in rice, established by different methods. Herbicide applications using drones are being tested but are yet to be approved by the Indian government. Efforts are also underway to use machine-vision technology, together with rapid data processing, to enable commercial automated devices and robotic machines to recognise weeds and crop-row patterns and facilitate the treatments against weeds. These methods are yet to be widely tested in rice. More research efforts are needed to have a holistic understanding of climate change effects on weeds in rice, their competition and management, even though such efforts were initiated in India.

The research on rice weed management needs to be intensified, focusing on climate-resilient integrated ecological weed management with a major emphasis on cultural and preventative weed management, integrated with the 'need-based' use of herbicides and precision weed management.

Keywords: rice weeds, herbicides, mechanical weed management, robotics, drones, automation, herbicide-tolerant rice

Introduction

Rice (*Oryza sativa* L.) is one of the most important staple foods in the world as it supplies the major food requirement for more than half of the world's population (Rao and Matsumoto, 2017; Rao et al., 2017a). Rice, being the prominent staple grain crop, in 2022-23, India produced 130.3 million tons (Mt) of rice (rainy season: 111.8 MT from 41.1 million hectares (Mha) in kharif and 18.5 MT from 5.3 Mha in rabi) (GOI, 2023). The estimates for the future are that the country would need to produce more than 400 Mt of food grains to meet the demand of an expected 1.65 billion people by 2050. This figure is about 41.2% of the total food grains (315.6 Mt) that India produced during 2022-23. To achieve this target, a major increase needs to come from India's national rice production systems.

Instead of wet- or dry-seeded (broadcast) rice, transplanting rice became popular in the Asian-Pacific region more than seven decades ago (Rao, 2017c). Nowadays, it is common to raise rice seedlings in a nursery and transplant 20–30-day-old seedlings in a puddled and flooded field. The conventionally puddled and flooded transplanted rice systems (TPR, or puddled, transplanted rice, PTR) depend on up to 5-7 cm of standing water and the already germinated rice seedlings to effectively suppress weeds in the paddies.

However, TPR requires immense labour and significant amounts of water, supplied mostly by irrigation. As a result, TPR is becoming potentially unsustainable due to declining water resources, reduced availability high cost of labour and increasing costs of diesel and electricity. Climatic change effects also exacerbate the current rice weed problems, especially due to changing moisture regimes and temperature fluctuations, which can cause high rates of evaporation from rice paddies.

Hence, there is an increasing trend in shifting the method of rice establishment among farmers from TPR to direct seeding of rice (DSR). At present, 23% of rice is direct-seeded, globally. In rainfed, upland areas in India, DSR is commonly adopted, but the upland system is usually one of low-productivity. Nevertheless, DSR technology has continued to be a key focus of research in the Asian-Pacific region, especially in India, in the last two decades.

Improving the DSR technology would offer considerable advantages, such as faster and easier planting, reduced labour and toil, earlier crop maturity by about 7–10 days, more efficient water use and higher tolerance of water deficit, and less methane emissions. DSR also eliminates the use of seedlings and related operations, such as seeding, nursery preparation and care of seedlings, pulling, bundling, transporting, and transplanting (Rao et al., 2017b;c; Yaduraju et al., 2017; Bhullar et al., 2018).

DSR has been considered a good alternative to TPR because of the yield potential of improved DSR, which is equivalent to TPR under good water management and weed control conditions. DSR is accomplished by either of the methods of water-seeding, wet-seeding or dry-seeding (Rao et al., 2017b;c). Presently, in South Asia, DSR is practised in about 26% of the total rice area (Saha et al., 2022).

Despite the advantages, it is also evident that many kinds of weeds are a serious problem in DSR, as dry tillage practices and aerobic soil conditions promote the germination and growth of weeds. The weed flora in rice fields comprises a mixture of species. The majority of the rice weed species have co-evolved with rice and are well adapted to the wet rice paddies, while a smaller cohort, often found in rice ecosystems, are adapted to semi-wet and drier conditions. All kinds of weeds, including broad-leaf weeds (BLWs) and the other two main groups, i.e. grasses (Poaceae) and sedges (Cyperaceae), could cause grain yield losses from 50 to 90% unless they are well controlled.

In general, weed problems in TPR are lower than those of DSR (Rao et al., 2007; 2017a;b; Kumar et al., 2016). Most estimates of rice yield losses in the three systems indicate that losses in TPR are generally in the range of 18-20% compared with 30-35% losses in wet-seeded rice and more than 50% in DSR (Rao et al., 2017c; Nagargade et al., 2018).

The rice crop, inevitably, has to compete with those weed species that co-evolved with it in the rice ecosystems for resources, i.e. space, water, nutrients and sunlight. Sometimes, the competition can be intense in poorly managed fields. In DSR, more than three flushes of weeds infest the rice crop during its lifecycle, presenting significant challenges (Nagargade et al., 2018).

Broadly, in India, Gharde et al. (2018) estimated that the total losses caused by weeds amount to nearly USD11 billion per annum in 10 major crops alone, of which rice accounts for USD 4420 million losses (Figure 1). Effective and economical weed management is, therefore, vital both for increasing agricultural productivity and farmers' income. Effective weed management is also a fundamental requisite for ensuring the quality of the rice that is produced for local consumption and export.

In India, rice weeds are primarily managed through manual and mechanical methods, which are quite expensive, accounting for 20-25% of the total cost of cultivation (TAAS, 2021). Manual weeding is nowadays not cost-effective because of labour shortages and increased labour costs. Herbicides are replacing manual weeding at a faster rate in rice as farmers are finding herbicides as a much more cost-effective alternative for managing weeds at critical times in the crop production cycle.

The use of herbicides has been increasing in the last decade in India at a much faster pace (15-20% annually). Herbicides constitute more than half of the total pesticides used globally. However, in India, the share of herbicides is only around 18% of the total pesticides, which is low compared to insecticides (40%) and fungicides (33.4%) (TAAS, 2021).

