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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).

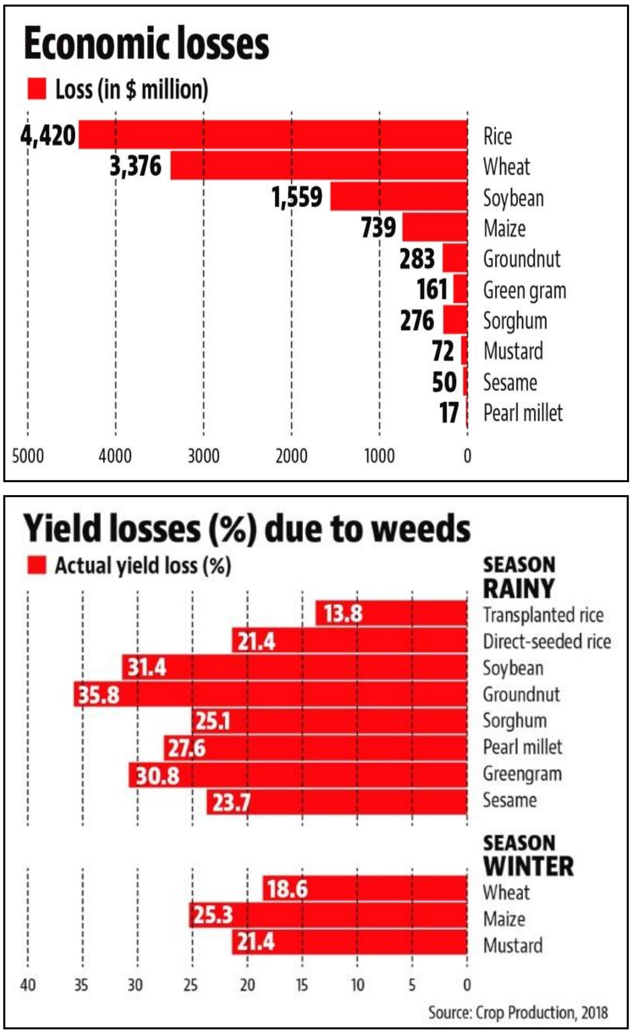

Figure 1 Losses caused by weeds significantly vary with the crop, growing season and location in India (Source: Gharde et al. 2018)

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	Thiruvananth apuram, 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	Thiruvananth apuram, 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	Thiruvananth apuram, 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	Thiruvananth apuram, 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

PERSPECTIVE

Weed Biological Control Status and Options for Sri Lanka

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Abstract

Invasive alien plants can cause significant losses in production and biodiversity, and due to the high costs of conventional control, biological control is often the only feasible long-term option for their management. Weed biological control was first attempted in Sri Lanka in 1865, with the introduction of *Dactylopius ceylonicus* to control prickly pear (*Opuntia monacantha*). Since then, 10 more biological control agents have been introduced into Sri Lanka to control an additional six weed species. Field surveys were conducted to record invasive weeds in Sri Lanka that had been targets for biological control in other countries to identify possible biological control options for Sri Lanka.

Over 70 sites were surveyed, covering eight of the nine provinces. Nineteen weed species that are considered invasive and the target of biological control elsewhere were sighted. Biological control attempts have been initiated in Sri Lanka against six of these species: Chromolaena (*Chromolaena odorata*), water hyacinth (*Pontederia crassipes*), two types of prickly pear (*Opuntia monacantha*, and *Opuntia stricta*), parthenium weed (*Parthenium hysterophorus*) and salvinia (*Salvinia molesta*), with mixed success. Introduced biological control agents were not found in all areas where their target weed species were sighted. Therefore, the re-distribution of some of these agents, as well as the introduction of additional biological control agents for chromolaena, lantana (*Lantana camara*) and parthenium weed, could be reconsidered, given the priorities attached to these species.

During the surveys, four biological control agents that had not been deliberately introduced into Sri Lanka were found on lantana, and one agent was found on Noogoora burr (*Xanthium strumarium*), presumably having spread from India. However, as lantana is not considered under adequate control, the importation of several other biological control agents that have been released worldwide could be investigated. There are good biological control prospects for numerous other weed species also, including alligatorweed (*Alternanthera philoxeroides*), Madeira vine (*Anredera cordifolia*), air yam (*Dioscorea bulbifera*), mile-a-minute (*Mikania micrantha*), two types of giant sensitive plants (*Mimosa diplotricha* and *Mimosa pigra*), parrot's feather (*Myriophyllum aquaticum*) and water lettuce (*Pistia stratiotes*).

Keywords: *Chromolaena odorata*, *Lantana camara*, *Mikania micrantha*, *Parthenium hysterophorus*

Introduction

Invasive alien plants in Sri Lanka can cause significant losses in terms of production (up to 50%) and biodiversity, as well as affecting fishing, water quality and supply, and human health (Gunasekera, 2009; Rajapakse *et al.*., 2012; Amarasinghe and Labrada, 2013; Ministry of Health, 2017). Controlling such weeds can be problematic.

Herbicides can be expensive and require repeated use if infestations are to be controlled effectively (Doeleman, 1989; Culliney, 2005). For instance, in coconut plantations, 20% of production costs are due to weed management (Senarathne *et al.*., 2003). Herbicides can also affect other species as well as have negative impacts on human health and the environment (Day *et al.*., 2012; Elledge *et al.*, 2014). Mechanical or manual control by physical removal can be labour-intensive. In addition, not all plant parts necessarily are killed, and due to the rapid regeneration of some weeds, populations can quickly return to high levels (Day *et al.*., 2012; Amarasinghe and Labrada, 2013).

Biological control is seen as an environmentally friendly, cost-effective and self-sustaining method to control many weeds (McFadyen, 1998; Culliney, 2005; van Wilgen and De Lange, 2011; Schwarzländer et al., 2018; Winston et al., 2021). It has been practised in 91 countries, involving the deliberate release of over 500 species against over 200 weed species, of which over 100 weed species have been severely impacted by at least one biological control agent in at least one country (Winston et al., 2021). The degree of host specificity testing and the large number of countries in which some biological control agents have been released, with no unpredicted off-target impacts, reinforces the low risk that biological control offers many countries in the management of their weeds (McFadyen, 1998; Julien et al., 2007; Day and Winston, 2016; Schwarzländer et al., 2018; Hinz et al., 2019).

Biological control can be used in many agricultural areas and cropping systems, as well as in natural ecosystems where weeds are not always actively controlled (McFadyen, 1998; Culliney, 2005; Winston et al., 2021). The cost of introducing known, tried, and proven biological control agents can be less than the cost of one treatment of herbicide in an average plantation. In the United States, costs of non-biological control range from about US$90 per ha to US$21,000 per ha, depending on the weed and habitat (Thayer and Ramey, 1986).

Biological control of weeds in Sri Lanka began in 1865, with the introduction of *Dactylopius ceylonicus* (Green) (Hemiptera: Dactylopiidae) to control prickly pear [*Opuntia monacantha* (Willd.) Haw.] (Cactaceae). Since then, 10 more biological control agents have been deliberately introduced to control six weed species, with variable success (Winston et al., 2021). Black sage [*Cordia curassavica* (Jacq.) Roem. & Schult.] (Boraginaceae), two types of prickly pear (*O. monacantha*, *O. stricta* (Haw.) Haw.) and salvinia (*Salvinia molesta* D. S. Mitch.) (Salviniaceae) are all deemed under successful biological control in most parts of Sri Lanka. However, chromolaena [*Chromolaena odorata* (L.) R.M.King & H.Rob.] (Asteraceae) and water hyacinth (*Pontederia crassipes* Mart.) (Pontederiaceae) are not under adequate control, despite biological control agents being deliberately released and having established (Winston *et al.*., 2021).

In addition to those biological control agents deliberately released in Sri Lanka, three other biological control agents have been reported in Sri Lanka. These are *Lantanophaga pusillidactyla* (Walker) (Lepidoptera: Pterophoridae), *Ophiomyia lantanae* (Froggatt) (Diptera: Agromyzidae) and *Insignorthezia insignis* (Browne) (Hemiptera: Ortheziidae). These have all been used as biological control agents against lantana (*Lantana camara* L. *sens. lat.*) (Verbenaceae) elsewhere and spread naturally into Sri Lanka, possibly from India (Winston et al., 2021).

Despite the successes of weed biological control, both in Sri Lanka and elsewhere in the world, no biological control agent has been deliberately released in Sri Lanka since 2005 (Winston et al., 2021). However, numerous weed species that have been listed as major weeds in Sri Lanka, including several weed species that are included in a national priority list, e.g., Madeira vine [*Anredera cordifolia* (Ten.) Steenis] (Basellaceae), chromolaena, lantana and mile-a-minute (*Mikania micrantha* Kunth) (Asteraceae), (Gunasekera, 2009; Rajapakse *et al.*., 2012; Ranwala *et al.*., 2012; CABI, 2024), have been targeted for biological control in at least one other country (Winston et al., 2021). Effective biological control agents for these weed species could be introduced into Sri Lanka to help with the management of these weeds if appropriate.

Following discussions with several weed researchers in Sri Lanka, a field survey was conducted to determine the presence and distribution of weeds in the country, particularly those that are targets of biological control elsewhere and to determine if any biological control agents are present. This paper documents weeds present in Sri Lanka that have been targeted for biological control in other countries and lists possible host-specific and effective biological control agents used elsewhere, which could be introduced into Sri Lanka to help manage these species. There has been no attempt to determine weed impacts in Sri Lanka as these have been covered in other publications (e.g. Rajapakse et al., 2012; Ranwala et al., 2012) or to prioritise weed species, as this should be left to the appropriate authorities.

Materials and Methods

Literature searches and personal correspondence

Prior to undertaking the 2013 field survey in Sri Lanka, a literature search was conducted to determine what weed species known to be targets for biological control, either in Sri Lanka or in other countries, have already been recorded in Sri Lanka. Records of all known weed biological control attempts or biological control agents present in Sri Lanka were extracted from Julien and Griffiths (1998). Discussions through direct contact or via email with researchers in Sri Lanka were held to determine if additional biological control attempts have been conducted since Julien and Griffiths (1998). These preliminary investigations provided a basis for which weed species and their biological control agents were likely to be seen during the field surveys.

Field survey

A three-week field survey was conducted throughout much of Sri Lanka in June-July 2013. Sites were chosen based on the presence of visible infestations of weeds encountered in each district or region visited or when weed species, previously unrecorded during the survey, were sighted.

At each site, only weed species known to be targets for biological control in Sri Lanka or in other countries were recorded. For all target species encountered, any biological control agent that was present was also recorded. The location and altitude of each site were recorded using a hand-held global positioning system (GPS) unit.

Analysis

Weed species that have been targeted for biological control in other countries and sighted during the field surveys were added to the list of weed species recorded for Sri Lanka in the literature. New biological control agents not previously recorded in Sri Lanka were added to those listed in Julien and Griffiths (1998). Due to the time passed since the initial survey, the list was later updated using Winston et al. (2021). This gave a comprehensive list of weed species in Sri Lanka that have also been the target for weed biological control in other countries.

The list of known biological control agents deliberately introduced into Sri Lanka and their status and the list of known biological control agents that have been recorded present in Sri Lanka but not deliberately introduced, were updated with new information acquired.

