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Review Paper

Advances in Weed Management – An Indian Perspective

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ABSTRACT

Weeds are one of the major biotic factors causing significant loss in productivity of different agro-ecosystems. Weed competes with crops for various resources, resulting in severe yield loss. In field crops, the loss caused due to weeds has a wide range of 15–90%, although it largely depends on the management strategies adopted. A multidisciplinary team comprising scientists, farmers, industry personnel, social workers, and policy-makers is required to implement new approaches for weed management. Relying on single method (manual/mechanical/cultural/ chemical) of weed control may lead to problems of shift in weed flora, herbicide resistance in weeds, adverse impact on ecosystem, establishment of perennial weeds, etc. This strategy needs to be replaced with multiple and integrated strategies in a system mode. Therefore, an integrated weed management (IWM) approach involving concept of 'many little hammers'and 'technological advancement' in a holistic manner is required to keep the weed pressure minimum. Development and use of sensor-based site-specific weed-management techniques, non-transgenic herbicide tolerant crops, nano-herbicides, safe and effective biocontrol agents, destruction of weed seeds, etc. will add new tools in weed management. This paper reviews the progress, strengths and weaknesses of different weed-management technologies developed in so far India and highlights future research needs.

Key words : Climate change, Conservation agriculture, Herbicides, Losses, Utilization, Weed management

INTRODUCTION

India will be the most populous country in the world by 2027, surpassing China. The human population of India is expected to reach nearly 1.5 billion in 2030 from the current population of 1.38 billion. Demand for food production would increase to 345 million tonnes by 2030 (Sharma, 2021) from the current food production of 309 million tonnes 2020-21. The country accounts for only 2.4% of global land to sustain around 18% of global population, with larger population of small and marginal farmers, who have a major role in food security of our country. It would be very difficult to feed the projected human population at the current crop production levels, and the increasing threats of global climate change on agriculture, decreasing water resources, and reduction in cultivable lands. Weeds have always been the major biotic constraint in crop production. Weed management is essential for agricultural production to meet future food requirements. In view of the emerging challenges in weed management due to extreme climate events, weed-seed dispersal through global trade, weed-flora shift and herbicide resistance in weeds, labour shortage, adverse impact of herbicides on the quality of crop produce, environment and human health etc. development of efficient weed-management technologies incorporating the interaction of environmental, economic and societal dimensions of agro-ecosystems is vital for increasing productivity, sustainability and farmer's income.

LOSSES CAUSED BY WEEDS

Unlike insects and pathogens where the effect on crop is visible, the damage done by weeds is often noticed. Of the total loss caused by various pests in agriculture, weeds account for 37%, followed by insects (29%), diseases (22%) and others including nematodes, rodents, mites, birds etc. (12%). Most of the crops during their early stage of growth are slow-growing. Weed seeds germinate along with crop seeds or many a times even before, and start competing with crops for vital growth resources (moisture, nutrients and solar radiation) resulting in severe yield loss.

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In addition, weeds also act as an alternative host of insects and pathogens, deteriorate the quality of produce, and reduce the input-use efficiency. Based on the study conducted at the ICAR-Directorate of Weed Research, Jabalpur, from 1,581 on-farm trials in different agro-ecological regions of the country, the actual yield loss due to weeds was estimated to be 14% in transplanted rice to as high as 36% in groundnut (Gharde *et al*., 2018). All together totals actual economic loss due to weeds in 16 major crops was estimated as ₹78,591 crore (1 crore = 10 million)/ annum (Fig. 1). However, the total economic losses will be much higher, if all the crops, and indirect effects of weeds on human and animal health, loss of biodiversity, nutrient depletion, reduction in grain quality, etc. are taken into consideration. It has been estimated that on an average, the weed control costs around ₹6,000/ha in the rainy (*kharif*) season crops and around ₹4,000/ha for winter (*rabi*) season crops, which comes to the tune of 33% and 22%, respectively of the total cost of cultivation (Yaduraju and Mishra, 2018).

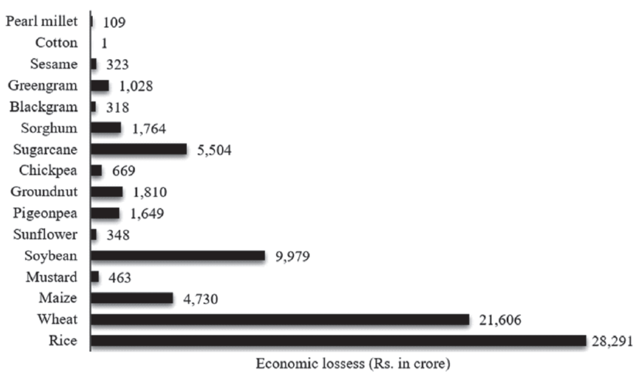


Fig. 1. Economic loss due to weeds in different crops in India
Source: Gharde *et al*. (2018)

WEED MANAGEMENT RESEARCH IN INDIA

Historically, weeds are being managed by the farmers adopting repeated tillage, crop rotation, manual/ mechanical weeding, growing cover crops, burning, puddling and stagnation of water in rice (*Oryza sativa* L.) etc. In India, sodium arsenite was the first chemical used in 1937 as an herbicide to control the wild safflower *Carthamus oxycantha* in Punjab. Later 2, 4-D was first evaluated in 1946 and introduced in 1948 for broad-leaf weed control. However, the systematic research on weed management in India was initiated by the Indian Council of Agricultural Research (ICAR) in 1952 with the inception of All India Coordinated Research Scheme in major crops like rice, wheat (*Triticum aestivum* L.) and sugarcane (*Saccharum* sp.). To give further impetuous on weed-management research, the weed-control section was started in the Division of Agronomy, Indian Agricultural Research Institute (IARI), New Delhi, in 1952, and Division of Weed Ecology and Control at the Indian Grassland and Fodder Research Institute, Jhansi, in 1967. The All India Coordinated Research Project onWeed Management (AICRP-WM) was started in 1978. To carry out the basic and strategic research on weed management, the National Research Centre on Weed Science (NRCWS) was established at Jabalpur Madhya Pradesh, during 1989, which was later upgraded to the ICAR-Directorate of Weed Science Research, in 2009 and renamed as the ICAR-Directorate of Weed Research (DWR) in 2014.