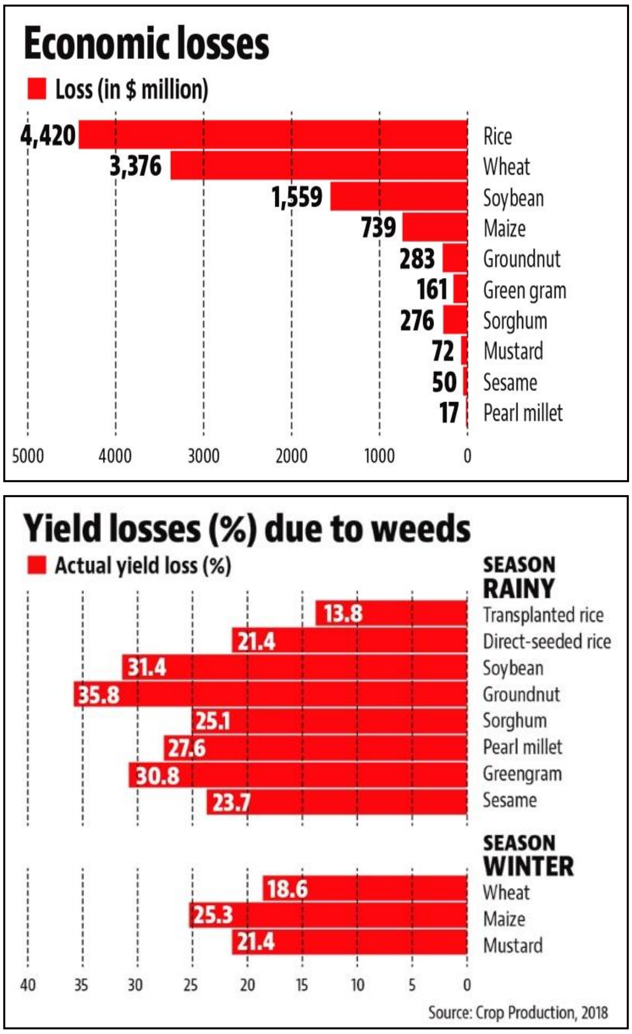

Figure 1 Losses caused by weeds significantly vary with the crop, growing season and location in India (Source: Gharde et al. 2018)

With regard to herbicide use, there are concerns in India about overreliance on chemicals as well as the repeated use of some herbicides. The concerns relate to the evolution of resistance in some difficult-to-control weeds, shifts in the weed flora, costs of the herbicides to farmers and concerns about potentially adverse effects on waterways and the general environment. Therefore, there is consensus about the urgent need to develop and adopt integrated ecological weed management strategies involving a range of holistic and integrated weed management approaches (Rao and Nagamani, 2010; Mahajan et al., 2014; Nagargade et al., 2018; Rao and Chandrasena, 2022).

The integrated weed management (IWM) approaches include preventive measures, such as the stale seedbed technique, summer tillage, precision land levelling, crop rotations and sowing methods. These can be complemented by cultural methods, including the use of competitive crop varieties, herbicide-tolerant crop varieties (HTCs), and manipulations of seed rates and crop residues, such as straw mulching. Additional methods include rotational cover crops and live mulching, brown manuring, water and nutrient management (especially organic amendments), manual and mechanical methods and bio-control agents for specific weeds, where available for use in rice systems (Nagargade et al., 2018; Rao et al., 2017; Rao and Chandrasena, 2022).

The objective of this brief review is to highlight the most significant recent research and extension work that has been conducted on rice weed management in India. Our attention was focused on reviewing the DSR production system with its use of new rice herbicides and their combinations, as well as application methods. We also reviewed the emerging trends in automation and mechanical weed management, critically assessing the information in the articles cited. In conclusion, we provide our views on what the outlook might be for the future of weed management in rice ecosystems, applicable to India and the broader Asian-Pacific region.

Emerging Rice Weed Problems

It is known that the rice-field weed composition has been changing with the shift in rice establishment methods and the adoption of various improved rice weed management practices (IRRI, 2024a). Changes in the weed flora occur as conditions are modified in the rice field environment due to various practices. Generally, the rice field is vulnerable to a large array of moisture-loving weed species that have long co-evolved with rice. Under the warm, tropical Indian climate, such species are known to flourish in most situations unless they are controlled.

In addition, other facultative species, those that usually occupy drier conditions but are able to adapt to wetter conditions, may also enter the rice agroecosystem due to encountering favourable growth conditions (such as altered water regimes in wetter seasons). New species could also be introduced via cultural practices, changing weather patterns or land uses. Hence, the continuous monitoring of the weed flora composition and changes must be a prerequisite for effective and sustainable weed management in rice.

Lists of the most common rice weeds under TPR and DSR are given by Rao and Matsumoto (2017) and Rao et al. (2007) and several of the other cited references. The '*Rice Knowledge Bank*' of the International Rice Research Institute (IRRI, 2024b) also provides lists of weeds in the Asian-Pacific region countries in which different species dominate in the rice-field weed communities.

The IRRI *Knowledge Bank* nominates a 'Dirty Dozen' of the most prevalent and dominant rice weeds in the tropical Asian-Pacific region, extending to parts of South-Western Asia. These are: rice flat sedge (*Cyperus iria* L.); umbrella sedge (*Cyperus difformis* L.); awnless barnyard grass [*Echinochloa colona* (L.) Link]; barnyard grass [*Echinochloa crus-galli* (L.) P. Beauv]; lesser fimbry [*Fimbristylis miliacea* (L.) Vahl]; linear-leaf water primrose [*Ludwigia hyssopifolia* (G. Don) Exell]; false daisy [*Eclipta prostrata* (L.) L.]; wrinkle grass (*Ischaemum rugosum* Salisb.); sedge [*Schoenoplectus juncoides* (Roxb.) Palla]; goose weed (*Sphenoclea zeylanica* Gaert.); red sprangletop [*Leptochloa chinensis* (L.) Nees] and wild rice (*Oryza sativa* f. *spontanea*). All of the above species are present in India. They are prevalent to varying degrees in rice ecosystems across all of the states and geographical regions.

Among the reported recent weed flora shifts in India is *Leptochloa chinensis*, which had not been previously considered a major rice weed in India. It has now become a major weed in the early-to-maturing stages of rice (Saha et al., 2021).

In Telangana, along with *L*. *chinensis*, wrinkle grass (*Ischaemum rugosum* Salisb.) and water couch (*Paspalum distichum* L.), along with algal blooms have emerged as significant problems, especially in wet-seeded rice (DSR)/dry converted wet rice (AICRP-WM 2022, 2023). These species have existed in India and neighbouring regions in rice fields and habitats more broadly associated with rice ecosystems. However, with the shifts in practices, they are being increasingly reported as becoming prominent as weed problems within rice paddies.

Other emerging rice weeds in DSR systems in Andra Pradesh include a Euphorbiaceae species – 'Suryavarti' [*Chrozophora rottleri* (Geis.) Juss. ex Spr.] and *Paspalum distichum* (in DSR) (AICRP-WM 2023). Furthermore, several species, well adapted to varying moisture levels have also increased in abundance. Examples are finger flat sedge (*Cyperus digitatus* Roxb.) in rice fields in Kerala (AICRP-WM 2022) and broad-leaf flowering rush [*Butomopsis latifolia* (D.Don) Kunth] [Alismataceae] and several *Polygonum* spp. [Polygonaceae] in deep water rice in Assam (AICRP-WM 2021).

The semi-aquatic perennial species – Cupscale grass [*Sacciolepis interrupta* (Willd.) Stapf], which has long been considered only as a minor weed associated with rice ecosystems, has now gained the status of a major troublesome weed in both wet-seeded and transplanted rice in Kerala. Rani and Menon (2019) reported this increased prevalence to the strong adaptations and the perennial habit of *Sacciolepis interrupta*, changing cultural practices and climatic variations, and possibly longer drier periods. More than two decades ago, Renu (1999) reported that the competition from *S*. *interrupta* alone could reduce rice grain yields by 50%.