From the known weeds present in Sri Lanka and biological control attempted elsewhere, a list outlining biological control agents that could be introduced into Sri Lanka if deemed appropriate was compiled. There was no attempt to prioritise which weed species should be studied, as this should be left to the appropriate organisations within Sri Lanka.

Results

A total of 71 sites, covering eight of the nine provinces in Sri Lanka, were sampled during the survey in 2013 (Figure 1). The Western Province was sampled the most times, with 17 sites sampled, while only one site in each of Sabaragamuwa and North Western Provinces was sampled. Only the Northern Province was not covered in the survey due to time constraints.

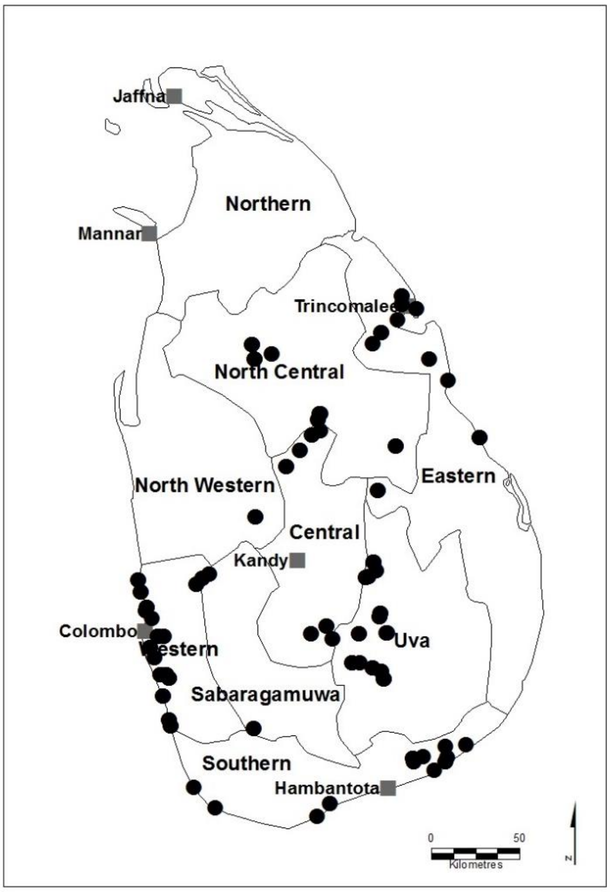


Figure 1 Sites in Sri Lanka that were surveyed in June-July 2013

Sites sampled ranged from 3 m above sea level (asl) in Eastern Province to 1902 m asl in Central Province and included sites in high rainfall areas around Nuwara Eliya Lake (average 1904 mm p.a.) in Central Province to drier regions around Hambantota (av. 1045 mm p.a.), Southern Province. Nineteen weed species that are known to be targets for biological control, either in Sri Lanka or in other countries (Winston et al., 2021), were seen during the survey (Table 1).

These included the three most important aquatic weeds in Sri Lanka, namely, water hyacinth, water lettuce and salvinia, which are also major weeds in many other Asian countries. Other major weed species that are biological control targets elsewhere and were found during the survey include chromolaena, lantana, mile-a-minute, two species of giant sensitive plants (*Mimosa* spp*.)* and parthenium weed. All are also widespread and problematic elsewhere in Asia.

Table 1 A list of weed species which have been targeted for biological control globally and were seen in Sri Lanka during the 2013 survey

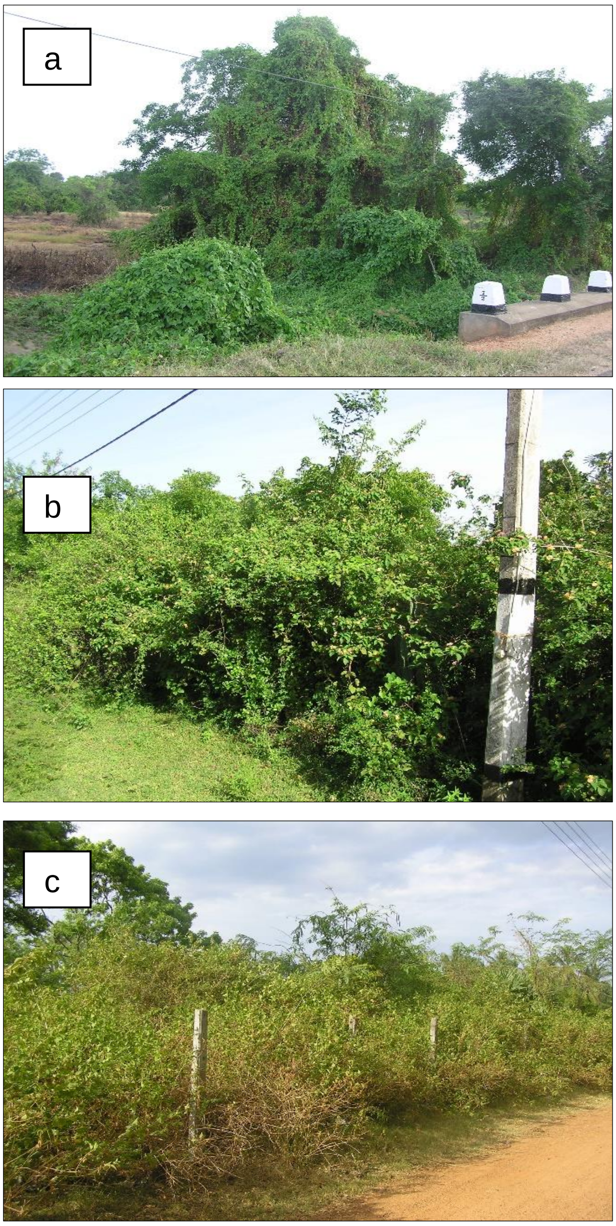
Family	Weed species	Common name	Habitat	Altitude where found (asl)
Amaranthaceae	*Alternanthera philoxeroides* (Mart.) Griseb.	alligator weed	aquatic	5-1900 m
Araceae	*Pistia stratiotes* L.	water lettuce	aquatic	5-175 m
Asteraceae	*Ageratina riparia* (Regel) R.M.King & H.Rob.	mistflower	riparian, cool, wet	600-1000 m
	**Chromolaena odorata* (L.) R.M.King & H.Rob.	chromolaena	grazing, roadsides	0-1000 m
	**Mikania micrantha* Kunth	mile-a-minute	farms, roadsides	0-1400 m
	**Parthenium hysterophorus* L.	parthenium weed	roadsides, fields	lowlands
	Xanthium strumarium L.	Noogoora burr	grazing, roadsides	600-700 m
Basellaceae	**Anredera cordifolia* (Ten.) Steenis	Madeira vine	riparian	~1300 m
Cactaceae	*Opuntia monacantha* (Willd.) Haw.	prickly pear	wastelands	5-277 m
	Opuntia stricta (Haw.) Haw.	prickly pear	wastelands	lowlands
Euphorbiaceae	*Jatropha gossypiifolia* L.	bellyache bush	wastelands	lowlands
Fabaceae	*Mimosa diplotricha* C. Wright	giant sensitive plant	grazing, roadsides	0-500 m
	**Mimosa pigra* L.	giant sensitive plant	grazing, roadsides	11-130 m
Haloragaceae	*Myriophyllum aquaticum* (Vell.) Verdc.	parrot’s feather	aquatic	600-1900 m
Malvaceae	*Sida acuta* Burm.f.	spinyhead sida	grazing, roadsides	0-400 m
Melastomataceae	*Miconia crenata* (Vahl) Michelang.	Koster’s curse	roadsides, higher altitudes	600-800 m
Pontederiaceae	**Pontederia crassipes* Mart.	water hyacinth	aquatic	5-1900 m
Salviniaceae	**Salvinia molesta* D.S.Mitch.	salvinia	aquatic	0-100 m
Verbenaceae	**Lantana camara* L.	lantana	grazing, natural forests	0-1800 m

* Weeds of National Significance in Sri Lanka (Rajapakse *et al.*., 2012)

The most widespread and most frequently found weed was mile-a-minute, which was found in all eight provinces covered in the survey and 63% of all sites sampled. Lantana was also found at 63% of all sites sampled but was only found in seven of the eight provinces surveyed. Chromolaena (52% of sites surveyed, seven provinces), spinyhead sida, *Sida acuta* Burm.f. (Malvaceae) (31%, six provinces) and water hyacinth (30%, six provinces) were also commonly found and widespread in Sri Lanka. Over

50% of the weed species found during the surveys were found at fewer than 10 sites each.

Of the weed species seen in the survey, six species have had biological control agents deliberately released against them in Sri Lanka. However, only three biological control agents that had been deliberately released, out of the eight that have reportedly been established, were found during the survey. These were *Cyrtobagous salviniae* Calder & Sands (Coleoptera: Curculionidae) on *S. molesta*, *D. ceylonicus* on *O. monacantha* and *Neochetina eichhorniae* Warner (Coleoptera: Curculionidae) on *P. crassipes*.



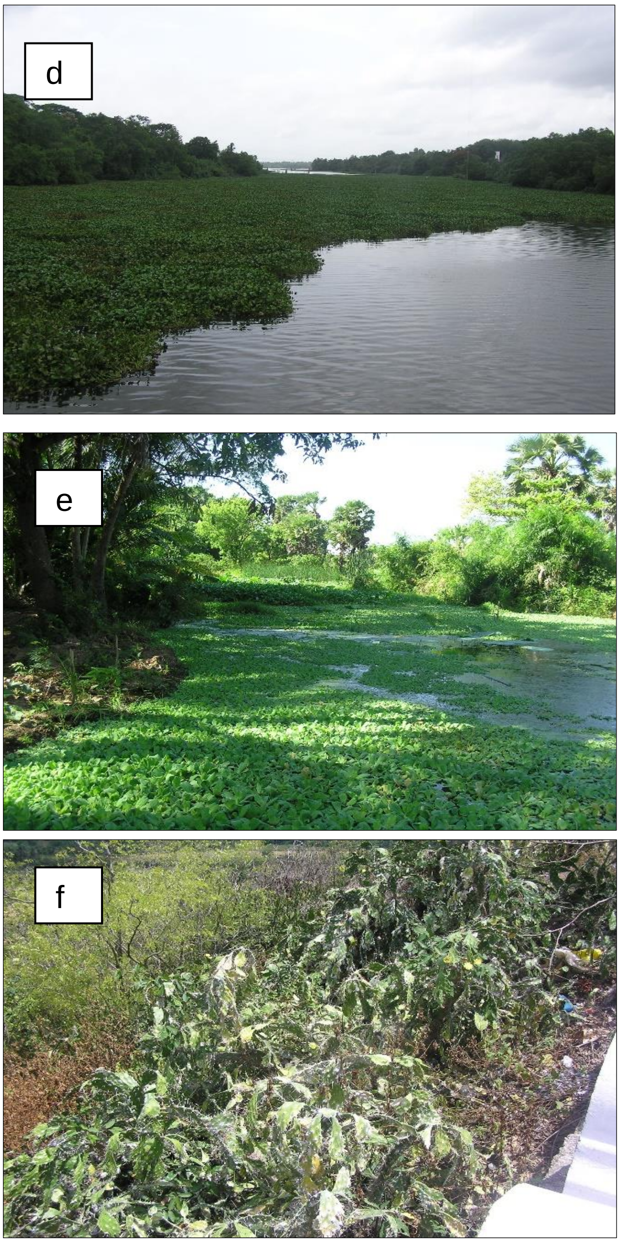


Figure 2. Various weed infestations in Sri Lanka: *M. micrantha* (a), *L. camara* (b), *C. odorata* (c), *P. crassipes* (d), *P. stratiotes* (e), *O. monacantha* damaged by *D. ceylonicus* (f).