The AICRP-WM, launched in 1978 with 6 centres, has been expanded to 23 centres in 2014 to carry out the need-based location-specific weed-management research in different agro-ecosystems of the country. At present, there are 17 regular and 7 voluntary centres under AICRP-WM, located in different State Agricultural Universities of the country. From more than 4 decades of research and technology dissemination, an enormous data on various aspects of weed management such as weed survey and weed-flora shift, weed biology and eco-physiology of crop-weed competition and yield loss, cultural, chemical and mechanical methods of weed management, estimation of herbicide residues in food-chain and environment have been generated by these centres. In a new era of 'big data' or 'digital farming', it will be interesting to see that how best we can use this data in strengthening our future weed-management research programme.

WEED MANAGEMENT IN ORGANIC AGRICULTURE

Organic agriculture is being promoted world over as an alternative system to conventional agriculture to reduce the over-reliance on chemical fertilizers and industrial pesticides, and to make the agriculture more sustainable. Under Indian scenario, the total area under organic certification process is 3.67 million hectare (2019–20). This includes 2.30 million ha cultivable area and another 1.37 million ha for wild harvest collection. India produced around 2.75 million tonnes (2019–20) of certified organic products which includes all varieties of food products *(http://apeda.gov.in/apedawebsite/organic/Organic_Products.htm,2021).*

Weeds have been recognized as the most serious threat in organic crop-production systems. However, very little attention has been given to research on weed-management in organic agriculture. Managing weeds as well as sustaining higher crop productivity is a major challenge in organic systems. The weed-control strategies for organic crops are based on the principles of prevention, tillage, stale seedbed, crop rotation, competitive crops and varieties, intercropping, planting geometry, mulches, smoother crops, soil solarization, nutrient and water management, efficient weeding tools and machinery, biological weed control etc. (Dubey, 2018). Harvest weed-seed control (HWSC) strategies through which weed seeds are collected before shedding in the field and destroyed appropriately, can be used to prevent viable weed seeds from entering into the soil seedbank. Different types of modern cultivators and weeder scan be used to facilitate mechanical weed management. Studying the long-term effect of these management practices on weed seed bank and weed shifts in the organic fields is important for understanding and devising strategies for weed management in organically grown systems.

Cultural methods

Cultural practices are the best suited for weed management in organic crops. In finger millet (*Eleusine coracana* Gaertn.) stale-seed-bed followed by inter-cultivation twice at 20 and 35 days after planting was effective in minimizing weeds (Patil *et al*., 2013). Intercropping of cowpea [*Vigna unguiculata* (L.) Walp.] in maize (*Zea mays* L.) is an effective method to reduce the weed density (Dubey, 2008). Mulching with fresh *Eupatorium* at 10 t/ha after earthing-up at 30 days after sowing (DAS) followed by soybean [*Glycine max* (L.) Merr.] green-manure incorporation and 1 hand-weeding at 45 DAS suppressed the weeds drastically and resulted in higher maize yield (Das *et al*., 2016). In organically grown crops, experimental results have proved the benefits of black polyethylene and crop-residue mulch in vegetable crops, maize and turmeric (*Curcuma longa* L.); *in-situ* incorporation of *Sesbania* at 30 days after sowing in rice, intercrop of cowpea and blackgram [*Vigna mungo* (L.) Hepper] in maize, green-leaf *Gliricidia sepium* (Jacq.) Steud. mulch in maize and turmeric, crop-residue mulch and hand-weeding in chickpea (*Cicer arietinum* L.) for managing weeds and obtaining optimum crop productivity under (Dubey, 2018). Mc Dade and Christians (2000) stated that in addition to organic mulches, there are a limited number of organically approved products, such as corn gluten meal, that have been shown to exhibit herbicidal properties. Significantly higher yield and reduction in weed density was reported in rice by applying rice bran 2 t/ha on 3 days after transplanting (DAT) followed by hand weeding at 35 DAS (Gnanasoundari and Somasundaram, 2014).

Mechanical methods

In India, manual weeding using traditional tools like sickle, *khurpi*, *kudali*, hand fork, animal-operated hoes are still common with small and marginal farmers. However, these tools are labour-intensive, ineffective in moist conditions, and involve drudgeries to operate. A wide range of inter-row weeders are available for use in different crops. The work rate of various weeding tools varies with respect to crop growth, weed intensity, soil condition, spacing, etc. from 300–500 man-hr/ha for *khurpi*, 200–300 man-hr/ha for hand and chopping hoes, 100–125 man-hr/ha for push-pull type weeder and 6–20 man-hr/ha for animal-drawn weeding tools (DAC&FW, GoI, 2018). The developed weeder performed very well with higher weeding efficiency and minimal crop damage.

In addition to weeding tools and implements, several efforts have been done by different researchers to come up with the best spraying technology suitable to the famers. The Punjab Agricultural University, Ludhiana under AICRP-WM programme has developed a sowing-cum-herbicide spraying seed-drill, named as Lucky seed drill. This machine has become very popular among farmers of Punjab and Haryana for sowing of direct-seeded rice and simultaneous spraying of pre-emergence herbicides like pendimethalin. Similarly, the Kerala Agricutlural University, Thrissur under AICRP-WM programme has developed 'KAU Weed Wiper' for effective application of higher doses non-selective herbicides viz., glyphosate or glufosinate ammonium, after emergence of weedy rice ear and before panicle initiation of rice to control 70–80% of weedy rice, thereby considerable reduction in weed seedbank in rice fields. Similarly, ICAR-DWR, Jabalpur, has also developed a sensor-based pre-emergence-herbicide applicator, that can be mounted on all type of seeders and planters and saves herbicide spay liquid by 7–16%, besides reduction in operational drudgery and increase in field capacity.