Recent Indian research has also shown that the incidence of lesser canary grass (*Phalaris minor* Retz.), a perennial grass, was drastically reduced in conventionally-tilled (CT) DSR- zero tiled (ZT) wheat cropping systems. However, in TPR, combined with conservation tillage wheat (TPR–CT), the prevalence of *Phalaris minor* has been gradually increasing in India (AICRIP-WM, 2023). Lesser canary grass, a native of the Mediterranean and Western Asia, is now globally spread. It was introduced across continents primarily as a pasture grass but has shown to have wide ecological amplitudes and occupy both upland, terrestrial habitats and lowland, damp habitats.

One of the major threats associated with the introduction of DSR in India is the evolution of weedy rice (*Oryza sativa*. f. *spontanea* Roshev.), which is one of the most difficult-to-control rice-field weeds in the world (Ajaykumar et al., 2022). Weedy rice is a hybridisation product, descending either from the perennial wild rice species (*Oryza rufipogon* Griff.) or cultivated rice (*Oryza sativa*) (Roy et al., 2023).

Abraham and Jose (2015) reported that weedy rice infestations have been spreading at an alarming rate in major rice tracts in large parts of India (such as West Bengal, Andhra Pradesh, Assam, Bihar, Karnataka, Kerala, Madhya Pradesh, Orissa, Tamil Nadu and Uttar Pradesh). Soni et al. (2019) reported that the spread of weedy rice has forced many Indian farmers to abandon rice cultivation due to the large reductions in crop yields and the efforts required to manage the infestations.

As highlighted by Mortimer et al. (2000), weedy rice has been a global problem for nearly three decades, particularly in South and Southeast Asia, South and North America, and Southern Europe. Given the trends of increasing weedy rice problems in the Asian-Pacific region (Rao et al., 2017a), we are of the view that the changes in rice production systems, moisture regimes, especially under a changing climate, and other factors, could make weedy rice a far greater problem in India than it currently is. Hence, weedy rice infestations in rice ecosystems across the Indian states require increased vigilance and immediate solutions where there is a possibility of further spread.

Improved Methods of Rice Establishment

The 'Tar-wattar' DSR technology

A novel method of direct seeding called 'Tar-wattar DSR' was introduced and popularised in 2020 in Punjab. 'Tar-wattar' means 'sufficiently high and workable moisture'. The method was developed by researchers at the Punjab Agricultural University (PAU). In the 'Tar-wattar DSR' method, the first irrigation is applied at about 21 days after sowing (DAS), which has many added advantages. These include (1) greater irrigation water saving due to minimal evaporation loss from drier surfaces, (2) lower weed emergence, (3) deeper rice root development and lesser nutrients leaching out, resulting and reduced incidence of nutrient deficiency, especially iron, (4) wider adaptability across different cropping areas, and (5) rice yield and profitability, comparable with TPR or higher (Bhullar et al., 2018; Yaduraju et al., 2021;).

In the improved TAR-wattar DSR technology, the date of sowing is advanced to the hot but drier part of the season (20 May to 10 June) for the irrigated zones instead of during the hot and humid part of the season (15 June onwards) (Lather, 2022). In Northwest India, the relative humidity during May is generally low (less than 30%), with negligible rainy days. These climatic factors are unfavourable to weed seed germination and growth, which makes improved 'Tar-wattar' DSR technology quite effective in controlling weeds even without the application of post-emergence (POST) herbicides.

Research indicates that depending on the weed flora in the field, at 15 to 25 DAS, in a moist field, when most weeds are at the two to four-leaf stages, herbicide treatments can be effectively undertaken in this system. As a result, the 'Tar-wattar' DSR technology has been widely adopted in Punjab, and the area under DSR increased to 172,000 acres in 2023. In the neighbouring State of Haryana also, the DSR area increased from 10,000 ha in 2019 to 25,000 ha in 2020, with many farmers adopting the technology (Yaduraju et al., 2021).

In Jammu also, the 'Tar-wattar' technology has led to higher returns. However, in Haryana, the technology has not performed well (AICRP-WM 2023). The disparity of yield outcomes means that this technology needs to be evaluated in different parts of India so that the cultivation areas most suitable for its adoption can be better identified.

Several studies conducted during the past decade have proven the advantages of DSR (Yadav et al., 2011; Bhullar et al., 2016). In the case of coarse dry-seeded rice, 63% of farmers reported a 10-20% reduction in irrigation water, 29 to 36% of farmers reported 20 to 30%, and the rest of the farmers reported a saving of >30% in DSR compared to PTR. Averaged over coarse grain rice and basmati, farmers practicing DSR saved 18-20% irrigation water compared to PTR. Previous research in this region has shown that it was possible to reduce the amount of irrigation water by 15-20% under DSR without reducing rice yields relative to the traditional PTR (Yadav et al., 2011; Bhullar et al., 2016).

Rice Cultivars

Competitive Varieties

Competitive crop cultivars are crucial components of IWM in all crop production systems (Ramesh et al., 2017). Rao and Nagamani (2010) argued that rice genotype competitiveness against weeds is a 'low-monitory input component' of IWM. Characteristics of highly competitive rice varieties include seed size, seedling vigour, plant height, higher tillering and fast growth at the early stages. The production of relatively large and droopy leaves (i.e. greater leaf area index, LAI), rapid canopy cover during vegetative growth, deep and prolific root growth and early maturity are also important in the competitiveness of rice varieties.

Several competitive rice varieties were identified in early studies and listed by Ramesh et al. (2017) and Dhillon et al. (2021). More recently, several other competitive rice varieties have also been identified in India and are summarised in Table 1. The adoption and integration of these cultivars must be an essential component of weed management in rice in either DSR or TPR systems.

The adoption of organic Farming is gaining importance in India as a solution to minimising the negative effects of modern agriculture, including the overuse of agrochemicals. Consumer demand has also risen, even in India, for foods that have been produced in systems that are free from chemical toxicants. In organic rice farming, weed management is much more critical to achieving an acceptable level of rice productivity.

The inclusion of competitive rice cultivars, such as those given in Table 1, is critical to managing weeds in the organic rice production system. Encouragingly, in an important two-year recent study, Meti et al. (2021) reported significantly lower total weed density and biomass, higher weed control efficiency and higher grain yield of dry DSR under an organic production system.

Table 1 Competitive Rice Cultivars Commonly Used in India

Competitive Cultivar	Competitive characteristics	Rice system	Reference
SAVA 134, PR 120 and PR 126	Grain yield, leaf area index (LAI), plant tillers at physiological maturity	DSR	Bansal et al., 2024
Hybrids: Arize 6444 and Arize Dhani,	Plant height, leaf area index, dry matter/hill (Arize 6444), number of tillers/m2 (Arize 6129)	TPR	Kumar et al., 2023
Bhalum-1	Plant height, The highest increase in shoot dry matter accumulation from 30 to 90 DAS	DSR	Shahane and Behera, 2022
R-1033-968-2-1 and Kakro	Early seed vigour, tall height, high yield potential and good competitive ability	DSR	Chaudhari et al., 2014
PR 12	Plant height – tall stature	DSR	Mahajan et al. 2014
IR 84899-B-183-CRA-19-1 and CR Dhan 40	Taller plants and higher LAI.	DSR	Kumar et al., 2016
Chongloiman and Kezie	Early canopy establishment, vigorous growth	DSR	Kikon and Gohain, 2018

The 'eco-friendly' production system used the rive cultivar GNV-1089 and compared a higher seed rate (25 kg ha^{-1}) with a standard seed rate of rice sown (20 kg ha^{-1}) as a method for weed suppression.

