A
Training Manual

"Integrated Weed Management Strategies under Changing Agricultural Scenario"

National Training (Virtual mode)

(28th August to 6th September 2024)

Organized by

Indian Society of Weed Science
&
ICAR-Directorate of Weed Research
Jabalpur

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PREFACE

Weeds have long been recognized as one of the most persistent challenges in agricultural production systems, directly impacting crop yields, resource utilization, and environmental sustainability. With the advent of changing climatic conditions, evolving new weed flora, and shifts in agricultural practices, the complexities of weed management have grown multifold. In this context, the need for a comprehensive and adaptive approach to weed management has never been more critical.

The **Training Manual on "*Integrated Weed Management Strategies under Changing Agricultural Scenario*"** has been developed as part of a collaborative effort between the **Indian Society of Weed Science and the ICAR-Directorate of Weed Research, Jabalpur**. This manual aims to provide an in-depth understanding of integrated weed management (IWM) strategies, combining traditional knowledge, advanced technologies, and innovative practices to tackle the emerging weed challenges in a sustainable manner.

The manual is designed to cater to a wide audience, including researchers, extension personnel, agricultural practitioners, and policymakers. It encompasses a diverse range of topics, such as the biology and ecology of weeds, the application of modern tools like remote sensing and hyperspectral imaging, the use of herbicides, and eco-friendly cultural and biological management practices. Emphasis has been placed on aligning these strategies with the dynamic agricultural scenarios shaped by climate change, resource limitations, and policy frameworks.

We hope that this manual serves as a valuable resource for knowledge dissemination and capacity building, empowering stakeholders to implement effective IWM strategies in their respective domains. We extend our gratitude to all contributors who have shared their expertise and insights to make this training manual comprehensive and relevant.

We trust that this manual will inspire innovative thinking, foster collaboration, and lead to sustainable solutions for managing weeds effectively under the ever-changing agricultural landscape.

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Chapter 1

Recent advances in weed management

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The current Indian population of 1454 million is expected to reach ~1666 million by 2047. To feed this population, the total food grain requirement of the country will be ~ 520 million metric tons by 2047. Global climate change, decreasing water availability, reduction in arable land, soil degradation, biotic and abiotic stresses, etc. are the other major concerns. Weeds pose a major threat to food security, biodiversity, ecosystem services and consequently to human health and wellbeing. Of the total loss caused by various pests in agriculture, weeds accounts for 37% followed by insects (29%), diseases (22%) and others including nematodes, rodents, mites, birds, *etc*. (12%). Uncontrolled weeds could cause global yield loss of major crops by around 34% (Oerke 2006). In India, Gharde *et al.* (2018) estimated the actual yield loss due to weeds in 16 major crops varied from 14-36% with economic value of USD 11 billion each year. The current (2023-24) total food grain production in India is ~330 million metric tons. Assuming an overall actual yield loss of 10% due to weeds, the total loss in grain production is ~33 million metric tons annually. Even if this loss could be reduced by half, grain production would increase by >16.5 million metric tons.

Major issues in weed management

- Non availability of farm labour and high labour cost
- Lack of efficient machinery/mechanical weeding tools
- Low adoption of IWM practices
- Increasing problem of herbicide resistance in weeds
- Management of weeds in conservation agriculture, organic and natural farming
- Management of alien invasive weeds
- Management of parasitic weeds
- Climate change impacts on weeds and crops

Recent advances in weed management

There have been many new developments in weed management research to address the emerging issues in weed management. These include:

- Understanding of weed biology and ecology, weed seedbank dynamics, influence of tillage practices on weed seed dormancy and germination.
- Automated weed control using remote sensing and imaging technologies such as drones, ground-based robots equipped with RGB cameras, developing the decision support system on weed management, thermal weed management (use of hot water and hot foam, steam, flame weeding, cryogenic weed control), electrocution (weed control via electric shock), use of abrasive grit.
- 'Harvest weed seed control' to reduce seed inputs to the soil seedbank for long-term weed control.

- Development of herbicide-tolerant crops (non-GM rice varieties namely; Pusa Basmati 1979 and Pusa Basmati 1985 tolerant to herbicide imazethapyr from ICAR-IARI, New Delhi; SAVA 134 and SAVA 127 of Savana Seeds, and CR Dhan-807 from ICAR-NRRI Cuttack, have been released). These varieties contain a mutated acetolactate synthase (ALS) gene helping farmers to spray imazethapyr, a broad-spectrum herbicide to control weeds.
- Genomics advancing to the next generation, RNA interference (RNAi) technology, plant genome editing (for identification of genes associated with herbicide resistance, reverting plant phenotypes from resistant to susceptible).
- Understanding the impact of climate change on crop-weed interactions and herbicide efficacy.
- Quick detection of multi-herbicide residues in food chain and environment, and their mitigation measures.
- Identification of crops and varieties for weed suppression and allelopathy.
- Use of diversified crop rotation and tillage system.
- Influence of crop diversification on weed dynamics and management.
- Integrated weed management in direct-seeded rice, minor millets and post-emergence herbicide in chickpea.
- Bio-based herbicides (use of soil microbes for herbicidal properties) and biocontrol of aquatic weed *Salvinia molesta* using insect *Cyrtobagous salviniae*.
- Use of nanotechnology and nano-herbicides (use of nano-enabled materials for the controlled release of herbicides).
- Management of parasitic weeds such as *Striga* in sugarcane with three-way herbicide (2,4-D+metribuzin+pyrazosulfuron) and using mycorrhizal consortia; and *Cuscuta* with 'Amarvel'-an organic product.
- Integrated management of herbicide resistant weeds.
- Integrated weed management in conservation agriculture, organic and natural farming.
- Data mining (for development of indices for strategic weed control).
- Weed risk assessment and quarantine (Plant quarantine provides a legislative framework to prevent the introduction and spread of new weeds in the country).
- Weed utilization for phytoremediation of polluted water, vermicomposting, mulching in natural farming, *etc*.
- Information technology for extension (multiple electronic resources including email, Facebook, 'X', Instagram, LinkedIn, Pinterest, Blogs, NetMeeting, Mobile apps and many more).
- Strong public-private partnership for technology development, dissemination and capacity building of stakeholders.

Chapter 2

Herbicide residue, persistence and degradation

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Herbicides are the chemicals which are employed to kill or control vegetation. Herbicides are the fastest growing class. Several herbicide molecules are introduced since the discovery of herbicidal activity of 2,4-D (2,4-dichlorophenoxyacetic acid) in 1941, to cater the need of the farmers. Recent herbicide development marked by the introduction of selective post-emergence herbicides in major crops such as sulfonylureas, imidazolinones and aryloxy phenoxy propionate *etc*. These herbicides provide excellent selectivity at extremely low dosage (few grams/ha). Herbicides help farmers in increasing crop yield, with efficient weed control.

Fate and persistence of herbicides in the soil

As soon as a herbicide is applied a number of processes immediately begin to remove the compound from the original site of application. For the herbicide which is intercepted by plants, the chemicals may be taken up by the plant itself may be washed off by precipitation onto the soil, may undergo photodegradation on plant surface or may volatile back into the air. Herbicides persistence in the soil is expressed as half-life or time required to degrades fifty percent of the original molecule (**Table 1**). However, the half-life is not absolute because it depends on the soil type, temperature, and concentration of the herbicide applied. Persistence varies with the nature of a chemical, soil properties and climatic conditions. The herbicide should persist long enough to check weeds until the end of critical period of weed competition but should not persist beyond the crop harvest, as it would be injurious to the sensitive crops grown in rotation. Very rapid loss of herbicides from soil will cause insufficient weed control, which is considered as unsatisfactory as their unduly long persistence within soil. Beside herbicides structure, soil conditions prevailing during and after the application of a herbicide as well as herbicide application methods influence the fate of the herbicides in the soil. Heavy rainfall in monsoon will cause greater leaching and runoff. Sandy soil would have a higher leaching potential than a clay soil due to larger pore spaces and lower CEC (Sondhia and Yaduraju 2005). Higher humidity enhances the soil microflora proliferation. Similarly, the persistence of herbicides in dry soil is greater as compared in wet soil.

Table 1. Half-lives of some herbicides in soil

Herbicide name	Half live (Days)	Herbicide name	Half live (Days)
Atrazine	13-58	Metribuzin	23-49
Butachlor	5-24	Metolachlor	8-27
Fluazifop-p-ethyl	8-24	Oxyfluorfen	19-29
Fluchloralin	12-13	Pendimethalin	15-77
Imazethapyr	57-71	Sulfosulfuron	3-8
Isoproturon	13-21	2,4-D	7-22

*Source: (Sondhia 2014, 2016)

A herbicide is said to be persistent when it may be found to exist in soil in its original or a closely related but phytotoxic form longer than one crop season after its original application (Sondhia 2005, Sondhia *et al.* 2015). Herbicide residues in crop produce above the safe level can cause health hazards to man and animal (**Table 2**). Ultimate fate of herbicide in soil depends on number of processes such as volatilization, leaching, runoff and degradation by microbes, chemical processes and photodecomposition

Effect of herbicides on microflora and fauna

Nowadays soil health and microbial diversity have become vital issues for the sustainable agriculture. Loss of microbial biodiversity can affect the functional stability of the soil microbial community and soil health. Generally, negative effects of herbicides on the population level or composition of species are decreased for a while but subsequently improves. Beneficial organism known to be affected negatively by specific herbicides includes nitrogen fixing bacteria (Rhizobium) and some mycorhizal fungi. Actinomycetes are relatively resistant to herbicides and affected at high concentration only. Fungi are probably the more sensitive to the majority of herbicides than are bacteria. Some strains of fungi and bacteria are also found to degrade herbicides in the soil (Sondhia *et al.* 2013, 2016). Apart from soil microflora, herbicide may have adverse or stimulatory effects on some beneficial soil fauna. Earthworms are perhaps the most important soil organisms in terms of their influence on organic matter breakdown, soil structural development, and nutrient cycling, especially in productive ecosystems. Isoproturon did not cause lethal effects at 1.4 g/kg soil on mature earthworm (*Lumbricus terrestris* L.) after 60 days.

Effect of herbicides on succeeding crop

Herbicide persistence in soil may injure succeeding crop. For example, injury to pea from sulfosulfuron is noted in field treated with sulfosulfuron in the previous year (Sondhia and Singhai 2006). Several substituted ureas, sulphonylureas, dichlobencil and 2, 3, 6-TBA often pose phytotoxic residues problems on crop land. Even a short residue herbicide like glyphosate has been reported to damage tomato transplants (Cornish 1992). Sometimes non-phytotoxic residues of previously applied herbicides may damage the rotation crop by interacting with the herbicide applied to the present crop. Most of the herbicides are absorbed through plant roots and underground absorptive sites besides they undergo number of degradation processes. Repeated application of the same herbicides in a mono crop sequence may cause accumulation of residues in soil, which in turn will affect the sensitive crops. Leaching of herbicides can

Table 2. Residues of some important herbicides in the soil, food grain and straw

Herbicides	Crop	Dose (g/ha)	Residues*		
			Soil	Grains	Straw
Butachlor	Rice	1000	0.005	0.012	0.029
Sulfosulfuron	wheat	25	BDL	0.010	0.004
Fenoxaprop-p	Wheat	100	0.089	0.0024	0.0013
Metsulfuron-methyl	Rice	4	BDL	BDL	BDL
Isoproturon	Wheat	1000	0.032	0.035	0.065
Oxyfluorfen	Rice	150-250	BDL	BDL	BDL
Imazethapyr	Soybean	100	0.016	0.210	BDL
Imazosulfuron	Rice	30-40	BDL	BDL	BDL
		50-60	BDL	0.006-0.009	0.009-0.039

*Source: (Sondhia, 2014)

cause crop injury due to transport of herbicide into the absorption zone of susceptible crop plants and accumulation of herbicides in toxic level in tolerant crop plants. In some experiments it was found that pre-emergence herbicides such as, butachlor, pretilachlor and anilofos applied at recommended doses continuously for four seasons in rice crop did not influence germination and yield of urdbean raised subsequently (Balasubramanian *et al.* 1999). Pretilachlor at 0.50 to 1.00 kg/ha, 2,4-D at 1.50 to 2.50 kg/ha, anilofos 0.40 to 0.60 kg/ha and pendimethalin 1.50 to 2.00 kg/ha applied as pre-emergence to transplanted rice did not affect succeeding wheat and peas crops but cucumber germination was reduced by 28% in 2.5 kg/ha dose but 2,4-D showed a greater level of persistence in soil (Gupta *et al.* 2000). Sulfosulfuron applied at 25, 50 and 100 g/ha in wheat crop did not show any adverse effect on succeeding maize and sorghum crop however, significantly affected the growth of lentil and pea (Sondhia and Singhai 2007). Residual effect of eight herbicides (pendimethalin, pretilachlor, triasulfuron, ethoxysulfuron, pyrazosulfuron-ethyl, carfentrazone-ethyl, 2,4-D amine and carfentrazone-ethyl + isoproturon) applied in strip–tilled wheat (*Triticum aestivum* L.) on the succeeding crop *i.e.,* mungbean, jute and sunflower were investigated in Bangladesh through bio assay techniques. Germination and crop growth of these succeeding crops were not affected by any of the herbicide residue applied in wheat. Somewhat, shoot lengths of mungbean and sunflower were increased in the herbicide treated plots but root lengths of some herbicide treated plots were decreased at a negligible rate compare to the control one (Zahari *et al.* 2018). Toxic and nontoxic effects of some important herbicides are given in **Table 3**.

Herbicide residues and mitigation strategies

When applied at recommended rates most herbicides breakdown within a few days or weeks after application and impose no restrictions on cropping options to the next year. Some herbicides however do not degrade quickly and can persist in the soil for weeks, months or years following application. The use of residual herbicides can be beneficial as the residues prevent growth of sensitive weed species throughout the season. These residues however can restrict the crops that can be grown in rotation. Various management techniques have been developed which can be adopted to minimize the residue hazards in soil.

Table 3. Effect of some important herbicides on succeeding crop

Crop	Herbicide	Dose (kg/ha)	Toxic	Nontoxic	Reference
Wheat	Sulfosulfuron	0.25-100	Pea, lentil	Sorghum, maize	Sondhia (2006, 2016)
Sorghum	Atrazine	0.25-1.0	-	Fingermillet Cotton	Jayakumar (1987)
Soybean	Pendimethalin,	0.450 t60	-	Wheat,	Yadav and Bhullar
	Imazethapyr + imazamox	60-70	-	barley, spinach, pea, raya,	(2014)
	Quizalofop	37.5-50	-	canola and sugarbeet	
Soybean	Imazethapyr	50	Sorghum	-	Singh *et al.* (2014)
	Pendimethalin	1.5	-	Sorghum and mungbean	
	Quizalofop-ethyl		-	Sorghum and mungbean	
Cotton	Fluchloralin	1.0	Cucumber	Fingermillet	Jayakumar *et al.* (1987)
	Oxadiazon	0.5-1.5		Foxtail millet	
	Oxyfluorfen	0.1-0.2		Mungbean	
	Pendimethalin	1.25			
Sunflower	Fluchloralin	1.0	Mungbean	Groundnut	Basavarajappa and
	Butachlor	1.0		Cowpea	Nanjappa (1994)
	Alachlor	1.0		Cucumber	
	Pendimethalin	1.0			

Hazards from residues of herbicides can be minimized by the application of chemicals at the lowest dosage by which the desired weed control is achieved. Herbicides such as carbamates, thiocarbamates and dinitroaniline are lost in the environment by surface volatilization. Tillage operations help in bringing deep present herbicide residues to soil surface which would aid in decontamination by volatilization. In case of deep ploughing the herbicide, layer is inverted and buried in deeper layers and thereby the residual toxicity reduced. Herbicides are inactivated by plant residues or organic matter incorporated into soil. Farm yard manure application is an effective method to mitigate the residual toxicity of herbicides. The FYM application at 10 t/ha or green manuring with sesbania to the soil found to mitigate the residual toxicity of atrazine, sulfosulfuron and dinitroanilines, pendimethalin, trifluralin fluchloralin and in sandy loam soil. If suspected residues, sensitive crop should be avoided and a tolerant crop can be grown. For example, when carry-over due to imazethapyr (Pursuit) is suspected, crops such as canola and flax should be avoided. Addition of absorbents, antidotes and safeners can also be used to priotect crop from herbicide drift. Activated charcoal (or carbon) can reduce herbicide contamination in specific areas and can also be used as a root dip to protect transplants (tomatoes, peppers, strawberries, ornamentals, *etc*.) from triazine or substituted urea herbicides. Antidotes or plant protectants are applied to the soil, crop seed or transplants to protect the crop from herbicide injury. The mode of action of antidotes may be due to deactivation or adsorption of the herbicide, preventing its absorption and translocation by the crop. *e.g.*, 1, 3-naphthalic anhydride (NA) and 2, 2-dichloro-N, N-diallyl acetamide can be used to minimize injury from EPTC. Decontamination of herbicide residues by means of controlled irrigation alone, or in combination with tillage, cropping and use of soil amendments has been achieved with success to mitigate residues.

Conclusion

Use of herbicides is increasing at a faster rate as compared to other pesticides. Newer molecules are added each year. Due to environmental and health concern, the regulatory requirements have been made longer. Herbicides have lower residue concern than other pesticides in view of their lower mammalian toxicity. Further contrary to other pesticides, herbicides are applied at planting or during early stages of crop growth, thus giving more time for degradation of the chemical in the plant and environment. Further the soil and climate conditions prevalent in the country enable faster degradation of the chemical. The fate of herbicides in the soil is a concern of many segments of society. The soil acts as an important buffer governing the persistence and fate of most herbicides in the environment. As long as soil system remains healthy, possible adverse effect from herbicides in the environment probably can be minimized. Herbicides in most instances when applied at recommended doses have not been detected in food chain or in soil at level that should cause concern.

Chapter 3

Integrated weed management in pulse crops

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Pulses are an important component of Indian agricultural economy next to cereals and oilseeds in terms of acreage, production and economic value. Pulses are an integral part of vegetarian diet of a large population in India. Besides being a rich source of proteins and essential amino acids; they also maintain soil fertility through biological nitrogen fixation in symbiotic association with Rhizobium bacteria present in their root nodules. Thus, pulses play a vital role as nitrogen fixing mini-factories, which help in sustaining crop productivity and soil health. Pulses are rich sources of protein and energy but in India, these are largely cultivated under energy starved conditions, mostly on marginal and sub-marginal land and more than three-fourth of the area under pulses is still rainfed resulting in poor crop productivity.

India is the largest producer of pulses in the world, with 25% share in the global production. The important pulse crops are chickpea (*Cicer arietinum*), pigeonpea (*Cajanus cajan*), mungbean (*Vigna radiata*), urdbean (*Vigna mungo*), field pea (*Pisum sativum*), lentil (*Lens culinaris ssp. Culinaris*), cowpea (*V. unguiculata*), lathyrus (*Lathyrus sativus L.*), frenchbean (*Phaseolus vulgaris*), horsegram (*Macrotyloma uniflorum*) and mothbean (*V. aconitifolium*. In India, production of pulses is 24.25 million tonnes with a very low average productivity of 881 kg/ha (2023-24). Among the potential pulse crops in the country, chickpea is a leading pulse crop which is grown in 9.59 million ha with annual production of 11.09 million tonnes registering an average productivity of 1151 kg/ha (2023-24). The productivity of pulses is low due to several factors. Mismanagement of weed problem is one of the major factors affecting yield of pulses adversely. Weeds create serious problem in cultivation of chickpea and reduce the yield up to 90%. The degree of reduction of yield in pulses depends on the density and duration of weed species and fertility status of soil.

Weeds are menace in pulses

One of the major problems encounter in the successful cultivation of pulses is the heavy infestation of weeds. The extent of loss depends upon nature and intensity of weeds and weed species, soil fertility, cultivars, density of the crop and duration for which weeds compete with the crop. For season long weed management, pre-emergence herbicide pendimethalin + manual weeding at 30-35 days after sowing is commonly recommended in chickpea, but its use is decreasing because of labour scarcity at critical time of weeding and increasing cost. Weeds are ubiquitous and eternal pest having prolific breeding and seeding abilities and efficient seed dispersal mechanisms. Weed management is often the costliest agronomic input. Hence, economically viable crop production and sustainable farm income largely depend on weed management. All weed control methods such as manual and mechanical, cultural, biological, chemical have inherent limitations. Single method could hardly provide desired level of weed control efficacy. Among these methods, herbicide is proven easier to apply, more efficient and cost-effective tool for weed management in diverse agro-ecosystems. Since its introduction, herbicide has been the major strategy for weed control in the developed countries, where it has revolutionized agriculture.

Limitation of weed management in pulses

Narrow-spectrum of weed control: Narrow-spectrum selective herbicides are either targeted towards grassy or broad-leaved species and cannot control diverse weed flora. Therefore, herbicide mixtures (tank-mix and/or pre-mix) are necessary to achieve broad-spectrum weed control that might increase cost of input and often difficult for farmers. Quizalofop-p-ethyl, propaquizafop-p-ethyl and clodinafop-propargyl can effectively control of grassy weeds but not broad-leaved weeds. These necessitate the use of herbicide mixtures in crops/systems.

Limited availability of post-emergence herbicides: Presently, pendimethalin 1000 g/ha as pre-emergence (PE) followed by hand weeding are being practiced for weed management in pulses. Also, pendimethalin does not control the later flush of weeds after one month of sowing. Very limited number of post-emergence herbicides available in pulses for efficient weed control. Further, two times application of herbicides (PE and PoE) are not feasible for pulse crops.

Shift in weed flora: Continuous use of a narrow-spectrum herbicide for years together might result in shift in weed flora. A crop field dominated by grass weeds for many years might gradually turn into broad-leaved weed domination after continuous use of grass-killer herbicide. Reverse may be true if there is continuous use of broad-leaved killer herbicides. In wheat, broad-leaved weed domination in the late 1960s and early 1970s changed to grass weed (A. ludoviciana/fatua, P. minor, Poa annua, Snowdenia polystachia) menace due to continuous use of broad-leaved killer herbicides such as 2,4-D, MCPA (phenoxyalkanoic acids) in India and in the world. Thus, repeated usage of a single herbicide causes shifting of weed flora and threat of future weed control programmes.

Toxicity to sensitive crop in rotation: Herbicides having higher persistence in soil can lead to residual toxicity in succeeding crops. Sensitivity of succeeding crops to fomesafen and imazamox residues was reported in maize, soybean, and chickpea. Similarly, imazamox and imazethapyr applied fields should not be cropped with mustard and mungbean in following season due to carry-over problems.

Herbicide resistant weeds: Continuous use of same herbicides over many years leads to selection pressure towards tolerant individuals ultimately leading to resistance development. Continuous use of isoproturon from 1980 as single herbicide for 10-15 years accentuated by poor application rates, spray techniques and timing resulted in evolution of resistance.

Integrated weed management (IWM)

Herbicide is a dominant weed control tool and more effective than other methods in modern agriculture. Notwithstanding, it cannot be a sole and complete solution/fool-proof strategy to the complex challenge that weeds present. Herbicides hardly attain 100% weed control because the spectrum of weed control by many herbicides is narrow. Therefore, developing effective, economical, eco-friendly and durable weed management strategies in the form of integrated weed management (IWM) are important paradigms in future weed research across crops and locations to achieve higher and sustained crop yield. The IWM is defined in a range of ways, but, at its core, is the idea that many weed management tools be used, in an integrated way, to manage weeds. Biotechnological approaches towards developing herbicide-tolerant crops and bio-herbicides, harnessing allelopathic potential of plants/micro-organisms and precision weed management using remote sensing and geographic information system (GIS), artificial intelligence/robotics are worth-mentioning for modern weed management and have been elaborated here for possible integration under IWM. However, before framing an IWM, certain principles/guidelines (*i.e.*, weed ontogeny and characteristics, critical weed competition period, climate/weather and soil conditions, whole-farm community approach, system approach, history of chemical weed control, follow-up weed prevention measures and farmers' socio-economic conditions) should be considered for diagnosis of a situation and to select suitable weed control options to be integrated for effective and durable management of composite weeds or particular problematic weeds in an area. Some of the recommendations of effective weed management in pulses are mentioned in **Table 1**.

Table 1. Weed management recommendations in pulse crops

Crop	Weed management practice	Reference
Kharif pulses		
Pigeonpea	Pendimethalin 0.75 kg/ha *fb* hand weeding at 30 DAS	Ali 1991
	Pendimethalin 0.75 kg/ha *fb* paraquat 0.48 kg/ha at 42 DAS	Padmaja *et al.* 2013
	Pendimethalin 1.0 kg/ha *fb* hand weeding at 45 DAS	Dhonde *et al.* 2009
	Trifluralin 1.0 kg/ha (PPI) *fb* 1 HW at 60 DAS	Malik and Yadav 2014
	Pendimethalin 1.0 kg/ha followed by imazethapyr 100 g/ha	Kumar *et al.* 2013, Kumar & Hazra 2012
Urdbean	Oxadiazon 0.75 kg/ha PE	Soni and Singh 1988
	Pendimethalin 0.75 kg/ha PE *fb* hand weeding at 25 DAS	Singh 2011
	Pendimethalin 1.0 kg/ha (PE) *fb* imazethapyr 100 g/ha (PoE) at 20-25 DAS	Kumar *et al.* 2013, Kumar & Hazra 2012
	Imazethapyr 55 g/ha at 15 DAS	Mandal *et al.* 2015
	Imazethapyr 35% + imazamox 35% (Odyssey 70 WG) 75 g/ha as PE + HW at 35 DAS	Tiwari *et al.* 2018
Mungbean	Pendimethalin 0.75 kg/ha PE *fb* hand weeding at 30 DAS	Parasuraman 2000
	Trifluralin 0.75 kg/ha (PPI), linuron 0.75 kg/ha and acetachlor 1.0 kg/ha (PE) *fb* hand weeding at 30 DAS	Malik *et al.* 2000
	Pendimethalin 1.0 kg/ha (PE) *fb* imazethapyr 100 g/ha (PoE) at 20-25 DAS	Kumar *et al.* 2013
	Clodinafop-propargyl + sodium-acifluorfen 122.5 g /ha at 15 DAS significantly	Nath *et al.* 2022
Cowpea	Pendimethalin 0.75 kg/ha PE *fb* hand weeding at 30 DAS	Parasuraman, 2000
	Pendimethalin at 0.75 kg/ha PE *fb* weeding at 5 WAS	Patel *et al.* 2003
	Pendimethalin 0.75 kg/ha as PE *fb* one hoeing at 20-25 DAS	Hanumanthappa, 2012
	Imazethapyr 40 g/ha at 20 DAS	Gupta *et al.* 2016
Horsegram	Hand weeding at 20 DAS	Patra and Nayak 2000, Anitha *et al.* 2003
Rabi pulses		
Chickpea	Pendimethalin 1.0 kg/ha PE *fb* quizalofop-ethyl 100 g/ha at 20-25 DAS	Kumar *et al.* 2015
Lentil	Pendimethalin 0.75 kg/ha *fb* hand weeding, metribuzin 250 g/ha as post-emergence (some varieties)	Yadav *et al.* 2013
Peas	Pendimethalin 1 kg/ha *fb* hand weeding	Dixit and Varshney 2009
Rajmash	Pendimethalin 1.0 kg/ha *fb* hand weeding	Ali 1988
Lathyrus	Trifluralin 0.75 kg/ha *fb* hand weeding, Trifluralin 0.75 kg/ha *fb* sethoxydim 0.3 kg/ha or metribuzin 250 g/ha	Wall and Friesen 1991
Spring/summer pulses		
Mungbean/ urdbean	Imazethapyr 80 g/ha (PoE) at 20-25 DAS	Kumar *et al.* 2016

Preventive methods

Restricting/stopping perpetuation of weeds from the existing stands of weeds in crop fields over the years is an approach toward prevention. Preventive measures could be: pure and clean crop seeds/ seedlings; seed act and seed certification; clean farm machineries and animals; well-decomposed farm yard manure (FYM)/ compost/sewage and sludge; weed control in nurseries; clean farm bunds, roadsides and other non-crop areas; clean irrigation channels and water and alternate irrigation systems; and enacting plant/weed quarantine law. These should be followed for a long period to restrict introduction and spread of weeds.

Physical (manual and mechanical) methods

Mechanical weeding is machine-intensive and can be adopted using tractor-drawn equipment in large farms under conventional agriculture. Some tractor-operated weeders are standard/high residue rotary hoe, spike-tooth/ spring tine harrow, flex-tine weeder, finger weeder, rotating wire weeder, pneumatic weeder. Except hand pulling and residue cover/ mulching, physical methods can hardly be recommended for conservation agriculture systems because soil disturbance is not permitted and residue is retained on the soil surface. This, however, is a boon in itself that continuous no tillage with residue can reduce annual weeds over times, but amidst weed dynamics. Brown manuring provides smothering effect and can control perennial weeds like C. rotundus, Cynodon dactylon. Digging-out underground perennating structures from deep soil layers can reduce perennial weeds considerably, but is labour-intensive and less economical. During hot summer months, soil solarization or deep ploughing for 3-5 years may lead to better control of perennial weeds. Flooding un-cropped field with 20-25cm standing water for 5-10 weekscan reduce perennial weeds like Cyperus sp., C. dactylon, and Convolvulus arvensis, but is more resource-exhaustive.

Cultural methods

It is well-known that a good/healthy crop is the best weed killer (Fletcher 1983). Being inherent recommended agro-practices for a crop, the cultural practices usually do not incur extra-cost for weed management. These practices include: competitive crops/crops cultivars, tillage, geometry, time, method, rate and depth of sowing. It also includes the kind, time, method and rate of fertilizers application time, method, and frequency of irrigation, intercropping, stale seedbed, brown manuring, crop rotation. Crop rotation can help to control some permanent weeds under mono-cropping. Cowpea (*Vigna unguiculata* L.), greengram (*Vigna radiate* (L.) Wilczek), black gram (*Vigna mungo* L.), soybean when was intercropped with maize, sorghum, and pearlmillet (*Pennisetum glaucum* L.) could manage weeds to a large extent.

Intercropping

Intercropping involves growing more than one crop in the same field at the same time. The crops may be seeded at the same time (mixed intercropping) or they may be seeded at different times (relay intercropping). Strip intercropping is a production system where different crops are grown in wide strips (usually the width of a seeder) in the same field. Intercropping can provide a number of benefits to a cropping system including stability, over yielding, and reduced chemical use (both fertilizers and pesticides). Research and experience from around the world have shown that intercropping and cover cropping systems tend to suppress weeds better than sole cropping systems. This is especially true with smother crops such as forage legumes inter seeded with a main crop such as a cereal. Intercropping grain crops can also be useful for suppressing weeds, especially when the desired crop is a poor competitor. The results of the experiment revealed that among the intercropping systems, maize + blackgram (1:1) intercropping recorded lesser total weed density and weed dry weight. Maize + blackgram intercropping along with pendimethalin 0.75 kg ha-1 as PE 3 DAS + one HW 25 DAS recorded higher weed control efficiency. Inclusion of pulses as intercrop in jute smothered dicot and sedge weeds upto 54%.

Mulching

Mulches control weeds through light exclusion, physical barrier to seeding emergence and allelopathy. Mulch includes clean straw, hay or manure, tar paper, saw dust, crop stubbles and black plastic etc. Residue mulching suppresses weeds, reducing recruitment and early growth of weeds, by (1) imposing a physical barrier to emerging weeds and (2) releasing allelochemicals in the soil. Rice residue mulch of 4-5 t/ha reduced the emergence of grass, broadleaf, and sedge species in the range of 73 to 76%, 65 to 67%, and 22 to 70%, respectively, compared with no residue control in zero till direct seeded rice. Despite the significant positive effects of mulches on weed suppression, the limited availability of residue for mulch during the rice season is a constraint. Therefore, growing short-duration catch crops such as mungbean during the fallow period between wheat harvest and rice planting and retaining the entire mungbean residue as mulch in rice is an effective weed management practice in rice-wheat system.