The Indian Institute of Technology (IIT), Kharagpur, has developed a microcontroller-based image-processing techniques and variable rate herbicide application (VRA) system. This system estimates the weed intensity within a row and actuates the solenoid valve to apply the herbicide accordingly (Tewari and Chetan, 2018; Chandel *et al*., 2018). The developed system uses non-selective herbicide and saves herbicide by 50–80%. In recent past, work on herbicide application through drones is also taken up in India and researchers are trying to optimize the operational parameters of drones for safe use of herbicides. New technologies for sensing crops and weeds in real time and robotic systems allow precise operation of mechanical tools and devices, to improve weed control and reduce operation costs. Development of robotic weed management system is also under progress at IIT, Kharagpur, Tamil Nadu Agricultural University, (TNAU), Coimbatore, Professor Jayashankar Telangana State Agricultural University (PJTSAU), Hyderabad and many other organizations. Preliminary studies indicated that, this technology has been found very effective in terms of efficacy, saving water, time and cost.

Allelopathy

The term ‘Allelopathy’ refers to any process involving secondary metabolites produced by plants, microorganisms, viruses and fungi that influence the growth and development of agricultural and biological systems (IAS, 1996). It includes any direct or indirect, harmful or beneficial effect of one plant (including microorganisms) on another. Crop and weed plants have the ability to produce allelochemicals into their environments to affect the growth of each other in their vicinity. However, very less success has been achieved so far at field levels. Of the 111 rice cultivars evaluated for allelopathic potential against [*Echinochloa crus galli* (L) Beauv.] at the International Rice Research Institute, Manila, Philippines, 11 cultivars in dry season and 21 in wet season had suppressed the weed growth by more than 50% (Olofsdotter and Navarez, 1996). Similarly in wheat, Wu *et al*. (1998) reported that, some cultivars significantly inhibited both the germination and the radicle growth of *Lolium rigidum* Gaud.

CHEMICAL WEED MANAGEMENT

Use of herbicides for weed management is increasing in modern agriculture. Globally, herbicides constitute about 53% of the crop protection market, followed by fungicides (23%), insecticides (17%) and others (7%), whereas in India, the share of herbicides is only around 17% of the total pesticides, which is quite low compared to insecticides (44%) and fungicides (37%) consumption (Figs. 2, 3). Although India is the fourth largest producer of crop-protection chemicals in the world, the average consumption is very low (< 500 g/ha) as against 10–12 kg/ha) in Japan. The annual herbicide consumption in India is around 40 g/ha as compared to 675–1,350 g/ha in many advanced countries. The use of herbicides is however increasing in the last one decade in India at a much faster rate (15–20% annually), but the total consumption in terms of quantity may not increase on the same pace due to replacement of traditional high-dose herbicide molecules by new generation low-dose high efficacy herbicides (Fig. 4). Currently, the use of herbicides is higher in wheat and rice, followed by plantation crops.

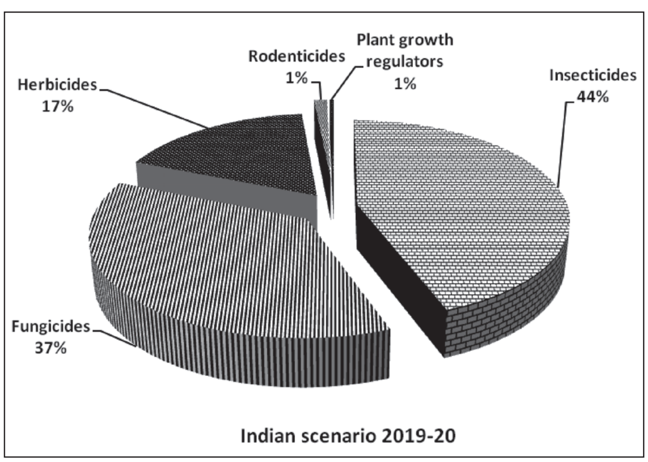


Fig. 2. Herbicide consumption in India
Source: *http://ppqs.gov.in/statistical-database* 2019–20 accessed on 24–07–2021

Herbicide resistance in weeds

Weed management using herbicides is becoming increasingly popular among the farmers owing to their fast action, high efficacy and lower cost. However, over-reliance and indiscriminate use of herbicides resulted in the evolution of herbicide-resistant weeds. Occurrence and wide spread of herbicide resistance (HR) in weeds is a global problem. Herbicide resistance is an inherited ability of a plant to survive and reproduce following exposure to a dose of herbicide that would normally be lethal to the wild plant. Resistance occurs with the repeated application of the same herbicide, or herbicides with similar modes of action on a weed population.

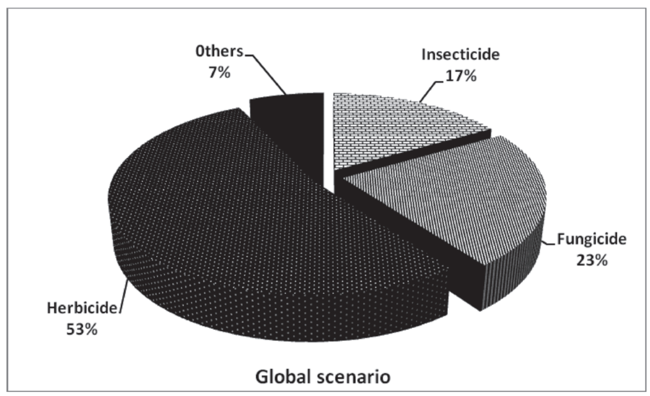


Fig. 3. Global consumption of herbicides 2019–20
Source: FAOStat, *http://www.fao.org/faostat/en/#data/RP/metadata*, accessed on 24–07–2021

Currently, there are 508 unique cases (species × site of action) of herbicide-resistant weeds globally, with 266 species (153 dicots and 113 monocots). Weeds have evolved resistance to 21 of 31 known herbicide sites of action and to 164 different herbicides *http://www.weedscience.org/* accessed on 20 October, 2021). Herbicide-resistant weeds have been reported in 94 crops in 71 countries (Heap, 2021). In India, *Phalaris minor* Retz. has developed multiple-herbicide resistance to PSII, ACCase and ALS inhibitors. Likewise, *Rumex dentatus* L. has evolved resistance against metsulfuron (ALS inhibitor) and cross-resistance to mesosulfuron + iodosulfuron, pyroxsulam, halauxifen + florasulam, while *Polypogon monspeliensis* (L.) Desf. has developed resistance against sulfosulfuron, mesosulfuron and pyroxasulam (Chhokar *et al*., 2015). In soybean, *Echinochloa colona* (L.) Link and *Commelina communis*