Other weed control methods used in the study design were the application of rice straw at two or three t ha^{-1} followed by (fb) hand weeding (HW) at 40 DAS and cono-weeder usage at 10, 20, 30 and 40 DAS; inter-cultivation (IC) with hand drawn hoe at 20 DAS fb HW twice at 25 and 50 DAS. The results proved that the total weed suppression and higher rice grain yields obtained by the higher seed rate treatments, combined with rice straw at two t h^{-1} + HW at 40 DAS, were comparable or better than the other treatments. Meti et al. (2021) concluded rice straw incorporation, integrated with hand weeding and mechanical weeding, as a viable technique for use in organic rice production systems.

Herbicide Tolerant (HT) cultivars

Herbicide-tolerant (HT) rice cultivars are tolerant of a specific herbicide or a group of herbicides to which rice is otherwise sensitive. The development of HT rice varieties in India targeted the selective control of difficult-to-control weeds, such as weedy rice.

The expectation was that HT cultivars would lead to reduced herbicide use regimes and much-increased weed control in the fields. Despite promising results, in India, HT rice was not introduced commercially until recently, largely due to community anxieties about the potential impact of genetically modified (GM) crops on human health and the environment. The resistance to the promotion and use of HT cultivars still prevails despite substantial scientific evidence demonstrating their safety (Yaduraju et al., 2021).

The herbicidal control of weedy rice continues to be a challenge because of the genetic and biochemical similarities between weedy rice to cultivated rice. The sequential application of the herbicide imazethapyr, at 100 g ha^{-1} early POST, at 14 DAS, followed by (fb) a second application (at 28 DAS) provided broad-spectrum weed control with the lowest density and biomass of all major weeds and higher grain yield of imazethapyr-tolerant HT rice under DSR ecosystem (Dubey et al., 2022).

Thus, HT rice could help in managing weedy rice in areas that are under threat from further infestations. While the limited amount of research that has been done demonstrates that HT varieties can be used effectively in DSR systems, there are various risks associated with the use of HT rice as gene flow may occur (Craig et al., 2014) via pollen and seed, resulting in contamination of nearby non-HT rice crops. Such an outcome may lead to the establishment of HT volunteer weedy rice in rice fields and nearby non-croplands, as hybridisation can occur between closely related congeners.

Strict adherence to HT rice stewardship guidelines, specifically developed for India, would be essential to manage the risks associated with HT rice when they are more broadly adopted in the country. The distribution of HT rice seeds without extensive training of farmers and field staff, as it is done now in India, runs the risk of severe HT weedy rice problems in future years. Ruzmi et al. (2021) recently highlighted that in Malaysia, the evolution and rapid spread of HT weedy rice has diminished the benefit and sustainability of the HT rice technology.

Two RobiNOweed® Basmati rice varieties, Pusa Basmati 1979 and Pusa Basmati 1985, the first non-genetically modified (non-GM) Basmati rice varieties tolerant to the herbicide imazethapyr, have been released recently by the Indian Agricultural Research Institute (ICAR-IARI) for cultivation in DSR systems in India (Figure 2). These new varieties are efficient water users and are expected to give increased yields with reduced CO_2 emissions (Grover et al., 2020; AgNews, 2024).

Figure 2 Field view of the PB 1121 herbicide tolerant (HT) near-isogenic lines (NILs) at (a) booting and (b) maturity (Source: Grover et al., 2020)

In addition to the imazethapyr-tolerant, non-GM varieties, two pioneering FullPage® HT rice hybrids (Sava 134 and Sava 127) have also been recently released in India for use in DSR. Engineered specifically for DSR, FullPage® HT rice hybrids are the product of a collaboration of *RiceTec* and *ADAMA*, integrating SmartRice® hybrid rice genetics, especially to optimise crop performance while reducing water usage (Adama, 2024).

New herbicides for Managing Rice Weeds

Different pre-emergence (PRE) herbicides (i.e., pendimethalin, oxadiazon, oxadiargyl, pretilachlor, pyrazosulfuron) and post-emergence (POST) herbicides (i.e., bispyribac-sodium, penoxsulam, fenoxaprop, azimsulfuron, metsulfuron, Bensulfuron, chlorimuron, ethoxysulfuron, triafamone, cyhalofop) are presently used in India in all rice growing areas. The results reported from different states and rice-growing areas reveal variable yield increases of rice under the herbicide regimes.

However, recent research is increasingly reporting good control of flushes of a broad spectrum of grasses, sedges and broad-leaf weeds (BLWs) that are problematic in most situations (Table 2). Some of the most effective herbicides, their combinations and application regimes for managing specific weeds in rice are summarised in Table 2 with citations.

PRE herbicides require optimum moisture conditions at the time of application, which is a significant limitation. However, if there are pre-monsoon showers during the short duration available for PRE, the only option available is to use POST herbicides to manage the diversity of weeds that may develop in a rice field. Reports indicate that the most effective POST treatments are when they are applied at the stage of 2-4 leaves on rice seedlings. At this stage, weeds are commonly reported to be also at their 2-3 leaf stages.

Table 2 New herbicides for managing weeds in rice established by different methods *

Herbicide	Rate g *a.i.* ha^{-1}	Time of application**	Observations on Weeds controlled	Reference	Location
Transplanted rice					
bensulfuron + pretilachlor *fb* triafamone + ethoxysulfuron	60 + 600 *fb* 60	PRE *fb* POST 25 DAT	Effective broad-spectrum weed control	Dhanapal et al., 2018	Bengaluru, Karnataka
penoxsulam + butachlor	820	0-7 DAT	Effective control of many grasses, sedges and BLWs	Yadav et al., 2019	Hisar, Haryana
penoxsulam + cyhalofop	135	15-20 DAT	Effective control of many grasses, sedges and BLWs	Yadav et al., 2018a;b	Karnal, Haryana
pretilachlor + pyrazosulfuron	615	0-5 DAT			
pretilachlor + pyrazosulfuron (pre-mix) *fb* bispyribac-sodium	600 + 15 *fb* 20	3 DAT *fb* 20 DAT	Effective control of major grass weed - *Echinochloa colona*	Bhagavathi et al., 2024	Selaiyur, Tamil Nadu
pretilachlor + bensulfuron (pre-mix) *fb* bispyribac-sodium	600 + 60 *fb* 20	3 DAT *fb* 20 DAT			