Site-specific/sensor-driven precision weed management

Site-specific weed management (SSWM), advocating control measures only where weeds are located at higher densities than those cause economic losses, offers economic and environmental benefits. Under usual patchy and scattered weed distribution in crop fields, site-specific, weed patch-specific or spot application of herbicide is more economical and less degrading to environment than blanket application. This reduces amount of herbicides as well as their intake into the environment. Band application with standard herbicide treatment at a half-recommended rate combined with mechanical weed control brought a satisfactory total weed reduction by 83–87%. Recently, artificial intelligence (AI) and robotics researches have geared up for weed management, which is one of the least mechanized aspects of agriculture. Robotic machines can be used to control weeds mechanically, chemically or through flame.

Possibilities for absolute mechanical weed control through robotics are being explored to potentially eliminate herbicides use in fields. Some agricultural robots for weed control are: Weed Master®, Weed Seeker® (for pot spraying), Tertill, RIPPA, Hortibot, Swag Bot, ASTERIX, AgBot II, Blue River Lettuce Bot 2, Naïo Technologies. Integration of site-specific information on the distribution, species composition and density of weeds and their effect on crop yield is decisive for successful SSWM.

Chemical method (herbicide)

Pendimethalin is the most popular herbicide used in all pulse crops. However, it is not effective in controlling all kinds of weeds for long periods. Imazethapyr, a POST broad spectrum herbicide, has been recommended for use in rainy-season pulses like pigeonpea, urdbean and mungbean. However, in winter-season pulses like chickpea, lentil and fieldpea, it has shown toxicity even at lower dose of 15 g/ha (Kumar *et al.* 2013). Clodinafop and quizalofop-ethyl can also be used as post-emergence in most pulse crops if only the grassy weeds are present in the field. Some of the commonly used herbicides in pulses and their time of application are listed in **Tables 2 and 3**.

Table 2. Herbicides recommended for mungbean, urdbean and pigeonpea

Herbicide (Trade name)	Dose (g/ha)	Product (g or ml/ha)	Application time	Remarks
Alachlor	2000-2500	4000-5000	0-3 DAS	Annual grasses and some BLWs
Fluchloralin	750-1000	1500-2000	Pre-planting	Annual grasses and some BLWs
Oxadiazon	250	1000	0-3 DAS	Broad spectrum weeds
Oxyfluorfen	100-125	400-500	0-3 DAS	Broad spectrum weeds
Pendimethalin	750-1000	2500-3000	0-3 DAS	Annual grasses and some BLWs
Quizalofop-ethyl	100	2000	15-20 DAS	Excellent control of annual grasses
Imazethapyr	50-100	500-1000	20-25 DAS	Broad spectrum weeds
Pendimethalin (PI) + Imazethapyr (PoE)	1250 + 100	4170 + 1000	0-3 (PI) and 20-25 (PoE) DAS	Broad spectrum weeds
Clodinafop-propargyl + Na-acifluorfen	187.5	1000	14-21 DAS	In mungbean for broad spectrum weeds

*Source: Dixit and Varshney (2009); modified by authors with suitable options.

Table 3. Herbicides recommended for chickpea, lentil and fieldpea

Herbicide	Dose (g/ha)	Product (g or ml/ha)	Application time	Remarks/ control
Fluchloralin	750-1000	1500-2000	Pre-planting	Annual grasses and some BLWs
Metolachlor	1000-1500	2000-3000	0-3 DAS	Annual grasses and some BLWs
Metribuzin (in peas)	250	350	0-3 DAS or 15-20 DAS	Annual grasses and some BLWs and sedges
Oxyfluorfen (in peas)	100-125	400-500	0-3 DAS	Broad spectrum weeds
Pendimethalin	750-1000	2500-3000	0-3 DAS	Annual grasses and some BLWs
Quizalofop-ethyl	50-100	1000-2000	15-20 DAS	Annual grasses
Pendimethalin (PI) + Quizalofop-ethyl (PoE)	1250 + 100	4170 + 2000	0-3 (PI) and 20-25 (PoE) DAS	Broad spectrum weeds
Topramezone (PoE)	20.6	600	14-21 DAS	Broad spectrum weeds

*Source: Dixit and Varshney (2009); modified by authors with suitable options

Herbicide mixture

Herbicide mixture might reduce/prevent the risk of herbicide resistance and/or delay the resistance development because of reduced selection pressure of herbicides. The development of resistant biotypes within the weed species happens slowly with herbicide mixtures of those having different mode of action. The frequency of occurrence of resistance usually becomes lowered in mixture compared to the frequency of occurrence of resistance by a single herbicide. It is the realization of maize farmers in the USA that atrazine+alachlor and atrazine+metolachlor mixtures kept away the development of resistance in weeds after first few reports of resistance. This could be due to alachlor and metolachlor reduced the doses of triazines, which reduced selection pressure. Similar is true in case of imazethapyr + quizalofop butyl in case of rainy season pulses like mungbean, urdbean and pigeonpea.

Way forward

To meet the future demand of burgeoning population, concerted research efforts will be needed to increase its productivity and meet the self-sufficiency of pulses in India. The good management technologies that are expected to have significant impact on pulses production need to be given priority. Among good management technologies effective weed management strategies must be on top priority. In future, following issues may be important to integrated for improving weed management in pulse crops:

- Develop cultivars with early growth vigour to suppress weed growth.
- Inclusion of in cereal-cereal systems needs to be promoted for restoring soil-fertility and to break the dynamics of weeds.
- Mechanical devices which are preferably machine driven are required for interculturing and weed control in pulse crops.
- Controlling broad-leaf weeds in pulses is a major issue but no effective herbicides are available in rabi pulses like chickpea and lentil. Identification of suitable herbicides and standardization of their doses and time of application is important.
- The main issue of conservation agriculture (CA) is efficient weed management. Therefore, technology for growing pulses in CA systems is required to be developed under different soil and climatic conditions.
- Development of herbicide tolerant cultivars of pulses will change of scenario of weed management in the coming years.
- Modern technologies such as AI, remote sensing, site-specific application, nano-technology, and drones must be included while formulating strategies for weed management in pulses.
- Under changing climate, it is expected to reduce the efficiency of herbicides. Thus, new herbicides and their dose and time of application need to be identified.
- Biological/ecological approaches must be included for long-term management of weeds.

Chapter 4

Effect of climate change on crop-weed interaction and herbicide efficacy

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It is the fact that the basic resources of light, water, nutrients and carbon dioxide are common for all terrestrial plants irrespective of the species or habitat. However, the plants that are designated as weeds, with certain special adaptive characters like dormancy, shorter life cycles, abundant seed production or vegetative reproduction potentials, variable dispersal mechanisms etc., have a competitive edge over cultivated crop plants because of their being evolved naturally at the fate of prevailing of climatic conditions. Under the conditions of changing climate, the weeds have potential to become a challenge to agricultural production and biodiversity as they possibly can out-compete crops.

Climate change

Climate change in the recent past is evidently linked to the human activities, primarily due to the burning of fossil fuels like coal, oil, and natural gas that create a blanket of pollutants (greenhouse gases), which traps sun's heat on earth (terrestrial re-radiation) and raises global temperatures, popularly known as global warming/greenhouse effect. The more of this pollution, such as carbon dioxide (CO_2), accumulates in the atmosphere, the more of the sun's heat gets trapped, and the warmer it gets on Earth. Carbon dioxide is the greenhouse gas that contributes the most (80%) to the warming, followed by methane (11%) and nitrous oxide (6%). The amount of CO_2 in the atmosphere has been increasing at an unprecedented rate since the industrial revolution, and today, the concentration of CO_2 in the atmosphere is 421 ppm which is about 50% higher than that in 1750 (280 ppm). If nothing changes, the global atmospheric CO_2 could reach 550 ppm by the year 2050 or 1000 ppm by the end of 21st century. Earth's temperature has risen by an average of 0.06° C per decade since 1850 and the rate of warming since 1982 is more than three times as fast (0.20° C) per decade. By adding CO_2 regularly to the atmosphere, the natural greenhouse effect is being supercharged causing atmospheric temperature to rise.

Effect of climate change on weeds

Rising atmospheric carbon dioxide and temperature can alter the growth and physiology of weedy plants. A few of the weed species may become inactive, while the rest may become aggressive invaders. Certain weed species possess the ability to survive and establish under changed climate by means of different dispersal and adaptive mechanisms and try to persist after they have become established

Weed shift and invasion: Weeds which are not adapted to the changing climate tend to shift to more favorable conditions. Native weeds, that are favored by changes in carbon dioxide, temperatures and rainfall will tend to become invasive by intensifying its population and range. It is predicted that alien weeds, such as *Parthenium hysterophorus* and *Chromolaena odorata* will be more aggressive under raised CO_2 level. Overall, increasing CO_2 and temperature may alter dominant weed species and increase weed problems.

Weed growth and biology: Increasing atmospheric CO_2 stimulates growth and development in several weed species. Due to changing climate, changes in timing of life-cycles are expected that will affect flowering, fruiting and reproduction as the flowering is the most thermal sensitive stage of plant growth.

Crop-Weed Competition: Changes in climatic factors such as increasing CO_2, temperature and precipitation can potentially influence crop-weed competition. The competitive effects of weeds on crops would depend on the physiological and biochemical responses, such as photosynthesis and metabolic pathways, of either or both of them. This differential response by C_3 and C_4 plants to higher CO_2 is specifically relevant to crop-weed competition because, most of the crops are C_3 plants and most of the weeds are C_4 plants. Under elevated CO_2 and warmer conditions, both C_3 and C_4 weeds are likely to be more competitive in both C_3 and C_4 crops. It is harder to manage weeds though they have photosynthetic pathways similar to that of competing crops. Elevated CO_2 concentrations would favor highly competitive C_3 weeds, such as lesser canary grass (*Phalaris minor* Retz.) and wild oat (*Avena ludoviciana*) in wheat (C_3) and weedy rice in rice (both are C_3).

Herbicide efficacy: Herbicides are preferred tool of weed management because of uniformity and ease of application, high efficacy, cost effective and time saving. Climate change factors would result in anatomical, morphological and physiological changes that could influence herbicidal uptake rates, besides translocation and overall effectiveness. Rising atmospheric CO_2 is likely to alter or negatively influence the performance of herbicides. Increasing CO_2 can increase leaf thickness and reduce stomatal number and conductance possibly limiting the uptake of foliar applied herbicides. Greater increases in biomass could result in dilution of applied herbicide and thereby reducing its efficacy. High concentration of starch in leaves, which commonly occurs in C_3 plants grown under CO_2 enrichment, might interfere with herbicide activity. Rising CO_2 can significantly reduce protein levels in plant tissues that would result in less demand for aromatic and branch chain amino acids, with a potential decline in the efficacy of herbicides. It is increasingly evident from the research findings that changing climate conditions may reduce the sensitivity (increase the tolerance) of weeds to some herbicides. For example, glyphosate-treated *Chenopodium album* grown under increased temperature and elevated CO_2 level exhibit reduced glyphosate sensitivity. Thus, the continued overreliance on glyphosate for weed control under changing climatic conditions may result in more weed control failures.

Bio-control of weeds: Climate change may indirectly affect bio-control of weeds by the way of its direct influence on the reproduction, survival, distribution and behavior of bio-agents especially insects. Feeding habits of insects may get affected due to changes in nutritional properties of weeds under high CO_2. Successfully adapted and established bio-agents may also get affected due to climate change. For example, feeding efficiency of *Zygogramma bicolorata* on *Parthenium* is reportedly decreased at the optimal temperatures above 27-30^{0}C. Similarly, reproduction and development of *Cyrtobagous salviniae*, a bio-control agent of *Salvinia molesta* may get affected due to rising temperature. Decreased plant palatability of Alligator weed *(Alternanthera philoxeroides*) under drought has reportedly caused reduction population growth of its bio-agent *Agasicles hygrophila* suggesting that drought can reduce the biological control of *Alligator weed* indirectly by interrupting plant–insect interaction.

Conclusion

The Changing climate especially ongoing increase in the concentration of the atmospheric CO_2 as well as potential changes in temperature and precipitation, may have important consequences for crop losses due to weeds. There may be a shift in the existing weed flora, which necessitates changes in planning and implementation of weed control programmes. The physiological plasticity of weeds and their greater intra-specific genetic variation compared with most crops could provide weeds with a competitive advantage in a changing environment. The changes in CO_2 concentration in the presence or absence of temperature have also been found to alter the herbicide efficacy. It may be concluded that the weeds, as they show greater genetic diversity, may become problematic under changing climate especially under high atmospheric CO_2 concentration and associated high temperature.

Chapter 5

Preventing exotic weeds through plant quarantine

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Import of plant material in bulk like food grains is always of high plant quarantine risk. Increasing trade and globalization coupled with liberalized policies further increase the risk of introduction of exotic weeds through bulk imports. Grain is defined as "seeds intended for processing or consumption and not for planting" (IPPC 2015) and grain commodities consist of bulk shipments of cereal, oilseed or pulse crops destined for use as human food, livestock feed or industrial products. Many weed seeds associated with grain crops in the field are harvested along with the crop and can be difficult to remove due to similarities in shape and size of the seeds. Depending on the destination and intended end use of the grain, some of these seeds may be introduced into new environments suitable for growth and establishment. Because large volumes of grain are traded internationally each year, this pathway may represent a considerable contribution to the spread of new weeds around the world. Several studies have reported large numbers of weed species found in sampled grain commodities and a number of globally important weeds of agriculture are thought to have been spread as contaminants in grain (Singh *et al.* 2005, 2014; Nagaraju *et al.* 2021; Dasari *et al.* 2022). The Government of India has legislated the Plant Quarantine (Regulation of Import into India) Order 2003, to regulate the import of plant material.

Plant quarantine is a mandatory requirement to regulate the entry of seed/planting material, plant products, living organisms etc. so as to prevent unintended entry of pests across nations.

Plant quarantine regulations for weeds in India

- Plant quarantine (regulation of import into India), Order, 2003
- Clause 3(12) and Schedule VIII of PQ Order, 2003
- 57 weed species are listed as quarantine weeds in the Order
- No consignment of seed or grain contaminated with quarantine weeds is permitted unless devitalized.
- Weed risk assessment

Weeds

- Weeds are just like other crop plants in size, form, morphological and physiological characters and belong to the plant families to which crop plants belong.
- Weed is a plant growing where it is not desired, highly competitive and aggressive in nature, wild and abundant, persistent and difficult to eradicate, harmful to human beings, animals and cultivated plants, grows spontaneously without being sown or cultivated and reproduce in abundance
- About 3500 plant species worldwide have been described as weeds.
- For Indian region, 169 species have been classed as weeds of agricultural lands.
- There are 975 weed species, which are present in other countries but not reported in India.

How do weeds gain entry into India?

Contaminant of crop seeds

The importation of weed seeds in grain has been found responsible for the entry of *Parthenium hysterophorus* and *Phalaris minor*.

Ornamental

Many plants introduced as ornamental have turned out to be serious weeds in India. These include, *Opuntia* sp., *Lantana camara* and *Eichhornia crassipes*.

Contaminants of packing material and feed

Importation of material such as straw and sawdust as packing material or feed provides a source of weed seeds.

Accidental import

Seeds and plant material of some species can adhere to clothes, shoes, aircraft tyres and body of animals and can be accidentally brought into India.

Machinery

Importation of used agricultural machinery imposes a substantial weed seed import risk.

Quarantine measures to prevent the introduction of exotic weeds into India

Introduction of exotic weeds into India should be prevented by suitable phytosanitary regulations. Imported seeds/planting materials should be subjected to thorough inspection by weed specialists at all point of entry. All imported used vehicles and agricultural machinery should be inspected and must be cleaned if contaminated with soil, straw, chaff or plant debris. Import of straw should be stopped. By raising the awareness of everyone to the risk that new plant importation can cause, we can reduce the impact of weed introductions. Besides, following suggestions are made for National Plant Protection Organization in this regard:

- Bulk imports of planting materials should be discouraged as far as possible because the weed introduction risk increases in proportion to the quantity of material. It is so because thorough examination and treatment of bulk consignments is difficult and the area under cultivation becomes too large for effective monitoring of the crops. If it becomes absolutely essential to import propagating material in bulk, it should be imported from seed companies/agencies reputed to produce seed/planting material under strict phytosanitary conditions.
- Bulk imports for consumption should be de-vitalized making them unfit for planting and these should be processed immediately on arrival under supervision of quarantine officials.
- All imports, whether for consumption or planting for commercial or for research purposes, should be done under 'Import Permit' only, and all conditions mentioned in the permit should be strictly followed.
- All the plant material being brought by passengers coming to India must be handed over to the plant quarantine officials for inspection at the international airports/seaports, where separate 'Plant Quarantine Counters' should be established urgently.

Table 1. World's major weeds, which are not reported in India

Country	Number of weed species
Australia, New Zealand	195
African countries	181
South East Asia and Japan	150
Middle East	118
South America	102
Europe	80
Central America	33
Russia	20

- At the international post-offices, all the mail should be passed through some kind of detection or scanning system as is done at the time of security check, and intercepted plant materials should be passed on to the plant quarantine officials for inspection. In fact, a plant quarantine official should be posted at each of the international post-offices to coordinate the interception of planting materials and their despatch to plant quarantine service for inspection before release.
- Domestic quarantine is as important as the international quarantine and, therefore, planting material should be moved from one state to another or from one place within a state to another under strict phytosanitary conditions.
- Effective linkages/cooperation should be established among various organisations/agencies involved in the import of plant material for effective Plant quarantine implementation and smooth flow of material.
- Weed risk assessment may be conducted before importing any new plant species.

Inspection and identification of weeds

In order to prevent the introduction of serious exotic weeds or of biotypes of existing weeds with their material, all imported plant/plant materials are subjected to critical examinations and only healthy material is released. Samples are examined for weed seeds by sieving through sieves of different pore sizes. Then they are critically and thoroughly examined using available standard methods such as-

Weed species of Quarantine significance to India

1. *Alectra vogelii*	16. *Cichorium pumilum*	31. *Leersia japonica*	46.*Senecio madagascariensis*
2. *Allium vineale*	17. *Cirsium vulgare*	32. *Lolium multiflorum*	47. *Solanum carolinense*
3. *Amaranthus blitoides*	18. *Conyza sumatrensis*	33. *Lonicera japonica*	48. *Striga aspera*
4. *Ambrosia maritime*	19. *Cordia crassavica*	34. *Matricaria perforata*	49. *Striga hermonthica*
5.*Ambrosia psilostachya*	20. *Cuscuta australis*	35. *Orobanche cumana*	50. *Thesium australe*
6. *Ambrosia trifida*	21.*Cynoglossum officinale*	36. *Orobanche minor*	51. *Thesium humiale*
7. *Anthemis cotula*	22. *Digitaria velutina*	37. *Oryza longistaminata*	52. *Thlaspi arvense*
8. *Apera spica-venti*	23. *Echinochloa crus-pavonis*	38. *Pennisetum macrourum*	53. *Urochloa plantaginea*
9. *Bromus secalinus*	24. *Fallopia japonica/ Polygonum cuspidatum*	39. *Polygonum lapathifolium*	54. *Veronica persica*
10. *Cenchrus incertus*	25. *Froelichia floridana*	40. *Proboscidea louisianica*	55. *Viola arvensis*
11. *Centaurea diffusa*	26. *Fumaria officinalis*	41. *Pueraria montana*	
12. *Centaurea maculosa*	27. *Galium aparine*	42. *Raphanus raphanistrum*	
13. *Centaurea solstitialis*	28. *Helianthus claifornicus*	43. *Richardia brasiliensis*	
14. *Centrosema pubescens*	29. *Helianthus ciliaris*	44. *Salsola vermiculata*	
15. *Chrysanthemoides monilifera*	30.*Heliotropium amplexicaule*	45. *Senecio inaequidens*	

Visual examination

Working samples are spread in a thin uniform layer on a clean white drawing sheet or in a white enamel tray and examined with the help of illuminated magnifier and all weed seeds are collected. Weed seeds are segregated into different types on the basis of their shape, size, colour, texture and the presence of any attachment. Segregated weed seeds are kept in screw caped vial and reference is written on the vial.

Microscopic examination

If the seeds are extremely small in size then stereoscopic binocular is used for weed seeds detection the seeds are placed in a glass Petri dish and examined under stereoscopic binocular microscope and weed seeds are segregated from the crop seeds with the help of forceps or camel hair brush.

Identification of weed seeds

Seed identification is a specialised field of taxonomy that has been developed over the past 50 years to meet the problem of labelling the crop and weed seed. Accurate identification of weed seeds is necessary for the correct labelling of weed seed and also for correct quarantine action. This requires skill and good judgement on part of seed analyst making the examination. The seeds of some kinds of plants are sufficiently distinctive that they are not easily confused with these of other kinds and their identification possess no problems. There are many groups of plants, however, in which seeds of one species may closely resemble those of another species. In some cases, one of these may be a crop plant and the other an undesirable or noxious weed like mustard and *Argemone mexicana* seeds.

Aids for identification

- With naked eyes, if seeds are large enough.
- Hand lens, if seeds are not clearly visible with naked eyes.
- Binocular microscope for extremely small seeds.
- Identification manual with colour photographs, drawings and description of important characteristics.

Identification techniques

Identification on the basis of morphological character

A collection of identified weed seeds is maintained as reference. The intercepted weed seeds are compared with reference collection for identification. Weed seeds are also identified on the basis of morphological characters by consulting identification keys.

Clues for identification

Following morphological characters of the seeds are more useful clues for identification. –

- Shape
- Size
- Peculiarities of surface structures like smooth or rough, pitting grooves, sculpturing.

- Colouring characteristics of hilum (attachment scar), mainly its shape, size and position
- Other noticeable characters like wings/ pappus, spines, awns, hairs.

Sometimes similar external morphological characteristics of different families or genera make identification difficult. hence, internal characters are examined for proper identification. These internal clues include:-

- Endosperm: amount, position and shape.
- Absence of endosperm.
- Embryo: size, shape, cotyledon, development, position, textures, thickness and inner markings of seed wall.

Identification on the basis of vegetative and floral characters

If the weed seeds could not be identified based on morphological characters, such seeds are grown in net houses in isolation under strict plant quarantine conditions to observe various vegetative and floral characters and on the basis of these characters, the weed species are identified.

Chapter 6

Weeds and weed management in rice and rice-based cropping systems

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India is one of the world's fastest growing economies and is one of the major producers of rice (*Oryza sativa* L.), which is the important staple food of more than half of the world's population. By 2050, India's population is projected to be 1.65 billion. By 2050, rice yield needs to be increased by 60% under changing climatic and economic scenario. The rice yield potential is limited by several climatic, abiotic and biotic factors, of which weeds are most prominent which needs to be managed in rice and rice-based cropping systems (RBCS) for attaining food and nutrition security in India and the world.

India has the largest national area of rice cropping (around 47 million ha). Much of this rice area is multi-cropped, and cropping patterns are very diverse. Of the 30 major cropping systems identified in India, RBCS are the most predominant. Rice-based cropping systems are major cropping system practiced in India, which include the rotation of crops involving cereals, pulses, oil seeds, cotton, sugarcane, green manures, vegetables, etc. Various RBCS have been reported from different parts of India ranging from rice-rice-rice to rice followed by different cereals, pulses, oil seeds, vegetables and fibre crops. The crop diversification with pulses, oilseeds and vegetables in RBCS helps in alleviating the poverty, generating employment, ensuring balanced food supply, and improving productivity and sustainability of the systems. Rice-rice (4.7 m ha), rice-wheat (9.2 m ha), rice-pulses (3.5 m ha), rice-vegetables (1.4m ha), rice-maize (0.57 m ha) are major RBCS in India. In addition, out of 47 m ha under rice in India, about 11.7 m ha area remains fallow. Any attempt to achieve food and nutrition security of India must include rice and RBCS. The common menace associated with all the crops in rice and RBCS is the weeds. Weeds are a leading contributor to crop losses among all biotic stresses, posing a serious threat to crops productivity and the average expenditure on weed control per acre varies between Rs. 3,700 and Rs. 7,900. Effectively managing weed infestations will play an important role in boosting productivity of rice and crops grown under based cropping systems for ensuring long-term food and nutrition security (Rao 2022).

Losses due to weeds

The data from 1,581 farm trials in 18 states collected by DWR indicated that weeds lead to India losing an average of $11 billion each year in 10 major crops, *viz*. groundnut (35.8%), soybean (31.4%), green gram (30.8%), pearl millet (27.6%), maize (25.3%), sorghum (25.1%), sesame (23.7%), mustard (21.4%), direct-seeded rice (21.4%), wheat (18.6%) and transplanted rice (13.8%). Actual economic losses were high in the case of rice (USD 4420 million) followed by wheat (USD 3376 million) and soybean (USD 1559 million). The nutrient removal by weeds were estimated as: 20-37 kg N, 5 to 14 kg P and 17 to 48 kg K in direct-seeded rice; 20-90 kg N, 2 to 13 kg P and 28 to 54 kg K in wheat; 15-39 kg N, 5 to 9 kg P and 21 to 24 kg K in ground nut. In other crops of RBCS too substantial nutrient losses due to weeds were reported. Yield losses due to weeds depend on the extent weeds are managed in farmers' fields. Sustaining the production levels of rice and RBCS and improving crops resources use efficiency demands devising and adoption of newer strategies for mitigating the detrimental-effects of weeds.

The learning objectives of my presentation is: a). understanding weeds and the menace caused by weeds and b). knowing weed management options for optimal crops productivity in rice and rice-based cropping systems.

Weeds of rice and rice-based cropping system

The rice and RBCS are infested with both upland and lowland weeds belonging to different categories of varying weeds classifications. In South and Southeast Asia alone, more than 1800 weed species grow in association with rice, more than are recorded for any other crop. A survey conducted revealed that variation occurs in dominant weed flora across different crops (**Table 1**), cropping systems, locations. Majority of the scientists reported *Parthenium hysterophorus* as the most invasive weed species as it invaded soybean, vegetable, wheat, upland rice, sorghum posing a severe threat during both kharif and rabi seasons. Weedy rice was the next problematic weed that had invaded both direct–seeded and transplanted rice fields in India. Of several weeds associated with each crop of RBCS, a few weeds predominate and cause crop yield losses.

Shifts in weed flora

The adoption of crops, cropping systems, method of crop establishment, tillage, irrigation are some of the factors that were reported to cause shifts in weed population in rice and RBCS. The weedy rice severity was observed to increase with adoption of direct-seeded rice in India. A few other examples of shifts in weed flora include: i.in a study on impact of cropping systems, an increase in dominance of *Echinochloa crus-galli*, *Fimbristylis milliacea* in transplanted rice (TPR) - wheat system, *E. crus-galli*, *Cyperus difformis* dominance increase in TPR- Pea- TPR system and increased dominance of *Cyperus rotundus* and reduced dominance of *E. crus-galli* in TPR-sugarcane system, was observed; ii.in a study on interaction between rice-wheat cropping system and tillage, under zero tillage increased dominance of *Echinochloa colona* and *Cyperus iria* with continuous zero tillage in rice and in wheat reduced density of *Avena ludoviciana* and *Chenopodium album* with increased density of *Medicago hispida*, compared to conventional tillage systems, was observed; iii. While understanding interaction of cropping systems, tillage and mulching, rice-wheat system was found to favour *Trianthema portulacastrum* while suppressed - *Solanum nigrum*; rice-maize system strongly suppressed - *T. portulacastrum* in different tillage systems but favoured - *P. oleracea* and *Solanum nigrum*; iii. Rice-lentil system suppressed both *T. portulacastrum* and *S. nigrum*. Thus, it is essential to monitor the shifts in weed flora for effectively managing weeds in rice and RBCS.

Integrated weed management: During crop growth, there is a particular time, the critical period of competition, in which the crop is very sensitive to weed competition. As a thumb rule, one third of the crops duration in the field is considered critical for crop weed competition. Thus, weeds must be managed during the first 25-33% of crop growth as it is at this the weeds are most competitive. Hand weeding and mechanical weeding using traditional mechanical weeders are still commonly used for managing weeds in rice and RBCS. However, in view of the increased cost, non-availability of labour and erratic rain that hinders use of hand weeding and mechanical weeders, farmers are favouring the use of herbicides that are relative cheaper with greater efficacy in managing weeds (Yaduraju *et al.* 2021). However, the non-availability of recommended herbicides at the needed time to farmers, the emergence of herbicide resistant weeds due to continuous herbicide use, the adverse effects of certain herbicides to environment and human health and other socio-economic factors are resulting in recommendations and use of integrated weed management (IWM) strategies. IWM relies on knowledge of cropping system effects on weed dynamics and suggests the use many different weed management tools in an integrated way to manage weeds while reducing herbicide reliance (Rao and Nagamani 2010). The direct-nonchemical weed control methods consist of mechanical, cultural, physical, and other methods, while the indirect-nonchemical weed control methods consist of preventive, cultural, and agronomic-ecological practices, and the combination of chemical and nonchemical control methods are included in integrated weed management strategies. A few of the components of IWM that were found effective in managing weeds in rice and RBCS include:

Preventive measures

Greater understanding and integration of preventive approaches in rice and RBCS may reduce the risks of herbicide resistance development, limit adverse effects of herbicides on human health and the environment, and lower the overall weed management costs. Certain of the preventive measures that are worth adoption include:

(i) Minimizing weed seed production in the field for managing weed seedbanks and to avoid weed seed dispersal in both time and space, prevention of seed production from neighbouring bunds, rice–fallow land and irrigation channels bordering cropped areas is equally important;

(ii) Minimizing dispersal of weed seeds into crops fields primarily by humans (e.g., as contaminants in crop seeds or through irrigation canals);

(iii) Promotion of seed predation in managing certain weed species in crop fields—especially where zero-tillage is used

(iv) promotion of seed decay for the management of certain relatively non persistent weeds in some cropping systems;

(v) strategies that stimulate fatal germination of weed seeds (e.g., stale seedbed)

(vi) prevention of weed germination and emergence in crops through mulching—especially in zero-till systems and especially here crop residues are not used as source of livestock feed;

Table 1. Weeds of economic importance in different crops as reported by weed scientists of India

Wheat	Rice	Soybean	Chickpea	Maize
Phalaris minor	*Echinochloa colona*	*Echinochloa colona*	*Chenopodium album*	*Echinochloa colona*
Avena ludoviciana	*Echinochola crusgalli*	*Cyperus rotundus*	*Avena fatua*	*Celosia argentia*
Chenopodium album	*Cyperus* spp.	*Euphorbia geniculata*	*Medicago denticulata*	*Cynotis axillaris*
Avena fatua	*Alternanthera* spp.	*Commelina communis*	*Chicorium intybus*	*Euphorbia hirta*
Cichorium intybus	*Cyperus rotundus*	*Dinebra retroflexa*	*Convolvulus arvensis*	*Melochia carchorifolia*
Medicago denticulata	*Commelina benghalensis*	*Physalis minima*	*Lathyrus aphaca/sativa*	*Cyperus* spp.
Parthenium hysterophorus	*Caesulia axillaris.*	*Trianthema* spp.	*Vicia sativa*	*Spilanthes acmella*
Vicia sativa	*Ammannia* sp.	*Alternanthera sessilis*	*Cyperus rotundus*	*Blainvillea acmella*
Convolvulus arvensis	*Dinebra* sp.	*Chenopodium album*	*Orabanche*	*Euphorbia geniculata*
Melilotus alba	*Eclipta alba*	*Convolvulus arvensis*	*Phalaris minor*	*Digera* spp.
Melilotus indica	*Fimbristylis millicea*	*Cynodon dactylon*	*Avena ludoricium*	*Ageratum* spp.
Rumex dentatus	*Dactyloctenium aegyptium*	*Digera arvensis*	*Euphorbia geniculata*	*Cyperus iria*

*Source: Rao *et al.* 2014

(vii) development of anaerobic germination (AG)-tolerant rice cultivars and complementary flooding strategies which can tolerate anaerobic conditions/flooding hold great potential for the suppression of weeds in DSR.

Preventive weed control measures alone are unlikely to be sufficient for the effective and economical management of weeds in rice and RBCS, but their integration with curative approaches should reduce weed management costs and increase both the likelihood of adoption of improved weed management technologies and crop establishment methods for realization of their benefits for food security.