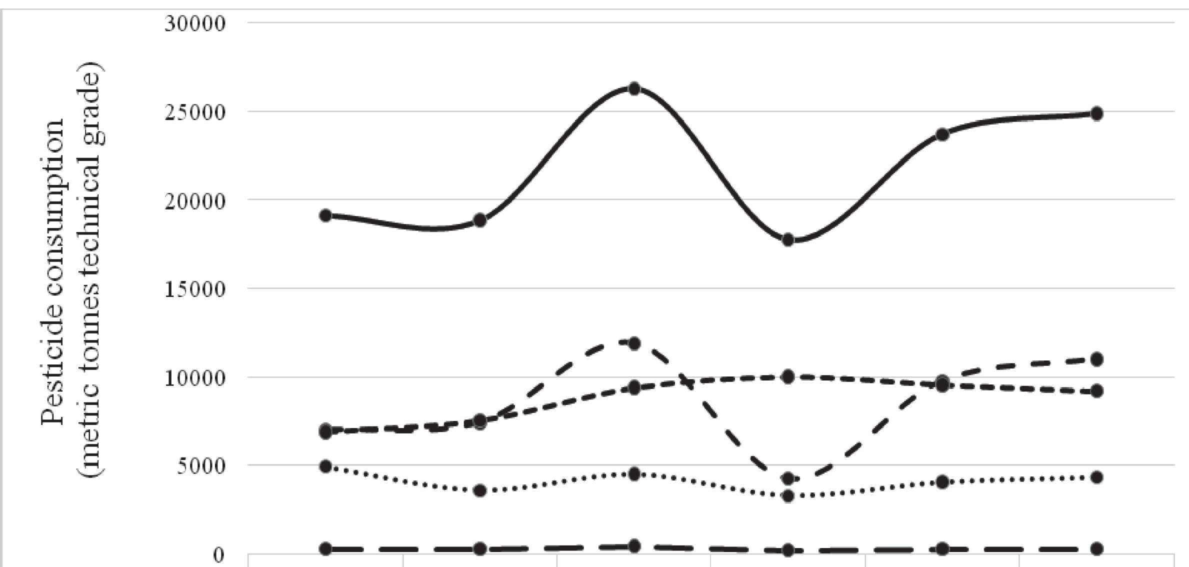
L. became resistant to imazethapyr (an ALS inhibitor) (ICAR-DWR, 2017–18; Chander *et al.,* 2019). In the same way, *Echinochloa crus-galli* and *Cyperus difformis* became resistant to bispyribac-sodium (an ALS inhibitor) in rice (ICAR-DWR, 2017–18). In India, weed management will be more herbicide-driven in the coming years, and the occurrence of herbicide-resistant weeds in the farmer's field makes weed management more difficult. Under the condition, understanding herbicide-resistance development and accordingly development of best management practice to minimize HR development is of foremost importance.

Herbicide-tolerant crops

Herbicide-tolerant (HT) crops have been developed to tolerate specific broad-spectrum herbicides, which kill the neighbouring weeds without harming the cultivated crop. The HT crops occupied (87.5 million ha or 45% of the 191.7 million ha of total biotech crops planted worldwide in 2018). The most common HT crops are the glyphosate- and glufosinate-tolerant varieties of soybean, corn, cotton (*Gossypium hirsutum* L.) and canola (*Brassica napus* subsp. *Napus*). Although several HT-crop varieties both transgenic (glyphosate resistance) and non-transgenic [(mutation breeding) imidazolinone resistance] have been developed and released in many countries in the past few years for commercial cultivation, this technology is in its initial stage of field evaluationin India. In view of severe weed problem in direct-seeded rice, Shobha *et al*. (2017) developed an EMS-induced rice mutant, HTM-22', exhibiting tolerance to a broad-spectrum herbicide 'imazethapyr', and identified the mutations imparting tolerance to the herbicide. At the ICAR-Indian Agricultural Research Institute, New Delhi, Grover *et al*. (2020) successfully developed HT NILs in the genetic background of popular Basmati rice variety, 'PB 1121' by introgression of mutated *AHAS* allele. This was the first report on the development of HT basmati rice.

Nanoherbicides

Indiscriminate use of herbicides have negative impact on crop production, ecosystem and human health. Use of nanoherbicides in weed management is a new strategy to address the problems of conventional herbicides. These are products where nanotechnology is used to enhance the efficacy or reduce the environmental footprint of a herbicide-active ingredient. These herbicides rely mostly on biodegradable polymeric substances that improves the efficacy of herbicides due to controlled release mechanisms. Precise and slow-release mechanism of nanocapsules provide season-long weed control, and exhaust the soil weed



	2014-15	15-16	16-17	17-18	18-19	19-20
Insecticide	7008	7440	11888	4274	9766	11016
Fungicide	6887	7531	9380	9997	9550	9177
Herbicide	4895	3566	4495	3266	4031	4314
Rodenticide	287.07	277.55	411	199.07	293.1	292.1
Total	19128.2	18856.85	26292.05	17777.5	23726.12	24889.1

Fig. 4. Pesticide consumption pattern in Indian agriculture
Source: *http://ppqs.gov.in/statistical-database* 2019–20 accessed on 24–07–2021