A further eight biological control agents, which were not intentionally released into Sri Lanka, were found during the survey, possibly having spread from India or brought in on imported plants. Five of these agents were new records for Sri Lanka: *Calycomyza lantanae* (Frick) (Diptera: Agromyzidae), *Crocidosema lantana* Busck (Lepidoptera: Tortricidae), *Passalora lantanae* (Chupp) U. Braun & Crous var. *lantanae* (Capnodiales: Mycosphaerella-ceae) and *Teleonemia scrupulosa* Stål (Hemiptera: Tingidae) on *L. camara*, and *Puccinia xanthii* Schweinitz on Noogoora burr *Xanthium strumarium* L. (Asteraceae).

In total, 17 biological control agents attacking nine weed species are now reported to be present in Sri Lanka (Tables 2 and 3). These agents are reported to have minimal to high impact on their respective target weeds and provide control of some of their target weed species in some areas (Winston *et al.*., 2021).

Table 2. Weed biological control agents (and their status) that have been deliberately introduced into Sri Lanka[a] (Winston et al., 2021)

Family	Weed species	Biological control agent introduced	Year introduced	Status[a]	Impact[a]
Asteraceae	**Chromolaena odorata* (L.) R.M.King & H.Rob.	*Apion brunneonigrum* Béguin-Billecocq	1975	Not established	
		Pareuchaetes pseudoinsulata Rego Barros	1973	Established	Variable
	**Parthenium hysterophorus* L.	*Zygogramma bicolorata* Pallister	2004	Not established	
Boraginaceae	*Cordia curassavica* (Jacq.) Roem. & Schult.	*Eurytoma attiva* Burks	1978	Established	High
		Metrogaleruca obscura (Degeer)	1978	Established	High
Cactaceae	*Opuntia monacantha* (Willd.) Haw.	*Dactylopius ceylonicus* (Green)	1865	Established[b]	High
Cactaceae	*Opuntia stricta* (Haw.) Haw.	*Dactylopius opuntiae* (Cockerell)	1925	Established	High
Pontederiaceae	**Pontederia crassipes* Mart.	*Neochetina eichhorniae* Warner	1988	Established[b]	Slight-variable
		N. bruchi Hustache	2005	Established	Slight-variable
Salviniaceae	**Salvinia molesta* D.S.Mitch.	*Cyrtobagous salviniae* Calder & Sands	1986	Established[b]	Variable-high
		Paulinia acuminata (De Greer)	1973	Not established	

* Weeds of National Significance in Sri Lanka; [a] From Winston *et al.*. (2021); [b] Seen during the survey

A total of 40 weed species reported as being present in Sri Lanka have been targeted for biological control in at least one country (Gunasekera, 2009; Rajapakse et al., 2012; Ranwala et al., 2012; CABI, 2024; Winston et al., 2021). Nine of these species are listed as weeds of national significance for Sri Lanka (Rajapakse *et al.*., 2012).

Of the 40 weed species that are present in Sri Lanka and have been targeted for biological control elsewhere, 19 species have highly effective biological control agents that are helping manage their respective weeds in other countries (Table 4). A further 21 weed species have biological control agents that cause only slight damage to their respective weed, or the impacts of the agent have not yet been assessed (Table 5).

Discussion

Eleven biological control agents targeting seven weed species have been deliberately introduced into Sri Lanka. Eight biological control agents have established from these introductions, with *Z. bicolorata* later establishing, following its natural spread from India, some 15 years later. In addition to *Z. bicolorata*, another eight biological control agents have spread naturally into Sri Lanka.

Thus, 17 biological control agents are now established in Sri Lanka, attacking nine weed species (Winston et al., 2021). Of the nine weeds that have biological control agents established in Sri Lanka, four weeds, namely black sage, two types of prickly pear and salvinia, are deemed under successful biological control in most parts of the country where their respective agents have established (Winston et al., 2021).

Table 3 Biological control agents that had naturally spread into Sri Lanka (Winston *et al.*., 2021)

Family	Weed species	Biological control agent	Guild	Impact
Asteraceae	*Parthenium hysterophorus* L.	*Zygogramma bicolorata* Pallister	leaf-feeding beetle	Unknown
Asteraceae	*Xanthium strumarium* L.	*Puccinia xanthii*[a] Schweinitz	rust pathogen	Slight
Verbenaceae	**Lantana camara* L.	*Calycomyza lantanae*[a] (Frick)	leaf-mining fly	Slight
		Crocidosema lantana[a] Busck	peduncle-boring moth	None
		Lantanophaga pusillidactyla (Walker)	flower-feeding moth	Moderate
		Ophiomyia lantanae (Froggatt)	fruit-feeding fly	Unknown
		Insignorthezia insignis (Browne)	stem sap-sucking bug	High
		Passalora lantanae (Chupp) U. Braun & Crous var. *lantanae*[a]	leaf pathogen	Slight
		Teleonemia scrupulosa[a] Stål	leaf sap-sucking bug	Slight

* Weeds of National Significance in Sri Lanka; [a] observed and reported in Sri Lanka for the first time in 2013

Table 4 Host-specific and effective biological control agents established elsewhere that could be introduced into Sri Lanka to help control their target weed species (Winston *et al.*., 2021).

Family	Weed species	Common name	Proposed biological control agent	No. of countries established	Overall impact elsewhere[a]
Amaranthaceae	*Alternanthera philoxeroides* (Mart.) Griseb.	alligator weed	*Agasicles hygrophila* Selman & Vogt	4	High
Araceae	*Pistia stratiotes* L.	water lettuce	*Neohydronomus affinis* Hustache	17	High
Asteraceae	*Ageratina adenophora* (Spreng.) R.M.King & H.Rob.	Crofton weed	*Passalora ageratinae* Crous & A.R.Wood	8	Variable
	Ageratina riparia (Regel) R.M.King & H.Rob.	mistflower	*Entyloma ageratinae* Barreto & Evans	4	High
			Procecidochares alani Steyskal	3	Variable
	**Chromolaena odorata* (L.) R.M.King & H.Rob.	chromolaena	*Cecidochares connexa* Macquart	11	Mainly high
	**Mikania micrantha* Kunth	mile-a-minute	*Puccinia spegazzinii* De Toni	5	Too early to assess
	**Parthenium hysterophorus* L.	parthenium weed	*Carmenta ithacae* (Beutenmüller)	1	High
			Epiblema strenuana (Walker)	4	High
			Listronotus setosipennis (Hustache)	1	Variable
			Puccinia xanthii var. *parthii-hysterophorae*	2	Variable
	Xanthium strumarium L.	Noogoora burr	*Epiblema strenuana*	4	Slight
Basellaceae	**Anredera cordifolia* (Ten.) Steenis	Madeira vine	*Plectonycha correntina* Lacordaire	1	Too early to assess

Family	Weed species	Common name	Proposed biological control agent	No. of countries established	Overall impact elsewhere[a]
Bignoniaceae	*Dolichandra unguis-cati* (L.) L. G. Lohmann	cat's claw creeper	*Carvalhotingis visenda* Drake & Hambleton	2	Medium
			Hedwigiella jureceki (Obenberger)	1	Too early to assess
Cactaceae	*Opuntia monacantha* (Willd.) Haw.	prickly pear	*Cactoblastis cactorum* (Berg)	19	High
Cactaceae	*Opuntia stricta* (Haw.) Haw.	prickly pear	*Cactoblastis cactorum*	19	High
Dioscoreaceae	*Dioscorea bulbifera* L.	air potato	*Lilioceris cheni* Gressitt & Kimoto	1	High
Fabaceae	*Mimosa diplotricha* C. Wright	giant sensitive plant	*Heteropsylla spinulosa* Muddiman, Hodkinson & Hollis	15	High
Fabaceae	**Mimosa pigra* L.	giant sensitive plant	*Carmenta mimosa* Eichlin & Passoa	3	High
			Macaria pallidata (Warren)	1	Variable
			Malacorhinus irregularis Jacoby	1	Variable
			Neurostrota gunniella (Busck)	1	High
Haloragaceae	*Myriophyllum aquaticum* (Vell.) Verdc.	parrot's feather	*Lyathia* sp.	2	High
Malvaceae	*Sida acuta* Burm.f.	spinyhead sida	*Calligrapha pantherina* Stål	5	High
Melastomatace ae	*Miconia crenata* (Vahl) Michelang.	Koster's curse	*Liothrips urichi* Stål	4	Mainly high
Verbenaceae	**Lantana camara* L.	lantana	*Aceria lantanae* (Cook)	2	Variable
			Falconia intermedia (Distant)	2	Medium
			Octotoma scabripennis Stål	7	Medium
			Ophiomyia camarae Spencer	11	Medium
			Uroplata girardi Pic	24	Mainly high

* Weeds of National Significance (Rajapakse *et al.*., 2012); [a] Winston *et al.*. (2021)

For the remaining weeds, namely, chromolaena, lantana, water hyacinth, parthenium weed and Noogoora burr, that have biological control agents established, adequate control has not yet been achieved (Winston et al., 2021). Black sage and its two biological control agents were not seen during the survey, presumably as the weed is reported to be under control (Winston et al., 2021) and, therefore, in very low densities. *Dactylopius opuntiae* (Cockerell) (Hemiptera: Dactylopiidae) was not seen on prickly pear (*O stricta*) at the only site where its target was found. This species is also deemed under control by its agent (Winston *et al.*., 2021). *Dactylopius ceylonicus* was particularly damaging to its host, the second prickly pear species (*O. monacantha*), at all the sites where it was observed. Both these control agents could be easily moved to new areas where their respective hosts are present without the agents.

Two of the aquatic weed species, e.g. water hyacinth and salvinia, that were widespread also did not always contain their respective biological control agents. As the agents, *Neochetina bruchi* Hustache and *N. eichhorniae,* both introduced to control water hyacinth and *Cyrtobagous salviniae* introduced to control salvinia, are highly effective (Winston et al., 2021), efforts could be made to re-distribute-them to areas in Sri Lanka where they are not already present.