Hand weeding

Hand weeding (HW) is most effective, if carried out at critical period of crops weed competition (CPCWC). But HW is labour-intensive, costly and time-consuming; involves high drudgery and stress on labour (bending all the time to remove weeds); difficult if the soil surface is not moist and loose; costly (if wages are high); difficulty in identifying and removing certain grassy weeds at early stages (e.g. weedy rice, *Echinochloa* spp.). However, HW is being used by farmers in rice and RBCS either alone or in combination with other methods. Depending on the crop, cultivar and its duration, one to four HWs, during CPCWC, are recommended for crops of RBCS.

Brown manuring

Brown manuring (BM) technique involves the simultaneous cultivation of green manure crops such as dhaincha, Sesbania, and sun hemp with rice. Green manure crops are later terminated using selective herbicides like 2,4 -D, whose application causes chlorophyll loss and a brown appearance, hence the term "brown manuring". Brown manuring with Sesbania and cowpea had positive responses in lowering weed density and increasing direct-seeded rice yield. The brown leaves of *Sesbania* spp. after the herbicide

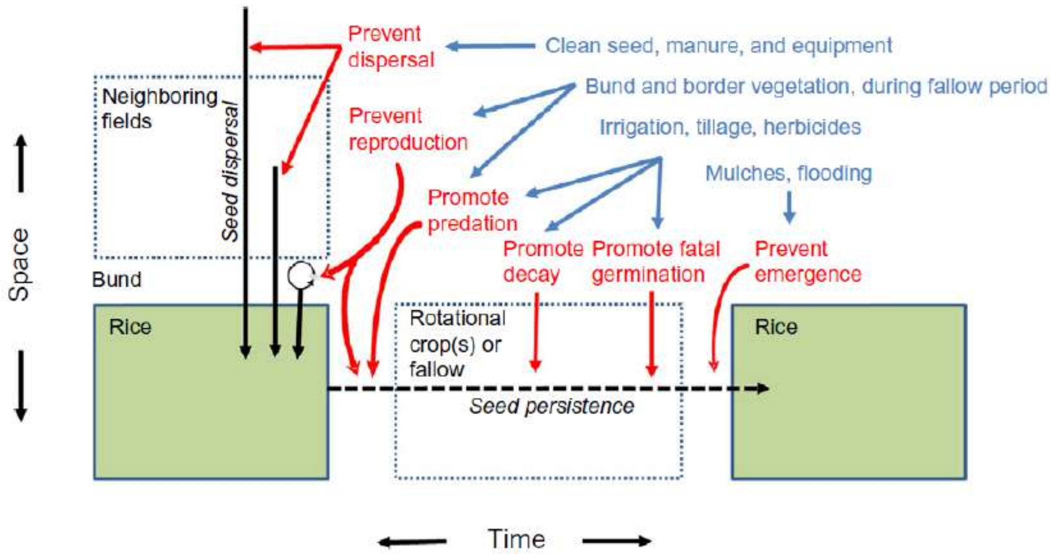

Fig. 1 Conceptual framework of preventive weed management in direct-seeded rice.

Source: Rao *et al.* 2017

application would serve the purpose of mulch and hence smother the weeds associated with rice. Sesbania BM with 15 kg seeds/ha and 2,4-D (0.50 kg/ha) applied at 25 days after seeding (DAS) was found to provide effective and eco-friendly weed management in maize, resulting in higher maize grain yield and enhanced farmers' profitability.

Crop competitiveness enhancement

Managing weeds with crop competition is an eco-friendly approach. Improved weed management could be gained by using competitive crop cultivars (with rapid early-stage growth, seedling vigor, faster leaf/shoot/root growth, taller height, faster canopy closing ability and allelopathic potential), crop density, seeding rate, direction of planting, and intercropping and with resulting enhancement of crop competitiveness against weeds. The variation in competitiveness and weed suppression among cultivars have been documented in rice, and to a lesser extent in wheat, maize and other crops of RBCS. Research has demonstrated that the integration of crop competitiveness with other methods, such as the use of herbicides and manual weeding, is successful in managing weeds in rice and RBCS.

Mechanical weeding

Running blade harrow is used as component of integrated weed management by the farmers in fields of direct-seeded rice and upland crops of RBCS. Improved weeding tools use results in labour saving (about 20-40 man days per hectare), better and timely weed control. Seeding/planting in straight rows is a prerequisite for mechanical weeding. It needs less labour and costs less than hand weeding. But mechanical weeding is: suitable for row-planted crops; timely inter-cultivation may not be practical and difficult in hardened soil or where water is limited; difficult to remove weeds within crop rows; only effective with young weeds (2- to 4-leaf stage); e) needs more labour (6-8 person-days per ha per weeding) than chemical weed control; may damage crop roots; g) the operation needs to be repeated; still some drudgery and stress on labour.

Power weeders are now available for rice which takes 2 to 2.5 hours for weeding one acre and one litre of petrol per hour and thus 5 to 6 acres of rice can be weeded in a day. For upland crops in RBCS also power weeders are available. Recently an integrated inter- and intra-row weeding systems (IIIRW) was developed, for deep rooted and widely spaced crops, by ICAR-Central Institute of Agricultural Engineering, Bhopal. Active rotary tines were used for intra-row weeding and passive tines for inter-row weeding in maize and pigeon pea crops. Weed mortality with the IIIRW system was 92.8% (Buried: 9.5%, Uprooted: 83.3%) in maize and 84.1% (Buried: 7.6%, Uprooted: 76.5%) in pigeon pea crops. IIIRW system has field capacity in ranges of 0.22–0.26 ha/h at recommended operating speeds within 0.50–0.56 m/s. The level of mechanisation in rice and RBCS in India is low (20 to 50%) and vast potential exists in using mechanical method in integration with other methods in rice and RBCS.

Herbicide use as a component of IWM

Herbicides recommended for weed management in rice and RBCS

The use of herbicides is the most economic and effective weed control practice; and therefore, the use of herbicides is increasing in India at a much faster rate of15–20% per annum, since last decade. In rice and rice based cropping systems, the use of herbicides is higher in wheat and rice, in India (Mishra *et al.* 2016). Details of recently recommended herbicides for rice established by different methods (Rao and Chandrasena 2024) and RBCS include:

Transplanted rice: Bensulfuron-methyl + pretilachlor *fb* triafamone + ethoxysulfuron; penoxsulam + butachlor; penoxsulam + cyhalofop; pretilachlor + pyrazosulfuron-ethyl (ready-mix); pretilachlor + pyrazosulfuron-ethyl (pre-mixed) *fb* bispyribac- sodium; pretilachlor + bensulfuron-methyl (ready-mix) *fb* bispyribac-sodium; pretilachlor + bensulfuron-methyl (pre-mixed) *fb* bispyribac-sodium; triafamone ; triafamone + ethoxysulfuron (pre-mix); triafamone + ethoxysulfuron (ready-mix); R-848 benzyl ester + cyhalofop-butyl (ready-mix).

Dry-direct-seeded rice: Bensulfuron-methyl + pretilachlor with safener (ready-mix) *fb* azimsulfuron *fb* metsulfuron-methyl and chlorimuron-ethyl (ready-mix); bispyribac-sodium + carfentrazone; bispyribac-sodium + ethoxysulfuron; bispyribac-sodium + 2,4-D sodium salt with adjuvant (WA); bispyribac-sodium + metamifop; cyhalofop-butyl + penoxsulam; Fenoxaprop p-ethyl + chlorimuron-ethyl + metsulfuron-methyl; oxadiagryl *fb* metsulfuron-methyl + chlorimuron-ethyl; oxadiargyl *fb* fenoxaprop-p-ethyl + ethoxysulfuron (Redy-mix); oxadiargyl *fb* bispyribac- sodium; oxadiargyl *fb* bispyribac-sodium; oxadiargyl *fb* penoxsulam + cyhalofop-buty (Redy-mix); pendimethalin *fb* florpyrauxifen-benzyl or halosulfuron-methyl; pendimethalin *fb* florpyrauxifen-benzyl or halosulfuron-methyl; pendimethalin + pyrazosulfuron; pendimethalin *fb* azimsulfuron + bispyribac-sodium *fb* 1 HW; penoxsulam + cyhalofop–butyl (ready-mix); penoxsulam + cyhalofop-butyl; pretilachlor *fb* azimsulfuron; pretilachlor or pyrazosulfuron-ethyl and bispyribac-sodium salt; pretilachlor *fb* penoxsulam + cyhalofop-butyl; pretilachlor *fb* penoxsulam + cyhalofop-butyl (Ready-mix); pyrazosulfuron + pretilachlor (pre-mix); pyrazosulfuron ethyl *fb* bispyribac-sodium; pyribenzoxim XR-848 benzyl ester + penoxsulam (ready-mix).

Wet-seeded rice: Bispyribac-sodium + metamifop; bispyribac-sodium with fenoxaprop-p-ethyl or cyhalofop-butyl (tank mix); cyhalofop-butyl+ penoxsulam (pre-mix); fenoxaprop-p-ethyl + penoxsulam; florpyrauxifen-benzyl + cyhalofop-butyl; florpyrauxifen-benzyl + cyhalofop- butyl /ha; flucetosulfuron; penoxsulam + cyhalofop-butyl; triafamone + ethoxysulfuron and triafamone + ethoxysulfuron (pre-mix)

Wheat: Pendimethalin; pyroxasulfone; sulfentrazone, pinoxaden, metsulfuron, 2,4-D, metribuzin, clodinafop propargyl, sulfosulfuron, carfentrazone-ethyl, clodinafop propargyl + metsulfuron-methyl, clodinafop propargyl + carfentrazone-ethyl, sulfosulfuron + metsulfuron, metsulfuron + carfentrazone, metribuzin + clodinafop, and metsulfuron+ iodosulfuron.

Maize: Atrazine, pendimethalin, metribuzin, 2,4-D, tembotrione, topramizone, pyroxasulfone atrazine + topramezone, atrazine + tembotrione, mesotrione + atrazine,halosulfuron

Groundnut: Pendimethalin, pendimethalin + imazethapyr, diclosulam, alachlor, butachlor, fenoxaprop-ethyl, quizalofop-ethyl, propaquizafop, imezathapyr, flauzifop-butyl, quizalofop-ethyl, fomesafen + fluazfop-p-butyl, propaquizafop + imazethapyr, Imazethapyr + imazamox, Na-acifluorfen + clodinafop, imazethypyr + quizalofop

Pulses

***Kharif* pulses** (greengram, urd bean, pigeon pea): Pendimethalin PE *fb* imazethapyr PoE

***Rabi* pulses** (chickpea, lentil, peas): Pendimethalin PE *fb* quizalofop-ethyl

Summer pulses (greengram, urd bean): Imazethapyr

Pulses in rice fallows: Butachlor, pendimethalin, fenoxaprop-ethyl, quizalofop-ethyl, cyhalofop-butyl, clodinofop-propargyl, propaquizafop, imezathapyr, fomesafen + fluzifop-butyl, acifluorfen + clodinofop-propargyl

Herbicide resistant weeds

The injudicious use of herbicides is resulting in the evolution of resistance to commonly used herbicides in targeted weed species. There is diversity of weed species in the rice-wheat cropping system, which has already evolved resistance to a few herbicides in India. In India, *Phalaris minor* has developed multiple-herbicide resistance to PSII, ACCase and ALS inhibitors; *Rumex dentatus* has evolved resistance against metsulfuron (ALS inhibitor) and cross-resistance to mesosulfuron + iodosulfuron, pyroxsulam, halauxifen + florasulam; *Polypogon monspeliensis* has developed resistance against sulfosulfuron, mesosulfuron and pyroxasulam; *E. colona* and *Commelina communis,* in soybean, became resistant to imazethapyr (an ALS inhibitor); *E. crus-galli* and *C. difformis* became resistant to bispyribac-sodium (an ALS inhibitor) in rice. Thus, a proper understanding of herbicide resistance, its evolution, and mechanisms and development of management methods is essential for adequately managing weeds in rice and RBCS.

Weeds use

The weeds usage is best method of managing them. Weeds can be utilized for several societal benefits (Chandrasena 2023). For example: a few weeds may be used as fodder but before the weeds set seed. The bunds in the farm may be used for raising improved fodder grasses to feed farm animals.

Several other methods were envisaged as components of IWM for managing weeds in rice and RBCS including: allelopathic crop varieties usage, herbicide tolerant crops use, cover crops and live mulching, water and nutrient management, conservation agriculture practices, biocontrol methods etc (Rao and Matsumoto 2017).

Conclusion

Better understanding on impact of climate change on crop weed balance need to be considered while choosing components of IWM to shift the crop weed balance in favour of crops. The integrated ecological weed management approaches are advocated for optimizing financial, social and environmental costs and benefits (Rao and Chandrasena 2022; Rao and Korres 2024). The ultimate objective of any recommended integrated weed management strategy for rice-and RBCS should be to increase income of the farmer through improved resource use and reduced cost of weed management while effectively and sustainably managing weeds

Chapter 7

Nanotechnology application in weed management

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Despite the efforts made by the management scientists, the productivity of crops has not been realized to its potential. This is attributed to low nutrient and water use efficiency by crops and stiff competition by the weeds and crop pests. Breaking this yield barrier through the new scientific approach, nanotechnology may bestow the expected result to increase the productivity of crops and meet the challenges of food security of the country in the coming years. Hence, the Indian Government is looking towards nanotechnology as a means of boosting agricultural productivity.

The term 'nanotechnology' encompasses a wider range of activities. 'Nano' is used in the world of science to mean one billionth. The Royal Society uses the following definition: "Nanotechnologies are the design, characterization, production and application of structures, devices and systems by controlling shape and size at nanometer scale." (RSRAE, 2004). At such scales, the ordinary rules of physics and chemistry no longer apply. For instance, materials' characteristics, such as colour, strength, conductivity and reactivity, can differ substantially between nanoscale and macro.

Current challenges in weed management

Weed management has traditionally relied on three primary strategies: mechanical, chemical, and cultural practices. Each of these methods has its advantages but also faces significant limitations that warrant the exploration of alternative approaches.

Mechanical weed management involves physical removal techniques such as tilling, mowing, and hand-pulling. While these methods can be effective, they often require significant labor and can lead to soil disturbance, which may inadvertently propagate weed seeds and exacerbate the problem. Additionally, mechanical control is not always feasible for large-scale operations or in areas with dense weed populations.

Chemical control through herbicides has been a mainstay in weed management, offering the advantage of quick and efficient weed suppression. However, the widespread use of herbicides has led to the emergence of herbicide-resistant weed species, making it increasingly difficult for farmers to achieve effective control. Resistance not only diminishes the efficacy of existing herbicides but can also lead to increased application rates and costs, creating a cycle of dependence on stronger chemicals.

Cultural practices, such as crop rotation and cover cropping, aim to disrupt the life cycles of weeds by altering their growth environment. While these practices can be beneficial, they often require careful planning and may not provide immediate results. Moreover, cultural methods may not be sufficient alone in the face of aggressive weed species that can outcompete crops.

The environmental impact of traditional weed management strategies cannot be overlooked. Herbicide runoff can contaminate water sources, affecting aquatic ecosystems and human health. Additionally, the reliance on chemical inputs raises economic concerns for farmers, as fluctuating prices and regulatory changes can significantly affect profitability.

These challenges underscore the necessity for new, innovative approaches to weed management that integrate sustainable practices and leverage advancements in technology. By addressing the limitations of traditional methods, we can move toward more resilient and environmentally friendly strategies in managing weeds.

Nanotechnology application in weed management

Although herbicides will continue to be the dominant technology in weed management programs, several problems have arisen from reliance on herbicides including herbicide movement to non-target areas, environmental contamination and development of herbicide-resistant weeds. Continuous exposure of plant community having mild susceptibility to an herbicide in one season and different herbicide in another season develops resistance to all the chemicals in due course and becomes uncontrollable through chemicals. The performance of herbicides in tropical environments can sometimes be erratic and inefficient. This is particularly true for soil-applied herbicides where high temperatures, intense rainfall, low soil organic matter and microbial activity results in rapid breakdown and loss through leaching. Further, the irrigation process decreases the herbicide concentration led to reduced weed control efficiency coupled with leaching and potential ground water pollution. Thus, the half-life period for many soil applied herbicides remains a very short period of time ranging from a few hours to a couple of weeks. Whereas some of the herbicide's parent material persist in soil for long time and results in residual toxicity problems. Furthermore, the herbicides available in the market are designed to control or kill the germinating or growing above ground part of the weed plants. None of the herbicides are inhibiting the viable underground propagating materials. It is time to think laterally to knock down the problems encountered in the management of weeds and herbicide residues with the new science nanotechnology. In India, the Tamil Nadu Agricultural University, Coimbatore pioneered in the areas of developing controlled release nanoherbicide formulations, season long weed control with slow-release herbicide, exhausting weed seed bank with nanoparticles and faster degradation of herbicide residue with metal nanoparticles for soil clean up.

Mechanisms of nanotechnology in weed control

Nanotechnology presents a range of mechanisms that can significantly enhance weed control strategies, addressing the limitations of conventional methods. Key applications include targeted delivery systems for herbicides, nano-enabled sensors for monitoring weed growth, and environmentally friendly nanoparticles that disrupt plant growth.

One of the most promising aspects of nanotechnology in weed control is the development of targeted delivery systems for herbicides. Traditional herbicides often affect non-target species and can lead to environmental contamination. Through nanotechnology, herbicides can be encapsulated in nanoparticles that facilitate site-specific delivery. This method allows for the direct application of herbicides to the target weed species while minimizing exposure to surrounding crops and beneficial organisms. The controlled release of herbicides from these nanoparticles can enhance efficacy, reduce the total amount of chemical applied, and lower the risk of herbicide resistance development among weed populations.

In addition to targeted herbicide delivery, nano-enabled sensors play a crucial role in monitoring weed growth and health. These sensors can detect specific biochemical markers or physical changes in weeds, providing real-time data on their growth patterns and stress responses. By integrating these sensors into agricultural practices, farmers can make informed decisions about when and how to intervene in weed management, thus optimizing resource usage and reducing unnecessary chemical applications.

Furthermore, environmentally friendly nanoparticles are being developed to disrupt the growth of weeds. These nanoparticles can interfere with critical biological processes in plants, such as photosynthesis or nutrient uptake, leading to stunted growth or even plant death. This method not only targets weeds effectively but also minimizes collateral damage to beneficial plants and microorganisms in the soil ecosystem.

Overall, the integration of these nanotechnology mechanisms into weed management practices holds the potential to revolutionize agricultural systems by providing more efficient, targeted, and environmentally sustainable solutions. Through these innovative approaches, farmers can better manage weed populations

Nanoherbicides to manage the perennial weeds

The task sounds simple but it remains unsolved over several decades. A perennial weed propagates/ survives through underground structures like rhizomes and stolon (*Cynodan dactylon*), tubers (*Cyperus* spp.) and deep root (Solanum elaeagnifolium). Cultural practices like ploughing, hand weeding and hoeing through implements increase the infestation of these perennial weeds rather than control. Tillage may have a harmful effect, instead of controlling it will help to spread through stem cuttings.

Compared to foliar absorption, root absorption is a simpler process. Roots do not have cuticles like leaves; although, mature roots may be covered by a suberized layer. This means that there are few barriers to herbicide absorption by plant roots. Since roots are essentially lipophilic, lipophilic herbicides will be readily absorbed. In fact, herbicides log Kow values are good predictors of root absorption and xylem translocation. Theoretically, absorption could occur anywhere the root system comes in contact with the herbicide. However, there is evidence to suggest that most herbicide absorption occurs in the area of few millimeters behind the root tip. This is the area where most water and nutrient absorption occurs and is characterized by a profusion of root hairs which is intended to increase the root surface area. The casparian strip is also less developed in this area. If we assume that herbicide absorption is primarily due to mass flow in the soil solution and diffusion in response to concentration gradients, then this area of the root is the likely location of most herbicide absorption. Molecular characterization of underground plant parts for a new target domain and developing a receptor-based herbicide molecule to kill the viable underground propagules is necessary. Selectivity of such herbicides can be increased by smart delivery mechanism with the help of nanoparticles.

Due to incredibly small proportions of nano-scale herbicides, which can easily blend with soil and reach the seeds that are buried below the reach of tillers and conventional herbicides. This approach will destroy the weeds even when the seeds are buried in soil and will prevent them from growing under most favourable conditions (Food quality news, 2006). As the nanoparticles are target specific, they can be used to kill the weeds and to get better yield. Herbicides like atrazine and triazine could be encapsulated to get an efficient release to the plants (Agri nanobiotech 2016).

Nanoherbicides for rainfed agriculture

Agricultural production in the rainfed areas depends on various factors which interact either to enhance output or to limit production. Among the factors limiting the production, weeds ranks top. Under rainfed conditions, water is the most important resource that decides the success or failure of the crop. Presence of weeds with well-developed root systems and more efficient in extracting moisture, become a threat to crop production in the rainfed areas.

A herbicide molecule broadcasted along with crop seed at the time of sowing should be available without degradation till the receipt of the next rain. To achieve this a new herbicide formulation have to be developed to release the active ingredients in a controlled manner based on the soil moisture stress. It should remain unaffected and disperse whenever a sufficient level of moisture is received. So that the weed seeds which will start germinating with the receipt of rain will get killed by the moisture based controlled formulations of herbicides. An experiment was conducted to engineer a core shell nanomaterial to load herbicide active ingredients for controlled release in rainfed agriculture (Kanimozhi and Chinnamuthu, 2012). Manganese carbonate core material was coated with suitable polymers such as sodium Poly Styrene Sulfonate (PSS) and Poly Allylamine Hydrochloride (PAH) by Layer-by-Layer method (LBL) to obtain water soluble core-shell particles. Hollow-shell particles were formed from the core-shell particles by etching process. These hollow-shell particles were loaded with pendimethalin herbicide using a passive method to get controlled release of herbicide active ingredient. It was observed that the formulation was remain intact even upto 230oC temperature and without any microbial degradation.

Detoxification of herbicide residue

Nanoscale particles represent a new generation of environmental remediation technologies that can provide cost effective solutions to the most challenging environmental clean-up problems. Nanoscale iron particles have large surface areas and high surface reactivity. They provide enormous flexibility in in situ applications. Research has shown that nanoscale iron particles can be effectively used for the transformation and detoxification of a wide variety of common environmental contaminants such as chlorinated organic solvents and chlorinated pesticides. Modified iron nanoparticles, such as catalysed nanoparticles have been synthesized further to enhance the speed and efficiency of remediation (Joo and Zhao, 2008).

Residual problems due to the application of atrazine herbicide pose a threat to widespread use of the herbicide and limit the choice of crops in rotation. Atrazine has high persistence (half life-125 days in sandy soils, (Cox, 2001) and mobility in some types of soils because it is not easily absorbed by soil (IPSC, 1990) and often causes contamination of soil and groundwater. In USA, atrazine has been classified as a Restricted Use Pesticide (RUP) due to its potential for groundwater contamination (Ware, 1986). In soils, atrazine undergoes abiotic hydrolysis to hydroxyatrazine, but this occurs very slowly unless dissolved organic matter is present or the soils are extremely acidic. Photolytic degradation of atrazine is slow with an estimated half-life in water about a year. It is generally biodegraded by soil microorganisms to hydroxyatrazine, desethylatrazine, or deisopropylatrazine, with subsequent metabolism to cyanuric acid. This may be followed by relatively complete degradation to CO2 (mineralization) within 20 weeks. Complete biodegradation (mineralization) of atrazine was not observed in either saturated or unsaturated soils, at different depths over a period of 120 days. Based on the in vitro study Susha and Chinnamuthu (2009) found that silver modified ferric oxide (Fe3O4)-CMC nanoparticles was superior in degrading the atrazine. They showed 82-88% atrazine was degradation within 24 hours of treatment.

A study was conducted to degrade the 2,4-D residues using photocatalytic behavior of nanopartilces. Titanium dioxide (TiO2) nanoparticles doped with platinum (Pt) particles was synthesized by sol-gel method. The electrons generated on the TiO2 surface by UV light illumination quickly move to Pt particle to facilitate the effective separation of the photogenerated electron and holes, resulting in the significant enhancement of photocatalytic activity. Pt plays a positive role as electron acceptor, more acceptor centers are provided with increasing Pt-doping, therefore the degradation rate for 2,4-D increases with the increase of Pt content (Abdennouri *et al.* 2015).

Future trends and innovations

The evolution of nanotechnology in weed management is poised to make significant strides in the coming years, driven by emerging technologies, anticipated regulatory changes, and the critical role of research in developing sustainable agricultural practices. As society increasingly seeks eco-friendly alternatives to conventional agricultural methods, the potential of nanotechnology to transform weed management cannot be overstated.

One of the most exciting developments on the horizon is the integration of artificial intelligence (AI) and machine learning with nanotechnology. These technologies could enhance the precision of nanoparticle application in the field. For example, AI algorithms could analyze real-time data from nano-enabled sensors to determine the optimal timing and dosage of herbicides, thereby maximizing efficacy while minimizing environmental impact. This synergy between AI and nanotechnology promises to create more efficient, data-driven approaches to weed management.

Regulatory frameworks are also expected to evolve in response to the growing use of nanomaterials in agriculture. As the safety profiles of various nanoparticles are thoroughly evaluated, regulatory agencies will likely establish guidelines that promote responsible use while ensuring environmental and public safety. This could lead to a more standardized approach to the approval and application of nanotechnology-based products in agriculture, fostering greater acceptance among farmers and consumers alike.

Research will play a pivotal role in this landscape, particularly in understanding the long-term effects of nanotechnology on ecosystems and human health. Collaborative efforts among universities, research institutions, and industry stakeholders will be crucial to investigating the potential risks and benefits associated with nanomaterials in agricultural settings. This research could lead to innovative solutions that not only address weed management challenges but also enhance soil health and biodiversity.

Furthermore, the drive towards sustainability will necessitate the development of biodegradable nanoparticles that can break down without leaving harmful residues in the environment. As consumer awareness of environmental issues increases, the demand for sustainable agricultural practices will likely push the industry toward these innovative solutions.

Conclusion

The integration of nanotechnology into weed management strategies represents a significant advancement in agricultural practices, offering numerous benefits that could enhance sustainability, efficiency, and overall productivity. By harnessing the unique properties of nanomaterials, farmers can not only improve the effectiveness of herbicides but also reduce their environmental impact. Targeted delivery systems and controlled release formulations enable precision in weed control, minimizing the exposure of non-target species and ecosystems to harmful chemicals. This shift towards more sustainable practices aligns with the growing demand for environmentally friendly agricultural solutions. Moreover, the potential of nanotechnology extends beyond herbicide application. The use of nano-enabled sensors for real-time monitoring of weed growth and health allows for timely interventions, optimizing resource usage and reducing unnecessary chemical applications. Furthermore, the development of environmentally friendly nanoparticles that disrupt weed growth presents an alternative approach, emphasizing the importance of integrating innovative technologies into traditional agricultural methods. In summary, the future of nanotechnology in weed management is bright, with advancements in AI, evolving regulatory landscapes, and ongoing research paving the way for sustainable agricultural practices that benefit both farmers and the environment.

Chapter 8

Herbicide tolerant crops: A new tool in weed management

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Since the discovery of 2,4-D in the 1940's, the herbicides have been the main stay for the management of weeds world over. Over the years, discovery and development newer molecules were made for management of specific weed problems. Herbicides have been responsible for increasing and sustaining the productivity of the crops by reducing the losses caused by the weeds. Presently, herbicides comprise about 45% of the total global pesticide market. However, its share in India is barely about 18%. Continuous use of herbicides belonging to the same class has led to the shifting of weed flora and more seriously the development of resistance to herbicides. This necessitated the use of alternate herbicides or herbicide mixtures. The Herbicide resistant weeds are a global problem. It is reported that, ccurrently, there are over 250 weed species (145 dicots and 105 monocots) infesting 86 cropping and non-cropping systems in 66 countries that have developed resistance to 160 different herbicides belonging to 23 families with as many sites of action (Heap 2016). The introduction of genetically modified (GM) herbicide tolerant crops (HTCs) enabled the use of non-selective herbicides that would control a wide spectrum of weeds including the perennial/parasitic weeds. GM crops are made by transferring the genes of commercial interest from one organism to another through genetic engineering. At a time when herbicide with new site of action was not forthcoming, HT technology provided an excellent alternative for the management of HR weeds, which was widely adopted. The HT technology was a land mark development in the history of weed management. The technology introduced in 1996 quickly found wide adoption among the farmers. In 2018, nearly 90% (including 41% with stacked traits) of the 192 mha of area planted with GM crop was under HTCs (ISAAA, 2018). Soybean (50% of total GMC area), maize (31%), cotton (13%) and canola (5.3%) are the major GM crops under cultivation. GM crops have been in cultivation in over 26 countries including 21 developing countries, involving over 17 million farmers. The leading countries that have adopted GMCs are- USA, Brazil, Argentina, Canada and India, collectively occupying 91% of the total biotech area. Although the crops resistant to atrazine, bromoxynil, imidazolines and glufosinate have been commercialized, glyphosate-tolerant crops have taken the prime position. The glyphosate tolerant soybean, corn and cotton occupied 82, 30 and 68% of the global acreage and the respective figures in the USA being 94, 89 and 89%. The average biotech crop adoption rate in the top five biotech crop-growing countries increased in 2018 to reach close to saturation, with USA at 93.3% (average for soybeans, maize, and canola adoption), Brazil (93%), Argentina (~100%), Canada (92.5%), and India (95%).

Very few agricultural technologies in the past have found such a large-scale adoption in such a short time as the HTCs. The phenomenal adoption of HTCs is attributed to the efficient, convenient and economical management of weeds with the application of a single herbicide. A range of herbicides either in mixtures or in sequence were traditionally used to control a wide spectrum of weeds. Some of these herbicides often had questionable record with respect to safety on crop, non-target organisms or on the environment. The HTC technology thus acted as a perfect example of ideal weed management option. The technology also favour in conservation agriculture (CA). Weed management under no-till condition with crop residues on the soil surface poses a serious challenge. Predominance of perennial weeds under no-till condition further exacerbated the problem. The HTC technology came as a viable alternate technology for weed management in CA.

Issues in adoption of HTCs

Despite the huge success of HTCs, the technology has not found favour in many countries. There is a growing criticism against all the GM technologies. The issue has been the subject of endless debates and discussion. The major concerns are summarized below:

Growing dependence on herbicides: Acute labour shortage and increasing wages are the main reasons for more and more famers to go for chemical control of weeds. The herbicides have no or little negative impact when used judiciously and as per recommendation. The benefits far outweigh risks associate with herbicide use. Overreliance on herbicides alone is however to be discouraged. Integrating other methods of weed control with herbicides is strongly advocated for long term sustainable management of weeds.

Development of super weeds: It is apprehended that pollens from HT crop may hybridize with its close/ wild relatives resulting in development of so-called super weeds. They are termed as super weeds as they defy control with the herbicide in use. This is a possibility if HT crop co-exist with its wild relatives. For instance, in rice this is likely to happen in areas where wild rice and weedy rice are grown nearby. However, such an event is unlikely to happen, if HT cotton, soybean or maize were to be grown in India, as wild relatives of these crops are not found in the country. A rigid view of the situation is therefore not proper.

Development of HR weeds: Continuous use of the same herbicide leads to the development of resistance in weeds. It is a global problem. As on 2016, there were 250 weed species (145 dicots and 105 monocots) infesting 86 cropping and non-cropping systems in 66 countries resistant to 160 different herbicides belonging to 23 families with as many sites of action [Heap 2016]. Same things hold true for use of herbicides associated with HTCs. However, glyphosate – the principal herbicide associated with HT technology, the resistance development in weeds was not taken seriously, as glyphosate belonged to the lower risk group. Expectations were proved wrong with the reports of increasing number of weeds showing resistance to glyphosate over the years. As on 2017, 38 weed species in 34 crops from 37 countries reported to have developed resistance to glyphosate (Heap and Duke 2017). The management of glyphosate- tolerant weeds has become a major challenge in many countries. Growing *Roundup-Ready* crops (brand name for glyphosate- tolerant crops) in successive years was the major reason for this situation. The problem could have been avoided or delayed, had rotation of crops and herbicides was strictly practiced from the beginning.