Table 1. List of promising herbicides for weed control in different crops

Crops	Recommended herbicides	
	Pre-emergence	Post-emergence
Rice (TPR)	Pretilachlor 600 g/ha, Pyrazosulfuron 20 g/ha, Pretilachlor + pyrazosulfuron 600 + 15 g/ha, Pretilachlor + bensulfuron 600 + 60 g/ha, Pendimethalin + pyrazosulfuron 900 + 20 g/ha, Penoxsulam + butachlor 820 g/ha	Bispyribac-Na 25 g/ha, Penoxsulam 22.5–25 g/ha, Bentazone 960 g/ha, Triafamone + ethoxysulfuron 62.5 g/ha, Flucetosulfuron 25 g/ha, Azimsulfuron 35 g/ha, Fenoxaprop + safener 60 g/ha, Metsulfuron + chlorimuron 4 g/ha, Cyhalofop 60 g/ha, Cyhalofop + penoxsulam 135 g/ha, Clomazone + 2, 4-D EE 250–375 g/ha,
Rice (DSR)	Pendimethalin 1.0 kg/ha, Pendimethalin + pyrazosulfuron 900 + 20 g/ha, Pretilachlor + pyrazosulfuron 600 + 15 g/ha,	Bispyribac-Na 25 g/ha, Penoxsulam 22.5–25 g/ha, Triafamone + ethoxysulfuron 62.5 g/ha, Azimsulfuron 35 g/ha, Fenoxaprop + safener 60 g/ha, Metsulfuron + chlorimuron 4 g/ha, Cyhalofop 60 g/ha, Cyhalofop + penoxsulam 135 g/ha,
Wheat	Pendimethalin 1.0 kg/ha, Pyroxasulfone 127.5 g/ha, Sulfentrazone 560 g/ha,	Clodinafop 60 g/ha, Pinoxaden 40–45 g/ha, Sulfosulfuron 25 g/ha, Metsulfuron 4 g/ha, 2,4-D 500 g/ha, Metribuzin 170–210 g/ha, Carfentrazone 20 g/ha, Metsulfuron + carfentrazone 4 + 20 g/ha, Mesosulfuron + iodosulfuron 12 + 2.4 g/ha, Sulfosulfuron + metsulfuron 30 + 2 g/ha, Clodinafop + metsulfuron 60 + 4 g/ha, Metribuzin + clodinafop 210 + 60 g/ha, Fenoxaprop + metribuzin 100 + 175 g/ha
Maize	Atrazine 0.5–1.0 kg/ha, Pyroxasulfone 127.5 g/ha,	Atrazine 1.0 kg/ha, Tembotrione 120 g/ha, Topramezone 25.2 g/ha, Atrazine + topramezone (500 + 25.2 g/ha), Atrazine + tembotrione (500 + 120 g/ha), Mesotrione + atrazine 875 g/ha, Halosulfuron 67.5 g/ha,2, 4-D 500 g/ha
Pearl millet	Atrazine 500 g/ha	2, 4-D 500 g/ha
Sorghum	Atrazine 500 g/ha	Atrazine 500 g/ha, 2, 4-D 500 g/ha
Barley	Pendimethalin 1.0 kg/ha	Pinoxaden 50 g/ha, Isoproturon 1.0 kg/ha, Metsulfuron 4 g/ha,2, 4-D 500 g/ha, Carfentrazone 20 g/ha, Metsulfuron + carfentrazone 4 + 20 g/ha
Mustard	Pendimethalin 1.0 kg/ha, Oxadiargyl 90 g/ha,	Isoproturon 1.0 kg/ha, Quizalofop 50 g/ha, Clodinafop 60 g/ha, Pinoxaden 50 g/ha
Soybean	Sulfentrazone 560 g/ha, Pendimethalin 1.0 kg/ha, Metlochlor 500 g/ha, Diclosulam 28 g/ha, Metribuzin 350-500 g/ha, Pyroxasulfone 127.5 g/ha,	Chlorimuron 9 g/ha, Imazethypyr 100 g/ha, Flauzifop-butyl 100 g/ha, Quizalofop-ethyl 50 g/ha, Propaquizafop 50–75 g/ha Haloxyfop 135 g/ha

Table 1. *Continued ...*

Crops	Recommended herbicides	
	Pre-emergence	Post-emergence
	Flumioxazin 125 g/ha, Pendimethalin + imazethapyr 1.0 kg/ha, Sulfentrazone + clomazone 350 + 375 g/ha	Fomesafen 150 g/ha, Bentazone 960 g/ha, Fomesafen + fluazfop-p-butyl 250 g/ha, Fomesafen + quizalofop 180+45 g/ha, Propaquizafop + imazethapyr 125 g/ha, Imazethapyr + imazamox 70 g/ha, Na-acifluorfen + clodinafop 245 g/ha
Groundnut	Pendimethalin 1.0 kg/ha, Diclosulam 28 g/ha, Pendimethalin + imazethapyr 1.0 kg/ha	Imazethypyr 100 g/ha, Flauzifop-butyl 125 g/ha, Quizalofop-ethyl 50 g/ha, Fomesafen + fluazfop-p-butyl 250 g/ha, Propaquizafop + imazethapyr 125 g/ha, Imazethapyr + imazamox 70 g/ha, Na-acifluorfen + clodinafop 245 g/ha, Imazethypyr + quizalofop 65.6 + 32.8 g/ha
Sunflower	Pendimethalin 1.0 kg/ha	Quizalofop-ethyl 50 g/ha, Clodinafop 60 g/ha
Sesame/niger	Pendimethalin 1.0 kg/ha	Quizalofop-ethyl 50 g/ha, Clodinafop 60 g/ha,
Linseed	Pendimethalin 1.0 kg/ha	Clodinafop 60 g/ha, Fluazifop-P-butyl 100 g/ha, Isoproturon 750–1,000 g/ha, Imazethapyr 75–80 g/ha
Greengram/blackgram	Pendimethalin 1.0 kg/ha, Pendimethalin + imazethapyr 1.0 kg/ha	Imazethypyr 80–100 g/ha, Na-acifluorfen + clodinafop 245 g/ha, Quizalofop-ethyl 50 g/ha, Fomesafen + fluazfop-p-butyl 250 g/ha, Propaquizafop + imazethapyr 125 g/ha, Imazethapyr + imazamox 70 g/ha
Pigeonpea	Pendimethalin 1.0 kg/ha Pendimethalin + imazethapyr 1.0 kg/ha	Imazethypyr 100 g/ha, Propaquizafop + imazethapyr 125 g/ha, Imazethapyr + imazamox 70 g/ha
Chickpea	Pendimethalin 1.0 kg/ha, Pendimethalin + imazethapyr 1.0 kg/ha	Quizalofop-ethyl 50 g/ha
Lentil	Pendimethalin 1.0 kg/ha	Quizalofop-ethyl 50 g/ha, Fenoxaprop-p-ethyl 80 g/ha
Pea	Pendimethalin 1.0 kg/haMetribuzin 0.25 kg/ha	Imazethapyr 100 g/ha, Quizalofop-ethyl 50 g/ha
Cotton	Pendimethalin 1.0 kg/ha Diuron0.75-1.5 kg/ha	Quizalofop-ethyl 50 g/ha, Pyrithiobac sodium 62.5 g/ha, Fenoxaprop-p-ethyl 100 g/ha, Pyrithiobac sodium + quizalofop 125 g/ha
Sugarcane	Atrazine 0.5-2.0 kg/ha, Amytrin 2.0 kg/ha, Metribuzin 1.0–2.0 kg/ha, Sulfentrazone 720 g/ha, Amytrine + trifloxysulfuron 937.5–1125 g/ha, Sulfentrazone + clomazone 700 + 750 g/ha	Halosulfuron 67.5 g/ha, 2, 4-D 2.0–3.5 kg/ha, Metribuzin 1.0–1.4 kg/ha, Metsulfuron methyl 6 g/ha, Topramezone + atrazine 25.2 + 500 g/ha, Tembotrione + atrazine 120 + 500 g/ha
Onion and garlic	Pendimethalin 1.0 kg/ha Oxyfluorfen 100–200 g/ha	Oxyfluorfen 100-200 g/ha, Quizalofop-ethyl 50 g/ha, Propaquizafop 62.5 g/ha, Propaquizafop + oxyfluorfen 148.75 g/ha, Quizalofop + oxyfluorfen 100 g/ha
Potato	Metribuzin 525 g/ha, Oxyfluorfen 100–200 g/ha	Paraquat (Early post-emergence at 5–10% potato emergence)