Herbicide	Rate g *a.i.* ha^{-1}	Time of application**	Observations on Weeds controlled	Reference	Location
pretilachlor + bensulfuron (pre-mix) *fb* bispyribac-sodium	660 *fb* 25	PRE 3 DAT *fb* POST 20 DAT	Effective control of all grasses, sedges and BLWs at all growth stages	Mohapatra et al., 2021	Sambalpur, Odisha
triafamone	40	PRE (0-3 DAT) or early POST	Effective control of many grasses, sedges and BLWs	Arthanari, 2023	Coimbatore, Tamil Nadu
triafamone + ethoxysulfuron (pre-mix)	60-67.5	early POST at 15 DAT	Effective control of many grasses, sedges and BLWs	Yadav et al., 2019	Karnal, Haryana
XR-848 benzyl ester + cyhalofop (pre-mix)	150	20 DAT	Effective control of many grasses, sedges and BLWs	Ramesha et al., 2022b	Raichur, Karnataka
Wet-seeded rice					
bispyribac-sodium + metamifop	70	15 DAS	Effective control of many sedges, grasses (*Isachne miliacea*) and BLWs	Raj and Syriac, 2016	Thiruvananthapuram, Kerala
bispyribac-sodium with fenoxaprop or cyhalofop (tank mix)	25 + 60 or 25, 80, 150	POST at 18 DAS, weeds at 3-4 leaf stage	*Leptochloa chinensis* and associated weeds. Fenoxaprop-p-ethyl and cyhalofop-butyl were ineffective in managing BLWs and sedges	Sekhar et al., 2020	Thiruvananthapuram, Kerala
cyhalofop+ penoxsulam (pre-mix)	150	20 DAS	Effective control of a broad spectrum of weeds and weed biomass	Menon, 2019	Thrissur, Kerala
triafamone + ethoxysulfuron (pre-mix)	67.5	12 DAS			
fenoxaprop + penoxsulam	60 + 26.7	20 DAS	Effective control of grasses, sedges and BLWs	Verma et al., 2023	Jabalpur, Madhya Pradesh
florpyrauxifen + cyhalofop	150 +125	15 DAS	Effective control of a broad range of grasses, sedges and BLWs	Mahapatra et al., 2023	Cuttack, Orissa
flucetosulfuron	25	10-12 DAS	Effective control of a broad range of weeds and reduced weed biomass	Arya and Syriac, 2018	Thiruvananthapuram, Kerala
triafamone + ethoxysulfuron	200	15 DAS	Controlled all major grasses, sedges and BLWs	Deivasigamani, 2016	Namakkal, Tami Nadu
Dry-seeded rice					
bensulfuron + pretilachlor (mix) *fb* azimsulfuron + metsulfuron + chlorimuron (mix)	500 *fb* 20 *fb* 4	PE *fb* PoE 25 DAS *fb* 45 DAS	Effective control of a broad range of weeds at various growth stages	Basu et al., 2021	Bapatla, Andhra Pradesh
bispyribac-sodium + carfentrazone	25+20	25 DAS	Significantly minimised weed density and biomass at different stages	Singh and Kumar, 2020	Fatehgarh Sahib, Punjab
bispyribac-sodium 25 g/ha + ethoxysulfuron	25+18	25 DAS			
bispyribac-sodium + 2,4-D sodium salt	30.0 + 814.5	PoE 18 DAS	Controlled weeds effectively throughout the crop growth period	Guru et al., 2020	Raipur, Chhattisgarh
bispyribac-sodium + metamifop	80 + 90	15 DAS	Reduction in the emergence of BLWs and reduction in the weed seed bank	Raj and Syriac, 2018	Thiruvananthapuram, Kerala
penoxsulam + cyhalofop-butyl	125 + 130	POST 15 DAS			
cyhalofop-butyl + penoxsulam	270	35 DAS	100% mortality of *E. glabrescens* and *L. chinensis*	Singh et al., 2019	Hissar, Haryana

Herbicide	Rate g *a.i.* ha^{-1}	Time of application**	Observations on Weeds controlled	Reference	Location
fenoxaprop-ethyl + chlorimuron + metsulfuron	60 +4	20DAS	Lower total weed biomass, except *Alternanthera triandra,* which recorded the highest biomass	Tiwari et al., 2020	Raipur, Chhattisgarh
oxadiargyl *fb* bispyribac- sodium	80 fb 25	3 DAS *fb* 25 DAS			
oxadiargyl *fb* metsulfuron + chlorimuron-ethyl	50 *fb* 2+2 *fb* 1 HW	1- 3 DAS *fb* 20 DAS *fb* 40 DAS	Both herbicide combinations gave good control of a broad spectrum of weeds	Yadav et al., 2018	Varanasi, Uttar Pradesh
pendimethalin *fb* azimsulfuron + bispyribac-sodium fb 1 HW	1000 fb17.5 +25 fb1 HW	1- 3 DAS fb 15 DAS fb 40 DAS			
oxadiargyl *fb* fenoxaprop-ethyl + ethoxysulfuron (mix)	90 *fb* 90+15	PE *fb* POST (NS)	Both treatments were effective in lowering the total weed biomass	Jaiswal and Duary, 2023	Sriniketan West Bengal
oxadiargyl *fb* penoxsulam + cyhalofop (pre-mix)	90 *fb* 180	PE *fb* POST (NS)			
oxadiargyl *fb* Bispyribac-sodium	100 *fb* 25	PE *fb* POST (NS)	Lowest density and biomass of BLW, grasses, sedges and total weeds	Koushik et al., 2024	Bhubaneswar , Odisha
pendimethalin fb florpyrauxifen-benzyl or halosulfuron-methyl	1000 fb 25 or 65.7	PRE 20 DAS	Pendimethalin controlled early weed flushes; florpyrauxifen controlled late-emerging weeds, including *Cyperus rotundus*	Gangireddy et al., 2019	Tirupati, Andhra Pradesh
pendimethalin + pyrazosulfuron	1150	PRE (after sowing on a moist field)	Pendimethalin controlled annual grasses and BLWs; pyrazosulfuron was effective against BLWs and sedges	Kaur et al., 2023	Ludhiana, Punjab
penoxsulam + cyhalofop (pre-mix)	135	POST 22 DAS	Effectively controlled the *Alternanthera sessilis*-dominated weed community	Chitale and Tiwari, 2021	Raipur, Chhattisgarh
pretilachlor *fb* azimsulfuron	450 *fb* 35	2-3 DAS *fb* 25 DAS	Lowest weed biomass with higher weed control efficiency	Kashid et al., 2019	Pune, Maharashtra
pretilachlor *fb* pyrazosulfuron + bispyribac-sodium	1250 *fb* 25-50	PRE *fb* 30 DAS	Lower biomass of weeds at 40 DAS and harvest	Patel et al., 2018	Navsari, Gujarat
pretilachlor *fb* penoxsulam + cyhalofop-butyl	600 *fb* 150	PRE *fb* POST (25 DAS)	Lowest overall weed density at harvest; Effective control of weeds including sedges - *Cyperus difformis* and *C. iria*	Puniya et al., 2023	Chatha, SKUAST-Jammu
pyrazosulfuron + pretilachlor (mix)	15+600	PRE 6 DAS	Increased broad-spectrum weed control (grasses, BLWs and sedges)	Choudhary and Dixit, 2018	Raipur (Chhattisgarh)
pyrazosulfuron ethyl *fb* bispyribac-sodium	20 g *fb* 25g	PRE *fb* 25 DAS	Good control of a broad spectrum of grasses, BLWs and sedges	Ramesha et al., 2017	Raichur, Karnataka
pyribenzoxim	60	POST 15 DAS	Lowest weed biomass	Soni et al., 2020	Jabalpur, Madhya Pradesh
XR-848 benzyl ester + penoxsulam (mix)	40.6	POST - 20 DAS	Superior control of BLWs and sedges. Penoxsulam effectively controlled grass weeds	Ramesha et al., 2022a	Raichur, Karnataka

* Chemical names of herbicides are given in Table 3; ** *fb*= followed by; DAS= days after sowing; DAT: days after transplanting; PRE = pre-emergence application; POST= post-emergence application (Most POST treatments are at 2-4 leaf stages of rice, around 15-18 DAS); BLWs - broad-leaved weeds; HW = Hand weeding; NS = not specified.