Safety of GM food*:* The presence of a 'foreign' gene is alleged to impact the quality and safety of the food and in turn the health of humans and animals. GM food has been subjected to the most elaborate tests ever carried out and no regulatory agency in any country has found any evidence of its adverse effect. Millions of people have been eating GM food in many countries for decades without any health issues is a proof of its safety.

Infringement of farmer's right: It is argued that the HT technology forces farmers to buy seeds from the seed companies each season. It is true with hybrid seeds also. It is not unreasonable to incur some extra cost in accessing a technology which is useful and profitable.

The future of GM crops in India

Bt cotton is the only GM crop which is being grown commercially in India. Despite its huge success, other similar technologies have hit the road block. Bt-brinjal, after 7-8 years of regulatory trials was approved for commercialization in 2009 by the GEAC – the statutory body responsible for approval of GMOs. But the government, under immense pressure from the anti-GM lobby declared in 2010, an indefinite moratorium on GM technology. The HT mustard technology developed even by a public institution (Delhi University) could not get through. All GM trials including HT cotton, maize are on hold. A clear-cut Government policy on GMOs is urgently needed to break the dead lock. While the Government is indecisive, the country is witnessing a large-scale illegal cultivation of HtBt-cotton in several parts of the country.

Conclusion

There is overwhelming support for HT technology by farmers and scientists. The Government must consider lifting the moratorium put on GM technology immediately. Farmers should be given access to new technologies that help them lower cost of cultivation and increase profits. Weed management accounts for 25-30% of the total cost of cultivation. Herbicides, on an average reduce the cost of weeding by 50-60%. The large-scale cultivation of HtBt cotton in large parts of the country is a clear reflection of the merits of the technology. The concerns on impact on GM technology on environment and of GM food on health and safety are scientifically unfounded. Attempts must be made to discourage biased, unsubstantiated and unscientific allegations leveled by the anti-GM lobby. It should not become an issue of emotion and politics. It should be remembered that no technology can solve all problems, no technology can last forever and problems do not remain the same. Serious efforts must be made to engage in public debate and share the right knowledge with all stakeholders, including decision makers. Learning from other countries, we need to develop a sound strategy to harness much of the benefits while avoiding the mistakes.

Chapter 9

Integrated weed management in millets

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Millets are a group of crops which are small seeded coarse grain cereals grown for food and fodder purposes. Millets are considered to be the earliest domesticated food crops in Asia and Africa, and are rich in diversity. Millets have been categorized in two groups, major millets *i.e.*, sorghum (*Sorghum bicolor* L.), pearl millet (*Pennisetum glaucum* L.) and minor or small millets comprising finger millet (*Eleusine coracana* L. Gaertn.), barnyard millet (*Echinochloa frumentacea* L.), little millet (*Panicum sumatrense* Roth ex. Roem. and Schult.), foxtail millet (*Setaria italica* L.), kodo millet (*Paslpalum scrobiculatum* L.) and proso millet (*Panicum miliaceum* L.). In India, during the past 50-60 years their cultivation and consumption reduced due to availability of high yielding varieties of rice and wheat. However, in recent years, owing to their high nutritional values and several health benefits, awareness to millets as nutri-cereals has increased and they are in high demand again. During 2022-23, millets in India were cultivated on an area of 12.70 million hectares with a production of 17.32 million tonnes. They are the prominent rain-fed crops and are physiologically very efficient. The productivity of millets is quite low which needs to be increased through development of better genotypes and optimum management practices.

Weeds are one of the major obstacles in increasing the productivity of millets especially during rainy season. These crops are relatively poor competitors for weeds especially during the early growth stages (first few weeks) of the crop. During this phase, millets grow slow compared to the weeds. Appropriate weed management would help improve productivity and input use-efficiency of these crops. When improved agricultural technologies are adopted, efficient weed management becomes even more important, otherwise the weeds rather than the crops benefit from the costly inputs.

Current challenges of weed management in millets

- Mostly grown in rain-fed area
- Poor crop management
- Less availability of selective pre and post-emergence herbicides
- Studies indicated disadvantage to millets compared to some weeds under elevated CO_2
- Response to pre-emergence herbicides is erratic –soil moisture plays a major role
- Herbicide-resistant weeds
- Management of parasitic weed - Striga

Crop-weed competition and yield losses

Weeds compete with crop for nutrients, soil moisture, space and sunlight. Millets are poor weed competitors in the early stage of growth. It is important to control weeds during the critical period of weed competition which is around 25-40 days after sowing/planting. If not controlled timely these harmful plants reduce the yield of sorghum (15-83%), pearl millet (16-94%), finger millet 55-61 and kodo millet by 46%. In addition, weed infestation causes increased cost of cultivation, reduction in quality of the produce, and acts as host for pests and pathogens. As most of the millet-lands sufferer from poor soil fertility due to their marginal nature, the removal of nutrient by the weed further deteriorates the situation. Similarly, depletion of soil moisture by weeds, may create a severe moisture deficit condition for the millets to grow.

Weed management options

Millets are primarily grown on under-nourished soils with poor crop management. Improper agronomic practices like broadcasting method of seed sowing and fertilizer application help in abundant growth of weeds. Weeds in these crops are mostly managed by weeding once at the early growth stage. Herbicide use is restricted due to non-availability of selective herbicides in millets. Different weed management options in millets could be:

i. Preventive methods
ii. Stale seed-bed
iii. Reduced crop row spacing
iv. Mulching
v. Intercropping with legume crops
vi. Inter-culture/weeding
vii. Herbicide-use in millets

Striga management in sorghum and pearl millet

- Application of atrazine 0.75 kg/ha pre-emergence *fb* 2, 4-D 0.5 kg/ha PoE
- Crop rotation with trap crop/catch crops *i.e.* soybean and cotton
- Intercropping of sorghum /pearl millet with groundnut, soybean and cowpea and green-manuring crops like *Sesbania*
- Hand weeding and mechanical weeding
- Reduce weed seed bank in soil

Table 1. Major weeds associated with millets

Grass	Broad-leaved	Sedge
Cynodon dactylon	*Acanthospermum hispidum, Achyranthes aspera*	*Cyperus rotundus*
Brachiaria ramose	*Ageratum conyzoides, Amaranthus viridis*	*Cyperus iria*
Digitaria sanguinalis	*Alternanthera sessilis, Boerhavia diffusa*	
Dactyloctenium aegyptium	*Celosia argentea, Commelina benghalensis*	
Dinebra retroflexa	*Convolvulus arvensis, Cleome viscosa*	
Eleusine indica	*Digera arvensis, Portulaca olerecea*	
Echinochloa colona	*Euphorbia hirta, Eclipta alba*	
Setaria glauca	*Trianthema portulacastrum*	
Paspalum paspaloides	*Tridex procumbens, Tribulus terrestris*	
Paspalidium flavidum	*Xanthium strumarium, Striga* sp. *(parasitic weed)*	
Sorghum halepense		

Table 2. Herbicide-use in millets

Millet	Herbicide	Dose (g/ha) & Time of application	Weeds controlled	Additional information
Sorghum, Pearl millet	Atrazine	1000, 1-2 DAS	GR & BL, Striga	1 weeding 30 DAS
	Pendimethalin 38.7%	675, 1-2 DAS	GR & BL	1 weeding 30 DAS
	Metolachlor	500, 1-2 DAS	GR	Under legume intercropping
	2, 4-D	500, 25 DAS	BL	1 weeding 40 DAS
Finger millet, Barnyard millet, Little millet	Atrazine	500, 1-2 DAT	GR & BL	1 weeding 30 DAT
	Oxyfluorfen	100, 1-2 DAT	GR & BL	1 weeding 30 DAT
	Pyrazosulfuron	20, 1-2 DAT	BL, SG & some GR	1 weeding 30 DAT
	Metsulfuron	4, 20 DAT	BL	1 weeding 40 DAT
	2, 4-D	500, 25 DAT	BL	1 weeding 40 DAT
Kodo millet	Metribuzin	150, 1-2 DAT	GR & BL	1 weeding 30 DAT
	Pyrazosulfuron	20, 1-2 DAT	BL, SG & some GR	1 weeding 30 DAT
	Pendimethalin 38.7%	675, 1-2 DAT	GR & BL	1 weeding 30 DAT
	Metsulfuron	4, 20 DAT	BL	1 weeding 40 DAT
	2, 4-D	500, 25 DAT	BL	1 weeding 40 DAT

Note: For transplanted minor millets, 25-30 days old seedlings may be transplanted without puddling the soil. There should not be water stagnation in the field. GR - grass; BL - broadleaved; SG – Sedge; DAS – days after sowing; DAT – days after transplanting

Future perspectives of weed management in millets

- Expansion of cultivation area to fertile and irrigated lands
- Good candidate crops under organic and natural farming
- Adoption of better crop management practices
- Development of weed competitive varieties
- Large scale screening of available herbicides
- Development of millet-specific herbicides
- Prominent rain-fed crops
- Wide adaptation-reliable harvest
- Novel Sources of Striga resistance from wild sorghum accessions
- Nuclear techniques to develop new sorghum lines resistant to *Striga*
- Development of Herbicide-resistant millet crop varieties
- Development of efficient weeding tools
- Integration of chemical, mechanical and cultural control measures

Chapter 10

Integrated weed management in vegetable crops

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Globally, around 374,000 plant species are known, and cultivating plants for economic purposes often promotes the growth of additional, unwanted species. These undesirable plants compete for above- and below-ground resources, with weeds posing the greatest threat to yield, causing up to a 37% reduction, followed by insects (29%), diseases (22%), and other factors (12%). These need serious attention to manage on time to ensure optimum productivity with quality produce. While India has achieved self-sufficiency in food grain production, nutritional security remains a concern. Vegetables are vital for meeting nutritional needs as they are rich in vitamins, minerals, and fiber, providing food security, earning foreign exchange, and supplying raw materials to industries. India ranks second in vegetable production, covering 11.11 million hectares and producing 20.96 million tonnes (2023–24). Vegetables account for 58% of the production in 38.8% of acreage devoted to horticulture.

Major weed flora

Vegetables are slow growing, especially during the initial stages, which makes vegetables sensitive to weed competition, which seriously impairs the quantity and also deteriorates the quality of the produce. All types (grasses, broad-leaved weeds, and sedges) are generally found in vegetable fields. The common grassy weeds are *Echinochloa colona, Dinebra retroflexa, Digitaria sanguinalis, Eleusine indica, Dactyloctenium aegyptium, Paspalum* spp., *Eragrostis* spp., broad-leaved weeds are *Alternanthera sessilis, Ageratum conyzoides, Euphorbia geniculate, E. hirta, Physalis minima, Leucas aspera, Ludwigia perennis, Commelina benghalensis, Cleome viscosa, Parthenium hysterophorus,* and *Phyllanthus niruri*, and sedges such as *Cyperus rotundus,* and *Cyperus iria* are major weeds.

Critical period of crop-weed competition and yield loss

This period is when weed offers maximum competition and seriously reduces the yield. Managing weeds during the period protects from yield loss. This information can be judiciously utilized for formulating weed management strategies for these crops. Later, emerged weeds will not pose any serious yield loss, however, management of weeds at a later stage significantly reduces the weed seed bank and reduce weed problems in subsequent years. The critical period for crop-weed competition and yield loss in vegetables is presented in **Table 1**.

Integrated weed management

The continuous use of herbicides with similar modes of action and uniform management practices has altered weed communities. Integrated Weed Management (IWM) is an essential approach for shifting crop-weed competition in favour of the crop. By combining multiple management practices rather than relying on a single method, IWM effectively keeps weed populations below economic thresholds. This systems approach incorporates cultural, mechanical, chemical, biological, and biotechnological control methods.

Table 1. Critical period of crop weed competition and yield reduction of vegetable crops

Crops	Critical period (days)	Yield reduction
Okra	15-30	40-80% (Patel *et al.* 2017)
Garlic	30-60	94.8% (Sanjay *et al.* 2009)
Cabbage	30-45	45-80% (Akshatha *et al.* 2018)
Cauliflower	25-30	50-70%
Onion	30-70	40-80% (Channapagoudar and Biradar 2007)
Tomato	30-45	92-95% (Bakht and Khan 2014)
Chilli	30-45	60-70% (Khan *et al.* 2012)
Carrot	15-20	90% (Singh *et al.* 2017)
Radish	15-20	86% (Singh *et al.* 2009)
Brinjal	20-60	30-35% (Syriac and Geetha 2007)
Potato	20-40	52% (Singh *et al.* 2005)
Vegetable peas	30-45	25-30%
Bottle gourd	30-45	40% (Dash and Mishra 2014)

Weed management practices

Preventive measures

- Use weed-free crop seed
- Use well-decomposed manure
- Use clean machinery/implements
- Inspect nursery stock/transplants
- Remove weeds near irrigation ditches, fence rows, rights-of-way, *etc*.
- Prevent the reproduction of weeds
- Use screens to filter irrigation water
- Restrict livestock movement
- Strict compliance with quarantine laws

Cultural management

- Stale seed bed
- Optimum plant population
- Selection of crop cultivars
- Optimum planting date
- Optimum planting geometry
- Crop rotation
- Selective stimulation of crop
- Use of live mulches or smother crops
- Intercropping

Mechanical measures

Mechanical methods involve the physical removal of weeds or by tools or implements. It is the oldest method adopted for weed control. Different methods are as follows

- Tillage
- Hand hoeing
- Hand pulling
- Flame weeding
- Digging
- Controlled burning

Some of the activities to be adopted using agricultural equipment for controlling certain weeds are presented in **Table 2**.

Chemical measures

Herbicide-based chemical control is often the most convenient and appealing weed management method for vegetable crops. Herbicides are applied pre-emergence and post-emergence, targeting weeds before the critical period of crop-weed competition. This approach fosters an optimal environment for the early growth and development of crops and is effective against morphologically similar, intra-row, and problematic weeds. **Table 3** lists herbicides that can be used in vegetable production.

Table 2. Mechanical measures for controlling weeds

Type of weeds	Activities	Equipment's
Annual weeds	Unearthing and fragmentation	Shallow cultivation
Non-dormant seed (*Bromus* spp.)	Deep burial	MB plow
Rumex and *Cirsium*	Fragmentation	Cultivator
Sorghum halepense	Dragging and exposure to surface	Cultivator or harrow
Cynodon dactylon	Dragging and removal	Cultivator or harrow
Cyperus rotundus or *Oxalis* spp.	Cutting, dug up for exposure to adverse condition	MB plow or disk plow

Table 3. Herbicides commonly used in vegetables

Herbicide	Dosage (kg/ha)*	Application time	Crops
Fluchloralin	0.85 – 1.0	Pre-plant incorporation	Tomato, okra, garlic, cabbage, cauliflower
Pendimethalin	0.75- 1.5	Pre emergence	Carrot, radish, potato, garlic, chilli, okra, tomato, brinjal, cabbage, cauliflower, etc.
Butachlor	2.0	Pre emergence	Transplanted tomato and cucurbits
Metribuzin	0.2-0.35	Pre or early post-emergence	Direct seeded and transplanted tomato and potato
Oxyfluorfen	0.24- 0.36	Early post-emergence	Direct seeded and transplanted onion and potato
Quizalofop – p- ethyl	0.04-0.05	Post-emergence	Tomato, brinjal, chilli
Fenoxaprop- p- ethyl	0.05-0.075	Post-emergence	Carrot, radish

*it is advised to test the above herbicides in smaller areas and based on crop and varietal safety larger area can be covered

Conclusion

Weed interference significantly reduces yields in vegetable crops. To minimize yield loss, it is crucial to keep weed density below threshold levels. Relying on a single method of control can lead to issues such as shifts in weed species, herbicide resistance, and the emergence of perennial weeds. Integrated weed management (IWM) addresses these problems by combining various weed control methods—cultural, mechanical, and chemical —in a balanced way. This approach avoids environmental harm while effectively managing weeds to prevent significant crop damage. Additionally, IWM reduces the weed seed bank, a major hidden threat to crop production. Therefore, IWM is the most sustainable option for agriculture.

Chapter 11

Integrated weed management in forage crops

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Trianthema portulacastrum and *Trianthema monogyna* were widely distributed in fodder crops during summer and rainy seasons. It produced flower continuously up to second fortnight of November with 224 to 504 seeds/plant and multiplied both by seeds (More than 80% germination of current seeds) and fragmented plant parts. Another broadleaf weed Celosia argentea preferred the growing condition of fodder sorghum and it produced 1,716 to 3,496 seeds/plant. The broadleaved weed *Coccinia grandis* was associated with fodder maize and sorghum, and produced 2,934 to 4,428 seeds/plant. Numerous seed production capacity of these weeds supported its high profile emergence**.** Three major broadleaf weeds *Coronopus didymus, Rumex dentatus* and *Cichorium intybus* appeared during 1st, 2nd, 3rd and 4th cutting of berseem during winter season, respectively. The weeds *Trianthema portulacastrum, Trianthema monogyna, Coccina grandis, Rumex dentatus* and *Cleome viscosa* had shown the character of endozoochory dissemination. Mixed cropping of fodder maize (Variety '*African Tall*') and fodder cowpea (Variety '*Bundel Lobia 2*') controlled *Trianthema* sp. successfully and maximum green fodder yield was obtained at 55 days after sowing beyond that cowpea showed competitive effect on maize. Turning the land from fodder sorghum to cowpea minimised distribution and seed production capacity of *Celosia argentea*. Mixed cropping of berseem (Variety '*Wardan*') + gobhi sarson (*Brassica napus* var. napus) and berseem (Variety 'Wardan') + rye grass (Variety 'Makkhan Grass') reduced infestation of *Coronopus didymus.* Growing of dual purpose (grain-cum-green fodder) wheat variety 'VL Gehun 829' reduced infestation of resistant biotype of *Phalaris minor*. *R. dentatus* has the endozoochorous mechanism of its dissemination and use of cattle shed water for irrigation cannot be recommended if the berseem fodder is infested with seeds of *R. dentatus*.

Weed flora in different fodder crops during *pre-Kharif* and *Kharif* seasons

Among the dominant weed flora *Trianthema portulacastrum, Trianthema monogyna* (Horse purslane) were highly obnoxious along with *Celosia argentea, Cleome viscosa, Coccinia grandis* and *Cyperus esculentus* (yellow nut sedge) appearing in all the fodder crops grown during summer and rainy season. The weeds *C. didymus, Poa annua, R. dentatus* and *C. intybus* were appeared during winter season.

Trianthema sp.

Biology: *Trianthema* is a terrestrial, annual, prostrate herb, up to 40 cm long. Its germination and emergence started with the rise of temperature at the terminal phase of the winter season (During 2nd fortnight of February to 1st fortnight of March) and it continued to grow up to the beginning of winter season with the appearance of several flushes. Growth of *Trianthema* was gradually restricted with the onset of winter season and it was perished completely during first fortnight of December. *Trianthema* produced flower continuously up to second fortnight of October and in case of mild winter it produced flowers up to 2nd fortnight of November. It produced fruits and seeds up to 2nd fortnight of December before it was perished completely. Each *Trianthema* flower produced 8 to 12 seeds and one mature

Trianthema plant under field condition produced 28 to 42 flowers altogether produced 224 to 504 seeds/ plant. 2 to 3% of the total current seeds germinated within 6 days after starting of imbibition, majority of the seeds germinated within 17 to 20 days after imbibition and remaining seeds germinated afterwards. In field condition initially a few seeds germinated after pre-sowing irrigation and reached to the flowering and seed setting stage when majority of the seeds started to germinate.

Propagation: *Trianthema* was propagated by seeds and fragmented plant parts. *Trianthema* propagated easily through the fragmented plant parts. More tillage operations resulted in more fragmentation of stems, which has put forth the new growth during the current season or into the next season once the external environmental conditions become congenial for growth and development. Incorporation of *Trianthema* at early stage (10 days old plant) affected its regeneration capacity by vegetative means. Seeds did not have the dormancy and germinated immediately after maturity. Rapid and continuous flowering was the important character for continuous persistence of *Trianthema* into different fodder crops grown during *pre-Kharif* and *Kharif* seasons.

Abiotic stress

Submergence: Emergence and growth of *Trianthema* was highly susceptible to high soil moisture and submerged condition. Water stagnation for the period of 1 to 2 days inhibited emergence and also restricted growth of *Trianthema.* Submerged condition also caused shifting of weed flora from broadleaved to several grasses.

Dissemination of *Trianthema*

Endozoochory:

i. Seeds of *Trianthema* easily passed through the rumen of animals and retained its viability into dung. Application of undecomposed compost/FYM (Farm Yard Manure) into the field caused introduction of the weed into the field and dissemination throughout the fields.

ii. Fragmented plant parts and roots through tillage operation

iii. Distribution of seeds through tillage operation

iv. Distribution of seeds through irrigation water

Celosia argentea

***Celosia argentea* was associated with fodder sorghum**

Biology: *Celosia argentea* preferred the growing condition of fodder sorghum. The mature weed produced 12 to 19 flowers and each flower produced 143 to 184 seeds, altogether produced 1,716 to 3,496 seeds/ plant. The weed showed aggressive growth and offered strong competition to fodder sorghum with the average weed population of 16 plants/m^2. Faster growth of *C. argentea* enabled the weed to compete successfully with fodder sorghum and the weed attained the height higher than fodder sorghum. The weed interfered in harvesting operation and reduced the quality of green fodder sorghum as the weed got mixed with the harvested fodder sorghum. The weed preferred to grow successfully during *Kharif* season and it continued to grow up to the beginning of winter season.

Propagation: The weed propagated only through the seeds. The current seeds have shown the dormancy in germination.

Dissemination:

i. The seeds were very lighter in weight and easily be distributed and disseminated by wind

ii. Distribution of seeds through irrigation water

iii. Distribution of seeds through tillage operation

Coccinia grandis

The weed was associated with fodder maize and fodder sorghum during *pre-kharif* and *kharif* season.

Biology: The weed emerged before the emergence of crop and suppressed the growth of newly emerged crop plants completely. The trailing habit of the weed completely intermingled with the crop canopy and thus restricted emergence of leaves and growth of the fodder crops. It not only reduced green fodder production but also reduced efficiency of harvesting operation and finally quality of green fodder.

One mature *C. grandis* plant produced 18 to 27 fruits and each fruit produced 136 to 164 seeds altogether produced total 2934 to 4428 seeds/plant. Numerous seed production capacity of this weed supported its high-profile emergence. Successful growth of this weed on undecomposed compost revealed that the seeds of the weed showed endozoochory dissemination and passed through the rumen of animals successfully. The results revealed that the seeds of *C. grandis* lost its germination capacity due to submergence and puddling operations adopted for berseem cultivation. Berseem cultivation during winter season under puddled condition reduced infestation of *C. grandis* in summer and *kharif* fodder crops.

Cleome viscosa

The weed was associated with fodder maize and fodder sorghum during *pre-Kharif* and *Kharif* season.

Single pod of *Cleome viscosa* produced 84 to 117 seeds and one mature *Cleome viscosa* plant produced 8 to 15 pods altogether produced 672 to 1755 seeds/plant.

The weed attained maturity much earlier than the harvesting stage of green fodder maize and sorghum. Like *Trianthema* and *C. grandis* the successful growth of this weed on undecomposed compost revealed that the seeds of the weed showed endozoochory dissemination and passed through the rumen of animals successfully.

Weed flora in different fodder crops during winter seasons

Weed flora in berseem

Three major broadleaf weeds (*C. didymus, Rumex dentatus, C. intybus*) appeared during 1st, 2nd, 3rd and 4th cutting of berseem throughout the fodder farm.

- Up to 1st cutting, *C. didymus* was the dominant weed. Atmospheric temperature during 2nd fortnight of October favoured rapid germination and initial establishment of the weed. Gradual fall of temperature during the month of November aggravated the growth of the weed. This weed covered the ground rapidly and took up its growth below the berseem canopy.
- After 1st cutting to 3rd cutting *R. dentatus* and *C. intybus* (kasani/chicory) were the dominant weeds. Cutting of weeds during 1st cutting of berseem and low temperature during the month of December triggered the vegetative growth of these weeds.

- After 2nd cutting these weeds gradually switched over from vegetative phase to reproductive phase and reached to the seeding stage before 3rd cutting during 1st fortnight of March.
- The grass *P. annua* started to appear during 2nd fortnight of January and became aggressive before 3rd cutting of berseem.
- *R. dentatus* has shown endozoochory dissemination and passed through the rumen of animals successfully. Application of undecomposed compost and, FYM and use of cattle shed water for irrigation caused rapid dissemination and large infestation of *Rumex* in new areas.

Intervention through crop husbandry and cultural practices for controlling weeds

Crop husbandry that reduced *Trianthema* infestation

- *Trianthema* appeared in almost all the crops grown during summer and rainy seasons except in puddled rice. *Trianthema* did not prefer puddled rice ecosystem due to submergence. Submergence in puddled rice acted as a good weed control agent.
- *Trianthema* appeared with the emergence of cowpea and continued to grow along with cowpea during its initial developmental stages. However, cowpea competed successfully with *Trianthema* at the later part of its phenophases and showed good smothering effect on the weed.

Mixed cropping of maize + cowpea for controlling *Trianthema*

Results revealed that mixed cropping of maize + cowpea (50% seed rate of both the crops) reduced infestation of *Trianthema* considerably. Cowpea started to show smothering effect on weeds at 20-25 days after sowing. Mixed cropping not only reduced infestation of weeds but also provided balanced green fodder of cereal and legume combination to the cattle. However, harvesting of the crops at proper stage was very important.

Harvesting of maize + cowpea mixed cropping

Time of harvesting was very important to harness the benefit of green fodder production of maize + cowpea mixed cropping. The results revealed that maximum benefit was obtained when both the crop was harvested at 55 days after sowing (DAS) at which both maize and cowpea have complementary effect on each other. Beyond this stage cowpea showed supplementary effect up to 65 DAS and after that it became competitive to maize causing yield reduction to the tune of 19.4 and 37.3%, respectively, compared to the yield obtained at 55 DAS.

Replacement of sorghum by cowpea for controlling *Celosia argentea*

Celosia argentea was associated with fodder sorghum as it grew well within the canopy of sorghum and reached to the top of the canopy. It reached to the seeding stage much earlier than the harvest of fodder sorghum. The fodder sorghum was severely infested with *C. argentea* and harvested fodder sorghum contained large quantities of *C. argentea,* which, in turn, reduced the quality of fodder sorghum. Intervention of turning the land to cowpea reduced population and seed production capacity of this weed. *C. argentea* usually produced on an average 2606 seeds/plant when the weed was associated with fodder sorghum. Turning the land to cowpea inhibited the growth and, development of *C argentea* and finally hampered seed production of this weed. This was due to trailing and prostrate growth habit of cowpea.

Almost 86% reduction in seed production of *Celosia argentea* due to turning the land to cowpea was recorded.

Mixed cropping of berseem and gobhi sarson (*Brassica napus var. napus)* for controlling *Coronopus didymus* in berseem, treating berseem seeds with 10% salt solution for controlling chicory and turning berseem field to oat cultivation and oat field to berseem cultivation for breaking cyclic perpetuation of weeds

- Growth of berseem was slow up to 1st cutting (up to 40 DAS).The weed *Coronopus didymus* took the advantage of slow growth of berseem and flourished aggressively below the canopy of berseem. Growing berseem+gobhi sarson (at the seed rate of 600-800 gm/ha) as mixed cropping offered strong competition to *C. didymus* and prevented its growth and spread within berseem. This intervention reduced spread and population of the weed during winter seasons. Besides, gobhi sarson also compensated low green fodder yield of berseem during 1st cut.
- Usually kasani/ chicory was found admixed with berseem seed. Since the size of chicory seed resembles with berseem seed, it became difficult to separate them by ordinary methods. Treatment of berseem seeds with 10% common salt removed the kasani/chicory seeds from berseem seeds. The chicory seeds being lighter in density than berseem seeds, floated on the surface of common salt solution while berseem seeds settled down at the bottom of container and thus chicory seeds were drained off and berseem seeds were collected.
- Turing the berseem fields to oat cultivation and oat fields to berseem cultivation became effective in breaking cycle perpetuation of *Coronopus, Rumex,* chicory and *Poa annua*. Oat acted as a very good smother crop because of its faster rate of tiller producing capacity and dense canopy development. Oat crop made the ecosystem completely unfavourable for growth and development of *Coronopus didymus, Rumex dentatus, C. intybus* and *P. annua.*
- Leaving the weeds on the bunds and field boundaries encouraged seed production of the weeds and during the turnaround time primary and secondary tillage operations distributed the weed seeds throughout the field. Removing the weeds (*R. dentatus* and *C. intybus*) from the bunds and field boundaries during 1st, 2nd and 3rd cutting of berseem reduced the chances of weed seed production and its distribution.

Mixed cropping of berseem and rye grass (makkhan grass) in un-puddled soil for controlling *C. didymus* in berseem

C. didymus was highly prevalent in berseem with higher absolute density and 100% absolute frequency under puddled condition. Growing of berseem and rye grass (makkhan grass) with 50% seed rate of both the crop in un-puddled condition has reduced the infestation of *Coronopus* at greater extent, which registered the absolute density of 5.8 no./m^2 and absolute frequency of 33.3% during 1st cut at 56 DAS (days after sowing) and absolute density of 2.27 no./m^2 and absolute frequency of 20% at 41 days after 1st cut. This was mainly due to high tillering capacity, faster growth and rapid coverage of ground surface which, in turn, made the condition unfavourable for *C. didymus* as this weed preferred to grow along with ground surface. Besides, the mixed cropping produced higher amount of balanced green fodder (Legume+cereal) with desirable crude protein content.

Intervention through ferti-seed-drill with high seed rate for controlling weeds

- Selection of quality seed of recommended variety - Bold seed with high germination percentage, took less time for germination and good vigour of seedling after emergence
- High seed rate - High density sowing (seed rate of maize 63 kg/ha)
- Sowing with the help of ferti-seed-drill with narrow spacing (15cm row to row distance) and placing of complex fertilizer.
- Top dressing with urea fertilizer and selective crop stimulation.

These practices have been implemented for growing fodder maize (African Tall) against broadcasting method of sowing. High plant density and faster growth of maize plants effectively restricted the growth of weeds already emerged beneath the crop canopy. Fast reaching to the grand growth phase with localised placement of fertilizer through ferti-seed-drill, judicious application of urea fertilizer and high plant density made the maize plants highly competitive with the weeds.

Control of resistant biotype of *Phalaris minor* by growing dual purpose wheat variety

Herbicide resistant *Phalaris minor* was recorded and the biotype showed resistant against the action of sulfosulfuron and clodinafop, however, it showed susceptibility against the action of pinoxaden. Apart from herbicide application for controlling resistant biotype, growing of dual purpose wheat (Grain-cum-green fodder) reduced infestation of resistant biotype after the 1st cut of wheat at 57 days after sowing for green fodder. High tillering capacity of dual purpose wheat after 1st cut suppressed the growth of *Phalaris minor* and the weed had lost the capacity of regrowth. The variety V L Geghun 829 has been found effective in terms of green fodder yield and grain yield. It has been observed that use of combine harvester led to the distribution of weed seeds (*P. minor* and *R. dentatus*) throughout the field. The wind thrust came behind the combine harvester caused distribution of weed seeds throughout the field.