TPR, Transplanted rice; DSR, direct-seeded rice seedbank (Chinnamuthu and Kokiladevi, 2007).

Herbicides and environment

Indiscriminate use of herbicides may pose residue problems, phytotoxicity to crop plants, residual effect on succeeding crops or non-targets organisms, groundwater and health hazards. For effective weed control, herbicide must remain in the soil long enough to provide satisfactory weed control and degrade to innocuous products when their purpose is accomplished.

Proper studies on adverse impacts of herbicides on human being and animals under Indian conditions have become more important in present context when Ministry of Agriculture & Farmers Welfare, GoI, has proposed the ban on use of 7 commonly used herbicides, viz. atrazine, butachlor, 2, 4-D, diuron, oxyfluorfen, pendimethalin and sulfosulfuron; and restricted use of glyphosate in 2020, because of incomplete bio-efficacy data. Recent advances in analytical techniques using the latest hi-tech analytical devices have made it possible to detect the presence of herbicide residues at micro level. Half-lives of herbicides in the soils are found to be varied from 5 to more than 140 days under fields and laboratory conditions. Studies demonstrated 80% samples with residues below the detection limit (BDL), 13.4% below maximum residue limit (MRL), and 6.6% samples were found to be above MRLvalues.

WEED MANAGEMENT IN CONSERVATION AGRICULTURE

Conservation Agriculture (CA) that endorses the minimum soil disturbance, crop-residue retention on soil surface and crop diversification with greater inclusion of legumes, is being extensively promoted in India as a practice to improve soil health, crop productivity and environmental sustainability. Weeds are one of the major bottlenecks in sustaining the productivity and large-scale adoption of CA system. Weed seeds present in soil are the major source of above-ground weed population. Under CA system, majority of the weed seeds remains on soil surface due to minimum soil disturbance. Effective weed-management strategy in a system mode exhausts the weed seedbank and weed severity. However, maintenance of crop residue cover on soil surface reduces weed emergence due to restricted transmission of light and release of allelochemicals. Some of the issues arising from long-term practice of CA, such as increased infestation of perennial grassy weeds [*Cynodon dactylon* (L.) Pers.] and sedges (*Cyperus rotundus* L.), problem of rice mealybug [*Brevenni arehi* (indinger)] (Mishra *et al*., 2019), nematodes (Baghel *et al*., 2020), and other insect-pests in CA-based rice–wheat (*Triticum aestivum* L.) production system need to addressed appropriately. Hence, regular monitoring and management of weeds, insect-pests and diseases (pest dynamics) is required to get the long-term benefits from CA technologies.

WEED-FLORA SHIFT

Weed density and species composition are significantly altered by crop-establishment techniques, crop rotations and crop management (including weed management) strategies. Conventional tillage in rice–wheat cropping system favoured the intensification of grassy weeds *Echinochloa colona* in rice and *Phalaris minor* in wheat (Malik *et al*., 2014). Continuous use of the same herbicide/group of herbicides with similar mode of actions leads to shift in weed flora. For example, due to continuous use of single herbicide to control the *E. colona* in rice has led to the emergence of hardy grassy weeds like *Leptochloa chinensis, Cynodon dactylon, Ischaemum rugosum,* and *Paspalum distichum* L.; sedges like *Cyperus* sp., *Scirpus* sp., *Fimbristylis* sp., *Eleocaris* sp. etc. (Bhatt *et al*., 2021). Similarly, with the successful control of grassy weed *Phalaris minor* in wheat, broad-leaf weeds like *Lathyrus sativus* L., *Convolvulus arvensis* L., *Medicago polymorpha.* L.; M. *denticulata* Willd., *Cichorium intybus* L. and *Cirsium arvense* (L) Scop., are gaining importance. Shift from puddle transplant rice to direct-seeding (DSR) is favoured by dominance of grassy weeds like weedy rice, *Digitaria sanguinalis* (L.) Scop., *Leptochloa chinensis* (L.) Nees, *Dactyloctenium aegyptium, E. colona* and *Cyperus* spp. These examples indicate that the existing herbicides though efficient, can not solve all the problems and therefore, new herbicides, herbicide mixtures and rotations, and their integration with other crop-management practices are needed to solve the emerging weed problems.

BIOLOGICAL WEED CONTROL

Biological control of weeds using virus, bacterium, fungus, nematode, insect, fish, bird, and other animals, is an effective method to control many problematic weeds besides being economical and eco-friendly. Biological control is especially useful in natural areas, forests, and rangelands, where very high specificity, low-cost, and permanent control are needed to reduce the density of an invasive exotic weed without harming the native species. The first documentation of successful biological weed control was recorded in India through the unintentional release of an insect, *Dactylopius ceylonicus* (Green) in 1795 for biological control of cactus (*Opuntia humifusa* var. *humifusa;* syn. *O. vulgaris* Mill.) in north India. The systematic study on biological weed control in India, was however, started in 1957 with the establishment of Commonwealth Institute of Biological Control (CIBC) at Bengaluru Karnataka, with its substations in different parts of the country. It was further strengthened by establishment of All India Coordinated Research Project on Biological Control of Crop Pests and Weeds (AICRP-BC and W) in 1977, and the Project Directorate of Biological Control (PDBC), which was further upgraded as National Bureau of Agriculturally Important Insects (NBAII). The research on biocontrol of weeds in India got momentum with the establishment of the NRCWS in 1989, later upgraded as ICAR-DWR in Jabalpur.