The application of several herbicides, either in combination or in sequence, is more useful than a single application in rice to effectively manage the broad spectrum of species encountered.

Herbicide Application Technologies

Spray Applications

Undertaking herbicide treatments with equipment that is unsuitable to achieve the coverage required has been a major problem in rice weed management in India. Most farmers use splatter-gun sprayers and knapsack sprayers equipped with single hollow cones for spraying rice fields. These do not cover the targeted weed populations adequately, which leads to sub-optimal performances. The incorrect use of equipment and inadequate water volumes for treatments have long been identified as major factors in the lower efficacy of herbicides in rice in several parts of India.

On the other hand, Improved herbicide treatments using tractor-operated multi-boom sprayers fitted with flat-fan nozzles have enhanced weed control by 93% in DSR and by 95 % in DSR-CT wheat, compared to standard farmer's practices (Hundal and Bhullar, 2023). The improvements that can be achieved simply by conducting the treatments correctly point to a vast scope for enhancing herbicide efficacy through the use of appropriate spray technologies.

Reviewing farmers' knowledge of herbicides and their adoption in rice production systems, Choudhary and Kumar (2023) recently highlighted the urgent need for policy interventions in this regard. Their view is to urgently implement, across the board, improved herbicide application training modules for rice farmers to increase rice production efficiently and sustainably.

A direct contact application (DCA) of broad-spectrum non-selective herbicides using a specially designed novel hand-held weed wiper device was developed and tested (Jose et al., 2020). It was highly energy efficient, less labour intensive, and eco-friendly compared to hand weeding, cutting of weedy rice ear heads or application of large quantities of herbicides using sprayers. This product is now marketed as 'KAU Weed Wiper' by M/s Raidco Ltd. for large-scale manufacturing and sale to farmers. The KAU Weed Wiper, developed by the Kerala Agricultural University (KAU) researchers, has become popular among the rice farming community in Kerala.

Drones and UAVs for herbicide applications

In India, labour costs account for about a third of the total rice production costs. Labour is used for hand weeding, monitoring of weed infestation extents and herbicide applications. However, labour is already scarce and costly as the agricultural labour workforce has decreased by 30.7 million (12% reduction). At the same time, labour wages have increased by 9.3% (Vaishnavi and Manisankar, 2022). A major trend in India that has been ongoing for several decades is the shifting of agricultural labour into non-agricultural sectors (Srivastava et al., 2020). This is an outcome of the reduction in farming profitability across all forms of agriculture.

Given the labour shortages, research on improving weed management in rice and other cropping systems has turned increasingly to Unmanned Aerial Vehicles (UAVs) and automation. UAVs, equipped with cameras and sensors, are well-suited for crop monitoring and pesticide spraying (Mogili and Deepak, 2018; CropLife International, 2020; Hafeez et al., 2022; Ozkan, 2024). UAVs can be used to deliver herbicides or other pesticides to inaccessible places, such as steep slopes and mountainous terrains where conventional spraying is not possible (Arthanari and Paul, 2022; Paul et al., 2023). Equipped with advanced sensors, they can provide real-time data to map weeds and precisely apply herbicides on targeted species during the growing season.

Conventionally, knapsack sprayers are the preferred method for herbicide application in rice fields. However, the shortage of trained labourers and the high risk of exposure to herbicides (and other pesticides) are major constraints. Moreover, spraying over large tracts of rice paddies with conventional sprayers involves time, energy, water, and toil for herbicide applicators. If successful, drones would offer an alternative technology for herbicide applications (Paul et al., 2023). However, there has so far been only limited research on the efficiency of herbicide treatments by drone applications (Figures 3 and 4).

Vijayakumar et al. (2022) recently reported on some initial drone herbicide application experiments at the Indian Institute of Rice Research (IIRI, Rajendranagar, Hyderabad). The findings were: (i) spraying herbicide from 2.5-3 m height above rice increased the drift hazard although it covered a large area (herbicide swath) in a single flight, (ii) lower height (preferably, 1.5 m above the crop) and still wind conditions (4 km h^{-1}) reduced the drift hazard in the field; (iii) flying the drone near the crop (1.5 m above the crop canopy), while reducing the spraying swath, increased the time and number of flights required to cover the same area of land.

Figure 3 Drones being tested for herbicide spraying. Note the spray tank underneath and the nozzles attached to the wings

Figure 4 A drone flying over a rice field (from Krishak Jagat, 2022)

Research by Paul et al. (2023) showed higher maximum net return, benefit: cost ratio, output energy and energy use efficiency with drone applications compared with knapsack applications in DSR. The reduced carrier water volume did not affect the herbicide efficacy. Martin et al. (2020) have already measured and demonstrated from the USA that such an effect is most likely because of increased droplet deposition that occurs on the abaxial surface of weed foliage from drone spraying compared with conventional spraying.

Drones research in the USA (Ozkan, 2024) has also shown that boom-spray applications with long booms may not become viable because of spray drifts (Figure 5). On the other hand, nozzles fitted on short booms that do not extend too far outside the rotors and produce relatively small droplets considerably reduce spray drift. However, drone research has shown that droplets in the fine or very fine categories are not useful because they are highly susceptible to spray drift without depositing on the target (CropLife International, 2020).

Figure 5 Unfavourable spray drift that can occur from a drone application with long booms (from Ozkan, 2024)

Considering the unique advantages of drone technologies in agriculture, in 2021, the Department of Agriculture & Farmers Welfare (India) produced Standard Operating Procedures (SOPs) with instructions for effective and safe operations and use of drones in pesticide and nutrient applications (Krishak Jagat, 2021). The SOPs were developed in consultation with all the stakeholders of this sector.

In India, the use of drones in agriculture is still in its early stages (Mogili and Deepak, 2018; Devi et al., 2020; Paul et al., 2023). However, there are visible efforts to accelerate smallholder farmers' access to this technology. Bayer (India) and Syngenta (India) are among the companies that have announced the initiation of commercial drone applications in agriculture (Krishak Jagat, 2022). However, herbicide applications in rice using drones are yet to be approved by the Indian government. Recently, India extended the interim approval for drone applications of already approved pesticides until April 2025 (Krishak Jagat, 2024).