Endozoochorus mechanism of dissemination of *Rumex dentatus*

Large infestation of *R. dentatus* due to use of cattle shed water contaminated with seeds of *R. dentatus* reduced wheat productivity up to 44% (2.14 t/ha) as compared to the grain yield 3.82 t/ha obtained from the plot irrigated with normal ground water. During second year, the entire field was irrigated with normal ground water and similarly carfentrazone was used at 25 DAS. These measures reduced the population of *R. dentatus* and weed showed declining trend up to 30, 71 and 79% reduction at 50, 65 and 80 DAS from 35 DAS. These results confirmed that *R. dentatus* has the endozoochorous mechanism of its dissemination and use of cattle shed water for irrigation cannot be recommended if the berseem fodder is infested with seeds of *R. dentatus.*

Chapter 12

Current herbicide development scenario: Reduced risk herbicides

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The development of Innovation is crucial in addressing the challenges posed by increasing resistance and climate change. Considering Key challenges, Bayer's vision to produce more, restore nature and scale regenerative agriculture to address the needs of farmers and society. These commitments are part of Bayer's broader vision to address global challenges at scale and contribute to a more sustainable future. Bayer follows a structured approach, from Early phase compound development to commercial proof of concept and regulatory approvals. Bayer's vision is to move from incremental innovation of traditional chemistry to breakthrough innovation, designing entirely new crop protection chemistries that are highly effective, precise, and sustainable. CropKey is an entirely new approach to the discovery of crop protection products which will allow Bayer Crop Science to reach new levels in precision and sustainability while being exceptionally effective. Today we have more scientific understanding about the makeup of living organisms and their complex biological processes in any given environment. Using AI and machine learning – the subset of AI that involves using algorithms to find patterns in data – we can identify the complex interdependencies between a theoretically unlimited number of organisms. AI singles out unique proteins present in the make-up of the pest species faster and with greater accuracy than ever before. These unique proteins can be thought of as "locks." The uniqueness allows us to be more precise in our research from the outset of the discovery process and helps to prevent unintended and off-target effects on the surrounding environment. We then need to design the crop protection molecule or "key" to inhibit this unique protein, thus preventing the pest.

What We've discovered so far

Using this innovative approach, we've developed Icafolin-methyl, the first new mode of action for horticulture and broadacre, post-emergent weed control in 30 years, which we expect to make available to farmers by the end of the decade, providing outstanding efficacy and a long-awaited solution to tackling herbicide resistance. It offers broad-spectrum control, especially effective against resistant grasses, and is designed with a favourable environmental and toxicological profile. This product support conservation tillage and no-till system, enhancing soil health. It stops the growth of a broad weed spectrum immediately, with residual activity enhancing soil health, and reducing erosion, weed seed return, and herbicide application frequency.

Innovative mode of action

Icafolin-methyl acts as a plant-specific microtubule assembly inhibitor, affecting plant physiological processes such as cold and salt stress adaptation, signalling between cells, and cell cycle functions (*e.g.*, mitosis).

Icafolin-methyl represents a significant advancement in herbicide technology, providing a novel site of action with a superior potency and spectrum which is fundamentally different from existing tubulin polymerization inhibiting herbicides. It is safe, effective, environmentally friendly, and offers farmers a powerful tool to combat resistant weeds and maintain crop health.

When used as part of an integrated system together with leading seeds and traits, biologicals, and in accordance with digital recommendations and precision application technology, our crop protection products empower growers to farm successfully while reducing the environmental impact of agriculture.

Application technology and digital solutions

The Digital Strategy for tailored weed management solutions in rice involves the use of digital tools, specific innovative flowable formulations, and drone application technology. This strategy aims to provide tailored solutions for farmers' pain points by offering a more precise, economical and sustainable approach to weed management.

Key components of this strategy include:

1. **Digital weed diagnosis**: Utilizing digital platforms to diagnose weed density and prescribe appropriate herbicides, for a more efficient weed management while reducing wastage or chemical impact on the environment.
2. **Specific innovative formulation**: Developing low dose self-dispersible formulations that maximize efficacy and offers application flexibility including Ultra Low Volume methods to minimize costs.
3. **Drone application technology**: Employing drones with dripping nozzles for precise and efficient herbicide application, while reducing operator risk exposure.

This approach not only reduces the amount and kinds of active ingredients in the environment but also enhances sustainability and cost efficiency. Bayer's commitment to developing reduced risk herbicides and sustainable crop protection solutions is paving the way for a future where agriculture is more efficient, resilient, and environmentally friendly.

Chapter 13

Recent advances in mechanized weed management

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Weeds are a perennial problem with the farmers and pose a serious biotic constraint in agricultural production systems globally. They are omnipresent and reduce yield and quality of crops substantially. Weeds compete with crop plants for moisture, nutrients and sunlight and can have a detrimental impact on crop yields and quality if uncontrolled. The weeds alone cause a loss of total agricultural production up to 37% and actual total economic loss of about USD 11 billion from 10 major crops of India if not managed properly. Therefore, weeding is the most important farm operation in agriculture to improve quality and quantity of crop production, but it is laborious. Further, the labour requirement for weeding depends on weed flora, weed intensity, time of weeding and soil moisture at the time of weeding and efficiency of the worker. Often several weeding's are necessary to keep the crop weed free. It has been estimated that on an average, the weed control costs around Rs. 6000/ha in *Kharif* crops and around Rs. 4000/ha for rabi crops, which comes to the tune of 33% and 22%, respectively of the total cost of cultivation of kharif and rabi crops. The data available at the ICAR-Directorate of Weed Research (DWR), Jabalpur shows that, with the traditional weed control methods, farmers are losing close to 15-20% crop yield. But, higher crop yield and nearly one-third of weed controlling cost can be reduced by using herbicides and mechanized weed controlling methods through improved spraying techniques and efficient mechanical weeders.

In India most of the farmers are performing weeding operations either by manually or by using different traditional and conventional tools like sickle, khurpi, kodali, powrah, hand forke, animal operated hoes etc. These tools are inefficient, time consuming, labour intensive and drudgeries to operate. The work rate of various weeding tools varied with respect to crop growth, weed intensity, soil condition, row and plant spacing and other factors. Thus, for khurpi it varied from 300-500 man-h/ha, for hand and chopping hoe varied from 200-300 man-h/ha, for push-pull type weeder it varied from 100-125 man-h/ha and for animal drawn weeding tools it varied from 6-20 man-h/ha. Likewise, for herbicide application, farmers are using inefficient sprayers with faulty application techniques. Moreover, application of herbicides through manually operated sprayers is laborious and drudgeries one and requires 18-20 man-h/ha. If, time available for spraying operations is limited (especially in *kharif* season) herbicides cannot be applied properly by manual sprayers. Some researchers reported that, performing of weeding operations through spade or by khurpi has to be performed in bending or squatting posture, which leads to increase in consumption by 30-50% more compared to performing weeding operations in sitting or standing position. All these parameters hinder the effective control of weeds and reduce the crop yield quality and quantity. Thus, efficient and effective weeding methods and tools are need of the hour, which can be achieved through mechanized weeding operations.

Mechanized weed management

Mechanization of weeding operation is the art and scientific application of mechanical aids to increase the farm power availability to control weeds effectively with less human drudgery and higher operational efficiency. Mechanized weed management includes both mechanical (physical), cultural as well as chemical methods, where tools, implements, sprayers, machine/ sensor based systems are used to control the weeds. The mechanization of agricultural activities increases the efficiency of farm labour and reduces time of agricultural operation by 15-20 per cent. India is an agriculture based country and more than 50% of its population is engaged in agriculture. The country has only 47% of agricultural mechanization and 33% to be precise for weed management with farm power availability of 2.71 kW/ha. These values are very low compared to advanced countries like USA, Western Europe, Russia, Brazil, China etc. The reason behind lesser mechanization are fragmentation of land (more than 63% of land holdings are less than one hectare), land topography, economic condition and education level of farmers, non-availability of suitable crop varieties, poorer irrigation facility, non-availability of suitable machines and seasonal short fall etc. Thus, increasing the farm power availability and developing suitable weeding tools are need of the hour.

Mechanical method of weed control

Mechanical method of weed control is a physical activity that inhibits unwanted plant growth. The physical activity involves both manual and mechanical weed control techniques, which manages the weed populations by removing, injuring, killing, or creating an environment which will be unfavourable for weed growth. Mechanical weed control is mainly associated with cultivating tillage, often referred to as tertiary tillage, but also primary and secondary tillage as well as mowing and cutting have strong impacts on weeds.

The cultivation tillage is inter-cultural operation involve the shallow tillage operations after the crop sowing or planting. Usually, it includes whole crop cultivation (full surface), inter-row cultivation (between crop rows) and intra-row cultivation (between crops), which are performed primarily to destroy the weeds present in the field and create favorable soil conditions for crop growth. Climate and soil type play an important role in the possibilities for mechanical weed control. Monitoring the early development of weeds is necessary for timing of weed harrowing at the optimum stage. Repeated intercultural operations under those conditions will not only discourage germination of weed seeds (which normally occurs in the soil layer) but also aids in conserving precious soil moisture. There are many types of mechanical weeders (soil disturbing tools) in the market that can use three main physical techniques for controlling weed:s

(1) Burying weeds

(2) Cutting weeds and

(3) Uprooting weeds.

Burial of weeds is accomplished through the action of tillage tools (and is usually done during land preparation when soil conditions are enhanced through tillage. The goals of tillage include reducing the soil strength, covering plant residue, rearranging aggregates and also removing weeds. Cutting and uprooting weeds are performed by mechanical tearing and breaking the weeds from the soil, and is usually done by mechanical cultivation after the crop is planted and has emerged. The majority of the manufacturers who sell mechanical weeders, produce weeders that are designed to control weeds between rows, or in the inter-row region. The cutting ad uprooting weeders available in the market can be grouped into three categories: full width cultivators, inter-row cultivators, and intra-row cultivators. However, the weeders can also be categorized as based on the cultivation practice: wetland and dryland weeders; based on the crop row space: narrow.

Mechanism of mechanical weed control

Weeds are vulnerable to mechanical control when they are small in size and are most sensitive from the white thread stage until the first true leaf begins to unfold. Weeding efficacy declines as weeds develop. The lethal effects of mechanical cultivators arise from soil disturbance. Mechanical cultivators uproots, breaks and buries the weeds in soil. All the operations works simultaneously. Uprooting reduces root function and increases desiccation rate if soil conditions are dry.

Chemical method of weed control

Herbicides are chemicals, which are designed to kill the unwanted plants (weeds) in cropping and non-cropping situations. Chemical method has become more popular, because of its ease, efficient and effectiveness in controlling weeds. Herbicide efficacy is influenced by weather, soil moisture, growth stage of crop and weeds, density of weeds, herbicide rate, application rate, droplet size etc. For successful usage of herbicides, their application must be accurate and uniform.

Nozzle selection and droplet size

Nozzle is a device which atomizes i.e. breakdowns the spray liquid into droplets and form the spray pattern. Nozzles determine the application volume at a given operating pressure, travel speed, and spacing. It is important to select a nozzle that develops the desired spray pattern and spray volume. The nozzle's intended use whether for broadcast or band application of herbicides determines the type of nozzle needed.

The droplet size of the broke down liquid is most important, because it affects both efficacy and spray drift of the applied herbicides. The droplet size less than 150 microns are more prone to drift. For better efficacy of the applied herbicides it is recommended to use the medium droplet size for contact, non-translocating herbicides and coarse droplet size for contact, translocating herbicides.

Recent advance in mechanized weed management

The recent development happening in the field of mechanized weed management can be classified in two ways:

Mechanized weed management with integration of AI/sensors/drones *etc*

It refers to the integration of the AI/sensors/drones for controlling the weeds according to their spatial variability within the field.

Mechanized weed management without integration of the AI/sensors/drones etc

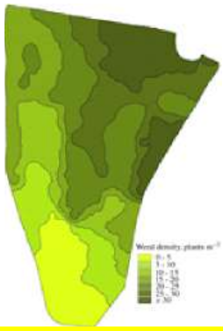
It refers to the development happening in the field of weed controlling tools and machines to reduce the human drudgery and to ease the weed controlling operations.

Mechanized weed management with integration of sensors

Weed infestations are often distributed heterogeneously in time and space within agricultural fields and occur in aggregated patches of varying size or in stripes. Practicing weed management techniques without considering a spatial variability of weeds will leads to loss of inputs and environmental pollution. Precision weed management is a site-specific weed management (SSWM) technique based on the field variability identified by the sensors and other instruments.

Necessity of site-specific management of weeds

- Present day situation is a site-specific management of agricultural inputs to increase profitability of crop production, product quality, and protect the environment.
- The weed density and weed distribution vary significantly from site to site within the crop field.
- If we manage a site specific weed control we can save 50-80% of herbicide and 30-90% of operating costs.



Weed distribution map

Herbicide rate application map

- With assistance of automation, the sensor based weeder can remove inter and intra row weeds simultaneously, with reduced human efforts and optimized resource requirements.

Precision weed management:

Precision agriculture is an approach, involves the information technology to ensures the crops and soil receive exactly what they need for optimum health and productivity. In other terms it is application of inputs at right place, at right amount and at right time for sustainable crop productivity. Weed populations have been found to be distributed heterogeneously in time and space within agricultural fields. They often occur in aggregated patches of varying size or in stripes along the direction of cultivation. Precision weed management is a site-specific weed management based on the field variability identified by the sensors and other instruments.

What is Sensor's….?

A sensor is a device that measures a physical quantity and converts it into a signal which can be read by an observer or by an instrument.

Existing sensors based row crop weeding systems

- Machine vision based systems
- GPS based systems
- Photoelectric sensor based systems
- Laser-thermal sensor based systems
- Electrocution / Microwave sensor based systems
- Robotic weed control

Machine vision system:

Machine vision is a optical sensor based system, which navigates the machine and simultaneously discriminates the weeds from crop. This type of system used either in the from of map-based approach or in real-time approach.

Main components of the system are:

- Image capturing device (by camera or optical sensors)
- Micro processors (image processing and system control)
- Weed control actuators

Schematic view of the machine vision system (Source: Tewari *et al.* 2014)

Operating methodology:

Image capturing by camera / by satellite (remote sensing)

Analysis of the original image

Image segmentation process

Decision-making approach

Controlling signals to the actuators

Actuation of spraying/mechanical hoes

Overview on the technology:

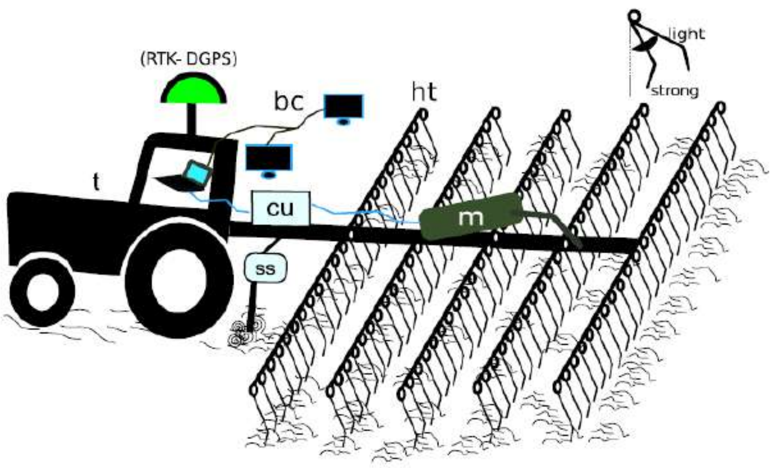
- The reliability of crop and weed recognition under field conditions varies from 60% to 95%.
- Under variable rate application of herbicides (VRA) the target deposition efficiency can increase 2.6-3.6 times that of a conventional sprayer with 72-99% reduction of non-target deposition.
- The sprayers can travel at 3.2-14 km/h with delivery accuracy 91%.
- Weed detection accuracy of the sensor was strongly dependent on model training and position relative to the training samples.
- The influence of shadows and ambient light effects the detection capacity of the sensors.

Global position system GPS:

Global positioning system (GPS) is a map based approach system, used to guide the vehicle during weeding operation. This system provides an absolute guidance with minimum errors.

The main components of the system are:

- GPS receiver as base station,
- RTK-GPS rover with antenna: should be mounted 3 m above the soil surface to maximize access to high quality satellite geometries and minimize GPS multipath error,
- Dual axis inclinometer: for ground level offset correction of GPS data,
- Embedded control system: to process and control the weeding system and
- Spraying / mechanical actuators



Schematic view of GPS system

Operating methodology:

Selection and division of a weed-infested field into square grids and locating the position of weed patches using the rover DGPS receiver.

⇩

Weed location data processing using GIS/GNSS software to generate an electronic weed distribution map.

⇩

Integration of the electronic weed distribution map with micro-processor, control modules and weed control actuators.

Photoelectric diffuse sensor based approach

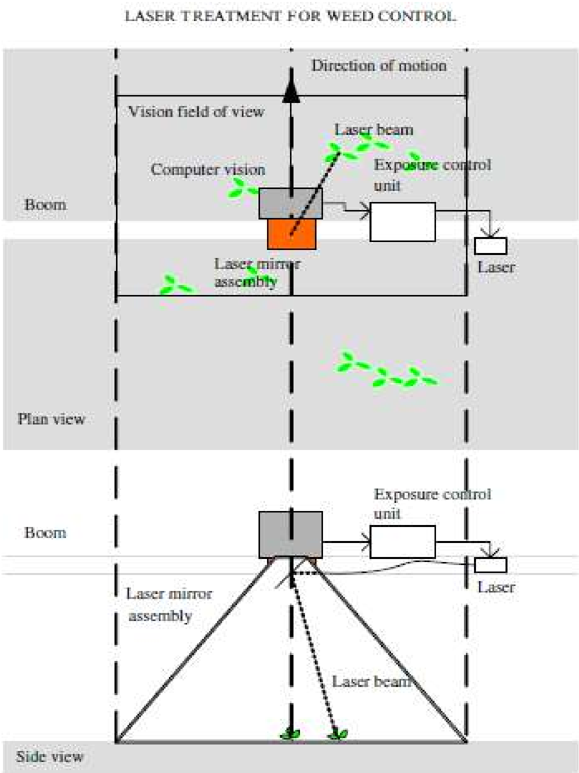
The sensor composed of a transmitter (light source) and a receiver module (a photocell). Transmitter sends a light beam, which hits an obstacle, part of the light will be diffused back and detected by the photocell and identifies as object. The system includes Ultrasonic sensor/ Infra red sensor/ LED sensors or any other object detection sensors with actuators for weed control.

Overview on the technology:

- The system can be operated at 0.8 to 1.6 km/h travelling speed without any crop fatalities.
- Very good knife path control (mean error < 0.8 cm) can be achieved by centering the actual uncultivated close-to-crop stem zone.
- The average worker's time required to hand hoe the intra-row will be 24-50 h ha^{-1} under control conditions, but it can be reduced to 10.2 h ha^{-1} by using intra and inter row weeder.
- System needs high accurate detection and precise actuation control system.

Laser-thermal weed controlling system

Laser-thermal system involves a application of laser radiations, which affect the thermal balance of a plant and partially destroys the plant tissue through thermodynamic heat transfer mechanisms (pyrolysis). Laser beams can selectively impair the growth of plants by destroying the sensitive growth centers, the so called meristems.



A laser weeding tool comprising a computer vision system that classifies weeds and identifies apical meristems from a top-down point of view; the laser is pulsed with a required dose of energy and uses a mirror, directed towards the targeted plant tissue

Overview on the technology

- The energy demand for laser weed control is about 20% compared to flaming (if weed density 50 plants per 1 m² and 50 kg propane gas/ha).
- Monocotyledonous 2-leaf-plants were damaged at high energy levels, whilst 4-leaf-plants were difficult to kill. But the dicotyledonous 2-leaf-plants will be damaged at moderate intensities.
- The influence of the spot position was important, as the unfocused treatment will result in decrease in lethality.
- Increase in lethal energy requirement of 1.3 J/weed for every 1% loss of laser spot coverage.
- System also requires a high spatial resolution.

Robotic weeding:

Robotic weeder is an autonomous operating weeding vehicle system. It sense and manipulate the crop and its environment in a precise manner with minimal requirement of materials and energy. Robotic weeders are usually a mobile platform consists of robotic arms / spray nozzles / electrode or any other weed controlling agent. The robotic arms can turn at all six degrees of freedom and robotic vehicles usually require a row spacing of 25 - 75 cm.

Core technologies of robotic weed control system:

- Mapping and guidance (Real-time Kinematic Global Positioning System (RTK GPS) or machine vision)
- Weed detection and identification (machine vision, hyperspectral imaging, photoelectric sensors *etc.*)
- Precision in-row weed control (micro-spray, cutting, thermal, electrocution *etc.*)

Schematic diagram of the robotic weeding (Source: Blasco *et al.* 2002)

Mechanized weed management without integration of the AI/sensors/drones *etc*

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 manual weeding in sitting or bending or squatting position, consumes 30-50% of more energy and leads to musculoskeletal disorders. Advancement happening to improve the operational efficiencies and drudgery reduction of the operator. A new innovation and some modification made to the existing weeding tools and spraying techniques.

Conclusion:

- Sensor based technologies are need of the future and site-specific management of weeds can be effectively achieved.
- Hyperspectral imaging technology more superior compared to other optical imaging technology.
- Real-time based weed control system is more efficient and less complex system.
- Initial cost of the machines is higher.
- Further research and safety risk factors to be considered in thermal weed control.

Chapter 14

Integrated weed management in oilseed crops

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India has achieved self-sufficiency in food production, yet true self-sufficiency also requires ensuring balanced diets for individuals. Oilseeds play a vital role in human health and are an essential part of the diet, providing high-quality protein, healthy fats, and fat-soluble vitamins like vitamin A. They contribute to food and nutritional security while also supplying raw materials to manufacturing industries. However, economically grown plants face various biotic and abiotic stresses. Biotic stresses alone can cause yield losses of 20-40%, with weeds being the leading cause of loss—up to 45% globally and 37% in India. In India, other yield losses are attributed to insect pests (29%), diseases (22%), and other pests (12%). Weeds are particularly challenging due to their rapid growth and reproduction, and they must be effectively controlled to prevent reduced crop yields. Under moisture-stressed conditions, yield loss from weeds can range from 10-98% in drylands and may even result in complete crop failure.

Importance of weed management in oilseed crops

The majority of oilseed crops are slow-growing during their initial stage of development. This invites the weeds to emerge and establish and compete for available resources. This ultimately reduces the crop yield and deteriorates the quality of the final product.

Crop weed competition and yield loss

Crop-weed competition is a detrimental interaction where plants vie for available resources, with both affected but weeds typically suffering less due to their superior adaptability. This competition causes significant yield loss in agricultural systems (**Table 1**), with losses varying by species, weed density, duration of competition, and prevailing soil and climate conditions. The first third of the crop's life cycle is particularly critical, as this period sees the most intense competition, leading to the highest and often irreversible yield losses.

Strategies for weed management in oilseed crops

Understanding weed biology, ecology, and the period of crop-weed competition is crucial for effective weed management in oilseed crops. Factors such as local conditions, environmental factors, labour

Table 1. Critical period of crop weed competition and yield loss due to weeds in oilseed crops

Crop	Critical period	Yield loss (%)
Sesame	15-45 DAS	15-40
Groundnut	21-56 DAS	15-75
Sunflower	30-45 DAS	54.6
Castor	30-60 DAS	30-35
Safflower	15-45 DAS	35-60
Rapeseed mustard	15-40 DAS	10-58
Linseed	20-45 DAS	30-40
Soybean	30-45 DAS	74

* Source: (Choudhary *et al.* 2022)

availability, weed pressure, and crop type must be considered when planning management strategies. Weed management involves both prevention and control, combining techniques for prevention, eradication, and control to manage weeds within a cropping system or environment.

There are many methods by which weed severity can be minimized, that are-

a. Preventive measures and b. curative measures (eradication and control measures) (Choudhary 2022)

Table 2. Weed control methods

Preventive	Curative				
		Control			
		Mechanical	Cultural	Biological	Chemical
• Sowing of weed-free seeds. • Use of clean implements. • Removal of weeds along the canal and irrigation channel • Care in transplanting seedlings/plantlets. • Use of well-rotten manure. • Avoiding the passing of cattle from weed-infested areas. • Crop management practices. • Enforcement of Weed Laws. • Quarantine methods	Eradication	-Tillage -Hoeing, -Hand weeding -Digging, -Mowing, -Burning, -Mulching -Soil solarization	-Selection of crops and varieties, -Stale seedbed -Sowing window -Planting geometry -Crop rotation, -Use of compost or manure, -Cover or smother crop -Water management, -Intercropping, -Nutrient management -Orientation of sowing/transplanting	-Plants-parasites, -Predators and - Pathogens	Detailed below

The selection of weed management practices largely depends on the availability of resources, costing of methods, and environmental conditions. Chemical methods of weed control are very effective in certain cases and have great scope provided the herbicides are cheap, efficient, and easily available.

Chemical method of weed management

The selectivity of certain chemicals allows them to control weeds in cultivated crops without harming the crops themselves, forming the basis of chemical weed control. This selectivity may be due to differences in morphology, absorption, translocation, or deactivation between weeds and crops. Herbicides provide a cost-effective alternative to cultural or mechanical weed control methods in oilseed crops, though herbicide-based management is still underdeveloped in most oilseeds, except soybean and groundnut. Pre-emergence (PE) herbicides are particularly valuable as they control weeds from the early stages of crop growth, while later-emerging weeds can be managed with selective post-emergence (PoE) herbicides. Effective chemical weed control requires field scouting to choose the appropriate herbicides based on weed type. Adhering to the 5Rs—right source, right herbicide, right dose, right time, and right application method—is essential for optimal weed control. Table 3 lists commonly used herbicides for oilseed crops.

Management of broomrape in Indian mustard and dodder in niger

Broomrape is a significant weed in mustard cultivation. Coating mustard seeds with 1.0 ppm of chlorsulfuron or triasulfuron has shown 70-98% control of Orobanche aegyptiaca, though seed treatment with sulfosulfuron was less effective. Post-emergence application of glyphosate at 25 and 50 g a.i./ha, combined with a 1% (NH„), SO„ solution at 25 and 55 DAS, demonstrated 63-100% control of this weed on

Table 3. List of herbicides for use in oilseed crops

Crop	Herbicide	Dose (kg/ha)	Time of application
Soybean	Metribuzin	0.50	PE
	Pendimethalin + imazethapyr	1.00	PE
	Diclosulam	0.022-0.026	PE
	Metolachlor	1.00	PE
	Sulfentrazone	0.72	PE
	Sulfentrazone + clomazone	0.35+0.375	PE
	Na-acifluorfen + clodinafop	0.245	PoE
	Imazethapyr	0.10	PoE
	Propaquizafop + imazethapyr	0.125	PoE
	Imazethapyr + imazamox	0.070	PoE
	Halauxifop-methyl	0.108-0.135	PoE
	Fomesafen + quizalofop	0.180+0.045	PoE
	Quizalofop + chlorimuron	0.0375+0.009	PoE
	Fluthiacet-methyl	0.0136	PoE
	Chlorimuron + fenoxaprop	0.009 + 0.08	PoE
	Fomesafen + fluazifop	0.22-0.25	PoE
	Bentazone	0.96	PoE
Groundnut	Pendimethalin	0.678	PE
	Diclosulam	0.022-0.026	PE
	Imazethapyr	0.10-0.15	E PoE
	Fenoxaprop	0.079	PoE
	Fluazifop-p-butyl	0.125-0.25	PoE
	Fomesafen + fluazifop	0.22-0.25	PoE
	Imazethapyr + imazamox	0.07	PoE
	Propaquizafop + imazethapyr	0.125	PoE
	Imazethapyr + chlorimuron	0.10+0.024	PoE
	Quizalofop + imazethapyr	0.0328+0.0626	PoE
Rapeseed and Mustard	Pendimethalin	0.678	PE
	Oxyfluorfen	0.15-0.25	PE
	Oxadiargyl	0.09	PE
	Isoproturon	1.00	PE or PoE
	Quizalofop	0.04-0.05	PoE
Sesame/ Niger	Butachlor (50%)	1.00-1.50	PE
	Oxadiazon (25%)	0.50-1.00	PE
	Pendimethalin (30 & 38.7%)	0.50-0.75 & 0.678	PE
	Isoproturon (70%)	1.00-1.50	PoE
	Propaquizafop 10% EC	0.10	PoE
	Fluazifop	0.25	PoE
Linseed	Pendimethalin (30% EC)	0.75-1.00	PPI & PE
	Butachlor (50%)	1.00-1.50	PE
	Oxadiazon (25%)	0.50-1.00	PE
	Propaquizafop (10% EC)	0.10	PoE
	Isoproturon (70%)	1.00-1.50	PoE
Sunflower	Pendimethalin (30% EC)	0.75-1.00	PPI & PE
	Oxadiargyl	0.10	PE
	Quizalofop	0.04-0.05	PoE
Safflower	Pendimethalin (30% EC)	0.75-1.00	PPI & PE
	Pyroxasulfone	0.1175	PE
	Sulfentrazone	0.105	PE
Castor	Metolachlor	1.0-1.5	PE
	Pendimethalin	1.5-2.0	PE
	Quizalofop-ethyl	0.05	PoE
	Fenoxaprop-ethyl	0.05	PoE

a large scale in farmers' fields. However, as per the government orders glyphosate can not be used in field crops other than tea. Dodder is an annual obligate stem parasite belonging to Cuscutaceae. Cuscuta is a major limitation for cultivation of niger {*Guizotia abyssinica* (L.f.) Cass.} in India. Application of pendimethalin 30 Ec 1.0 kg/ha as PE followed by hand removals are found to be effective in management of dodder.

Integrated weed management in oilseed crops

Relying solely on herbicides for weed management is discouraged due to environmental concerns and the risk of resistance in weeds. A more effective approach combines multiple weed control measures along with sound crop husbandry practices. Integrated weed management (IWM) is a cost-effective, reliable method that farmers can easily adopt within a broader management plan. Combining rotary hoeing and cultivation with herbicides provides better weed control and higher soybean yields than herbicides alone. While pre-emergence (PE) herbicides offer broad-spectrum control of initial weed flushes, some weeds emerge later and require additional control methods. To prevent weed seed spread, it's important to keep weeds from seeding, ensure harvesting equipment is free of weed seeds, and use clean seeds for all crops in rotation. Research in India has identified several key IWM practices that deliver excellent weed control, boost crop yields, and increase returns without harming crops. However, herbicides should be selected based on the specific weed flora, as effectiveness varies across weed species.

Conclusion

Weed interference significantly reduces yields in oilseed crops, with the severity depending on factors like weed density, competition duration, and weed types. Maintaining weed density below threshold levels is essential to minimize yield loss, especially during the first four weeks of growth. Relying solely on one control method can lead to problems like weed flora shifts, herbicide resistance, and the establishment of resilient weed species. Adopting Integrated Weed Management (IWM), which combines methods such as cultural, mechanical, chemical, biological, and biotechnological approaches, allows for effective weed control without harming the environment. IWM also helps reduce weed seed recruitment and depletes the weed seed bank, making it an effective, efficient, and sustainable strategy for oilseed crops.

Chapter 15

Management of parasitic weeds in field crops

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Field dodder (*Cuscuta* spp.), broomrapes (*Orobanche* spp.), witch weed (Striga spp.) and loranthus are the major parasitic weeds reported in the country. Dodder and broomrape are holo-parasitic and completely dependent on their host for survival, whereas witch weed and mistletoe are hemi-parasitic (semi-parasitic) with photosynthetic leaves.

Broomrape (*Orobanche* spp.)

The parasitic weed Orobanche spp. is an obligate holoparasite that attacks many broadleaf crops and weeds, causing severe yield and quality loss in harvested products. The genus Orobanche is estimated to contain as many as 150 species of which *O. ramosa, O. aegyptiaca, O. crenata, O. cernua* and *O. minor* are economically important. In India, it is a major parasite in tobacco in parts of Karnataka, Andhra Pradesh, Tamil Nadu, Gujarat, mustard in parts of Gujarat, Madhya Pradesh, Uttar Pradesh, Rajasthan, and in vegetables such as brinjal, tomato, potato, etc. It causes 30-75% in tomato, 50% in broad bean, 50-60% in tobacco and 30-70% in tobacco and mustard

Management strategies: Soil solarization during summer months desiccates the weed seeds and reduces the soil seedbank. Use of trap crops such as sorghum, pearl millet, maize, chilli, castor, sesamum, niger, soybean, linseed, amaranthus, turmeric, greengram, horsegram, cowpea, redgram, blackgram, lucerne and sunhemp produce the root exudates and cause the suicidal effect for broomrape. Taking trap crops in rotation, broomrape seeds will germinate and die and their seed bank in soil will be reduced. High level of nitrogen has been found to reduce its infestation in tobacco and tomato but also reduced the yield of tomato. Flooding the field suppress the broomrape as the seeds of parasite do not survive an extended period of inundation

Selective control of broomrape with herbicides in crops is very difficult. Several herbicides, growth regulators and soil fumigants have been tested for the control of broomrape with varying degrees of effectiveness. Soil fumigation with methyl bromide (350 kg/ha) prior to planting provides effective control of broomrapes. Pre-plant incorporation of trifluralin and fluchloralin 1.5-2.0 kg/ha has been found to reduce the infestation of broomrape in sunflower, tomato and tobacco. Glyphosate, a foliage-applied, nonselective herbicide, has proved very effective against broomrape without causing any adverse effects on broad bean crop when applied at very low rates (60-200 g/ha).