In India, release of Mexican beetle (*Zygogramma bicolorata* Pallister) in 1983 against *Parethenium hysterophorus* L. is a successful example of biological weed control. Recently, seed weevil *Smicronyx lutulentus* dietz. has been imported at Bengaluru, Karnataka, for biological control of *Parthenium* (Sreerama *et al*., 2018). *Bactra verutana* was another insect bio-agent used against *Cyperus rotundus*. Successful control of aquatic weeds *Salvinia molesta* (D.) Mitch. by insect weevil *Cyrtobagous salviniae* calder & Sand, imported from Australia, and *Eichhornia crassipes* mart. by *Neochetina eichhorniae* warner and *N. bruchi* Hustache imported from the USA in 1982 have also been reported (Sushilkumar, 2015). Efforts have been made for biocontrol of other invasive weeds, viz. *Lantana camara* (L.), *Chromolaena odorata* (L.) R. King & H. Rob., *Eupatorium adenophorum* Spreng, *Mikania micrantha* Kunth using insects. However, these were not very successful due to various reasons including heavy parasitism by native parasitoids. In addition, amicrocyclic rust fungus, *Puccinia spegazzinii* D. Toni, was identified as apotential classical biological control agent against invasive weed *M. micrantha,* imported from Trinidad and Tobago. The rust was released in Assam (now Asom) and Kerala but failed to establish.

Although, several microbial products (mycoherbicide), viz. DeVine from fungi *Phytophthora palmivora* Butler against strangler college wine *Morrenia odorata* (Hook. & Arn.) Lindl., (based on *Colletotrichum gloeosporioides* f. sp. *aeschynomene*) to control Northern Jointvetch *Aeschynomene virginica* (L.) Britton & al., ABG5003 (*Cercospora rodmani* conway) against *E. crassipes*, BioMal® (*Colletotrichum gloeosporioides* f. sp. *malvae*) against round-leaved mallow *Malva pusilla* Sm., *Alternaria cassiae* Jurair & A. Khan against sicklepod *Senna oblusifolia* (L.) H.S. Irwin & Barneby; syn. *Cassia obtuifolia* L. and a bacterial product Stumpout® (*Cylindrobasidium leave* (Pers.) Chamuris) for suppressing regrowth from cut stumps of bigleaf maple *Acer macrophyllum* pursh have been developed, patented and commercialized in advanced countries, their efficacy in India has not been evaluated. Kaur *et al*. (2014) reported the rust fungi, *Puccinia abrupta* var. *Partheniicola* (Jackson) Parmelee and *Puccinia xanthii* var. *parthenii-hysterophorae*, can be used to control *Parthenium*.

It has been found that, biological control is too slow, not able to control all weeds, involves a costly and cumbersome process for import of biocontrol agents, requires a test of its host specificity, and high rate of failure of bioagents, may involve risk for non-target plants.Classical biological control agents are self-perpetuating, self-contained and self-regulating; once they are established, further investments in control are not necessary.

WEED MANAGEMENT UNDER CHANGING CLIMATE

Increasing CO_2 levels and temperature, and change in rainfall pattern (intensity and frequency) have a substantial impact on crop-weed interaction and efficacy of weed-management practices. Therefore, a complete understanding of weed interactions under different ecosystems and management practices will be required for developing successful weed-management strategies. Elevated levels of CO_2 increase the photosynthesis and growth of several weeds especially C_3 species and more competitive with C_4 crop plants.However, Naidu and Paroha (2008) from ICAR-DWR, Jabalpur reported that, elevated CO_2 has increased the growth and biomass accumulation of C_4 weeds like *Amaranthus viridis* L. They further reported that, *Parthenium hysterophorus* may grow more vigrously under higher CO_2 levels, and become more competitive. Under such conditions, a higher dose and frequent application of herbicides may be needed which may not be economical and environment-friendly. Increased activities of soil enzymes, viz. dehydrogenase, fluorescein diacetate (FDA) hydrolysis, and urease in weeds rhizosphere, but not in the crops rhizosphere, of rice–wheat cropping system was observed (Sarathambal *et al.,* 2016), indicating the competitive advantage of CO_2 enrichment in favour of weeds. Changing climate also minimizes the herbicide efficacy and make weed management more difficult. Changes in CO_2, light, temperature and humidity can change the performance of some group of herbicides. Studies conducted at the ICAR-DWR, Jabalpur revealed that, under elevated CO_2, wild oat [*Avena sterilis* subsp. *ludoviciana* (Dusie) Gillet & Magne; syn. *Avena ludoviciana*] seeds matured 2 weeks earlier than those grown under ambient conditions. He further observed that, the CO_2 enrichment decreased the efficacy of the herbicides, and the time taken for the complete mortality of the weeds was prolonged at elevated CO_2 levels. The high CO_2 concentration delayed the mortality of weeds by 9, 7 and 3 days, respectively, in case of isoproturon, clodinafop and glyphosate.

UTILIZATION OF WEEDS

In spite of the technological advancement in weed management and concerted efforts made by the scientists, policy-makers, farmers and other stakeholders, some of the problematic weeds like water hyacinth, eupatorium, lantana, parthenium, ipomoea, etc. are widely spreading aquatic environment, forest plantation, non-cropped areas, grassland and roadside at the cost of many other useful vegetation.Therefore, a holistic approach including utilization of weeds as a source for vermicomposting material, biochar, essential oils, soil amendments, biofuel and bioenergy, etc. through appropriate technologies may help in management of these weeds.Vermicomposting of such weeds before flowering and seed setting has enough potentiality for use in organic farming. Several aquatic species have the ability to remove heavy metals from water, including water hyacinth [*Eichhornia crassipes* (Mart.) solms] pennywort (*Hydrocotyle umbellate* L.), and duckweed (*Lemna minor* L.). Water hyacinth accumulated higher average concentration of nickel, cadmium, copper, iron and manganese to the extent of 20.9, 1.14, 59.5, 6171 and 352 mg/kg respectively (Khankhane *et al*., 2014). The higher accumulation of nickel, iron and manganese by water hyacinth may be due to its strong metal-absorbing ability. Barman *et al.* (2000) observed high accumulation of iron and chromium in *Alternanthera sessilis* (L.) R. Br. Ex DC. and *Cynodon dactylon* (L.) Pers.