The experiences from herbicide spraying using drones at the IIRR, Hyderabad, revealed the need for further research to standardise spray volumes and concentrations, as well as optimal conditions under which drone applications can be used for better weed management (Vijayakumar et al., 2022).

In our view, the use of drones offers the potential for targeted crop protection, contributing to improved crop productivity and sustainability in farming practices. However, there are still significant constraints to overcome in scaling up drone-based herbicide application technologies, especially in areas dominated by smallholder farmers. In addition to the fine-tuning of the technology, UAV-based herbicide applications would also require special licenses and specially trained operators with data analytics expertise. Furthermore, before the technologies can be widely promoted, there will have to be mandatory requirements and mechanisms for crop health and environmental safety monitoring and reporting. Research in rice production systems will need to urgently focus on such issues.

Mechanical Weed Management - Robotics and Automation

As reported by many research groups across India, labour shortages have led to higher costs for hand weeding, which are among the primary reasons for farmers abandoning rice cultivation. As an option of labour-saving and affordability for weed control in rice, the attention on mechanical weeding in India has been increasing. We find this trend as an important step in the right direction.

Saha et al. (2023) recently reported that the aggregate economic impact due to the adoption of improved Ambika rice weeder by rice farmers in Chhattisgarh alone was about INR 69,650 million (INR 6965 crores) as per 2011-12 prices for the period 2012-13 to 2019-20. Other detailed reviews on improved mechanical weed management tools and techniques and their use in a variety of agroecosystems also show significant benefits. Kumar et al. (2022) and Chethan et al. (2024, in this Issue) have covered the topic comprehensively providing details of the progress in research on mechanical weed management in India.

In developed countries, commercially available automated devices and machines are increasingly used to recognise weed populations in cropping fields and crop row patterns, as well as intra- and inter-row weed control performances. These devices have machine vision technology combined with computers and data processors, which enable highly efficient field monitoring performances (Fennimore et al., 2016). Such technologies may not be economically viable and technically feasible on a large scale in India due to the socio-economic conditions and limitations of farmers.

Other limiting factors for developing high levels of automation for mechanical weeding equipment and machines include the geography of the terrain, the locations and the high degree of variations in the weed flora across smallholding farms and crops in India. Nevertheless, as discussed by Chandel et al. (2018, 2021) and Kumar et al. (2019, 2020, 2022), significant efforts have been made in India to develop intra-row weeder prototypes that integrate electronic control systems for managing weeds in several cropping systems. Whether the new machine vision technologies can be integrated with mechanical weeders for applications in rice remains a research question still to be investigated.

There are a few remotely-controlled and sensor-integrated robotic weeders, which are still under intense research and development, such as the Mizunigol® robotic weeder for rice in Japan. In 2017, a Swiss Company, ECO Process & Solutions, developed the MoonDino® robot to autonomously perform weeding in rice paddies. The robot was officially launched in 2021 and is now commercially available at a price of US $ 53,000 and has already been in practical use in developed countries, such as Japan and the USA (Figure 5).

Figure 6 MoonDino Robotic weeder can be used for mechanical weeding immediately after sowing on dry and submerged land, with GPS-guided precision

Central to the MoonDino design are the dual functions of its wheels, which are uniquely shaped to perform weeding operations effectively. The wheels allow the MoonDino to move across the paddy fields with ease, targeting weeds without disrupting the growth of rice plants. This capability is especially beneficial immediately after sowing, where traditional hand weeding can harm the developing rice seedlings. By automating the weeding processes, the robot significantly reduces the need for manual labour, allowing farmers to allocate their resources more efficiently (Future Farming, 2020).

However, the suitability of robotic weeders to different topography and geographical conditions is still a researchable issue. In India, as of today, no work has been conducted related to autonomous weed management or sensor-based robotic weeders for adoption in rice. Research and development in this aspect will be a future game changer for rice cultivation in India. (C. R. Chethan, ICAR-DWR, Jabalpur, 18 June, pers. comm.).

Climate Change and Implications

Climate change is likely to result in global range expansions of many weed species (migration or introduction into new areas) and also cause changes in their life cycles as species evolve. Weed migrations to new areas may result in significant changes in the structure and composition of weed communities in natural and managed ecosystems (Ramesh et al., 2017). Monitoring the likely changes in weed communities and assessing whether climate change modifies the competitiveness of weeds in rice needs to continue in all states of India. Our review finds that, thus far, apart from the increasing weedy rice infestations and the encroachment of several new semi-aquatic species, including *Phalaris minor* and sessile joyweed (*Alternanthera sessilis*), the weed flora changes reported in India (AICRP-WM, 2021; 2022;2023) are not profound.

However, monitoring those changes in rice weed floras in different cultivation areas and regions is one of the most effective strategies to reduce the spread of new weeds and manage them effectively by taking rapid response early actions. Our view is that novel herbicides are among the best solutions to become an integrated component of arresting the spread of potentially problematic species early.

Species distribution models (SDMs) are the most commonly utilised tool for investigating the effects of climate change on weed distribution. Modelling has highlighted that under future climatic scenarios, the possible expansion of horse purslane (*Trianthema portulacastrum* L.) and goat weed (*Ageratum conyzoides* L.), both of which are widely distributed terrestrial weeds, abundantly found in DSR systems (Singh et al., 2024).

The elevated CO_2 and temperature and their interactions will certainly exert an influence on weed growth and competition against crops, which ultimately influence crop yield losses in futuristic climate change scenarios (Rao and Korres, 2024). In one recent study, reported as the first study of climate change effects on rice yields, conducted at the ICAR Directorate of Weed Research (ICAR-DWR) in Jabalpur, Madya Pradesh, Pawar et al., 2022) demonstrated how weed interference severely impaired rice yields under elevated CO_2 (eCO2) and higher temperature (ET). In the study, eCO_2 (ambient 550 ppm compared with 550±50 ppm CO_2) increased the yields of rice grown weed-free. However, ET (ambient ± 2^0C) had a deleterious effect on yields. Under the combined effect of eCO_2 and ET, the adverse effect of ET was negated.

In this important study, rice was grown in competition with a broad-leaf species - smooth joyweed (*Alternanthera paronychioides* A. St.-Hil.) and a grass *Leptochloa chinensis*. The competition with smooth joyweed resulted in a rice yield reduction of 79.7% (ambient CO_2), 83% (under eCO_2), 63% (under ET) and 62% (under eCO_2+ET). It was evident that the two climate variables had a much more profound growth stimulatory effect on the broad-leaf species than on the grass.

With *L. chinensis*, rice yield reductions were 28% (ambient CO_2), 37% (under eCO_2), 52.4% (under ET) and 51% (under eCO_2+ET). The study proved that different weed species and rice would respond differently to the changes in key climate parameters (Pawar et al., 2022).