Table 5 Host-specific biological control agents that are causing slight damage to the target weed elsewhere and that could be introduced into Sri Lanka to help control their target weed species (Winston et al., 2021)

Family	Weed species	Common name	Proposed biological control agent	No. of countries established	Overall impact elsewhere[a]
Bignoniaceae	*Spathodea campanulata* P.Beauv.	African tulip tree	*Colomerus spathodeae* (Carmona)	2	Too early
Cabombaceae	*Cabomba caroliniana* A.Gray	cabomba	*Hydrotimetes natans* Kolbe	1	Too early
Cyperaceae	**Cyperus rotundus* L.	nut grass	*Antonina australis* Froggatt	1	Slight
			Athesapeuta cyperi Marshall	3	Slight
			Bactra venosana (Zeller)	4	Slight
			Bactra verutana Zeller	1	High
Euphorbiaceae	*Jatropha gossypiifolia* L.	bellyache bush	*Stomphastis thraustica* Meyrick	1	Too early
Fabaceae	*Acacia dealbata* Link	silver wattle	*Melanterius maculatus* Lea	1	Medium
	Acacia decurrens Willd.	green wattle	*Melanterius maculatus* Lea	1	Medium
	Acacia longifolia (Andrews) Willd.	Sydney golden wattle	*Melanterius ventralis* Lea	1	Medium
			Trichilogaster acaciaelongifoliae (Froggatt)	2	Medium
	Acacia mearnsii De Wild.	black wattle	*Melanterius maculatus* Lea	1	Medium
	Acacia melanoxylon R.Br.	Australian blackwood	*Melanterius acaciae* Lea	1	Medium
	Caesalpinia decapetala (Roth) Alston	Mauritius thorn	*Sulcobruchus subsuturalis* (Pic)	1	Slight
	Leucaena leucocephala (Lam.) de Wit	leucaena	*Acanthoscelides macrophthalmus* (Schaeffer)	23	Slight
	Parkinsonia aculeata L.	parkinsonia	*Eueupithecia* spp.	1	Slight
			Penthobruchus germaini (Pic)	1	Slight
	Prosopis juliflora (Sw.) DC.	mesquite	*Algarobius prosopis* (Le Conte)	10	Slight
			Evippe sp. #1	1	Variable
			Neltumius arizonensis (Schaeffer)	4	Slight
	Ulex europaeus L.	gorse	*Agonopterix umbellana* (Fabricius)	3	Slight
			Exapion ulicis (Forster)	4	Slight

Family	Weed species	Common name	Proposed biological control agent	No. of countries established	Overall impact elsewherea
Fabaceae	*Ulex europaeus* L.	gorse	*Sericothrips staphylinus* Haliday	3	Slight
			Tetranychus lintearius Dufour	5	Slight-medium
	Vachellia nilotica subsp. *indica* (Benth.) Kyal. & Boatwr.	prickly acacia	*Acaciothrips ebneri* (Karny)	1	Too early
			Bruchidius sahlbergi Schilsky	1	Slight
			Chiasmia assimilis (Warren)	1	Variable
Hydrocharitaceae	*Egeria densa* Planch.	Brazilian waterweed	*Hydrellia egeriae* Rodrigues-Junior	1	Too early
	Hydrilla verticillata (L.f.) Royle	hydrilla	*Hydrellia pakistanae* Deonier	1	Variable
Melastomataceae	*Miconia calvescens* DC.	miconia	*Colletotrichum gloeosporioides* (Penz.) Penz. & Sacc. f. sp. *miconiae* Killgore & L.Sugiyama	3	Slight-variable
Passifloraceae	*Passiflora tarminiana* Coppens & V.E.Barney	banana poka	*Septoria passiflorae* Sydenham	1	Variable
Poaceae	*Arundo donax* L.	giant reed	*Rhizaspidiotus donacis* (Leonardi)	2	Medium
			Tetramesa romana (Walker)	3	Medium
Pontederiaceae	**Pontederia crassipes* Mart.	water hyacinth	*Eccritotarsus catarinensis* (Carvalho)	1	Variable
			Megamelus scutellaris Berg	2	Medium-variable
			Niphograpta albiguttalis (Warren)	7	Mainly slight
			Orthogalumna terebrantis Wallwork	5	Slight-medium

* Weeds of National Significance (Rajapakse *et al.*., 2012); Winston *et al.*. (2021)

For other weed species, e.g., chromolaena, lantana and parthenium weed, only some of their respective biological control agents are present in Sri Lanka. *Pareuchaetes pseudoinsulata* Rego Barros (Lepidoptera: Erebidae), a biological control agent for chromolaena, is often only seasonally abundant (Day et al., 2013a) and populations may have been low during the time of these surveys. This may be why it was not detected.

The gall fly *Cecidochares connexa* Macquart (Diptera: Tephritidae) is proving very effective at controlling chromolaena in many countries in the Pacific, Asia and Africa (Day *et al.*., 2013b; Day and Winston, 2016; Winston *et al.*., 2021). Several additional and effective biological control agents for lantana and parthenium weed could also potentially be introduced into Sri Lanka to help improve the control of these weeds (Day *et al.*., 2003; Dhileepan and McFadyen, 2012; Winston *et al.*., 2021).

Literature searches show that there are at least 140 invasive weed species reported in Sri Lanka, of which 40 have been targeted for biological control in at least one other country. Numerous biological control agents, considered to be host-specific and highly effective, i.e. having a moderate to high impact on their target weed elsewhere, have not been confirmed to be present in Sri Lanka. While some of the weeds in Sri Lanka that are not targets for biological control may be causing significant impacts on agriculture and the environment, there is merit in considering tried and proven biological control agents that have already been successfully utilised in other countries, even if the weed may not necessarily be the highest priority.

This is because all the native range surveys and host specificity testing have already been conducted elsewhere. Thus, it becomes a very cheap and effective way to help manage many weed species (Julien et al., 2007). However, prior to importing any biological control agent, it is worth conducting more detailed field surveys to determine the presence of some biological control agents, especially those that have been established in the region, such as in India.

A total of eight biological control agents, which were not deliberately introduced, have now been found in Sri Lanka (Winston et al., 2021). So, it is possible that other biological control agents established in India such as the chromolaena gall fly, may also be present but in low numbers and not detected in this study or by others.

Biological control of weeds offers a viable and cost-effective solution to managing many of Sri Lanka's worst weeds (Doeleman, 1989; Room and Fernando, 1992; McFadyen, 2008). Conventional control methods such as the use of herbicides, slashing or fire are not feasible in all areas where the weeds occur. Nor are these methods sustainable due to large areas affected or the large and prolonged seed banks (Culliney, 2005).

Fire cannot be used around plantations and crops due to possible damage to existing trees. The use of herbicides around crops is also risky due to the possible damage to crops and fruit and the health risks to farmers. Herbicides are also expensive and require multiple treatments to be effective (Doeleman, 1989; Culliney, 2005). In general, herbicides cannot feasibly be used in large areas. Slashing and manual control are time-consuming, and weeds can easily re-shoot from broken fragments and rootstocks (McFadyen, 1998; Day et al., 2012; Amarasinghe and Labrada, 2013).

The results of one of the few weed biological control projects undertaken by Sri Lanka, i.e. the introduction of *Cyrtobagous salviniae* from Australia for the management of salvinia during the 1980s, is testimony to how Sri Lanka has already benefitted from this transfer of technology (Room and Fernando, 1992). The cost of this transfer of technology is minimal in comparison to the huge costs that have been incurred by other countries for testing agents for their specificity or on-going conventional control.

The return on investment in the biological control of salvinia in Sri Lanka was estimated at 53:1 in cash and over 1600:1 in terms of labour costs (Doeleman, 1989). Apart from the high financial benefits, Doeleman (1989) also highlights how successful biological control of salvinia opens up new prospects for other weeds where chemical control is not feasible.

When considering the introduction of new biological control agents into Sri Lanka, it might be prudent to check what plant species were included in previous host specificity testing conducted elsewhere. This is because host specificity testing conducted in one country may not include particular species important to other countries. For example, *Neochetina bruchi* has been tested against over 250 plant species in 10 different countries, with each country testing plant species of particular economic or cultural importance to their own country (Julien *et al.*., 1999).

In another example, the rust *Puccinia spegazzinii* De Toni (Pucciniaceae) was tested against 130 plant species prior to its release against mile-a-minute in India (Ellison *et al.*., 2008; Kumar *et al.*., 2016). It was then tested against another 58 species prior to its introduction into China (Fu *et al.*., 2006), 104 species in Taiwan (S. S. Tzean, unpublished data) and another 11 species prior to its introduction into Papua New Guinea and Fiji (Day *et al.*., 2013c), as the original testing did not include plants important to those countries.

Including the studies conducted in Australia, where numerous other species were tested, 287 plant species have now been tested for susceptibility to the rust (Day and Riding, 2019), and the agent has been deliberately released into nine countries and has established in six of those (Winston et al., 2021).

Overall, there are many opportunities to improve the management of weeds in Sri Lanka using biological control (Tables 4 and 5). This paper lists some of the host-specific and most damaging biological control agents that have been utilised elsewhere, and that could be used in Sri Lanka if considered appropriate. A wealth of information is already available on biological control agents that have been tested for their specificity by countries such as Australia (Julien *et al.*., 2012) and South Africa (Moran *et al.*., 2011) and released worldwide (Winston *et al.*., 2021). Due to the costs involved in host specificity testing, as these have to be conducted in appropriate quarantine facilities (Julien *et al.*., 2007), it is recommended that more emphasis is placed on the use of known, tested and effective biological control agents for the management of some of Sri Lanka's worst weeds. This paper deliberately has not prioritised weeds, as this is a decision that is best made by the relevant authorities in Sri Lanka.

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REVIEW

Opportunities for Improved Mechanical Weed Management in India

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Abstract

India is an agricultural country, with more than 40% of its population engaged in agriculture and allied sectors. About 62.9% of the people involved in agriculture-related activities are females, who perform the majority of the most arduous activities. Most of these operations are time-consuming drudgeries that require much energy. Weeds are one of the significant constraints in crop production in India and can cause up to 37% of yield losses. Timely weed management is essential to reduce crop-weed competition, especially during critical periods, to ensure the quantity and quality of the produce. In India, most farmers (more than 86%) are smallholders and farm on fragmented and marginal lands with low-cost production methods. Most still rely mainly on hand weeding with simple, traditional tools for weed management in all major crops.

Manual weeding is one of the most tedious and laborious jobs in agriculture. It has been estimated to consume up to 25% of the total labour requirement in agricultural production. The use of traditional tools still results in the loss of 10-15% of crop productivity in Indian agriculture. India has an estimated farm power availability of 3.045 kW/ha and weed management mechanization of around 32% across all crops. Our review finds that the adoption of mechanical weeders in India is greatly hindered by smaller land holdings, farmers' economic conditions, high initial cost of machines, high repair and maintenance costs, and non-availability of weeders and repair services at the village level. Other significant obstacles are inadequate awareness of advanced weed management technologies, cropping systems, and patterns.

However, in our view, based on literature and research experience across many regions in India and crops, improved mechanized weed management practices could save one-third of the weed management costs. Therefore, in Indian agriculture, there is tremendous scope for increasing the mechanization level of weed management, focusing on input use efficiency and sharing available tools and equipment at the village level. Increased mechanization would improve farming net profits and reduce the drudgery of labour-intensive field operations.

A critical requirement is the further development of low-cost, ergo-refined weeders, which are suitable for small and marginal land holding sizes. This review finds the Government of India's scheme "Sub-Mission on Agricultural Mechanization (SMAM)" as providing a fresh, single window for improving the mechanization of weed management in India through more innovative designs.