Witch weeds (*Striga* spp.)

Striga species (family Scrophulariaceae), known as witch weeds, are root parasites. Although there may be as many as 50 species of witch weeds, only a few are important in Asia viz., *Striga hermonthica,* S. asiatica (S. lutea), *S. gesnerioides, S. euphrasoides* (S. *sanguistufolia*). All these species parasitise the roots of grasses. A Striga plant produces several thousands of seeds, which remain viable in the soil up to 20 years. It causes 20-100% yield losses in sorghum and millet and 20-90% in maize depending on its infestation and management practices.

Management strategies: Cultural practices such as stubble cleaning in sorghum and millet fields after harvest, crop rotation with non-hosts and with catch crops such as early maturing sorghum, fodder millet, etc., mixed cropping without host crops, fertilizer management with high doses of nitrogen as top dressing, chemicals including synthetic Striga germinators such as ethylene or strigol analogues (GR-7 and GR-45) in the absence of cereal host crop and use of resistant or tolerant varieties. Intercropping with legumes such as soybean, cowpea or groundnut within the cereal (sorghum) row can significantly reduce the numbers of Striga coming to maturity. Fertilizer, especially nitrogen, tends to reduce, or at least delay, Striga emergence and can be used to further reduce the numbers of parasite that need to be hand-pulled to prevent seeding. Use of 2,4-D as post emergence has been found effective against Striga but it may need to be repeated. In sugarcane, pre-emergence application of atrazine 1.0 kg/ha + hand weeding at 45 DAP with an earthing up at 60 DAP combined with post-emergence spraying of 2,4-D Na salt 5 g/l (0.5%) + urea 20 g/l (2%) at 90 DAP or mixed application of atrazine + 2, 4-D or metribuzin + 2,4-D at 100% or 75% of recommended doses applied after final earthing up i.e. around 100 days after planting (usually when Striga starts emerging) and subsequent 2-3 applications at an interval of 30-40 days can effectively control this parasitic weed. Post-em application of three-way herbicide (2,4-D + metribuzin + pyrazosulfuron) and using mycorrhizal consortia at planting were also effective.

Dodder (*Cuscuta* spp.)

Cuscuta (field dodder) also known as Amarbal or Akashbel, is an invasive, obnoxious parasitic weed that attaches itself to stem and leaf of vide variety of host plant species. There are about 150 species of genus Cuscuta, among them, *C. compestris*, and *C. reflexa*, are more common in India. C. campestris poses a serious problem in field crops viz., oilseeds (niger and linseed), pulses (blackgram, greengram, lentil and chickpea especially in rice-fallows) and fodder crops (lucerne and berseem) in the states of Andhra Pradesh, Chhattisgarh, Gujarat, Orissa, West Bengal and parts of Madhya Pradesh under rainfed as well as in irrigated conditions. *C. reflexa* is a problem on shrubs and small tree crops. The yield reductions due to *Cuscuta* are reported to the tune of 60-65% in chillies, 30-90% in greengram, 25-34% in blackgram, 60-80% in niger, 87% in lentil and 85.7% in chickpea, 50% in linseed, 56% in soybean, 72% in sesame and tomatao, 17% in pigeonpea, 18% in groundnut, 91% in greengram and 60-70% in alfalfa depending upon its intensity of infestation.

Management strategies: Use of Cuscuta seed free crop seeds is the best strategy for its management in lucerne and berseem. Cuscuta does not parasitize any members of the poaceae, hence rotation of host crop with any cereals as wheat, rice, maize, etc., or broadleaved crop such as cotton will be helpful in its management. Lucerne cv. 'LLC-6' and 'LLC-7' are moderately tolerant. Greengram cv. 'M-2', blackgram cv. 'T9' and linseed cv 'Garima' are reported as tolerant to Cuscuta infestation. Growing of cluster bean in mixed cropping or in a rotation as a trap crop also reduces its infestation. Cuscuta germinates relatively shallowly in the soil. Repeated use of Amarvel'-an organic product, as post-emergence also helps in checking Cuscuta infestation. Cuscuta can be controlled by pre-emergence application of pendimethalin 1.0 kg/ha in oilseeds and pulses or 0.50-0.75 kg/ha as early post-emergence (14 days after sowing) in lucerne and berseem can be used for satisfactory control. Paraquat or glyphosate (1% solution) can be used for spot spraying.

Loranthus

Loranthus is the largest genera (having 600 species) under sub family Loranthoideae (family Loranthaceae). *Loranthus longiflorus, L. ampullaceus, L. cochinchinensis, L. elasticus, L. pentandrus* etc. are some common species. L. longiflorus is acommon parasite on subtropical trees. The plant bears beautiful orange or scarlet flowers in dense, one-sided up curved axillary clusters. Viscum is another genera of the sub family Viscoidae (family Loranthaceae). *V. articulatum, V. album* are the most common species occurring in Himalayas. They depend on their hosts for water, and under wet conditions may do little harm. Under drought stress, however they often cause death of infected branches. In India a wide range of species occur, of which *Dendrophthoe falcata* is perhaps the more common, damaging many fruit, ornamental and forest tree species. The weed occurs on the terminal growing point resulting in stunted growth of the tree, which affects timber value considerably. Lopping the affected portion of the tree in the initial stage itself will make its control easy.

Chapter 16

Weed management in conservation agriculture-based cropping systems: Challenges and research needs

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Conservation agriculture (CA) is a concept for resource-saving agricultural crop production that strives to achieve acceptable profits with high and sustained production levels while concurrently conserving the environment. CA is characterized by a set of principles and practices that emphasise on the protection of soil health, water resources and biodiversity (Das et. al., 2021). CA expanded from 1.0 million ha in eight countries in 1970 to 205.4 m ha in 102 countries in 2019, accounting for 14.7% of global agriculture area. It is adopted in more than 50% of cropped land of Argentina, Australia, Brazil, Canada, Paraguay, South Africa, Uruguay and USA. In India, the area under CA increased from 1.5 M ha during 2013–2014 to 3.5 M ha in 2018–2019 (Kassam *et al.* 2022). CA have three key principles: minimal soil disturbance through reduced or no-tillage method, permanents soil cover using the crop residues or cover crops and diversified crop rotations. These principles collectively contribute to soil conservation, reduced erosions and enhanced water retention, increases carbon sequestration. CA plays a vital role in mitigating the effect of climate change, improving food security and promote long-term agriculture sustainability. It has the capacity to mitigate, reverse and counterbalance many negative effects of traditional agriculture, such as declining soil health (organic matter depletion, soil structure degradation, reduced infiltration, compaction), higher surface runoff and erosion, secondary salinization and sodicity problems, higher biotic interference and declining biodiversity (natural and agro-ecosystems) susceptibility to climatic variability and global warming and air and ground water pollution.

Why conservation agriculture

The agriculture sector is currently facing a multitude of emerging challenges that threaten its sustainability and productivity. One of the major concerns is the declining factor productivity, in which the output per unit of input is decreasing. This is accompanied by increasing costs, declining or stagnating yield and income, putting immense pressure on farmers. Additionally, the deteriorating soil health, declining biodiversity, higher biotic interferences and receding groundwater levels further exacerbate the situation. The energy crisis adds to the woes, making it difficult for farmers to access affordable and reliable energy sources. Moreover, secondary salinization, sodicity and pollution pose significant threats to agricultural lands. The sector is highly susceptible to climate variability, making it challenging for farmers to adapt the changing weather patterns. Furthermore, the higher global warming potentials and climate changes contributes to the overall instability in agriculture. Lastly the changing land-use pattern further complicates the situation. These challenges require immediate attention and innovative solution to ensure the long-term sustainability of the agricultural sector.

Conservation agriculture principles

Minimum soil disturbance: On reducing or eliminating tillage, it prevents soil erosion, maintains soil structure, retains soil moisture more effectively and prevents C-oxidation. This approach also minimizes the disruption of soil organisms and beneficial microorganism, ensuring a balance and fertilized ecosystem.

By keeping the soil undisturbed, CA supports sustainable farming practices that protect the environment, improves soil quality and enhance crop productivity. Overall, it helps preserve the integrity and health of the soil.

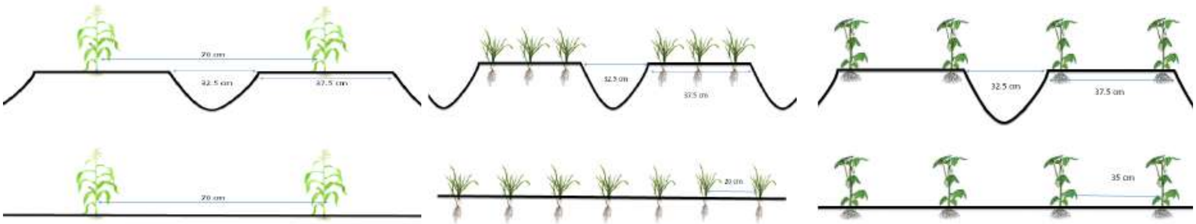
Permanent soil cover: A permanent soil cover such as crop residue, cover crops or mulch plays a critical role in CA. It acts as a protective barrier that shields the soil from the impact of raindrops, which can lead to erosion and soil degradation. This covering also helps in retaining the soil moisture, reducing evaporation and improving water-use efficiently. Additionally, it acts as insulation, regulating soil temperature and providing a favourable environment for beneficial soil organism. By preventing direct exposure to environmental stressors, a permanent soil cover support soil structure, fertility and overall health contributing to sustainable and productive farming practices.

Crop rotation and diversification: In CA, crop rotation and diversification are essential as it helps in maintaining soil health and reduce the risk of pest and disease outbreak. Different crops have varying nutrients requirements and growth patterns, which prevents the depletion of specific nutrients in the soil and disrupts the life cycle of pests and diseases. This practice enhance soil fertility, reduces the needs for synthetic inputs and supports sustainable and environment friendly farming.

Conservation agriculture practices

Permanent raised bed planting with residue: A raised bed system (**Figure 1**) is a type of agricultural practice where crops grown on raised beds (0.4-1.0 m width) alternated by furrows. The benefit of this system is that it saves seeds by 15-20% and nutrients by 25%. This reduces cost of cultivation as well as increases yield by 10-20% and helps in better management of *Phalaris minor* weed, which are often a problem in rice-wheat cropping system. The system also improves soil organic carbon, soil structure and microbial population leading to overall improvement in soil health. Crops that can be grown using this system include wheat, cotton, pigeon pea, maize, soybean, vegetables, sugarcane *etc*.

Zero/no tillage with residue: The zero till-cum-fertilizer drill, happy/ turbo seeder is an innovative farming tool that offers numerous benefits for growers. By seeding directly into the residue of the previous crop, farmers can save significant amount of fuel (60-80%), water (20-30%), time and money compared to traditional tillage methods. Additionally, the reduced soil disturbance from zero-till planting helps minimize erosion, loss of organic matter (OM), improves soil structure and microbial population. It also helps in increasing yield by 10-15% and reduces weed growth, particularly *Phalaris minor* in wheat fields, while the crop is less likely to suffer from terminal heat stress due to the extra moisture retained under the residue retention/mulch.



(a) Maize crop (rainy season) (b) Wheat crop (winter) (c) Mungbean crop (summer)

Figure 1. Permanent raised bed planting with residue (Top figure in each pair): (a) maize crop (rainy season), (b) wheat crop (winter), (c) mungbean crop (summer) compared with conventional till (CT) crop planting.

Brown manuring

Brown manuring (BM) is a temporary live and dead mulch. It is the simultaneous growing/cultivation of rice and *Sesbania* crops for a short period 25-30 DAS. After 25-30 days of co-culture, the *Sesbania* plants are knocked down by herbicides such as 2,4-D 0.5 kg/ha or bispyribac-Na at 20 g/ha in rice. It has been found to be an effective method for controlling weeds and reducing the population of perennial weeds like *Cyperus rotundus*. This treatment can achieve around 40-50% weed control. But, *Sesbania* BM has been found to promote the growth of plant parasitic nematodes (PPN) and the population of free-living nematodes. In contrast, *Crotalaria juncea* BM reduces the population of PPN.

Why weed management challenges in CA

In India, agri-production worths Rs. 1.48 lakh crores (21.14 billion USD), is lost due to various pests/ diseases/weeds (MoA). Pests usually reduce 20-40% of total food production (FAO, 2021). Typically, weeds alone contribute to nearly one-third of the total loss. Weeds are most underestimated crop pest in tropical agriculture although it causes higher yield loss than that caused by other pests/diseases. Total economic loss of approximately 11 billion USD annually occurs in India due to weeds from 10 major field crops in 18 States of India (Table 1). Weeds have evolved over the periods in response to changing cropping practices, by adapting and occupying niches left available in the agroecosystem. Forces created by our cropping practices over the evolutionary time have led to the weed diversity we observe today. Weed infestation and its preponderance are influenced by seeds and sowing practices, tillage, weed control options, fertilization, residue management, cropping systems and input consumptions. The continuous adoption of a particular practice may either increase or decrease the infestation of a particular species of weed and over time the diversity of weeds can gradually alter. Weeds pose a severe challenge in the initial years of adoption of CA. The reduced tillage/ zero tillage (ZT) in CA minimizes/restricts the opportunity to control weeds mechanically before crop sowing. Hence, it causes a paradigm shift in weed diversity, dominance and community composition as compared to the conventional tillage (CT).

Weed ecology and dynamics

Agroecosystems impart selection pressure on weed communities that inevitably result in weed population shifts (Owen and Zelaya, 2005). Weed ecology has an influence on weed dormancy and germination which are the two important survival mechanism of weeds. Weed diversity may gradually vary over time as a result of the persistent adoption of one or few practices that either increase or decrease the infestation of particular weed species. The changes in soil microclimate as a result of CA based systems leads to a paradigm shift in weed germination and emergence. Weed shift towards perennials have been observed in CA systems (Das et. al., 2018; Das and Sharma, 2022). Perennial weeds thrive well in zero/no till (ZT/NT)systems as the root system is not disturbed and herbicides used to manage annual weeds are less effective against perennial weeds. Under ZT, perennial monocots

Table 1. Annual economic loss in different crops due to weeds (million USD) in India (Gharde *et al.* 2018)

Crop	Annual economic loss due to weeds (million USD) in India
Rice	4420
Wheat	3376
Soybean	1559
Maize	739
Groundnut	283
Sorghum	276
Green gram	161
Mustard	72
Sesame	50
Pearl millet	17

pose greater challenge than the perennial dicots. Perennial monocots like *Cyperus rotundus* (Purple nutsedge), *Saccharum spontaneum* (Tiger grass), *Cynodon dactylon* (Bermuda grass) and *Sorghum halepense* (Johnson grass) reproduce from underground vegetative structures, tubers, rhizomes, stolon, corms etc. Perennial dicot weeds such as *Polygonum plebejum* (Indian knotweed) and *Alternanthera philoxeroides* (alligator weed) have been observed in CA-based rice–wheat system plots, while in CA based rice – mustard system, *Sonchus arvensis* (sow thistle) was the dominant weed.

The infestation of *Cyperus* species increased tremendously in different CA based systems after 6 years (**Table 2**). The triple ZT rice-wheat-mungbean and rice-mustard-mungbean systems with three crops residue (MBR+ZT DSR - RR+ZTW/ZTM -WR/MR+ZTSMB) had higher population of *C. rotundus* than that of *C. esculentus.* In rice-mustard system, *C. rotundus* was higher than *C. esculentus* in all CA-based double and triple ZT systems (DZT/TZT), while in rice-wheat system, *C. esculentus* had higher population than that of *C. rotundus* in all CA-based double and triple ZT systems. The weed flora shift in rice under CA based rice-wheat system after five years showed an increase in *Euphorbia microphylla* under ZT DSR-based CA. The population of *Cyperus rotundus* was highest in TZT– R, but reduced due to ZTDSR +BM+R system. *Dinebra retroflexa* increased, whereas *Alternanthera philoxeroides* decreased in TZT DSR with or without residue (+R or -R) plots.

Table 2. *Cyperus* dynamics in DSR under RWS and RMS at IARI, New Delhi (after 6 years)

Treatment	*Cyperus esculentus* (no./m^2)		*Cyperus rotundus* (no./m^2)	
	Rice-wheat	Rice-mustard	Rice-wheat	Rice-mustard
WR/MR+ZT DSR- RR+ ZTW/ ZTM	44.0	0.0	17.3	73.3
WR/MR+ZTDSR+BM-RR+ ZTW/ ZTM	18.7	10.1	9.3	34.7
MBR+ZT DSR - RR+ ZTW/ ZTM - WR/MR+ZTSMB	12.0	6.1	69.3	101.3
PTR-CTW/CTM	0	0	0	0

WR, wheat residue; MR, mustard residue; DSR, direct-seeded rice; RR, rice residue; ZTW, zero till wheat; ZTM, zero till mustard; BM, brown manuring; MBR, mungbean residue; SMB, summer mungbean; PTR, puddled transplanted rice; CTW/CTM, conventional till wheat/mustard

In rice and mustard crops, the occurrence/appearance of weeds across the plots of CA and CT treatments was noted throughout the crop growing cycle depending on their occurrence, early or late, and weed species were identified (Das *et al.* 2020). Weed flora appeared in CT-based TPR and CA-based direct-seeded rice (DSR) systems over the years were *Echinochloa colona* (L.) Link., *Echinochloa crus-galli* (L.) Beauv., *Leptochloa chinensis* (L.) Nees., *Dactyloctenium aegyptium* (L.) P. Beauv. Willd., *Cyperus rotundus* L., *Cyperus esculentus* L., *Dinebra retroflexa* L., *Euphorbia microphylla* Lam., *Eclipta alba* Hassak, *Alternanthera philoxeroides* (Mart.) Griseb. and *Fimbristylis miliacea* L. (**Table 3**). Among them, five weeds, namely, *E. colona*, *D. aegyptium, C. rotundus*, *C. esculentus,* and *E. microphylla* were absent in all the five years of study in CT-based puddled transplanted rice (PTR) system (**Table 3**). But, under the CA-based DSR, *E. colona*, *D. Aegyptium,* and *C. rotundus* were present in every year, and *C. esculentus* appeared in 4th year and *E. microphylla* appeared in 3rd year onward. *Echinochloa crus-galli* appeared during all five years in PTR, but was absent during initial three years and appeared only in 4th year onward in DSR. *Leptochloa chinensis* and *D. retroflexa* appeared in 3rd year onward in CA-based DSR, but in 4th and 5th year onward, respectively in CT-based PTR. *Eclipta alba* and *Fimbristylis miliacea* were absent during initial three years (2012-13 to 2014-15) in both PTR and DSR systems, but suddenly appeared in 4th crop cycle onward in both the systems. Similarly, the CT- and CA-based mustard was infested with *Sonchus oleraceous* L., *Melilotus indica* (L.) All., *Anagallis arvensis* L., *Coronopus didymus* (L.) Smith, *Chenopodium album* L., *Phalaris minor* Retz, *Rumex dentatus* L., *Spergula arvensis* L., and *Polygonum aviculare* L. (**Table 4**). Among these weeds, *M. indica, A. arvensis, C. album* and *Rumex dentatus* appeared concurrently in both CT and CA plots in all five years. *Phalaris minor* was present during all five years in CT (Table 4), but appeared in 3rd year onward in CA plots. Similarly, *S. arvensis* and *S. oleraceous* appeared in CT plots in 3rd year, whereas in CA plots in 4th year onward.

Crop residues

Crop residue plays a crucial role in the complex agricultural ecosystem, affecting various aspects of weed management. Crop residues left on the field after harvest can serve as a physical barrier to weed seed germination as well as a potential habitat influencing weed seeds reserve/bank by providing a microenvironment conducive to germination. However, weed seed bank can be affected by several factors, such as predation, microbes/pathogens, and seed viability. Some of the effect of crop residues on weeds are discussed below:

Table 3. Weed dynamics/occurrence in the CT- and CA-based rice under rice - mustard system over the years (Visual observations)

Weeds	CT-based TPR					CA-based DSR				
	2013-14	2014-15	2015-16	2016-17	2017-18	2013-14	2014-15	2015-16	2016-17	2017-18
Echinochloa colona	-	-	-	-	-	+	+	+	+	+
Dactyloctenium aegyptium	-	-	-	-	-	+	+	+	+	+
Cyperus rotundus	-	-	-	-	-	+	+	+	+	+
Cyperus esculentus	-	-	-	-	-	-	-	-	+	+
Euphorbia microphylla	-	-	-	-	-	-	-	+	+	+
Echinochloa crus-galli	+	+	+	+	+	-	-	-	+	+
Leptochloa chinensis	-	-	-	+	+	-	-	+	+	+
Dinebra retroflexa	-	-	-	-	+	-	-	+	+	+
Alternanthera philoxeroides	-	-	+	+	+	-	-	+	+	+
Eclipta alba	-	-	-	+	+	-	-	-	+	+
Fimbristylis miliacea	-	-	-	+	+	-	-	-	+	+

" – " indicates absence, whereas " + " indicates presence of particular weeds; CT = conventional tillage; TPR = transplanted puddled rice; DSR = direct seeded rice.

Table 4. Weed dynamics/occurrence in the CT- and CA-based mustard under rice - mustard system over the years (Visual observations)

Weeds	CT-based mustard					CA-based mustard				
	2013-14	2014-15	2015-16	2016-17	2017-18	2013-14	2014- 15	2015-16	2016-17	2017-18
Melilotus indica	+	+	+	+	+	+	+	+	+	+
Anagalis arvensis	+	+	+	+	+	+	+	+	+	+
Chenopodium album	+	+	+	+	+	+	+	+	+	+
Rumex dentatus	+	+	+	+	+	+	+	+	+	+
Phalaris minor	+	+	+	+	+	-	-	+	+	+
Spergula arvensis	-	-	+	+	+	-	-	-	+	+
Sonchus oleraceous	-	-	+	+	+	-	-	-	+	+
Polygonum aviculare	-	-	+	+	+	-	-	+	+	+

" – " indicates absence, whereas " + " indicates presence of particular weeds; CT = conventional tillage; TPR = transplanted puddled rice; DSR = direct seeded rice.

Table 5. Weeds affected by the allelopathic crop residues (Das 2008)

Allelopathic crops	Weeds affected by the allelopathy
Sorghum	*Abutilon theophrasti, Setaria viridis, Amaranthus hybridus, Phalaris minor*
Maize	*Chenopodium album, Amaranthus retroflexus, Digitaria sanguinalis*
Cassava	*Amaranthus* spp., *Digitaria sanguinalis*
Cucumber	*Echinochloa crus-galli, Amaranthus retroflexus*
Rye	*Digitaria sanguinalis, Chenopodium album*
Sweet potato	*Cyperus rotundus, Cyperus esculentus*

Crop residues physical effect

Crop residues serve as a physical barrier, which lowers the availability of light to weed seeds and reduces the rate of seedlings germination and emergence. In addition, it conserves moisture, and moderates or regulates temperature by acting as an insulator.

Crop residues chemical effect

Allelopathy and allelochemicals play an important role in CA towards weed dynamics but less/ hardly studied. Allelopathy is highly operating in cropping systems like rice-mustard, rice-wheat and maize-mustard. In these systems, allelopathic crop residues can have a significant impact on weed management and crop performance. Through long-term research, it has been found that rice residue shows some allelopathic effects on mustard, and mustard residue on direct-seeded rice in rice-mustard cropping system. Allelopathy may exert a stronger effect on small sized weed seeds compared to larger and deeper sown crop seeds. Allelopathic compounds released by crops can influence the germination, root growth and establishment of both crop and weed seedlings (**Table 5**).

Weed seed bank

A weed seed bank is the reserve of viable weed seeds present in soil and is maintained/governed by a dynamic equilibrium of weed seed rain, germination, predation, and decay. The seed bank is almost inexhaustible as it is replenished by seed rains. Under ZT, there is little opportunity for the freshly rained weed seeds to go deeper into the soil, therefore, they remain primarily on the top with the largest concentration in the 0-2 cm soil layer and no fresh weed seed is observed below 5 cm soil depth (Chauhan and Johnson, 2009). Some strategies to reduce seed rains, which contribute to the seed bank are: i) use of certified seeds or clean seeds free of weeds; ii) minimize the weed entry and establishment in a new area; iii) prevent invasive and alien weeds; iv) cleaning of farm implements and machineries before and after use; v) application of well rotten compost, and vi) cleaning of farm bunds. Herbicides and crop residues have potential role (**Table 6**) in reducing weed seed bank (Susha *et al.* 2018).

Table 6. Weed seed bank reductions in maize and wheat in different treatments (Susha *et al.* 2018)

Treatment	Weed seed (no. m^{-2}) 2010-11			2011-12			Mean reduction (%)
	Maize	Wheat	Total	Maize	Wheat	Total	
UWC	409.3	848.1	1257.4	395.3	804.6	1199.9	-
Atrazine + pendimethalin	150.7	586.3	736.9	135.7	481.3	617.0	45.0
Atrazine + mustard residue	155.3	592.1	747.4	155.0	497.2	652.2	43.1
Pendimethalin + imazethapyr	62.7	384.8	447.5	56.3	353.2	409.6	65.1
Brown manuring	156.3	615.3	771.6	140.7	522.4	663.1	41.6
WFC	423	348.0	771.0	407.0	359.7	766.7	37.4

Weed seed predation

Seed predation can play a role towards weed management in CA. It may reduce the effect of herbicides on weed population or its effect may be complementary to that of herbicides, if predators' actions are followed by herbicides applications. It depends on several factors such as type and quantity of residue, soil, weather and nature of native predators. By removing the new or fresh weed seeds from the soil surface, seed predators can help reduce the amount of weed growth or development. This approach not only benefits the environment but also reduces the risk and labor costs. However, the CT practice distributes weed seeds across soil layers, which causes additional difficulty in managing weeds through seed predation.

Chemical methods/ herbicides

The CA system is much dependent on herbicides for controlling weeds. Of course, the efficiency of herbicides varies across crops, soils, seasons, and environments. A proper crop husbandry practice will be complementary to herbicides and would render better weed management under no-till situations. Usually, less persistent, non-selective herbicides like glyphosate, paraquat or glufosinate-AM are recommended before crop sowing for ensuring weed-free conditions for crop germination. Pre-emergence herbicides may have lower efficacy in controlling weeds in CA systems due to the presence of crop residues, which can absorb/bind herbicides and may not allow herbicides to be in intimate/direct contact with the germinating weed seeds or seedlings and favour the weed seedlings to escape the applied herbicides. However, the efficacy of pre-mergence herbicides may be enhanced by applying them at little higher doses than recommended with a higher volume rate of water application. On the other hand, the post-emergent herbicides are very few that may not suffice for all crops. Several pre- emergence and post emergence herbicides are now available to effectively manage weeds in major crops like rice, wheat, soybean, cotton, sugarcane, pulses and oilseeds under CA (**Table 7**).

Chemical weed management in CA should be viewed in the perspectives of several imminent/ urgent considerations/issues like efficiency, economics, herbicide residue hazards and environmental sustainability, which are mentioned/discussed below.

Table 7. Herbicides for pre- and post-emergence use in CA in different crops

Crop	Pre-emergence	Post-emergence
Rice	Pendimethalin 1.0 kg/ha; pretilachlor (S) 750 g/ha; pyrazosulfuron 25 g/ha	Cyhalofop+ penoxsulam 135 g/ha (pre-mix); bispyribac-Na 25 g/ha; ethoxysulfuron 20 g/ha; fenoxaprop-p-ethyl 60 g/ha, cyhalofop-butyl 100 g/ha
Maize	Atrazine 1.0 kg/ha	Tembotrione 100 g/ha; topramezone 25.2 g/ha; halosulfuron-methyl 60 g/ha
Soybean	Metribuzin 350-500 g/ha; pendimethalin 750 g/ha + imazethapyr 75 g/ha (tank-mix)	Propaquizafop + imazethapyr 125 g/ha (pre-mix); Imazethapyr 100 g/ha; Na-acifluorfen + clodinafop 245 g/ha (pre-mix)
Pigeon pea	Pendimethalin 1.0 kg/ha	Quizalofop-ethyl 50 g/ha; imazethapyr 100 g/ha
Cotton	Pendimethalin 1.0 kg/ha	Quizalofop-ethyl 50 g/ha; pyrithiobac-Na 62.5 g/ha
Sugarcane	Atrazine 1.0 kg/ha; pendimethalin 1.0 kg/ha	Halosulfuron-methyl 90 g/ha
Wheat	Pyroxasulfone 127.5 g/ha (resistant P. minor area); pendimethalin 1.0 kg/ha	Clodinafop + metsulfuron (60+4) g/ha; clodinafop + carfentrazone (60+20) g/ha; sulfosulfuron + metsulfuron (25+4) g/ha;
Mungbean	Pendimethalin 1.0 kg/ha	Imazethapyr 100 g/ha

Efficiency:

The efficiency of a herbicide may be enhanced by the following ways:

- 5R stewardship (Right choice, source, dose, time and method) to be followed for applying herbicides
- Pre-emergence application with higher dose of herbicide and higher volume rate of water depending on crop residue level may be advocated.
- Non-selective systemic herbicide to be applied during off-season/lean period for perennial weeds.
- Post-emergence herbicides if available may be preferred to pre-emergence ones.
- Herbicide mixture and rotation may be followed: broad-spectrum herbicides having different modes of action for wider weed control and delaying weed resistance.
- Clean water, right sprayer and expertise in handling sprayers and herbicides.
- Granular herbicide may be more preferred to ensure higher selectivity and crop safety.

Economics

- Cost and availability of herbicide: herbicides should be at lower cost, affordable by the farmers and these herbicides should be available in the market.
- Availability and access to sprayers: Farmers should have access to sprayers because the herbicides have to be applied through sprayer for higher efficacy.

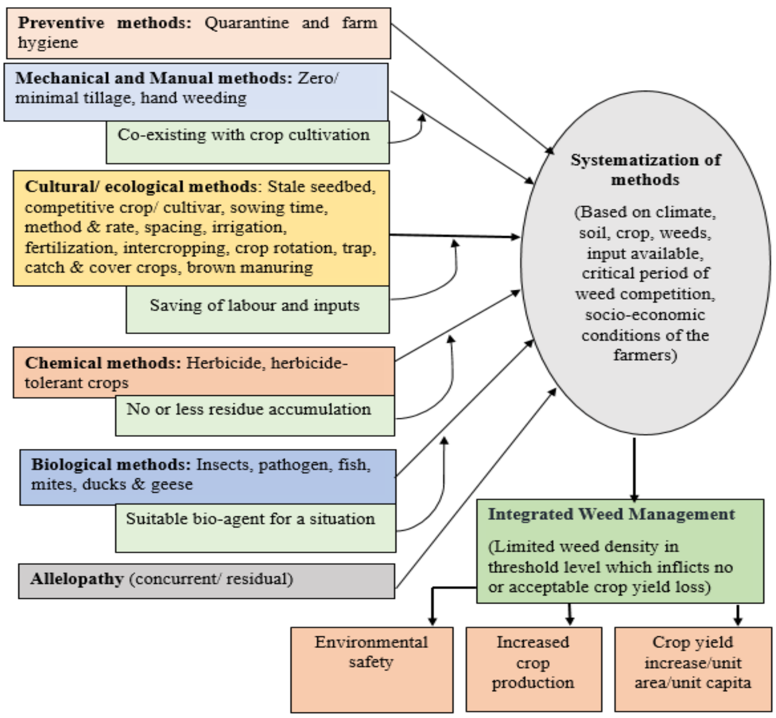


Figure 2. Schematic representation of integrated weed management (IWM)

Environmental/ecological sustainability

- Herbicides persistence in soil and crops and long-term residual effects should be monitored adequately.
- Non-target toxicity to soil micro-flora and fauna needs to be studied periodically and on long-term basis.
- Pollution of water bodies to be studied periodically and on long-term basis.
- Weed resistance and shift over the years

Herbicide- tolerant crops (HTCs)

Adoption of biotech crops including herbicide tolerant crops (HTCs) and CA-based technologies have grown hand-in-hand over the past 25 years. In 2016, HTCs occupied 86.5 million hectares, which is approximately 47% of the 185.1 million hectares of biotech crops planted globally. The most common are the glyphosate and glufosinate tolerant varieties. HTCs facilitate adoption of no-till practices in selected crops, but may restrict crop rotations. HTCs must be grown in conjunction with other weed control methods, particularly rotational use of herbicidal mode-of-actions to avoid resistance. However, herbicide resistant weeds are an issue that requires IWM and new innovations in biotechnology. Transgenic HTCs are not approved in India till date. However, gene-mutated inheritance has been studied in some crop varieties like rice, wheat, maize and chick pea. Herbicide tolerant rice and wheat through mutagenesis have been already developed. Their adoption would further add to the weed control efficiency in CA.