Conclusions

As reviewed in our essay, rice production systems in India are undergoing many changes that require continuous study and adaptation responses. Even before the effects of eCO_2 are felt, the changes in rainfall patterns and temperature regimes are likely to modify the rice weed communities and farmers' responses and how they address weed problems in their fields. Affordability, sustainability, and environmental concerns regarding herbicides and mechanical weed management necessitate the need for location-specific, 'needs-based' and climate-resilient weed management technologies for rice cultivated under different establishment methods in different states of India.

As we argued previously (Rao and Chandrasena, 2022), Climate-Resilient Integrated Weed Management (CRIWM) is based on the principles of ecological weed management (Rao and Korres, 2024). CRIWM supports the use of diverse weed management techniques based on the weed flora encountered in the field, the associated bio-physical environment and the available and affordable resource base of the farmers.

CRIWM includes: (a) preventive measures (cultural) to curtail weed seed production, reducing the soil seed bank and weed seed dissemination; (b) soil solarisation and stale seedbed techniques to reduce weed seedling recruitment; (c) application of components of conservation agriculture (i.e., minimal tillage, mulching with crop residues, crop rotations and weed suppressive cover crops, rotated with rice), (d) competitive rice varieties, (e) improved methods of rice establishment, such as DSR and (f) the use of biological control agents, where possible. Other complementary methods would be the incorporation of appropriate herbicides and their combinations, as well as mechanical weed management techniques, applied correctly to maximise weed control benefits.

In addition to the above, the incorporation of artificial intelligence (AI), machine learning, automated 'smart' machinery, robotics and drones for the detection and mapping of weeds and monitoring of crop health, as well as herbicide applications, are all positive developments that would contribute to 'site-specific' and 'needs-based' rice weed management.

As shown in our review, a great deal of research effort has been directed in India at improving rice production systems, including DSR and improved herbicide regimes and their effective applications for rice. Research on mechanical weed management and efforts at automation are also intense. These research and development efforts will undoubtedly contribute to increased rice production in the short-to-medium term and eventually, help in meeting the rice productivity challenge that the country is facing.

We conclude with the observation that one of the greatest challenges that agriculture in India faces is to motivate and train the next generation of agriculture, science and engineering graduates, as well as weed scientists, to undertake inter-disciplinary weed management research.

We recommend a much stronger emphasis than we can presently discern from our review of digital technologies involving AI and machine learning. These have to be the basis of 'futuristic', effective and economically viable CRIWM strategies for rice. We also contend that such novel and 'smart' computer science-driven technologies are particularly attractive to the 'next generation' of weed scientists and may contribute to their improved participation in the agriculture sector.

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Table 3 Common and chemical names of herbicides used in this paper

Common name	Chemical name
2,4_D Sodium salt	*(2,4-dichlorophenoxy)acetic acid*
azimsulfuron	*N-[[(4,6-dimethoxy-2-pyrimidinyl)amino]carbonyl]-1-methyl-4-(2-methyl-2H-tetrazol-5-yl)-1H-pyrazole-5-sulfonamide*
bensulfuron-methyl	*2-[[[[[(4,6-dimethoxy-2-pyrimidinyl)amino]carbonyl]amino]sulfonyl]methyl]benzoic acid*
bispyribac-sodium	*2,6-bis[(4,6-dimethoxy-2-pyrimidinyl)oxy]benzoic acid*
butachlor	*N-(butoxymethyl)-2-chloro-N-(2,6-diethylphenyl)acetamide*
chlorimuron-ethyl	2-[[[[(4-chloro-6-methoxy-2-pyrimidinyl)amino]carbonyl]amino]sulfonyl]benzoic acid
cyhalofop-butyl	(R)-2-[4-(4-cyano-2-fluorophenoxy)phenoxy]propanoic acid
ethoxysulfuron	2-ethoxyphenyl [[(4,6-dimethoxy-2-pyrimidinyl)amino]carbonyl]sulfamate
fenoxaprop-p-ethyl	(6)-2-[4-[(6-chloro-2-benzoxazolyl)oxy]phenoxy]propanoic acid
florpyrauxifen-benzyl	4-amino-3-chloro-6-(4-chloro-2-fluoro-3-methoxyphenyl)-5-fluoropyridine-2-carboxylic acid
flucetosulfuron	1-[3-[[[[(4,6-dimethoxy-2-pyrimidinyl)amino]carbonyl]amino]sulfonyl]-2-pyridinyl]-2-fluoropropyl methoxy acetate
halosulfuron-methyl	3-chloro-5-[[[[(4,6-dimethoxy-2-pyrimidinyl)amino]carbonyl]amino]sulfonyl]-1-methyl-1H-pyrazole-4-carboxylic acid
methbenzthiazuron	1-(1,3-benzothiazol-2-yl)1,3- dimethylurea.
metamifop	*(2R)-2-[4-[(6-chloro-2-benzoxazolyl)oxy]phenoxy]-N-(2-fluorophenyl)-N-methylpropanamide*
metoxuron	*N*'-(3-chloro-4-methoxyphenyl)-*N*,*N*-dimethyl urea
metribuzin	4-amino-6-(1,1-dimethylethyl)-3-(methylthio)-1,2,4-triazin-5(4H)-one
metsulfuron-methyl	2-[[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino]carbonyl]amino]sulfonyl]benzoic acid
oxadiargyl	*3-[2,4-dichloro-5-(2-propynyloxy)phenyl]-5-(1,1-dimethylethyl)-1,3,4-oxadiazol-2(3H)-one*
pendimethalin	*N*-(1-ethylpropyl)-3,4-dimethyl-2,6-dinitrobenzenamine
penoxsulam	*2-(2,2-difluoroethoxy)-N-(5,8-dimethoxy[1,2,4]triazolo[1,5-c]pyrimidin-2-yl)-6-(trifluoromethyl)benzenesulfonamide*
pinoxadem	8-(2,6-diethyl-4-methylphenyl)-1,2,4,5-tetrahydro-7-oxo-7H-pyrazolo[1,2-d][1,4,5] oxadiazepin-9-yl 2,2-dimethylpropanoate
pretilachlor	2-chloro-N-(2,6-diethylphenyl)-N-(2-propoxyethyl)acetamide
pyrazosulfuron ethyl	*5-[[[[(4,6-dimethoxy-2-pyrimidinyl)amino]carbonyl]amino]sulfonyl]-1-methyl-1H-pyrazole-4-carboxylic acid*
pyribenzoxim	diphenylmethanone O-[2,6-bis[(4,6-dimethoxy-2-pyrimidinyl)oxy]benzoyl]oxime
pyroxasulfone	3-[[5-(difluoromethoxy)-1-methyl-3-(trifluoromethyl)pyrazol-4-yl]methylsulfonyl]-5,5-dimethyl-4H-1,2-oxazole
sulfosulfuron	*N*-[[(4,6-dimethoxy-2-pyrimidinyl)amino] carbonyl]-2-(ethyl sulfonyl) imidazol [1,2-a]pyridine-3-sulfonamide
triafamone	2-((4,6-dimethoxy-1,3,5-triazin-2-yl)carbonyl)-1,1,6'-trifluoro-N-methylmethanesulfonanilide