Keywords: mechanical weed management, mechanical weeding tools, mechanized farming

Introduction

India is an agriculture-based country, with more than 40% of its population engaged in agriculture and allied activities. Agriculture provides employment, food security and demand for industrial goods and services. Agriculture and allied sectors are the largest employers in India's workforce (Vemireddy and Choudhary, 2023). While playing a pivotal role in supporting 17% of the global population (Rao, 2024), agriculture contributed 14.45% to India's gross domestic product (GDP) in 2023-24 (Statistics Times, 2024). About 45.5% of the total workforce (62.9% female and 38.1% male workers) is involved in the agricultural and allied sectors (PIB, 2023).

Among the most significant challenges faced by Indian agriculture are (a) the ever-increasing food demand, (b) labour shortages, (c) inadequate mechanization of agricultural activities and (d) higher input costs. Urbanization, better opportunities available in the non-agricultural sector and uncertainties in agriculture as a vocation are factors that lead the workforce to migrate from the farming sector to non-agricultural industries. A drop in the percentage share of the labour force from the current figure of about 40-45% to 34.6% by 2030 has been estimated (Kapur et al., 2015).

Indian agriculture is mainly characterized by its land holdings (Table 1). The total land holdings increased from 138.35 million in 2010-11 to 146.45 million in 2015-16. However, the operational area has decreased from 159.59 million ha in 2010-11 to 157.82 million ha in 2015-16. The per capita availability of land has decreased from 1.15 ha in 2010-11 to 1.08 ha in 2015-16 (PIB, 2020).

As per Agriculture Census, 2015-16, India had 86.1% of small and marginal farmers (up to 2.0 ha), 13.35% of medium farmers (2.0 to 10.0 ha) and a very small number (0.57%) of large farmers (more than 10.0 ha). The small and marginal farmers cultivated about 47% of the area, medium farmers cultivated 44% of area and large farmers cultivated only about 9% of the total area cultivated during 2015-16.

An increasing population in India has resulted in fragmentation of land and smaller per capita land holding sizes. The smaller size of per capita land holdings affects the economic conditions of the farmers. It limits the suitability of such farms for large-sized machinery. This effect is an obstacle to the effective mechanization of agriculture. Most Indian farmers now own farms that are, on average, less than 1.4 ha. Bringing new technologies and practices and integrating them with a large population of poor farmers scattered over a large country is also a hugely challenging task for profitable agriculture.

Table 1 Classification of land holdings in India

Category	Size class
1. Marginal	< 1.0 ha
2. Small	1.0 - 2.0 ha
3. Semi- Medium	2.0 - 4.0 ha
4. Medium	4.0 - 10.0 ha
5. Large	> 10.0 ha

(Source: PIB, 2019)

Besides affecting agro-biodiversity and natural water bodies, weeds are a significant biotic constraint in crop production. They compete with crops for nutrients, moisture, sunlight and space, reducing crop yields by as much as 37% (Tewari and Chethan, 2018). In 2018, Gharde et al. estimated crop yield loss due to weeds in 10 major crops in India and reported that yield losses due to weeds varied depending on the crops, soil type, geographical location, cropping condition, and weed management practices followed.

The highest yield loss of around 35.8% was recorded in groundnut (*Arachis hypogaea* L.). This was followed by losses of 31.4% in soybean [*Glycine max* (L.) Merr.], 30.8% in green gram [*Vigna radiata* (L.) Wilczek], 27.6% in pearl millet (*Pennisetum glaucum* L.), 25.3% in maize (*Zea mays* L.), 25.1% in sorghum [*Sorghum bicolor* (L.) Moench], 23.7% in sesame (*Sesamum indicum* L.), 21.4% in mustard [*Brassica juncea* (L.) Czern.], 21.4% in direct-seeded rice (*Oryza sativa* L.), 18.6% in wheat (*Triticum aestivum* L.) and 13.8% in transplanted rice (*Oryza sativa* L.).

Most Indian farmers still use traditional and age-old weed control practices despite losing 15-20% of crop yield to weeds (Chethan et al., 2018). In India, on average, weed control costs are around INR 6000 ha^{-1} in the *kharif* (rainy) season and INR 4000 ha^{-1} in the *rabi* (winter) season, accounting for 33% and 22% of the total cost of cultivation, respectively (Yaduraju and Mishra, 2017).

Among the standard weed control methods, biological and cultural methods have limitations concerning managing a significant diversity of weeds under most cropping conditions. Chemical weed management is biologically productive and economically superior, but herbicide use has an environmental cost (Slaughter et al., 2008). On the other hand, mechanical weed management is very effective in controlling weeds without negative impacts on the environment (Tewari and Chethan, 2018).

Mechanical Weed Control and Tillage Operations

Mechanical weed control involves the physical removal of weeds using mechanical tools and implements. Weed control is an integral part of primary and secondary tillage, which are the initial steps taken to prepare a field for cropping (ASAE, 2004; 2005). The choice of tools and implements used in tillage, as well as the time and frequency of their use, depend on the type of crop to be sown and the weeds encountered in the land that need to be prepared for cropping. Further, the soil type, soil moisture, agro-climatic condition, field size and shape also influence the type of tillage and weeding equipment (Rueda-Ayala et al., 2010).

Primary and Secondary Tillage

In simple terms, primary tillage is the first breaking of the soil, which loosens the soil but leaves it with a rough texture in large lumps. Primary tillage can effectively control the weeds by burying their seeds or propagules to a depth from which they cannot emerge (Cloutier and Leblanc, 2001; Mohler, 2001; Cloutier et al., 2007). For example, problematic perennial weeds in Indian farming, such as purple nutsedge (*Cyperus rotundus* L.), creeping thistle (*Cirsium arvense* (L.) Scop.], coltsfoot (*Tussilago farfara* L.) and wild wormwood (*Artemisia vulgaris* L.), can be effectively controlled by burying their bulbous or rhizomatous propagules deep, preventing or slowing emergence. Some of the implements used for primary tillage are mouldboard ploughs, disc ploughs, rotary ploughs, diggers and chisel ploughs (ASAE, 2004; 2005).

Secondary tillage is the second breaking of the soil, producing finer soil and sometimes shaping the rows, preparing the seed bed for planting. Secondary tillage may also involve mixing fertilizers, lime, manure or any other soil amendments. Seedbed preparation is the final secondary tillage operation except when used in the stale or false seedbed technique for controlling weeds (ASAE, 2004). Secondary tillage tools include the rotatory plough and various types of harrows (e.g., disc, spring-tyne, radial blade and rolling harrows).

Both primary and secondary tillage, undertaken before crops are sown or planted, improve the surface area of soil such that the roots of germinating seeds or juvenile plant roots can easily take up water and nutrients from it. Weed control is an integral part of these activities. During these tillage operations, weeds are uprooted and mixed with soil. Tilling increases soil aeration and the soil's water-holding capacity while killing and burying weeds (Kurstjens and Perdok, 2000; Kurstjens and Kropff, 2001).

Cultivation tillage (tertiary tillage)

Cultivation tillage refers to activities that are undertaken after the planting and emergence of a crop. The primary objective of cultivation tillage is to control emerging weed species at early development stages. Cultivation tillage aims to create a non-competitive environment and conditions for crop growth (Vanhala et al., 2004; Rueda-Ayala et al., 2010). The depth of operation in cultivation tillage varies from 2 to 6 cm and can destroy the weeds in several ways.

The passage of a cultivator over a field wholly or partially buries and uproots the weeds and breaks weed roots encountered by the cultivator (Rasmussen, 1991; Kurstjens and Perdok, 2000). Cultivation tillage is more effective in dry soils than wet soils, as weeds often die by desiccation. However, death and decay and the mortality rate of weeds decrease under moist conditions. Cultivating the soil when it is too wet will also damage the soil structure and may possibly spread perennial weeds (Cloutier and Leblanc, 2001).

Cultivation tillage includes whole-crop cultivation (full surface), inter-row cultivation (between crop rows) and intra-row cultivation (between crops). Depending on the severity and condition of the weeds, cultivation tillage may be carried out during the early emergence of crops. Weeds, such as the use of microwave weeders, which kill weed seeds. However, cultivation tillage is by and large an activity that targets weeds after the emergence of the crop and needs to be done with care to not disturb crop plants.

Broadcast (Full-width) Cultivation

Broadcast cultivation involves cultivating the soil with the same intensity, both on the rows and in between the crop rows. It is done before or after crop emergence, depending on the requirements. Common implements used for this purpose are implements, such as chain harrows and flex-tyne harrows.

Inter-row cultivation

Inter-row cultivation refers to the cultivation of soil between the crop rows to loosen the soil and kill weeds at the same time. This method ensures minimal risk to the crop and usually provides excellent weed control. The major limitations are the growth stages of the crop and weeds. Inter-row cultivation weeding should be done within the critical period of crop-weed competition. Otherwise, the luxurious growth of weeds may clog the cultivators and lead to poor weeding.

The weeders used for inter-row cultivation are khurpi, wheelhoes, rotary weeders, wetland weeders, engine-operated weeders, tractor-operated weeders, self-propelled weeders and robotic weeders.

Intra-row cultivation

Intra-row weeding refers to the cultivation of soil within crop rows. There are increased risks of intra-row weeders damaging crops while performing weeding. Therefore, intra-row cultivation requires both precision and accuracy and experienced operators to perform a weeding operation. The weeders used for intra-row cultivation are finger weeders, torsion weeders, air blow grit weeders, cycloid weeders and brush weeders.

Types of Mechanical Weeders

Mechanical weeders are classified on the basis of soil type, cropping condition, power source, sensor system for detection, weed removal, etc. (Table 2). It is well known that the efficacy of mechanical weeding declines as the weeds develop. Weeds are more vulnerable when they are in their young growth stages. However, weeding efficiency also varies significantly with the type of device used.

Table 2 Types of Mechanical Weeders

Criteria	Classification	Tools
Power source	Manual weeding tools	Khurpi, grubber, straight blade hoe, wheel hoe and cono weeders.
	Animal drawn weeders	Sweeps, duck foot cultivator and harrows.
	Power operated weeders	Self-propelled rotary weeders, tractor-operated rotary weeders, cultivators and brush cutters.
Crop condition	Broadcast weeders	Spring tyne, rolling, chain harrows and rotary hoes.
	Inter-row weeders	All types of sweeps, including hoes and shovels, rotary weeders and brush weeders.
	Intra-row weeders	Rotary weeders, brush weeders, torsion weeders, finger weeders and sensor-based robotic weeders.
Soil engagement	Soil engaging type	All cultivating tools.
	Non-soil engaging type	All weed-cutting tools, e.g. mowers and brush cutters.
Sensing system	Sensor-based system	Sensor and robotic weeders. These include mechanical actuators/ optical/ ultrasonic/ infrared red/ laser/ thermal, and microwave weeders.
Weeding system	Thermal weeders	Various types of Microwave/ laser/ infrared/ steam/ hot air blown/ electric/ flame weeder
	Non-thermal weeders	All conventional weeding tools

(Source: Tewari and Chethan, 2018)

The control of weeds by mechanical means depends on the degree of soil disturbance caused by the weeding implements. The mechanical weeders simultaneously uproot, cut and bury weeds during the weeding operation (Melander et al., 2017). If soils are dry, uprooting weeds reduces their root anchorage and increases the desiccation rate. Burying weeds in the soil destroys them effectively (Rasmussen, 1991).