Integrated weed management (IWM)

The three CA concepts are interconnected and interactive enough to reduce weed problems over time. To develop sustainable and effective weed management strategies in CA systems, it would be wise to integrate approaches (Figure 2) such as stale seed bed, uniform and dense crop establishment, cover crops, crop residues, crop rotations and practices for enhanced crop competitiveness with a combination of pre- and post-emergence herbicides. As a result, a variety of weed management measures are required to widen weed control spectrum and efficacy for long term crop production.

Research needs and ways forward

- Availability of scale-appropriate seeder machine, creation of self-help group and custom hiring center and farmers' acquaintance with farm machinery for CA successful CA adoption.
- Quantifying crop residue allelopathy on crops, weeds and microbial community structures.
- Selective broad-spectrum wider-window post-emergence herbicides for controlling perennial weeds after pre-emergence herbicide use in crops.
- Dynamic herbicide recommendation/herbicide rotation involving 5-R stewardship for arresting weeds insurgence and resistance.
- Monitoring herbicides residue (non-selective and selective) under long-term CA system.
- Mutation-induced herbicide tolerant or transgenics crops.
- Newer herbicide application techniques (AI/Drone) for higher efficiency.
- ZT may be alternated with CT in every 5-6 years of ZT and deep summer ploughing, soil solarization to arrest perennial weeds.

Chapter 17

Weed management in natural farming

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The Green Revolution successfully achieved food security but also brought about new challenges, such as decreasing factor productivity and inefficient nutrient utilization. Substantial increase in input costs has led to a decline in crop income over the years. Though, per hectare real value of output increased for most crops in recent years, but the rise in the cost of inputs like fertilizers, pesticides, etc. was much higher, resulting into reduced farm income. Moreover, green revolution technology is now giving diminishing the economic returns to the farmers, more amount of nutrient application is needed to maintain the productivity level. It is also degrading the agro-ecosystem as synthetic chemical fertilizer and pesticides affect soil health by killing millions of microbes present in the soil which are important for sustaining plant life. This has necessitated the search of alternate farming methods like organic and natural farming.

Difference between natural farming and organic farming

Cost: Unlike Natural farming, Organic farming requires the use of large amounts of organic fertilizers and manure, e.g. FYM and vermi-compost. It is more expensive than natural farming.

Effort: Unlike Organic farming, "In natural farming, decomposition of organic matter by microbes and earthworms is encouraged right on the soil surface itself, which gradually releases nutrients into the soil."

Environmental effect: It is often argued that organic farming contributes more CO_2 to the atmosphere compared to natural farming.

The Economic Survey of India emphasized the importance of natural farming as one of the alternative farming practices for improving the farmer's income, in the backdrop of declining fertilizer response and farm income.

Natural farming concept

Natural Farming is a chemical-free farming system with modern understanding of ecology, resource recycling and on-farm resource optimization.

It is based on on-farm biomass recycling with major stress on biomass mulching, use of on-farm cow dung-urine formulations; maintaining soil aeration and exclusion of all synthetic chemical inputs.

It is considered as a cost-effective farming practice with scope for increasing employment and rural development.

Major objectives of natural farming

i. Preserving natural flora and fauna

ii. Restoring soil fertility and production and biological life

iii. Efficient utilization of land and natural resources (light, air, water)

iv. Reducing input cost of agricultural production by using natural / local based inputs

v. Improving economic conditions of farmers

Scenario

There are many working models of natural farming all over the world, the zero budget natural farming (ZBNF) as planned by Padma Shri Subhash Palekar is the most popular model in India. It refers to the process of raising crops without using chemical fertilisers and pesticides or any other external materials. Instead, farmers use low-cost locally-sourced natural concoctions, inoculums and decoctions based on cow dung, cow urine, jaggery, lilac, green chillies and many other such natural ingredients.

Andhra Pradesh, Karnataka, Himachal Pradesh, Gujarat, Uttar Pradesh and Kerala are among the leading states fallowing natural farming. Currently, the acceptance and adoption of natural farming systems are at early stages and gradually gaining acceptance among the farming community. As of now more than 10 lakh ha area is covered under natural farming in India.

Natural farming practices

It is naturistic way of farming given by Subhas Palekar for the farming of marginal and small farmers using desi cow's products. According to Palekar only one desi cow is required for 30 acres. Desi cow is suggested as native cow breed have greater microbes' population compared to exotic counter parts and desi cow is more adaptable to Indian conditions, less disease susceptibility and it is easily manageable by the resource poor farmers.

***Beejamrut*:** It is a fermented cow-based product used for protecting seeds from soil and seed borne disease in their early establishment. It is not a nutrient source but microbial load and growth hormones. It is used to treat the seeds before sowing. For preparation of Beejamrut 5 kg desi cow dung is taken in a piece of cloth, tied and dipped in 20 l water for overnight, then squeezed to get the soluble matter in the water; 50 gm of lime is added to 1 litre water and kept overnight to get it fully dissolved and cooled; finally add the lime, 5 l desi cow urine and one handful of soil from bund to the prepared cow dung extract and mix well. It is enough for treating 100 kg seeds.

***Jeevamrut*:** It is a microbial liquid that encourages rapid biological activity and earthworm activity in the soil, thus making nutrients available to the crop). Jeevamrut is a 200-liter mixture of 10 kg of desi cow dung, 10 liters of desi cow urine, 2 kg of jaggery, 2 kg of gram flour and and one handful of soil from bund. The mixture is properly fermented by keeping it under well aerated condition for about 8-10 days in shade, and then used. One acre of land needs 200 liters of jeevamrut. For best results, apply twice a month at 15-day intervals.

Besides the liquid formulation jeevamrut, a solid formulation named *ghanjeevamrut* is prepared by mixing 100 kg air-dried desi cow dung, 3 liters of desi cow urine, 1 kg of jaggery, 1 kg of gram flour and one handful of soil from bund. Cakes are made by using this mixture, which are air dried for about 10 days in shade. It can be stored for 1 year, ground the cakes to make powder before use. It is applied @ 300 kg/acre at the time of final land preparation.

***Mulching*:** Mulch provides the definite microclimate needed for the proper growth, multiplication, and activity of beneficial microorganisms introduced by Jeevamrut, and also prevents weed growth. Straw/residues of the preceding crop is used as mulch material. By managing soil temperature, maintaining soil moisture and lowering soil evaporation, mulching is an effective means of manipulating the crop growing environment to boost crop productivity and quality.

Besides the straw mulch legumes are grown in between the rows of main crop, which contributes nitrogen through biological fixation and also acts as live mulch. The idea of intercropping is praiseworthy both theoretically and practically that includes better yield, better use of resources, reduction in insect-pest and weed damage, and improved soil fertility.

***Whapasa*:** It is the soil microclimate in which soil organisms and crop roots can live safely due to the availability of adequate air and necessary moisture.

Plant protection

Application of a solution containing fermented butter milk, Jeevamrit and water (1:4:10) during milky stage of the crop is prescribed as preventive measure for disease and insect control. According to Subhas Palekar, disease control and prevention in natural farming can be done by locally sourced concoctions like Neemasatra, Agniastra and various others.

Activity	**Rationale**
Before sowing	
Suitable plan of Crop Rotation	If the same crop is planted year after year, the likelihood of a certain set of species emerging is higher.
Stale seedbed	Plough the land, apply irrigation, and allow the weeds to grow for 2-3 weeks, then kill the weeds using a rotavator and immediately sow the crop.
Use of weed free seeds	Use clean and weed free seeds.
Selection of Variety	Use weed suppressing variety of the crop, e.g. fast growing cultivars, if available.
After sowing	
Narrow crop spacing	Narrow row widths and a higher seeding density will reduce the biomass of later-emerging weeds by reducing the amount of light available for weeds located below the crop canopy.
Intercropping	Growing a leguminous smother crop between rows of the main crop. It is an essential component of natural farming.
Mulching	Apply preceding crop residues to cover soil surface. It is an essential component of natural farming.
Water management	Proper water management helps create conditions that are less favorable for weed growth while supporting the needs of cultivated crops, e.g.,drip irrigation; irrigation through furrows made at the interval two crop rows is prescribed for natural farming, wherever possible.
Manual/mechanical weeding	Weeds should be controlled manually/mechanically if its growth is high enough to affect crop yield. Weeds shouldn't be permitted to flower, this aids in reducing the weed seed bank.
Field Scouting	It involves the systematic collection of weed and crop data from the field (weed distribution, growth stage, population, crop stage etc.). The information is used, in the short term, to make immediate weed management decisions to reduce or avoid economic crop loss. In the long term, field scouting is important in evaluating the success or failure of weed management programs and for making sound decisions in the future.
Bio-herbicide	So far no recommended bioherbicide is available.
After harvesting	
Cover cropping	The land should not be kept fallow. Highly competitive crops may be grown as short duration 'smother' crops within the rotation. Often, the primary purpose of living mulch is to improve soil structure, aid fertility or reduce pest problems and weed suppression may be merely an added benefit.
Seasonal tillage	One of the most successful cultural practices to slow the spread of perennial weeds in crop cultivation is the use of summer or off-season tillage.

Constrains towards adoption of natural farming

A study conducted in the state of Andhra Pradesh involving the practicing ZBNF farmers revealed that, besides the low level of production during initial years, difficulty to manage weeds is one of the top 5 constraints preventing large scale adoption of natural farming.

Weed management in natural farming

The traditional manual method, which is very costly, is still being practiced to manage weeds under natural farming system in India as so far no bio-herbicide is available. Besides high cost, availability of agricultural labourer during peak weeding season due to sudden rise in manpower requirement is a bottleneck towards timely weeding operation.

Weed management in natural farming focuses on sustainable method to control weeds without relying on synthetic chemicals. Hence, the primary goal of weed management strategy for natural farming system is to prevent weeds, rather than reacting to existing populations. This can be achieved by reducing inputs to and increasing outputs from the weed seed bank in the soil. Although, non-chemical weed control methods are available in the literature, but none of the single method is effective for all weeds. Hence, possible methods, as mentioned below, are to be suitably integrated for effective and long-term weed management in a given cropping system ecology.

Chapter 18

Weed utilization

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Weeds, traditionally regarded as undesirable plants in agriculture, have recently garnered attention for their vast potential in areas such as food security, sustainable agriculture, medicine, and environmental remediation. Their resilience, adaptability, and wide availability make them a valuable resource in an era where sustainability and resource efficiency are of paramount importance. This lecture note explores the current and future perspectives of promoting weed utilization, focusing on their culinary, pharmaceutical, agricultural, environmental, and economic potential.

Culinary usage of edible weeds

Global usage

Edible weeds have long been used in traditional diets across various regions of the world, owing to their rich nutritional content and availability. Weeds such as amaranth, purslane, and dandelion are packed with vitamins, minerals, and antioxidants, making them excellent additions to diets. The following table summarizes the culinary usage of edible weeds in different regions, with a special focus on India:

Culinary usage in India

In India, many edible weeds are integral to traditional diets, particularly in rural areas. Amaranth, lamb's quarters (bathua), and purslane are commonly used in dishes like saag, stir-fries, and curries. These plants are highly nutritious and often serve as affordable alternatives to cultivated vegetables, especially for rural populations.

Global perspective

Weeds like dandelion and nettle are popular in Europe and North America, often used in salads, teas, and cooked dishes. In East Asia, shepherd's purse and wild mustard are used in soups and dumplings. These plants offer a rich source of vitamins, minerals, and antioxidants, making them valuable for enhancing dietary diversity and nutrition.

Table 1. Culinary usage of edible weeds

Weed	Culinary Usage	Region	Description
Amaranth (*Amaranthus* spp.)	Saag (greens), stir-fried, added to curries	India (especially rural areas)	Known as "Chaulai" in Hindi, amaranth leaves are stir-fried or cooked in lentils and curries.
Purslane (*Portulaca oleracea*)	Salads, soups, stir-fry	India, Middle East, Mediterranean	Used as a tangy green in salads and soups; known as "Kulfa" in India, often added to lentils and vegetable dishes.
Dandelion (*Taraxacum officinale*)	Salads, sautéed, herbal tea	Europe, North America	Young leaves are used in salads, while older leaves are cooked. Dandelion root is used for herbal tea.
Nettle (*Urtica dioica*)	Soups, tea, pesto	Europe, India (Himalayan region)	Known as "Bichhu Buti" in India, nettle leaves are cooked in soups or boiled and used like spinach.
Pigweed (*Amaranthus retroflexus*)	Saag, stir-fry, added to stews	India, Africa	In India, used in traditional dishes like "saag" (leafy green curry) and stir-fried with spices.

Table 2. Pharmaceutical usage of edible weeds

Weed	Pharmaceutical Use	Health Benefits
Brahmi (*Bacopa monnieri*)	Herbal Supplement, Memory Enhancer	Improves cognitive function, reduces anxiety, used in Ayurveda.
Dandelion (*Taraxacum officinale*)	Diuretic, Liver Health, Digestive Aid	Supports liver detoxification, aids digestion, reduces inflammation.
Nettle (*Urtica dioica*)	Anti-inflammatory, Antihistamine, Pain Reliever	Used for treating arthritis, allergies, and joint pain.
Purslane (*Portulaca oleracea*)	Antioxidant, Anti-inflammatory	Rich in omega-3 fatty acids, reduces inflammation and promotes heart health.
Red Clover (*Trifolium pratense*)	Hormonal Balance, Menopausal Symptom Relief	Contains phytoestrogens, used to relieve menopausal symptoms.

Pharmaceutical usage of edible weeds

Many edible weeds have medicinal properties and have been traditionally used in herbal medicine systems around the world. These weeds contain bioactive compounds such as flavonoids, alkaloids, and tannins, which have therapeutic effects. The table below highlights the pharmaceutical usage of some common edible weeds:

Weeds like brahmi and dandelion are gaining popularity in alternative medicine for their potent medicinal properties. For example, brahmi is widely used in Ayurveda to enhance memory and reduce stress. Similarly, dandelion is known for its liver detoxifying properties and is often consumed in the form of tea or supplements.

Future research in medicinal weeds

As interest in herbal medicine grows, there is significant potential for further research into the medicinal properties of weeds. This could lead to the development of new pharmaceutical products, particularly as more consumers turn to natural remedies for health and wellness.

Weed utilization in vermicomposting

Weeds are not only beneficial for human consumption but also play an important role in organic farming. Vermicomposting, a process where organic matter is broken down by worms, can convert weed biomass into nutrient-rich compost. Weed utilization for vermicomposting is an innovative and sustainable approach to managing weed biomass while enhancing soil fertility. Vermicomposting involves the use of earthworms, primarily Eisenia fetida (red wigglers), to decompose organic matter, converting it into nutrient-rich compost. Weeds such as water hyacinth, parthenium, and amaranth are often considered agricultural nuisances, but when processed through vermicomposting, they break down into high-quality organic fertilizer. This process not only recycles weed biomass that would otherwise be discarded or burned but also enriches the compost with essential nutrients like nitrogen, phosphorus, and potassium, crucial for plant growth. Additionally, vermicomposting improves soil structure, moisture retention, and microbial activity, making it an eco-friendly alternative to chemical fertilizers. Using weed biomass in vermicomposting provides a dual benefit of weed management and sustainable agricultural practices. The following table highlights the nutrient content of vermicompost made from different weeds:

Weeds like water hyacinth and parthenium can be used to produce high-quality vermicompost, rich in essential nutrients like nitrogen, phosphorus, and potassium. This compost can improve soil fertility and structure, promoting sustainable farming practices while reducing the need for chemical fertilizers.

Table 3. Nutrient contents in weed based vermicompost

Weed	Nitrogen (N)	Phosphorus (P)	Potassium (K)	Organic Matter (OM)	Other Nutrients
Water Hyacinth (*Eichhornia crassipes*)	1.5-2.0%	0.5-0.8%	1.0-1.5%	40-50%	Calcium, Magnesium
Parthenium (*Parthenium hysterophorus*)	1.2-1.5%	0.4-0.6%	0.8-1.0%	30-40%	Iron, Zinc
Lantana camara	1.0-1.4%	0.3-0.5%	0.7-0.9%	35-45%	Manganese, Sulfur
Amaranthus (*Amaranthus* spp.)	1.4-1.8%	0.5-0.7%	1.2-1.6%	40-50%	Calcium, Magnesium
Cynodon dactylon (*Bermuda Grass*)	1.3-1.7%	0.5-0.7%	1.1-1.4%	40-50%	Potassium, Zinc

Weeds in environmental remediation

Weed utilization for phytoremediation is a promising and eco-friendly technique to restore contaminated soils and water bodies. Certain fast-growing weeds, such as **parthenium**, **lantana**, **water hyacinth**, and **sunflower**, possess the unique ability to absorb, accumulate, or degrade toxic substances like heavy metals, pesticides, and organic pollutants from the environment. These plants are resilient and thrive in adverse conditions, making them ideal candidates for cleaning up polluted areas. For example, **water hyacinth** is effective in absorbing heavy metals such as lead, mercury, and cadmium from water bodies, while **parthenium** has been shown to remove contaminants from soil. This natural method offers a cost-effective and sustainable alternative to conventional remediation techniques, which are often expensive and energy-intensive. After the phytoremediation process, safe disposal methods such as composting, incineration, or pyrolysis must be employed to handle the contaminated biomass properly, preventing the reintroduction of pollutants. Utilizing weeds for phytoremediation not only mitigates environmental pollution but also leverages unwanted plant species for ecological restoration and soil health improvement.

The mechanism of phytoremediation involves several pathways, depending on the type of contaminant and plant species. **Phytoextraction** occurs when plants absorb contaminants, such as heavy metals, through their roots and accumulate them in their tissues. **Phytodegradation** involves the breakdown of organic pollutants (like pesticides) by plant enzymes. **Phytostabilization** reduces the mobility of contaminants in soil, preventing their spread by trapping them in the plant's root zone. In **rhizofiltration**, plant roots filter and absorb contaminants from water. **Phytovolatilization** involves the uptake of pollutants, which are then converted into less harmful forms and released into the atmosphere through transpiration. These mechanisms make phytoremediation a versatile, eco-friendly, and cost-effective method for addressing environmental contamination. The table below outlines various disposal techniques for phytoremediator plant biomass:

Table 4. Safe disposal techniques of phytoremediator plant biomass

Disposal Technique	Brief Description	References
Composting (Controlled)	Suitable for plants absorbing organic pollutants; composting breaks down biomass without releasing contaminants.	EPA Guidelines on Composting
Incineration	High-temperature incineration destroys organic contaminants, but requires careful handling of metals.	Khan *et al.* 2013, *Phytoremediation of Hazardous Wastes*
Landfilling	Hazardous waste landfills are used to isolate contaminated biomass, preventing contaminant leaching.	Cunningham *et al.* 1997, *Phytoremediation of Contaminated Soils*
Pyrolysis	Converts biomass into biochar, immobilizing metals and reducing environmental risks.	Beesley *et al.* 2011, *Biochar in Contaminated Land*

Table 5. Commercially available products from edible weeds

Product Name	Weed Used	Type of Product	Brand/Manufacturer	Key Benefits
Nettle Tea	Stinging Nettle (*Urtica dioica*)	Herbal Tea	Traditional Medicinals	Anti-inflammatory, supports urinary health and detoxification.
Dandelion Root Coffee	Dandelion (*Taraxacum officinale*)	Coffee Substitute	Dandy Blend	Caffeine-free, supports liver health, aids digestion.
Purslane Oil	Purslane (Portulaca oleracea)	Facial Oil	Herbivore Botanicals	Rich in Omega-3, moisturizes and nourishes the skin.
Brahmi Powder	Brahmi (*Bacopa monnieri*)	Herbal Supplement (Powder)	Organic India	Enhances memory, cognitive function, stress relief.
Chaulai Atta (*Amaranth Flour*)	Amaranth (*Amaranthus spp.*)	Gluten-Free Flour	Jiwa Organic	High in protein, gluten-free, used in baking and cooking.

These techniques are crucial for managing contaminated plant biomass safely. Techniques like **pyrolysis** and **vitrification** offer long-term stability by immobilizing contaminants, while **incineration** effectively destroys organic pollutants.

Commercially available products from edible weeds

Weeds have great commercial potential, especially in the health and wellness industry. The table below lists some commercially available products made from edible weeds:

The commercial products highlight the growing market for weed-based products in the health, skincare, and food industries. Brands such as **Organic India** and **Traditional Medicinals** have capitalized on the medicinal and nutritional benefits of edible weeds, creating a variety of products ranging from teas to skincare oils.

Future perspectives of promoting weed utilization

The potential of weeds extends far beyond their traditional roles in agriculture and medicine. Here are ten key future perspectives on promoting weed utilization:

- **Sustainable Food Source:** Edible weeds can be promoted as a sustainable, nutritious food source, helping to address food security issues in regions affected by climate change or resource scarcity.
- **Low-Cost Agricultural Input:** Weeds can be used as organic fertilizers or in vermicomposting, reducing dependency on chemical fertilizers and enhancing soil health in an eco-friendly manner.
- **Alternative Medicine:** With their rich phytochemical content, many weeds have medicinal properties. Research can promote the use of weeds like **Brahmi** and **Dandelion** in alternative and complementary medicine systems.
- **Economic Opportunities for Farmers:** Farmers can benefit economically by harvesting and selling edible weeds, either in raw form or processed into products like powders, teas, and supplements, creating new income streams.
- **Phytoremediation Applications:** Weeds with the ability to absorb pollutants and heavy metals can be utilized in large-scale phytoremediation projects, helping to restore contaminated environments.

- **Weed-Based Bioenergy:** Fast-growing weeds can be explored as a source of biomass for renewable energy production, including biofuels, biogas, or biochar, contributing to the renewable energy sector.
- **Climate-Resilient Crops:** Weeds that naturally thrive in harsh, adverse conditions can be bred or utilized as climate-resilient crops, providing solutions for regions facing water shortages and degraded lands.
- **Promotion of Local and Indigenous Knowledge:** Many rural communities traditionally use edible weeds in their diets and medicine. Promoting weed utilization will help preserve this indigenous knowledge and biodiversity.
- **Urban Agriculture Integration:** With the rise of urban farming, edible weeds can be cultivated in cities on rooftops, community gardens, and vacant lots, offering a low-maintenance, nutrient-rich food source.
- **Research and Innovation:** Increased scientific research into the nutritional, medicinal, and ecological benefits of weeds can lead to the development of novel products, driving innovation in industries like pharmaceuticals, nutraceuticals, and cosmetics.

Conclusion

Weeds, once viewed solely as agricultural nuisances, offer an array of benefits across multiple domains. From serving as sustainable food sources to aiding in phytoremediation and bioenergy production, promoting the utilization of weeds is essential for building a more sustainable and resilient future. Their widespread availability, adaptability, and valuable properties make them a significant resource for addressing challenges in food security, environmental conservation, and health care. As research and innovation continue to expand the applications of weeds, their importance in various sectors is likely to grow, offering new opportunities for economic development and ecological sustainability.

Chapter 19

Current status of biological control of weeds and future perspectives

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The biological control of invasive alien plants species (weeds) has had a long and successful record dating back to the late 1800s when the first introductions of cochineal insects were made to target cacti. Up until 2018 there have been 1555 intentional releases of 468 biological control agent species used against 175 species of target weeds in 48 plant families, in 90 countries. Although the USA, Australia, South Africa, Canada and New Zealand have been the most active countries, the greatest need for the implementation of this form of weed suppression is in resource poor countries. Weed biological control is more relevant now than ever before with an increasingly discerning public, greater human health awareness, greater environmental awareness and the possible evolution of resistance of weeds to herbicides. These factors, coupled with initiatives such as the European Union Green Deal which aims to halve pesticide use by 2030 augurs well for a global increased reliance on biological control.

In terms of the science of weed biological control, public and government perceptions of the safety of the science have largely been allayed, and pre-release testing ensures that a risk assessment framework can be used to make decisions regarding releases. However, biological control practitioners will always be questioned regarding the safety of their science and must be prepared to offer rational, science-based and balanced answers. Post-release evaluation is still neglected and there is the need to improve how projects are assessed. Funders of biological control efforts, users of the technology and society on the whole need to be better informed as to the return on investment of biological control. Thus, there needs to be more research into how biological control has alleviated the ecological and economic impacts caused by the weeds, and ultimately reduced the reliance on herbicides.

In an increasing litigious society there will be an increasing number of regulations regarding the collection, movement and use of genetic material. It is encouraging to see how the biological control community has not dismissed this added administrative burden, but rather engaged with it. This philosophy must continue.

Challenges include

- engaging more with growers for the uptake of biocontrol agents, particularly with capacity building through Farmer Field Schools and plant clinics;
- better linking research with extension services and growers;
- incentivizing growers' participation in biocontrol training programmes;
- enhancing communication and knowledge dissemination on the safety and effectiveness of BCAs – with and between growers, extension services and policymakers, as well as through education curriculums;

- improving regulatory frameworks, including by simplifying registration requirements to ensure the affordability of BCAs and reduce the time to get new products to growers;
- encouraging harmonization of regional regulatory frameworks, with mutual recognition of regulatory decisions;
- ensuring approaches recognize the considerable differences that exist countries, user communities and stakeholders; and
- increasing collaboration between the private and public sectors to finance the transition

The driving forces in weed management are many and varied, and they continue to develop and change. Biological control is in an ideal position to be the primary player in integrated weed management systems provided it meets the challenges stated above.

Chapter 20

The wild oat menace in Australian agriculture: A story of persistence, adaptation, and control

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Wild oats, an invasive grass weed, have changed the landscape of Australian agriculture since its arrival in the early 19th century. Probably transmitted by infested wheat and barley seeds, it spread across all the states. This invasive species has become a problem for Australian grain growers because it is highly competitive, produces abundant seeds, and is resistant to several herbicides. With two dominant species, *Avena fatua* (AF) and *Avena ludoviciana* (AL), wild oats have become a serious threat in Australia, demanding integrated and innovative control strategies.

Biological characteristics and early detection

Wild oat plants, often referred to by Australian growers as "black oats" or "bearded oats", have distinct features that distinguish them from wheat and barley early in their development. They grow from fibrous root systems, with cotyledons that remain underground and leaves that rotate against the clock, a characteristic that makes them easy to spot. The presence of large ligules and the absence of auricles further differentiate wild oat seedlings from other cereal crops. AF and AL can be differentiated at the maturity stage as seeds of AL shatter in pairs, while AF seeds shatter individually.

Impact on crop yields

The invasive nature of wild oats has led to considerable losses in Australian agriculture. If left unmanaged, wild oats can cause up to 80% yield reduction in winter crops, such as wheat and barley. The competitiveness of wild oat plants arising from their aggressive growth and ability to match crop emergence timing leads to direct competition for resources. Research trials in Gatton, Queensland, indicated that just 15 wild oat plants/m^2 could reduce chickpea yields by more than 80%. Overall, wild oats infestations account for an estimated AU$ 28 million in annual revenue losses for Australian grain growers, making efficient management essential to the economic viability of these areas.

Adaptation and herbicide resistance

Over time, wild oats have slowly adapted to different agricultural practices, evolving resistance to multiple herbicide groups, including glyphosate. This resistance has compelled researchers and farmers to explore alternative methods of control. Wild oat's high seed production, coupled with its dormancy behaviour and staggered germination, allows it to persist in fields, even after multiple herbicide applications. Wild oats have the ability to produce seeds under water-stress conditions, and AL has a relatively higher water tolerance than AF. Additionally, wild oats often serves as an alternative host for various cereal diseases, including cereal cyst nematode and crown rot, further complicating the management practices to attain profitability.

Emergence patterns and seed persistence

The germination and emergence patterns of wild oats vary by species and environmental conditions, particularly temperature and soil depth. Studies indicate that *AL* has a higher germination rate at alternating (12 h light/12 h dark) temperatures of 20/10°C and 25/15°C, while *AF* prefers 20/10°C. Field observations in Queensland confirm that AL typically emerges earlier than AF, with peak emergence occurring in May and June following rainfall, emphasising the need for prolonged weed control measures.

Wild oat's ability to germinate from a range of soil depths, particularly 2 to 5 cm, further complicates its control. Seeds buried deeper than 10 cm or left on the soil surface tend to decay faster, while those at shallow depths may persist longer. Research on seed persistence has shown that wild oats seeds at the surface or deeper depths have about six months of half-life, but that at shallow depths (2 cm), the same seeds can survive (half-life) up to 18 months. Soil aeration and moisture are critical factors in the process of seed decomposition; heavier soils slowing down the decay process.

Seed production and dispersal potential

Wild oat's prolific seed production is a major factor in its persistence. Under fallow conditions, early cohorts (May-optimum planting time for most winter crops) produce significantly more seeds than late cohorts (July-a mid winter month) in the season. For example, early-emerged AF and AL cohorts yield between 3,300 and 4,000 seeds per plant, while late-emerged cohorts produce only a fraction of that amount. Moreover, seed retention varies by crop competition, with wheat and chickpea crops showing different levels of seed retention across wild oat populations. In crops like wheat, wild oats can produce thousands of seeds per square meter, which underscores the importance of timely control to prevent seed dispersal and maintain manageable seed banks in the soil.

Strategies for control and management

Given the complexity of wild oats management, integrated control strategies have emerged as the most effective approach. High seeding rates, delayed planting, and selective herbicide applications have shown promise in controlling wild oats infestations. For instance, early-planted wheat at a high seeding rate (200 seeds/m^2) has been observed to suppress AL growth and seed production. Delayed planting of wheat in eastern Australia, typically in June, can help reduce early wild oats emergence, allowing growers to use pre-sowing tillage and herbicides effectively.

Pinoxaden, a herbicide that targets *AL*, has proven effective when applied at specific growth stages (Z12 and Z33) in wheat. Delayed application at Z33 reduces wild oat biomass and seed production without compromising wheat yield. This approach demonstrates the promise of precision herbicide use to help minimise the crop losses caused by wild oats. However, research has also shown that early-planted wheat can benefit from pyroxasulfone, triallate and trifluralin. Among these, pyroxasulfone-treated plots have shown higher yields, suggesting it a viable option for early-planted wheat in fields with high wild oat infestations.

No-tillage systems have also been explored for wild oat management. Research indicates that no-tillage can reduce wild oat seed production by about 30% compared to conventional tillage, which may offer sustainable control for growers aiming to reduce soil disturbance.

Conclusion

The spread of wild oats in Australia is a challenge for growers. High seed production, delayed germination, high levels of herbicide (to Group 1 and 2) resistance, and high competitive ability have made wild oats one of Australia's most problematic weeds. Targeted herbicide spraying, the use of high seeding rates, and manipulating planting times have all worked to suppress wild oat infestations and maintain yields. The story of wild oats in Australia emphasises the importance of adaptive management in agricultural systems. Australian farmers and scientists need to stay alert, as wild oat evolves resistance. The lessons of the war on wild oats demonstrate the importance of ongoing research, innovation and collaboration between agronomists, researchers and producers. Through cultural, chemical and mechanical control approaches, Australia's farming community can minimise the impacts of this weed, enabling sustainable and profitable crop yields for decades to come.

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Multiple choice question bank on training lectures

1. **Which recent technology has been increasingly used for precision weed management?**
   - ✅ **a) Drones**
   - b) Hand weeding
   - c) Traditional tillage
   - d) Crop rotation

2. **What is the purpose of using bioherbicides in modern weed management?**
   - a) To increase chemical herbicide effectiveness
   - ✅ **b) To provide an environment friendly alternative to synthetic herbicides**
   - c) To enhance soil fertility
   - d) To prevent crop disease

3. **Which recent development in weed management involves the use of Artificial Intelligence (AI)?**
   - a) Herbicide resistance breeding
   - ✅ **b) AI-powered weed detection and spraying systems**
   - c) Manual scouting of fields
   - d) Increased herbicide application rates

4. **What is the role of cover crops in the context of recent advances in weed management?**
   - a) They enhance weed growth
   - b) They act as natural herbicides
   - ✅ **c) They suppress weeds by outcompeting them for resources**
   - d) They increase the need for chemical herbicides

5. **In major crop production systems, what is a key benefit of integrating cultural practices into weed management strategies?**
   - a) Reduces the need for crop diversification
   - ✅ **b) Enhances the effectiveness of chemical control by disrupting weed life cycles**
   - c) Increases dependency on herbicides
   - d) Eliminates the need for mechanical control

6. **How does crop rotation contribute to integrated weed management in cereal production systems?**
   - a) It simplifies weed management by using the same herbicide each season
   - b) It increases the soil weed seed bank
   - ✅ **c) It reduces weed pressure by altering the competitive environment for weeds**
   - d) It makes herbicide applications unnecessary

7. **Which of the following is a major challenge in implementing integrated weed management strategies in large-scale agriculture?**

   a) Availability of diverse herbicides

   ✅ **b) Complexity of managing multiple weed control tactics**

   c) High cost of chemical herbicides

   d) Decreased crop yield

8. **In the context of major crop production systems, what role do cover crops play in integrated weed management strategies?**

   a) They require frequent herbicide applications

   b) They serve as a habitat for weed proliferation

   ✅ **c) They improve soil health while suppressing weed growth**

   d) They decrease the need for crop rotation

9. **Why is understanding weed biology crucial in developing effective weed management strategies?**

   a) It allows for the indiscriminate use of herbicides

   ✅ **b) It helps in predicting weed emergence and growth patterns**

   c) It reduces the need for crop rotation

   d) It eliminates the need for mechanical control

10. **Which aspect of weed biology is most important for determining the timing of weed control measures?**

    ✅ **a) Weed seed dormancy and germination patterns**

    b) The colour of the weed leaves

    c) The weed's ability to resist herbicides

    d) The height of the weed at maturity

11. **How does the knowledge of weed reproductive strategies contribute to weed management?**

    a) It encourages weed growth

    ✅ **b) It helps in targeting weed species during their most vulnerable stages**

    c) It reduces the effectiveness of cultural control methods

    d) It makes herbicides less effective

12. **What role does understanding weed competition with crops play in integrated weed management?**

    a) It highlights the need for increased herbicide usage

    ✅ **b) It emphasizes the importance of crop-weed interaction timing**

    c) It reduces the necessity of monitoring weed populations

    d) It focuses solely on mechanical control methods

13. How does rising atmospheric CO_2 levels due to climate change impact crop-weed interactions?

a) Weeds become less competitive against crops

✅ **b) Weeds may become more competitive due to enhanced photosynthesis**

c) Crops outcompete weeds more easily

d) No significant impact on crop-weed interactions

14. Which of the following is a potential effect of increased temperatures on herbicide efficacy?

a) Improved herbicide absorption by crops

b) Reduced weed resistance to herbicides

c) Decreased volatilization of herbicides

✅ **d) Faster degradation of herbicides in the soil, reducing their effectiveness**

15. Climate change-induced changes in rainfall patterns can affect herbicide application by:

a) Reducing the need for herbicides

b) Making post-emergence herbicides more effective

✅ **c) Increasing the risk of herbicide runoff and reduced effectiveness**

d) Improving herbicide persistence in the soil

16. How might climate change alter the geographical distribution of weed species?

a) Weeds will only thrive in cooler regions

✅ **b) Certain weed species may expand into new areas with more favourable conditions**

c) Weed species will decline globally

d) Weeds will be restricted to their current habitats

17. What is a key principle of conservation agriculture that impacts weed management?

✅ **a) No-till or minimum tillage**

b) Continuous tillage

c) High herbicide usage

d) Monocropping

18. How does crop residue retention in conservation agriculture influence weed management?

a) It promotes weed growth by providing a habitat

✅ **b) It suppresses weed emergence by creating a physical barrier**

c) It requires more herbicide application

d) It decreases soil moisture, reducing weed growth

19. In a conservation agriculture-based cropping system, what role does crop rotation play in integrated weed management?

a) It has little impact on weed populations

b) It helps break weed life cycles and reduces specific weed species

c) It increases the reliance on chemical weed control

d) It favors the proliferation of perennial weeds

20. Which of the following is a challenge in implementing integrated weed management in conservation agriculture systems?

a) Reduced weed pressure due to tillage

b) Dependence on a single weed control method

c) Difficulty in managing herbicide-resistant weeds without tillage

d) Increased soil erosion

21. What is the primary cause of herbicide resistance in weed populations in India?

a) Use of organic farming practices

b) Repeated and over-reliance on the same herbicide

c) Introduction of new crop varieties

d) Increased rainfall patterns

22. Which of the following is a common weed species in India known for developing resistance to herbicides?

a) *Phalaris minor* (Littleseed canary grass)

b) *Cyperus rotundus* (Purple nutsedge)

c) *Amaranthus viridis* (Slender amaranth)

d) *Chenopodium album* (Lambsquarters)

23. What is the significance of herbicide-tolerant crops in managing herbicide-resistant weeds in India?

a) They reduce the need for crop rotation

b) They allow for the effective use of specific herbicides without damaging the crop

c) They eliminate the need for mechanical weed control

d) They increase the growth rate of weeds

24. Which herbicide-tolerant crop has been a subject of debate and limited adoption in India due to environmental and regulatory concerns?

a) Bt cotton

b) Herbicide-tolerant rice

c) Glyphosate-tolerant maize

d) Glufosinate ammonium-tolerant mustard

25. What is the primary purpose of herbicide rotation in managing herbicide-resistant weeds?

a) To reduce the cost of weed management

✅ **b) To prevent weeds from becoming resistant to a single mode of action**

c) To increase herbicide application frequency

d) To promote faster weed growth

26. How do tank mixtures of herbicides help in controlling herbicide-resistant weeds?

a) By diluting the concentration of each herbicide

b) By reducing the need for crop rotation

✅ **c) By combining herbicides with different modes of action to target multiple weed species**

d) By increasing the overall volume of water used in application

27. Which of the following is a potential risk of improper herbicide rotation in weed management?

a) Enhanced crop growth

✅ **b) Development of cross-resistance in weeds to multiple herbicides**

c) Increased soil fertility

d) Better control of susceptible weeds

28. What is an important consideration when selecting herbicides for a tank mixture to control both resistant and susceptible weeds?

✅ **a) Using herbicides with complementary modes of action to reduce resistance**

b) Selecting herbicides with the same mode of action

c) Increasing the dosage of a single herbicide

d) Avoiding herbicides with residual activity

29. What is the primary objective of plant quarantine in the context of weed management?

a) To promote the growth of exotic plants

✅ **b) To prevent the introduction and spread of exotic weeds**

c) To regulate the sale of herbicides

d) To encourage international trade of plant materials

30. Which of the following is a common method used in plant quarantine to prevent the entry of exotic weeds?

a) Increasing the use of chemical fertilizers

b) Promoting the cultivation of non-native species

c) Reducing the monitoring of imported goods

✅ **b) Inspecting and certifying imported plant materials for weed contaminants**

31. How can the introduction of exotic weeds impact local ecosystems if not controlled by plant quarantine measures?

a) They can increase biodiversity

✅ **b) They can outcompete native species and disrupt ecosystems**

c) They improve soil fertility

d) They have no significant impact on local ecosystems

32. Which international agreement plays a significant role in the global regulation of plant quarantine to prevent the spread of exotic weeds?

✅ **a) The International Plant Protection Convention (IPPC)**

b) The Montreal Protocol

c) The Kyoto Protocol

d) The Paris Agreement

33. What is a major challenge of weed management in direct-seeded rice compared to transplanted rice?

a) Weeds are easier to control in direct-seeded rice

✅ **b) Direct-seeded rice is more susceptible to early weed competition due to the absence of water as a natural suppressor**

c) Herbicide options are more limited in direct-seeded rice

d) Weeds are less competitive in direct-seeded rice

34. Which cultural practice is recommended as part of integrated weed management in direct-seeded rice to suppress weed growth?

a) Broadcasting seeds at random

✅ **b) Uniform seed sowing at optimum depth**

c) Delayed planting of rice

d) Avoiding the use of pre-emergence herbicides

35. What role do pre-emergence herbicides play in the integrated weed management of direct-seeded rice?

a) They are not recommended for use in direct-seeded rice

b) They should be applied only after the weeds have emerged

✅ **c) They help control weeds before they emerge, reducing early competition with the rice crop**

d) They are used to increase the growth rate of rice

36. In direct-seeded rice, how can crop rotation contribute to integrated weed management?

a) By reducing soil fertility

b) By promoting the growth of the same weed species each season

✅ **c) By disrupting weed life cycles and reducing weed seed banks in the soil**

d) By making weeds more resistant to herbicides

37. What is a key advantage of using crop rotation in a rice-based cropping system for weed management?

a) It eliminates the need for herbicides

✅ **b) It helps in breaking the life cycle of specific weed species that are adapted to rice fields**

c) It allows continuous flooding, which suppresses all weeds

d) It reduces the need for mechanical weeding

38. Which of the following is an effective cultural practice for managing weeds in a rice-based cropping system?

✅ **a) Maintaining proper water management to suppress weeds during critical growth stages**

b) Broadcasting seeds without any soil preparation

c) Avoiding the use of organic fertilizers

d) Delaying the planting of rice beyond the optimal season

39. How can the integration of mechanical weeding complement chemical control in a rice-based cropping system?

a) By increasing herbicide resistance in weeds

✅ **b) By reducing the reliance on herbicides and targeting weeds that escape chemical control**

c) By replacing the need for crop rotation

d) By decreasing the effectiveness of pre-emergence herbicides

40. What is the role of cover crops in an integrated weed management strategy for a rice-based cropping system?

a) They increase the weed seed bank in the soil

b) They delay the rice planting season

c) They require increased herbicide application

✅ **d) They suppress weed growth by providing ground cover and competing for resources**

41. What is a significant challenge in managing weeds in pulse crops compared to other crops?

a) Pulses are naturally resistant to most weeds

b) Weeds are less competitive in pulse crops

✅ **c) Pulses grow slowly during their early stages, making them more vulnerable to weed competition**

d) Pulses require more herbicide than other crops

42. Which cultural practice is most effective in reducing weed pressure in pulse crops?

a) Late sowing of pulse crops

✅ **b) High seeding rate to increase crop competition against weeds**

c) Avoiding crop rotation

d) Continuous irrigation

43. How can intercropping with cereals benefit weed management in pulse crops?

- **a) It provides additional ground cover, which suppresses weed emergence**
- b) It increases the growth rate of weeds
- c) It requires more herbicide use
- d) It makes weed control more difficult

44. What is a key consideration when selecting herbicides for use in pulse crops as part of an integrated weed management strategy?

- a) Herbicides should have a broad-spectrum activity to target all types of weeds
- b) Herbicides should be applied at high doses to ensure weed control
- **c) Herbicides should be selected based on their compatibility with the specific pulse crop to avoid crop injury**
- d) Herbicides should be avoided altogether in pulse crops

45. Which digital technology is most commonly used for real-time weed detection in precision agriculture?

- a) Global Positioning System (GPS)
- b) Blockchain technology
- c) Automated irrigation systems
- **d) Remote sensing with drones or satellites**

46. How does machine learning contribute to precision weed management?

- a) By replacing the need for human intervention in all farming activities
- **b) By analyzing large datasets to improve weed identification and optimize herbicide application**
- c) By reducing the need for any weed management practices
- d) By increasing the amount of herbicide required for effective weed control

47. What is the primary advantage of using digital technologies for weed management in precision agriculture?

- a) Increased herbicide usage across entire fields
- b) Elimination of the need for traditional farming equipment
- c) Complete automation of all farm activities
- **d) Enhanced ability to target weeds selectively, reducing overall herbicide use**

48. Which of the following is a potential challenge in adopting digital technologies for weed management?

- **a) High initial costs and the need for technical expertise**
- b) The technologies are fully developed and require no further innovation
- c) The technologies do not integrate with existing farming practices
- d) Lack of support from government policies

49. How does nanotechnology enhance the effectiveness of herbicides in weed management?

a) By increasing the volume of herbicides required

✓ **b) By improving the targeted delivery of herbicides to specific weed species**

c) By making herbicides more susceptible to environmental degradation

d) By reducing the need for precise application timing

50. What is a potential benefit of using nanocarriers in herbicide formulations?

a) They make herbicides less effective against resistant weeds

b) They increase the cost of herbicide production significantly

✓ **c) They allow for the controlled release of herbicides, reducing environmental impact**

d) They reduce the shelf life of herbicides

51. Which of the following is a challenge in implementing nanotechnology for weed management?

✓ **a) Potential concerns about the environmental and human health impacts of nanoparticles**

b) Lack of effectiveness in targeting specific weed species

c) Inability to combine with traditional herbicides

d) Limited availability of nano-based herbicides

52. What is one of the roles of nano-sensors in weed management?

a) Detecting herbicide resistance in crops

b) Reducing the need for weed management practices

c) Preventing the growth of beneficial plants

✓ **d) Detecting weed presence and density with high precision**

53. What is one of the most significant recent advancements in mechanized weed management?

a) Manual weeding tools

✓ **b) Automated weeders with artificial intelligence (AI) for selective weed removal**

c) Use of heavy tillage equipment for weed control

d) Increased reliance on hand-pulling weeds

54. How do camera-guided weeders contribute to precision weed management?

✓ **a) By identifying and removing weeds while avoiding crop damage**

b) By randomly removing plants from the field

c) By applying herbicides uniformly across the field

d) By requiring constant manual operation and oversight

55. Which recent technological innovation has improved the efficiency of mechanized weed control in row crops?

a) Use of drones for herbicide spraying

b) Adoption of deep plowing for weed management

✅ **c) Development of in-row mechanical weeders with real-time plant recognition**

d) Implementation of manual hoeing techniques

56. What is a potential advantage of robotic weeders over traditional mechanical weed control methods?

a) They are more expensive to operate

✅ **b) They can operate autonomously, reducing labour requirements**

c) They are less effective in dense weed infestations

d) They are only suitable for large-scale farming operations

57. What is a major challenge in weed management for millet crops?

a) Millets are naturally resistant to all weeds

✅ **b) Millets are often grown in arid and semi-arid regions where weeds compete heavily for limited resources**

c) Weeds do not significantly impact millet yields

d) Herbicides are not effective in millet cultivation

58. Which of the following is a recommended cultural practice in integrated weed management for millet crops?

✅ **a) Maintaining optimal plant density to enhance crop competition against weeds**

b) Delayed sowing to allow weeds to establish first

c) Avoiding any form of mechanical weeding

d) Reducing the use of fertilizers to limit weed growth

59. How can crop rotation contribute to effective weed management in millet cultivation?

a) By continuously planting the same crop to reduce weed pressure

b) By increasing the frequency of herbicide application

✅ **c) By disrupting the life cycles of specific weed species that are adapted to millet fields**

d) By eliminating the need for mechanical weeding

60. What is the role of herbicides in an integrated weed management strategy for millet crops?

a) They should be the only method used for weed control

b) Herbicides are not recommended for use in millet crops

✅ **c) They should be used in combination with cultural and mechanical practices to manage weeds effectively**

d) They should be applied only during the harvest season

61. Which cultural practice is commonly used in vegetable crops as part of an integrated weed management strategy?

a) Use of plastic mulches to suppress weed emergence

b) Continuous irrigation to promote weed growth

c) Avoidance of crop rotation to maintain weed populations

d) Over-reliance on a single herbicide for weed control

62. Which of the following factors is crucial when selecting herbicides for use in vegetable crops?

a) The herbicide should be broad-spectrum and non-selective

b) The herbicide should be applied at high doses regardless of crop sensitivity

c) The herbicide should be compatible with any crop, regardless of its growth stage

d) The herbicide should have a short residual effect to avoid harming subsequent crops

63. What is a major consideration when using pre-emergence herbicides in vegetable crops?

a) They are ineffective in controlling perennial weeds

b) They need to be activated by irrigation or rainfall to ensure effectiveness

c) They should be avoided in sandy soils

d) They only work in organic farming systems

64. In an integrated weed management program for vegetable crops, what is the advantage of combining mechanical weeding with herbicide application?

a) It reduces the need for herbicides altogether

b) It increases the overall cost of weed management

c) It helps target weeds that escape herbicide treatment, improving overall weed control

d) It decreases crop yields

65. What is a key challenge in managing weeds in grass and forage crops?

a) Weeds have no impact on the quality of forage crops

b) Forage crops are often grown in mixed stands, making selective weed control difficult

c) Herbicides are not effective in controlling weeds in forage crops

d) Forage crops naturally suppress all weed growth

66. Which cultural practice is important in an integrated weed management strategy for grass and forage crops?

a) Maintaining dense stands to reduce weed invasion

b) Delaying planting to allow weed establishment

c) Avoiding crop rotation to keep the same weed species

d) Overgrazing to control weed growth

67. How can mowing contribute to weed management in grass and forage crops?

a) By spreading weed seeds across the field

b) By encouraging the growth of perennial weeds

✓ **c) By preventing weeds from reaching the seed-producing stage, thereby reducing weed seed banks**

d) By damaging the forage crop more than the weeds

68. What is a consideration when using herbicides in grass and forage crops?

a) Herbicides should be applied at the same rate regardless of crop type

✓ **b) Selective herbicides must be chosen to target weeds without harming desirable forage species**

c) Herbicides should be avoided completely in forage crops

d) Herbicides are only effective in annual grass crops

69. What is the primary motivation for developing reduced-risk herbicides in the current agricultural scenario?

a) To increase the potency of herbicides

b) To lower the cost of herbicide production

c) To eliminate the need for integrated weed management practices

✓ **d) To reduce the environmental and health impacts associated with traditional herbicides**

70. Which of the following is a characteristic of a reduced-risk herbicide?

a) High persistence in the environment

b) Broad-spectrum activity that affects all plant species equally

✓ **c) Selective action that targets specific weeds with minimal impact on non-target species**

d) Increased application rates compared to traditional herbicides

71. What is a significant challenge in the development and commercialization of reduced-risk herbicides?

a) Lack of interest from the agricultural industry

✓ **b) Higher research and development costs compared to traditional herbicides**

c) Limited effectiveness against herbicide-resistant weed species

d) Reduced efficacy in all weed management scenarios

72. Why is there a growing need to launch reduced-risk herbicides in modern agriculture?

✓ **a) To address the rising concern over herbicide resistance and promote sustainable agriculture**

b) To completely replace all other weed management practices

c) To increase the shelf life of herbicides

d) To increase the dependence on chemical weed control methods

73. What is meant by herbicide residue in the context of agricultural fields?

a) The immediate impact of herbicides on target weeds

b) The effectiveness of herbicides over time

c) The initial concentration of herbicide applied to the field

✓ **d) The amount of herbicide remaining in the soil, water, or plants after application**

74. Which factor most significantly influences the persistence of a herbicide in the environment?

a) The color of the herbicide

✓ **b) The chemical structure and properties of the herbicide**

c) The size of the field where the herbicide is applied

d) The time of day when the herbicide is applied

75. How does microbial degradation affect herbicide persistence in the soil?

a) It increases the toxicity of herbicides

b) It enhances the long-term effectiveness of herbicides

✓ **c) It breaks down herbicides, reducing their persistence in the soil**

d) It prevents herbicides from being absorbed by plants

76. What is a potential consequence of long-term herbicide persistence in agricultural soils?

✓ **a) Accumulation of herbicide residues that can harm non-target organisms and subsequent crops**

b) Improved crop yields due to prolonged weed control

c) Increased biodiversity in the field

d) Enhanced degradation of organic matter in the soil

77. What is a fundamental principle of integrated weed management (IWM) in natural farming?

a) Relying solely on chemical herbicides

b) Using only mechanical methods for weed control

✓ **c) Combining multiple weed control methods to minimize the impact of weeds while maintaining soil health**

d) Allowing weeds to grow freely to enhance soil fertility

78. Which of the following practices is commonly used in natural farming to manage weeds?

a) Continuous use of synthetic herbicides

b) Frequent deep tillage to expose weed seeds

c) Monoculture cropping systems

✓ **d) Use of cover crops and mulching to suppress weed growth**

79. How can crop rotation contribute to weed management in natural farming systems?

a) By increasing the diversity of crops, which disrupts the life cycles of specific weed species

b) By planting the same crop year after year to reduce weed pressure

c) By increasing the reliance on chemical weed control

d) By preventing the growth of any weeds

80. What is the role of manual weeding in an integrated weed management strategy in natural farming?

a) It should be the only method used for weed control

b) It is used in conjunction with other methods to manage weeds effectively while minimizing the impact on the environment

c) It increases the use of chemical herbicides

d) It is unnecessary if cover crops and mulching are used

81. What is a common cultural practice used in integrated weed management for wheat crops?

a) Planting wheat at high density to outcompete weeds

b) Applying herbicides only once during the growing season

c) Using continuous wheat cropping without rotation

d) Avoiding any form of soil disturbance

82. How does crop rotation benefit weed management in wheat production?

a) By increasing weed populations that are adapted to wheat

b) By disrupting the life cycles of weed species specific to wheat fields

c) By using the same herbicides continuously

d) By increasing the need for additional herbicide applications

83. Which herbicide application strategy is often recommended for managing weeds in wheat crops?

a) Applying herbicides at the same rate throughout the entire growing season

b) Using pre-emergence herbicides followed by post-emergence herbicides for effective control

c) Applying herbicides only once during the harvest period

d) Avoiding herbicide use and relying solely on mechanical weeding

84. What role does integrated weed management play in reducing herbicide resistance in wheat crops?

a) It encourages the use of a single herbicide type repeatedly

b) It involves the use of multiple weed control methods and herbicides with different modes of action to reduce the risk of resistance

c) It eliminates the need for any herbicide use

d) It focuses only on mechanical weed control methods

85. Which weed is commonly used in vermicomposting to enhance compost quality?

a) Pigweed (*Amaranthus* spp.)

b) Dock (*Rumex* spp.)

c) Bindweed (*Convolvulus arvensis*)

✅ **d) Common lambsquarters (*Chenopodium album*)**

86. How can using herbicides like trifluralin in oilseed crops benefit weed management?

a) By controlling only post-emergence weeds

✅ **b) By providing residual soil activity that helps control weeds before they emerge**

c) By increasing weed seed production

d) By enhancing the growth of weed species

90. Which of the following is a major weed commonly found in oilseed crops like canola and soybeans?

a) Common lambsquarters (*Chenopodium album*)

b) Barnyard grass (*Echinochloa crus-galli*)

c) Pigweed (*Amaranthus* spp.)

✅ **d) All of the above**

91. What is a characteristic feature of wild mustard (*Sinapis arvensis*) that makes it a problematic weed in oilseed crops?

✅ **a) It is highly competitive and can rapidly dominate fields**

b) It is resistant to all herbicides

c) It provides beneficial shade to oilseed crops

d) It enhances soil fertility

92. What is a key characteristic of parasitic weeds like dodder (*Cuscuta* spp.) and broomrape (*Orobanche* spp.)?

a) They produce their own food through photosynthesis

✅ **b) They parasitize other plants by attaching to their stems and extracting nutrients**

c) They are completely unrelated to other plants

d) They grow in isolation without affecting surrounding plants

93. Which of the following methods is commonly used to manage parasitic weeds in agricultural fields?

✅ **a) Using resistant crop varieties and crop rotation to disrupt the life cycle of parasitic weeds**

b) Frequent irrigation to promote weed growth

c) Applying the same herbicide repeatedly

d) Allowing the parasitic weed to grow without intervention

94. Which of the following weeds is commonly consumed as a leafy vegetable in India and is known for its high nutritional value?

a) Amaranth (*Amaranthus* spp.)

b) Bermuda grass (*Cynodon dactylon*)

c) Wild mustard (*Sinapis arvensis*)

d) Crabgrass (*Digitaria* spp.)

95. How do weeds such as water hyacinth (*Eichhornia crassipes*) contribute to phytoremediation of contaminated water bodies?

a) By providing shade to reduce algal blooms

b) By absorbing and accumulating pollutants like heavy metals and nutrients from the water

c) By releasing toxins that degrade pollutants in the water

d) By increasing the temperature of the water to speed up degradation processes

96. What is a primary goal of biological control in weed management?

a) To use natural enemies, such as insects or pathogens, to suppress weed populations

b) To completely eradicate all weed species from an area

c) To increase the use of chemical herbicides

d) To promote the growth of weeds for ecological purposes

97. Which of the following is a successful example of biological control of a weed?

a) The release of the rust fungus *Puccinia punctiformis* to control yellow starthistle (*Centaurea solstitialis*)

b) The use of glyphosate to manage dandelion (*Taraxacum officinale*)

c) The introduction of genetically modified crops to resist weeds

d) The application of pre-emergence herbicides for crabgrass control

98. What is a major challenge associated with biological control of weeds?

a) High cost of implementation compared to chemical controls

b) The possibility of the biological control agent becoming a pest itself or affecting non-target species

c) Lack of scientific research supporting biological control methods

d) Immediate and complete eradication of target weed species

99. Which insect is commonly used for the biological control of the invasive weed Kudzu (*Pueraria montana*)?

a) *Aphalara itadori* (Japanese knotweed psyllid)

b) *Neochetina eichhorniae* (water hyacinth weevil)

c) *Pseudomonas syringae* (bacterium)

d) *Rhinocyllus conicus* (weevil)

100. What is the role of *Neochetina eichhorniae* in controlling the invasive water hyacinth (*Eichhornia crassipes*)?

a) It feeds on the roots and leaves of the water hyacinth, reducing its growth and reproduction

b) It acts as a pollinator for the water hyacinth

c) It enhances the growth of water hyacinth by providing nutrients

d) It competes with water hyacinth for sunlight but does not damage it

101. Which of the following insects is used for the control of the invasive weed Canada thistle (*Cirsium arvense*)?

a) *Tetramesa romana* (stem borer)

b) *Microsiphum avenae* (aphid)

c) *Hylobius transversovittatus* (root weevil)

d) *Cassida rubiginosa* (thistle tortoise beetle)

102. What is a significant benefit of using insects for the biological control of invasive weeds?

a) They provide a permanent solution without the need for further management

b) They are effective in controlling weed populations with minimal environmental impact compared to chemical methods

c) They completely eliminate all invasive weed species from an area

d) They require frequent reapplication and high costs

103. Which of the following insects is used for the biological control of *Parthenium hysterophorus* in India?

a) *Zygogramma bicolorata* (leaf beetle)

b) *Cactophagus spinolae* (cactus weevil)

c) *Orobanche ramosa* (broomrape)

d) *Rhinocyllus conicus* (weed weevil)

104. What is the role of *Lixus concavus* in controlling the invasive weed Siam weed (*Chromolaena odorata*) in India?

a) It acts as a pollinator for the weed

b) It enhances the growth of the weed

c) It feeds on the roots and stems of the weed, leading to reduced growth and reproduction

d) It competes with the weed for soil nutrients but does not damage it

105. Which pathogen has been used for the biological control of *Lantana camara* in India?

a) *Puccinia lantanae* (rust fungus)

b) *Fusarium oxysporum* (fungus)

c) *Alternaria eichhorniae* (water hyacinth pathogen)

d) *Phoma clematidina* (stem rot pathogen)

106. What is a significant challenge in the biological control of weeds in India?

a) Lack of native weed species that can be targeted

b) High cost and extensive application requirements

c) Difficulty in finding suitable and effective biological control agents for diverse weed species and ecological conditions

d) Over-reliance on chemical herbicides and reduction in biological control efforts

107. Which of the following weeds is commonly used for phytoremediation of contaminated soils due to its ability to accumulate heavy metals?

a) Common ragweed (*Ambrosia artemisiifolia*)

b) Mustard greens (*Brassica juncea*)

c) Redroot pigweed (*Amaranthus retroflexus*)

d) Creeping Charlie (*Glechoma hederacea*)

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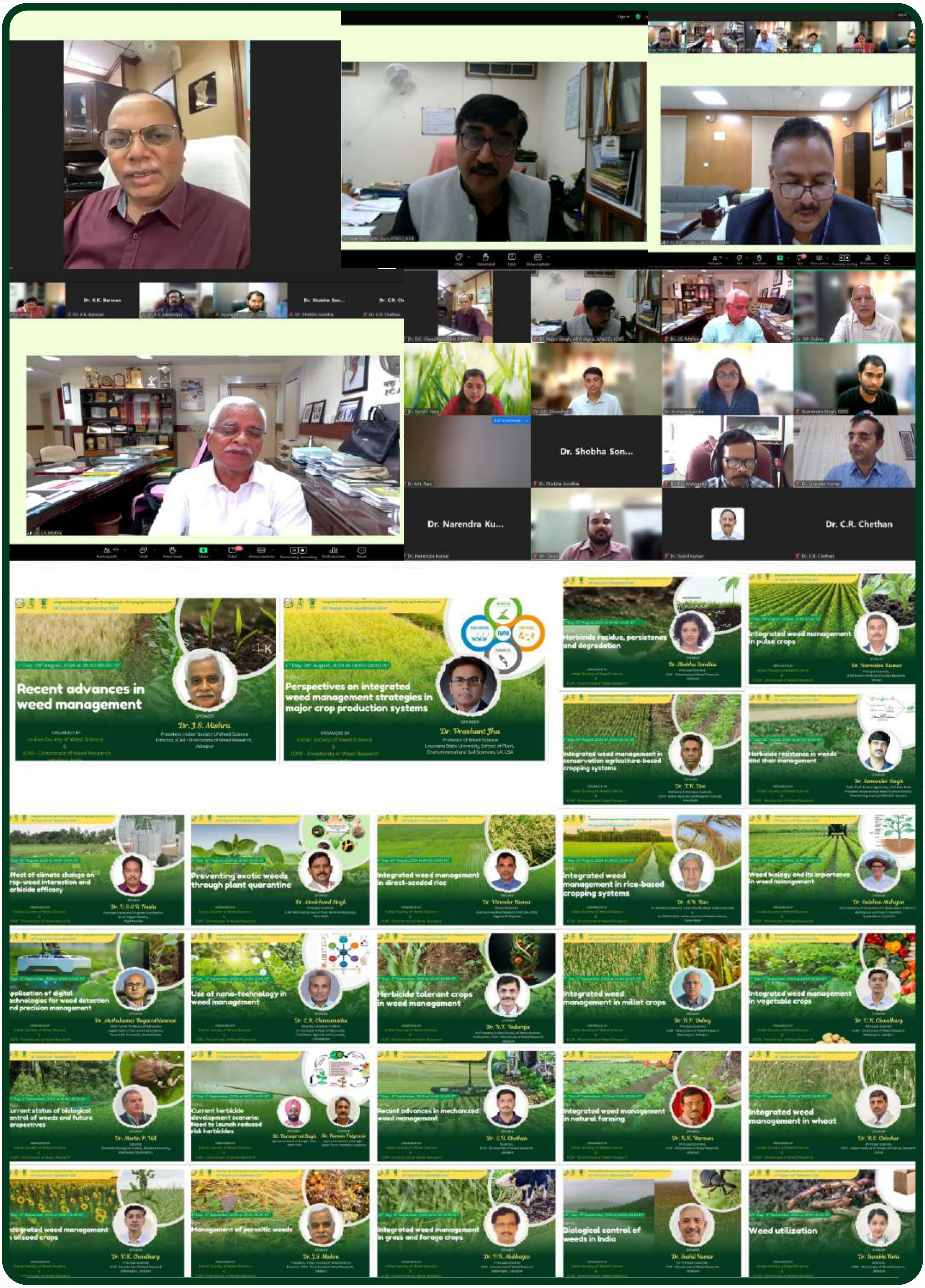
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