A soil burial depth of six cm will kill most of the weeds, regardless of species and growth (Merfield et al., 2020). Therefore, soil tillage needs to be performed to achieve a soil cover of six cm to kill weeds if they have surpassed the seedling stage (Melander and McCollough, 2021). The above mechanism holds true for tyne-type weeders. However, blade-type and share-type hoes can also cut weeds with several mature leaves and uproot them at relatively advanced growth stages (Melander et al., 2005).

Weeding activities in India are the most laborious and costly operations. They involve a great deal of energy-intensive activities compared to other agricultural operations (Chethan et al., 2020). The majority of Indian farmers still use small-capacity, less efficient, manually-operated weeders, such as kodali, khurpi, powrah, sickle, locally made hoes and hand-held forks. Only a small proportion of farmers are able to afford tractor-operated weeders (Appendix 1).

Manual weeding accounts for up to 25% of the total labour requirement, depending on the condition of the field (Nag and Dutta, 1979; Chethan and Krishnan, 2017). If conducted well, manual weeding provides a near 'weed-free' environment. Undertaking one- to two-hand weeding operations during the critical period of crop-weed competition usually results in satisfactory weed control. However, the non-availability of experienced workers during this crucial period limits the success of manual weeding operations in most crops. The resulting inadequacy of weed control greatly affects crop yields and quality.

In recent times, engine-operated weeders, suitable for small landholdings, have gained increasing popularity among Indian farming communities. The cost of these machines is cheaper. They also require fewer repairs and maintenance compared to tractor-operated and other bigger machines.

Problems with Mechanical Weed Management

Several recommendations were made to adopt mechanical weed management in different crops (Appendix 2). However, the lack of awareness about mechanical weeders, higher initial cost and non-availability of machines, fragmentation of lands, requirement of highly skilled operators, rural landscape, migration of labourers from the agricultural sector, etc, makes it difficult to adopt mechanical weed management under the Indian scenario.

More than 86% of Indian farmers have fragmented lands with a land size of less than 2 ha. These farmers are economically poor compared to large farmers and totally dependent on inefficient, drudgery-prone and time-consuming traditional weeding tools. On average, the khurpi requires 500-600 man-h/ha, the grubber requires 330-500 man-/ha, manually operated hoes require 50-100 man-h/ha, and animal-drawn weeders require 6-20 man-h/ha of manpower to perform the weeding operations (Tewari and Chethan, 2018).

The operation of most of these tools requires bending and squatting postures, which require 30-50 % higher energy compared to weeding operations performed in standing or sitting posture (Chethan et al., 2018). Thus, manual weeding using small tools is a costly affair in India.

In India, two to three mechanical weeding operations have been recommended for most crops. Generally, mechanical weeding is done 15-20 days after the sowing of the crop. It needs to be repeated depending on the severity of the weed infestations. The time available to perform weeding operations in most crops is limited. If weeding is not conducted within this window, it could result in the luxurious growth of weeds and adverse effects on the crops.

The non-availability of gender-friendly weeding tools and implements is also a major drawback for not adopting mechanical weed management. In India, more than 62% of the agricultural labourers who perform the majority of the weeding operations are females. However, the implements and machines developed in India are largely based on the anthropometric parameters of male workers. These weeders are not suitable for female workers, most of whom have less muscle mass than male workers. As a result, female labourers are often handicapped in the use of existing machines for weeding operations. Further, the non-availability of weeder sale centres, custom hiring centres, repair and maintenance centres, and farm machinery banks also greatly influences the non-adoption of mechanical weeders.

Other issues, mainly faced at village levels, include the difficulty of finding a skilled operator, inefficiency of unskilled operators, inappropriate way of handling the machines, delays or lack of repair services and high fuel consumption. All such factors contribute to the non-adoption of mechanical weeders.

A survey has been conducted to study the reasons for non-adopting mechanical weeders at the farmers' level (Figure 1). It showed that 22% of the respondents did not adopt the weeders because of the machine cost. About 20% of them did not adopt because of the non-availability of hiring facilities, and 8% of them did not adopt because of the higher hiring cost (Vemireddy and Choudhary, 2023).

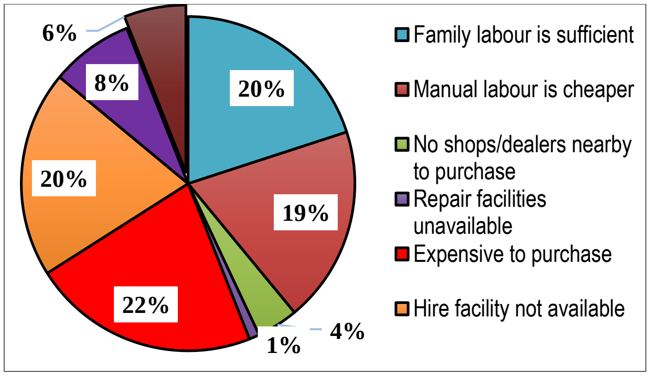

Figure 1. Response of the labourers for adopting mechanical weeders

Adopting advanced weeders, incorporating a global positioning system (GPS)-guided tractor-operated weeders, sensor-based weeders, robotic weeders, laser weeders and microwave weeders, may not be possible in the present-day situation in India. The farmers' economic conditions and capacity to afford the high-cost machines are very poor compared with the farmers of developed nations. Therefore, Indian farmers are in great need of low-cost, cost-effective, ergo-refined weeding tools that are suitable for both small-to-medium-sized and larger landholdings.

The data compiled by the ICAR-Directorate of Weed Research, Jabalpur and AICRP-Weed Management (a network-coordinated research programme) shows a tremendous scope for adopting improvised mechanical weeders, which are cost-effective and efficient for controlling the weeds. Improving and mechanizing weed management practices could save one-third of the weed control cost (Chethan et al., 2020). Given that small and marginal farmers comprise the largest portion of the Indian farming community, priority research should focus on developing weeding machines and implements that such farmers can afford.

Opportunities for Mechanized Weed Management

Mechanized weed management attempts to increase the farm power availability to perform the different weed control operations. It is our experience that mechanized weed management greatly enhances the quality of weed control work, timeliness of operation, operator productivity and comfort.

The level of agriculture mechanization in India is about 40 to 47%, with an average farm power availability of 3.045 kW/ha during 2021-22 (Mehta et al., 2023). This mechanization level is lower compared to other countries such as the USA (95%), Western Europe (95%), Soviet Union (80%), Argentina (75%), Brazil (75%) and China (59.5%) (Vemireddy and Choudhary, 2023).

The mechanization level of weeding operations, interculture and plant protection operations is just about 30 to 32% during 2020-21, which is less than the overall agricultural mechanization in India.

The adoption of various types of weeders, discussed herein and the mechanization of weeding operations are greatly influenced by factors including the crops grown, soil conditions, the agro-ecological zone and the cropping season.

Thus, a huge variation in mechanization levels for weed management practices for different crops has been observed (Figure 2). The wheat crop had the highest mechanization of 50%, and oil seeds and millet crops had the lowest mechanization of around 20% for weed control operations (Mehta et al., 2023).

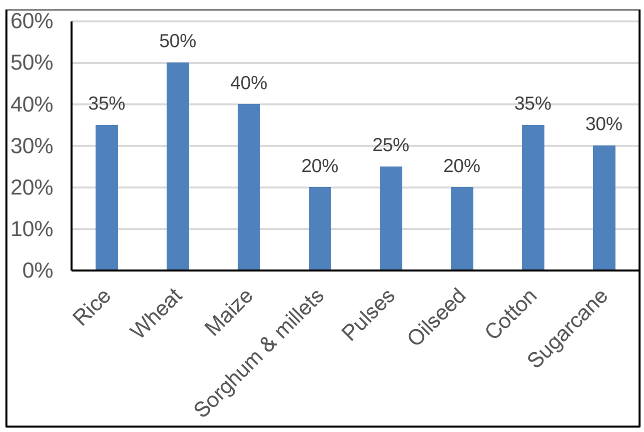

Figure 2. Mechanization level for weed management in major crops

Agricultural mechanization has been identified as a critically important area crucial for India's agricultural development to achieve the second green revolution.

In India, the level of mechanization in weed management could be increased by the following:

- Introducing improvised, highly efficient animal-drawn and small engine-operated power weeders for small holdings.
- Developing multi-task, operator-friendly, refined power weeders suitable for small-to-medium holdings.

- Improving accessibility to tractor-drawn-implements, power tillers and small tractors for medium-sized holdings.
- Improving access to high-power tractors and machines, sensor-based weeders and advanced machines like GPS-guided vehicles for large holdings.

Recognizing the importance and need for agricultural mechanization, the Government of India initiated a scheme called “Sub Mission on Agricultural Mechanization (SMAM) under the National Mission on Agricultural Extension and Technology (NMAET) during 2014-15. The main objective of this scheme is to provide a “single window” for all the activities related to agricultural mechanization for accelerated agricultural growth (PIB, 2023).

Under the scheme, various activities, such as establishing a Farm Machinery Bank (FMB), High-tech Hubs, Custom Hiring Centres (CHC) and the distribution of agricultural machines, have been conducted. In addition, the scheme provides financial assistance to farmers, rural youths, FPOs, Village Panchayats, Cooperative societies and farmer-registered societies.

The main aim is to increase the mechanization level in small and marginal land holdings and reach areas where the mechanization level is lower. These activities have resulted in expanding the cropped area, increasing the cropping intensity and production and increasing the average farm power availability from 2.02 kW/ha in 2016-17 to 3.045 kW/ha in 2021-22 (Vemireddy and Choudhary, 2023; Mehta et al., 2023).

Conclusion

Indian agriculture is mainly defined by small and marginal farmers. Mechanical weed management in Indian agriculture is limited by the fragmentation of land, smaller land holdings, farmers’ economic conditions, their education level, awareness about advanced technologies, seasonal variations and cropping patterns.

Nevertheless, mechanical weed management is a critically important tool that has a tremendous scope for improvisation within the existing technologies. A low-cost, ergo-refined, operator-friendly weeding tool that is best suited to small and marginal farmers can be developed. It is expected that most farmers will be able to afford to purchase or hire such a tool.

There is also tremendous scope for improving the average farm power availability to 4.0 kW/ha by the end of 2030. The activities under the “Sub Mission on Agricultural Mechanization (SMAM)” scheme enhanced the mechanization level at the small and marginal farmers' level and are the best possible solution to increase India’s mechanization level for weed management.

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Appendix 1

Table 3 The popular mechanical weeders used in India

Khurpi: Mode of use: A sharp, straight tool operated in sitting and squatting positions. Used for: Inter and intra-row weeding. Suitable crops: all types of crops cultivated in dryland. Field capacity: 0.0016 - 0.002 ha/h Approximate cost: INR 150 – 500 **https://www.indiamart.com**	
Straight Blade Hoe: Mode of Use: it is a long-handled hand tool operated in a standing position by pulling action. Used for: Inter and intra-row weeding. Suitable crops: all types of crops cultivated in dryland. Field capacity: 0.002 - 0.003 ha/h Approximate cost: INR 300 - 400 **https://www.walmart.com/ip/1-2-Inch-Shank-Cotton-Hoe-W-60-Inch-Handle/261045508**	
Grubber weeder: Mode of Use: it is a hand tool operated in sitting and squatting positions by pulling action. Used for: Inter and intra-row weeding. Suitable crops: all types of crops cultivated in both wetland and dryland. Field capacity: 0.002 - 0.02 ha/h Approximate cost: INR 300 – 2000 **https://www.indiamart.com**	
Twin wheel hoe: Mode of Use: it is a push-pull type weeder operated in a standing position. Used for: Inter row weeding. Suitable crops: all types of crops cultivated in dryland. Field capacity: 0.015 – 0.019 ha/h Approximate cost: INR 1500 – 3000 **https://www.desertcart.in/products/39567254-hoss-double-wheel-hoe**	
Cycle wheel hoe: Mode of Use: it is a push-pull type weeder operated in a standing position. Used for: Inter row weeding. Suitable crops: all types of crops cultivated in dryland. Field capacity: 0.017 – 0.019 ha/h Approximate cost: ₹ 1500 – 2500 **https://www.amazon.in/Attachments-Loosening-Digging-Weeding-Agriculture/dp/B0BM6F4KY5**	

Peg type hoe: Mode of Use: it is a push-pull type weeder operated in a standing position. Used for: Inter row weeding. Suitable crops: all types of crops cultivated in dryland. Field capacity: 0.005 – 0.006 ha/h Approximate cost: ₹ 800 – 1200 **https://www.farmech.dac.gov.in**	
CRIJAF Nail weeder: Mode of Use: it is a push-pull type weeder operated in a standing position. Used for: Inter row weeding. Suitable crops: Jute and other crops in sandy and sandy loam soil. Field capacity: 0.013 - 0.015 ha/h Approximate cost: ₹ 1500 – 2000 **https://www.moglix.com/unison-uei-1174-dry-land-weeder/mp/msnpkep4dr6q9g**	
Brush cutter (Weed cutter): Mode of Use: It is a non-soil-engaging type of weeding tool that cuts weeds above the ground by rotating fibre wire or cutting blades at higher speeds parallel to the ground. The weeding operation is performed in a standing position. Used for: Inter and intra-row weeding. Suitable crops: all types of crops irrespective of soil type. Field capacity: 0.2 - 0.3 ha/h Approximate cost: ₹ 15,000 - 25,000 **https://www.machinemart.co.uk/p/einhell-gc-bc-36-4-s-377-cc-petrol-brush-cutte/**	
Cono weeder: Mode of Use: it is a push-pull type weeder operated in a standing position. Used for: Inter row weeding. Suitable crops: Transplanted rice and SRI method. Field capacity: 0.012 – 0.015 ha/h Approximate cost: INR 1800 – 2000 **https://www.indiamart.com**	
Mandava Weeder: Mode of Use: it is a push-pull type weeder operated in a standing position. Used for: Inter row weeding. Suitable crops: Transplanted rice and SRI method. Field capacity: 0.012 – 0.015 ha/h Approximate cost: INR 500 - 1200	 (Source: WASSAN, 2006)

Three-row Raichur weeder: Mode of Use: it is a push-pull type weeder operated in a standing position. Used for: Inter row weeding. Suitable crops: Transplanted rice and SRI method. Field capacity: 0.036 – 0.06 ha/h Approximate cost: INR 1000 - 3000	 (Source: : WASSAN, 2006)
Finger weeder: Mode of Use: it is a push-pull type weeder operated in a standing position. Used for: Inter row weeding. Suitable crops: Transplanted rice and SRI method. Field capacity: 0.012 – 0.016 ha/h Approximate cost: INR 1000 – 1200 **https://ksnmdrip.com/products/drum-seeder/finger-weeder-wetland-weeder**	
Japanese weeder: Mode of Use: it is a push-pull type weeder operated in a standing position. Used for: Inter row weeding. Suitable crops: Transplanted rice and SRI method. Field capacity: 0.03 – 0.05 ha/h Approximate cost: INR 1500 – 3000 **https://www.indiamart.com**	
Animal-drawn hoes: Mode of Use: The hoe or sweeps are attached to the mainframe and pulled by a pair of animals. The number of rows varies from single row to multiple rows. Used for: Inter row weeding. Suitable crops: crops cultivated in dryland. Field capacity: 0.15 – 0.35 ha/h Approximate cost: INR 3000 – 6000 **https://www. economictimes.indiatimes.com**	

Brush cutter- rotary weeder: Mode of Use: It is a soil-engaging weeding tool. A separate rotary tiller is attached to the brush cutter in place of the fibre wire/cutting blade. The rotary tiller tills the soil and cuts weeds. The weeding operation is performed in a standing position. Used for: Inter and intra-row weeding. Suitable crops: all types of crops irrespective of soil type. Field capacity: 0.1 - 0.2 ha/h Approximate cost: INR 15,000 - 30,000/- **https://transvilleagrong.com/shop/agricultural-equipments/agro-handheld-power-weeder/**	 
Lowland paddy power weeder: Mode of Use: It is a soil-engaging weeding tool. A rotary tiller attachment is made to cut the soil and weeds. The weeding operation is performed in a standing position. Used for: Inter-row weeding. Suitable crops: crops cultivated in wetland conditions (transplanted rice and direct seeded rice). Field capacity: 0.1 - 0.2 ha/h Approximate cost: INR 15,000 - 30,000 **https://m.indiamart.com/proddetail/sharp-garuda-paddy-weeder-22668721997.html**	
Engine-operated rotary weeder: Mode of Use: It is a soil-engaging weeding tool. A rotary tiller attachment is made to cut the soil and weeds. The weeding operation is performed in a standing position. Used for: Inter-row weeding. Suitable crops: crops cultivated in both wetland and dryland. Field capacity: 0.1 - 0.4 ha/h Approximate cost: INR 20,000 - 50,000 **https://www.amazon.in**	
Self-propelled rotary weeder: Mode of Use: Weeding elements are a self-propelled type and are operated by an engine. A rotary tiller attachment is made to cut the soil and weeds. The weeding operation is performed in a standing position. Used for: Inter-row weeding. Suitable crops: crops cultivated in dryland. Field capacity: 0.18 - 0.45 ha/h Approximate cost: INR 50,000 - 75,000 **https://www.indiamart.com**	

Power cultivator: Mode of Use: Weeding elements are a self-propelled type and are operated by an engine. Sweep blades are attached to the mainframe to cut and uproot the weeds. The weeding operation is performed in a standing position. Used for: Inter-row weeding. Suitable crops: crops cultivated in dryland. Field capacity: 0.20 - 0.50 ha/h Approximate cost: INR 30,000 – 2,50,000 **https://www.indiamart.com**	
Tractor-operated sweeps/ earthing-up bund former: Mode of Use: the weeding unit (duck foot sweeps/ earthing-up unit, etc.) is mounted on a three-point linkage of the tractor and operated by tractor drawbar power. Used for: Inter-row weeding. Suitable crops: crops cultivated in dryland, especially suited to crops like potato (*Solanum tuberosum* L.), sugarcane (*Saccharum officinarum* L.), pigeon pea [*Cajanus cajan* (L.) Millsp.], maize, soybean, etc. Field capacity: 0.25 - 0.50 ha/h Approximate cost: INR 30,000 - 80,000 https://www.indiamart.com	
Tractor-operated inter-row rotary weeder: Mode of Use: the rotary weeding unit is mounted on a three-point linkage and operated by tractor P.T.O. Used for: Inter-row weeding. Suitable crops: crops cultivated in dryland, especially suited to crops sown in larger row spacing. Field capacity: 0.25 - 0.6 ha/h Approximate cost: INR 50,000 - 1, 00,000	 (Source: Singh, 2022)
Tractor-operated inter-row cultivator: Mode of Use: the cultivator unit is mounted on a three-point linkage and operated by tractor drawbar power. Used for: Inter-row weeding. Suitable crops: crops cultivated in dryland, especially suited to crops sown in larger row spacing. Field capacity: 0.25 - 0.6 ha/h Approximate cost: INR 30,000 - 70,000 **https://www.youtube.com/watch?app=desktop&v=TGEa3sC6SZ8** (Cotton Inter-cultivation)	
Riding type weeders: Mode of Use: it is a developed version of walk-behind type weeders. A weeding element is attached to the rare side of a base frame, and sitting arrangements are made for the operator. Used for: Inter-row weeding. Suitable crops: crops cultivated in dryland. Field capacity: 0.15-0.20 ha/h Approximate cost: INR 40,000 - 60,000 **https://www.amazon.in**	

Appendix 2

Table 3 Recommended Mechanical Weed Management Practices for Major Crops in India

Weed management practice	Reference
Rice	
Dry-Direct Seeded Rice (D-DSR)	
– One mechanical weeding (MW) by finger weeder at 15-20 days after sowing (DAS) followed by (fb) one round of hand weeding (HW) in rainfed uplands and lowlands	Saha and Patra, 2013
– Two MW by finger weeder at 15 and 30 DAS fb one HW at higher weed infestation conditions in rainfed uplands and lowlands	
– MW thrice at 20, 40 and 60 DAS	Saravanane, 2020
– Cono-weeder twice at 20 and 40 DAS/ days after transplanting (DAT)	Dubey et al., 2017
– One hoeing at 12 DAS fb one HW at 30 DAS	Nagargade et al., 2024
Wet-Direct Seeded Rice (W-DSR)	
– One MW by finger weeder at 15-20 DAS in moist saturated soil fb one HW in rainfed shallow lowlands and irrigated condition	Saha and Patra, 2013
– Cono-weeder twice at 20 and 40 DAS/DAT	Dubey et al., 2017
Transplanted rice (TPR)	
– MW by cono weeder at 22-30 DAS in rainfed shallow lowlands and irrigated condition	Saha and Patra, 2013
– Cono-weeder twice at 20 and 40 DAS/DAT	Dubey et al., 2017
– MW starts from 10 – 12 days after transplanting to till crop permits operation at every 10 days interval	WASSAN, 2006
System of Rice Intensification (SRI)	
– Cono-weeder twice at 20 and 40 DAS/DAT	Dubey et al., 2017
– One hoeing at 12 DAS fb one MW at 30 DAS	Nagargade et al., 2024
– MW starts from 10 – 12 days after transplanting to till crop permits operation at every 10 days interval	WASSAN, 2006
Soybean	
– One hoeing at 15 DAS and HW at 30 DAS	Jadhav and Kashid, 2019
– One hoeing at 20 DAS along with HW twice at 30 and 60 DAS	Shete et al., 2008; Dhaker et al., 2015
– HW at 20 and 30 DAS and hand hoeing at 20 and 30 DAS	Chaudhari et al., 2016
– Inter-cultivation at 20 and 40 DAS	Patel et al., 2015
Maize (Sweet corn)	
– Two manual hoeing at 15 and 30 DAS	ICAR-IIMR, 2024
– Two MW by wheel hoe/ hand grubber at 20 DAS and 40 DAS	Mishra, 2022
– One hoeing	Sharma et al., 2000
– Hoeing at 20 DAS fb by 2 HW at 20 DAS and 40 DAS	Pathak et al., 2015
– Soybean intercropping + 1 MW (20 DAS)	Saini et al., 2013
– Two MW 20 and 40 DAS + mash intercropping	
Wheat	
– One MW by twin wheel hoe/ hoe/grubber/khurpi/sweep type cultivator/ other weeders at 35 – 40 DAS	Mishra, 2021
Chickpea (*Cicer arietinum* L.)	
– One to two MW by twin wheel hoe/ hoe/grubber/khurpi/sweep type cultivator/ other weeders at 35 – 40 DAS, depending on the weed intensity	Mishra, 2021

– One hand hoeing 30 DAS	Sahu et al., 2023
– Application of pendimethalin 1.0 kg/ha as pre-emergence (PE) + hand hoeing at 30 DAS	Singh and Jain, 2017
Pigeon pea	
– Two mechanical weed management at 25-30 DAS and at 45-50 DAS	Yaduraju and Mishra, 2005
– Two hoeing at 40 and 70 DAS	Kumar et al., 2019
Green gram	
Hand hoeing at 25 DAS and 40-45 DAS by wheel hoe	Ahmad and Rana, 2016
Application of pendimethalin at 1.0 kg ha-1 as PE *fb* rotary weeding at 15-20 DAS	Muthuram et al., 2017
Black gram (*Vigna mungo* L.)	
– Interculture at 15 DAS *fb* quizalofop-ethyl 50 g/ha 30 DAS	Balyan et al., 2016
– Horse gram	
– Hand hoeing at 25 DAS and 40-45 DAS by wheel hoe	Ahmad and Rana, 2016
– Rice bean	
– Hand hoeing at 25-30 AS and at 40-45 DAS by wheel hoe	Ahmad and Rana, 2016
French bean (*Phaseolus vulgaris* L.)	
Two hoeing	Ahmad and Rana, 2016
Cowpea (*Vigna unguiculata* L.)	
– Application of pendimethalin 0.75 kg/ha as PE *fb* one hoeing at 20-25 DAS	Hanumanthappa et al., 2012
Ground nut	
– Application of pendimethalin @ 2.5 to 3 l/ha or Oxyflourfen @ 1.5 to 2.0 l/ha *fb* one inter-cultivation	ICAR-DGR, 2024
– Inter-cultivation and HW at 15, 30 and 40 DAS	
– Hoeing at 10-15 DAS and at 35-40 DAS (for earthing up)	
Mustard	
– MW at 25 DAS + HW at 50 DAS	Ghasal et al., 2022
– Application of pendimethalin 1.0 kg ha-1 as PE + quizalofop-p-ethyl 0.04 kg ha-1 as PoE + HW and inter-cultivation at 40 DAS	Jangir et al., 2018
– Application of pendimethalin 1 kg/ha *fb* hand hoeing at 35 DAS	Singh and Kumar, 2020
– Application of pendimethalin 30% + imazethapyr 2% EC 1 kg/ha as PE *fb* MW at 30 DAS	Sanketh et al., 2021
Finger millet [*Eleusine coracana* (L.) Gaertn]	
Drill-seeded finger millet cultivation	
– Hoeing twice by wheel hoe between rows + intra-row manual weeding *fb* HW twice at 20 and 40 DAS	Kujur et al., 2018
– Inter-cultivation twice at 20 and 40 DAS *fb* HW once at 35 DAS	Ramamoorthy et al., 2002
– Inter-cultivation once *fb* HW twice at 30 and 45 DAS	Ramamoorthy et al., 2010
– MW at 20 and 40 DAS	Dubey and Mishra, 2023
– Inter-cultivation at 25 DAS + one HW at 45 DAS	
– MW at 20 DAS	
Transplanted finger millet cultivation	
– Hoeing twice at 20 and 35 DAP *fb* HW once at 45 days after planting (DAP)	Patil et al., 2014a
– Hoeing (wheel) thrice at 20, 30 and 40 DAP *fb* HW once at 45 DAP	Patil and Reddy, 2014
– Stale seedbed technique *fb* inter-cultivation twice at 20 and 35 DAP; passing wheel hoe at 20, 30 and 40 DAP + one HW at 45 DAP	Patil et al., 2013

– Stale seedbed technique in combination with inter-cultivation twice at 20 and 35 DAP or passing wheel hoe at 20, 30 and 40 DAP with one hand weeding for weed management	Patil et al., 2014b
– Stale seedbed with inter-cultivation twice at 20 and 35 DAP	Patil et al., 2014b
Pearl millet	
– Deep summer ploughing to control all weeds	Dubey and Mishra, 2023
– Deep summer ploughing *fb* post-emergence application of tembotrione 100 g/ha at 15-20 DAS to control Cyperus rotundus	
– Two MW	
– Inter-culturing *fb* HW at 20 and 40 DAS	Das et al., 2013
– Hand weeding + inter-culturing at 35DAS	Munde et al., 2012
– Two HW/hoeing at 15 and 30 DAS	Chaudhary et al., 2022
Little millet (*Panicum sumatrense* L.)	
– Inter-cultivation twice at 20 and 40 DAS	Dubey and Mishra, 2023
– Two to three inter-cultivations *fb* one hand weeding. The first inter-cultivation should be before 20 DAS and the second before 35 DAS	
Foxtail millet (*Setaria italic* L.)	
– Stale seedbed technique + inter-cultivation twice at 25 and 45 DAS	Dubey and Mishra, 2023
– Inter-cultivation at 25 DAS + 1 hand weeding at 45 DAS	
Potato	
– Hoeing at 20 DAP + hand weeding at 40 DAP	Gupta et al., 2019
– Hand hoeing at 20 and 40 DAP	Bhullar et al., 2015
– Two earthing-up operations at 25 DAP and 55 DAP	Chethan et al., 2022; Chethan et al., 2019
Onion (*Allium cepa* L.)	
– Three MW by duct hoe at 20, 40 and 60 days after transplanting (DAT)	Hembrom et al., 2023; Barla and Upasani, 2019
Sugarcane (*Saccharum officinarum* L.)	
– Three hoeing at 1st, 4th & 7th week after ratoon initiation	Kumar et al., 2014
– Application of metribuzin 1 kg/ha as PE *fb* 1 hoeing at 45 days after ratoon initiation	
– Three hoeing at 30, 60 and 90 days after harvesting (DAH) of the main crop	Krishnaprabu, 2020
– Application of pendimethalin 2.0 kg/ha + Sesbania (brown manuring) + hand hoeing at 90 DAP	Fanish and Ragavan, 2020
– Application of metribuzin at 0.88 kg/ha at 3 DAH *fb* hoeing at 45 DAH *fb* 2,4-D at 1.0 kg/ha at 90 DAH of main crop	Waghmare et al., 2018
– Application of atrazine at 1.0 kg a.i/ha after 2-3 DAP + 2,4-D sodium salt at 1.0 kg a.i/ha at 60 DAP + manual hoeing at 90 DAP	ICAR-IISR, 2024
Cotton (*Gossypium hirsutum* L.)	
– Application of pendimethalin 1.0 kg/ha PE *fb* pyrithiobac sodium 62.5 g/ha PoE at 25 DAS *fb* one hoeing at 45 DAS	Veeraputhiran, 2023
– MW by power tiller at 25 and 45 DAS	
– Application of pendimethalin 1.0 kg/ha PE *fb* weeding by power tiller at 25 and 45 DAS	
– Application of pendimethalin 1 kg/ha *fb* weeding by power weeder	Nalini and Chinnusamy, 2019
– Two MW by power weeder at 25 and 45 DAS	

Obituary – Dr. Duong Van Chin (Vietnam)

Editor's Note

A former Asian-Pacific Weed Science Society (APWSS) President, Dr. Duong Van Chin, passed away recently. He was the President of APWSS in 2005 and Vice President of the Weed Science Society of Vietnam when he organized the 20th APWSS Conference. The 20th Conference was held at the Rex Hotel in Ho Chi Ming City during 7-11 November 2005. The central theme of the highly successful Conference was '*Six Decades of Weed Science Since the Discovery of 2,4-D (1945-2005)*'.

The Conference attracted many international participants and was considered one of the best-organized events. The Editor recalls attending the Conference and appreciating the effort to publish full peer-reviewed articles, including the Proceedings (740 pages).

Dr. Duong served in the Weed Science & Farming Systems Department at the famous Cuu Long Delta Rice Research Institute (CLRRI), Omon Cantho, Vietnam. As evident in the long list of research articles Dr. Duong produced, in collaboration with others, he spent most of his research career on rice weeds and their management, rice herbicides, allelopathy as a tool in weed management, biological weed control and diversification of farming systems to improve productivity.

Some of Dr. Duong's most significant publications can be accessed via Researchgate (https://www.researchgate.net/scientific-contributions/Duong-Van-Chin-78834325).

L-R, Dr. Cuong Nguyen (CLRRI), Dr. Ho Le Thi (CLRRI), Dr. Duong Van Chin and Dr. Hisashi Kato-Noguchi, Kagawa University, Japan

Dr. Duong also had very long collaborative partnerships with Japanese weed scientists, especially Dr. Hisashi Kato-Noguchi (see photo below) and his team. He also established productive collaborations with the *International Rice Research Institute* (IRRI), as reported in *the IWSS Newsletter* (Sep 2011), USA and Australian weed researchers. The Editor is aware that these collaborations made highly significant contributions to the development of weed science in the APWSS region. In 2010, Dr. Duong wrote a crucial national report (book) on 50 Years of weed research in Vietnam. His partner in that effort was Dr. Ho Le Thi, the current Vice President of APWSS) [1].

The Journal and our Society will miss an outstanding researcher, a founder of weed research in Vietnam and a mentor to many weed scientists in Vietnam, the APWSS region and beyond. As we say goodbye, we express our deep and heartfelt condolences to his family, students and the Weed Science Society of Vietnam.

[1] Duong Van Chin and Ho Le Thi. 2010. Fifty years of weed research in rice in Vietnam. Book: Vietnam-fifty years of rice research and development. Editors: Bui Ba Bong, Nguyen Van Bo, Bui Chi Buu. Hanoi Agriculture Publishing House. 414 pages: 283-292. ISBN - 978-81-931978-7-5.

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FIRST ANNOUNCEMENT

10th International Workshop on Biological Control and Management of Eupatorieae and other Invasive Alien Plants

Kerala Forest Research Institute (KFRI), Kerala, India | 11 - 14 February 2025

The International Workshop on Biological Control and Management of Eupatorieae and other Invasive Alien Plants will be organized under the patronage of the Kerala Forest Research Institute (KFRI), India, the International Organisation for Biological Control (IOBC), the Food and Agriculture Organization of the United Nations and the Asia-Pacific Forest Invasive Species Network. Earlier workshops in this series discussed the biological control of invasive alien plants such as *Chromolaena odorata* and *Mikania micrantha*. This workshop will evaluate the success, status and future prospects of the biological control of these species and the scope and options for biological control of the other major invasive plants widespread in the Asia-Pacific region and beyond. KFRI, the workshop venue, is located in the lap of the Western Ghats, which is one of the hotspots of biodiversity and a World Heritage Site. Invasive alien plants, especially the members of Eupatorieae and other species are widespread in most of the habitats in the region, posing significant impacts on the environment, wildlife, agriculture, and the livelihoods, especially of economically weaker communities. Climate, land-use change and forest degradation promote invasion by alien species and threats from these are predicted to increase in the future. Management of invasive alien plants in the region is mostly attempted through physical and chemical measures, which are not long-term and sustainable solutions. Biological control is considered the most suitable management approach to contain the problem, especially when the species are widespread.

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