WEEDS OF QUARANTINE SIGNIFICANCE AND WEED RISK ANALYSIS

Increasing trade and globalization coupled with liberalized policies have increased the risk of introduction of exotic weeds through bulk imports. Import of grain and seeds for propagation as well as for consumption could be a source of introduction of exotic weeds into India (Singh *et al*., 2018). Weed seeds have been intercepted on many occasions from these bulk shipment. A number of weed species, which were not reported earlier in India, have been detected at plant-quarantine units of the National Plant Protection Organization. Inspection data showed that grain shipments contain a variety of contaminants including seeds of quarantine weeds and the species not reported from India (Moolchand *et al*., 2000). The National Invasive Weed Surveillance (NIWS) team has traced 5 invasive weeds, which came to India through wheat import during 2007–08. Weed Risk Analysis (WRA) scores revealed that, all the intercepted exotic weed species have the potential to become serious weed in Indian agriculture. Plant Quarantine (Regulation of Import into India) Order 2003, of the Destructive Insects and Pests Act (1914) provides a legislative framework for the application of measures to prevent the introduction or spread of insect, disease and weed pests affecting plants. The ICAR-National Bureau of Plant Genetic Resources (NBPGR), New Delhi, is the nodal agency that facilitates exchange of plant germplasm meant for research between India and different countries. It has the power vested by the Plant Protection Adviser to the Government of India, under the Plant Quarantine (Regulation of Import into India) Order 2003, of the Destructive Insects and Pests Act (1914) to carry out quarantine examination and according clearance of the plant germplasm including transgenic imported for research purpose. In order to ensure effective implementation of Plant Quarantine (Regulation of Import into India) Order 2003, it is essential that all imported seed samples are free from weeds of quarantine importance. Therefore, all samples imported through ICAR-National Bureau of Plant Genetic Resources, New Delhi, are examined at Division of Plant Quarantine for the presence of weed seeds, especially to determine the presence of quarantine weeds. All the weed seeds are removed from seed samples and only weed- free samples are released and made available to the importer.

MANAGEMENT OF PARASITIC WEEDS

Parasitic weeds are becoming major constraints to many crops in Indian agriculture. Field dodder (*Cuscuta* spp.), broomrapes (*Orobanche* spp.), witch weed (*Striga* spp.) and loranthus are the major parasitic weeds reported in the country. In India, *Orobanche* spp. have emerged as a major threat to production of rapeseed–mustard group of crops in northern Rajasthan, Haryana, Punjab, and north-West Madhya Pradesh. In Andhra Pardesh, 50% area (40,000 ha) under tobacco (*Nicotiana tabacum* L.) is infested with broomrapes and causing 50% crop losses. Yield losses due to *Orobanche* spp. in tobacco-growing areas of Tamil Nadu, Gujarat, Karnataka and Maharastra is also reported to be 50–60%. *Cuscuta* is a major problem in niger [*Guizotia abyssinica* (L. f.) Cass.], Lucerne (*Medicago staiva* L.), berseem (*Trifolium alexandrinum* L.), lentil (*Lens culinaris* Medikus), linseed (*Linum usistatissimum* L.) and many more crops. The loss in seed yield of the host crops due to *Cuscuta* densities from 1 to 10 plants/m^2 ranged from 27.7–88.3%, 39.3–98.4%, 49.1–84.0% and 54.7–98.7%, respectively, in summer greengram (*Vigna radiata* L.), R. Wilezek niger, lentil and chickpea (Mishra, 2009). Heavy crop losses (15–75%) are caused by *Striga asiatica* in sorghum and sugarcane in Maharashtra, Karnataka, Andhra Pradesh and Tamil Nadu.

In tobacco, application of glyphosate at 0.5 kg/ha 60 DAS and imazaquin at 0.01 kg/ha at 30 DAS significantly reduced (75–80%) the infestation of broomrape and increased the yield of tobacco by 43% (Dhanapal, 1996). Application of neem-cake (200 kg/ha) lower the *Orobanche* shoots (62%) and increased the dry leaf yield by 51% (Chinnusamy, 2012). In irrigated Indian mustard, glyphosate applied twice at 25 g/ha at 30 DAS, followed by

50 g/ha at 55 DAS provided 65–85% control of *Orobanche* even up to harvesting (without any crop injury) with yield improvement from 12 to 41% over the traditional farmers' practice in different years of the study (Punia, 2014). Pendimethalin 0.5–1.5 kg/ha applied as pre-emergence controlled *Cuscuta* in niger, blackgram [*Vigna mungo* (L.) Hepper], linseed, onion (*Allium cepa* L.), chickpea and lentil (Mishra, 2009). However, in lucerne and berseem, pendimethalin at 0.50 kg/ha applied at 2 weeks after sowing was found safe and effective against *C. campestris* Yunck (Mishra, 2009). Pre-emergence application of metribuzin or atrazine at 1.0 kg/ha followed by trash mulching at 3–5 t/ha between sugarcane rows at 60 days after planting (DAP) provided effective control of *Striga* in sugarcane (Singh *et al*., 2001). At TNAU, Coimbatore, pre-emergence application of atrazine 1.0 kg/ha on 3 days after planting (DAP) + hand-weeding at 45 DAP with an earthing up at 60 DAP combined with post-emergence application of 2,4-D sodium salt at 5 g/litre (0.5%) + urea 20 g/litre (2%) at 90 DAP provided complete control of *Striga asiatica* in sugarcane. Directed spray of paraquat at 5 ml/litre on the emerging *Striga* plants was effective to reduce future seed bank.

MANAGEMENT OF WEEDY RICE

Weedy rice is becoming a major challenge in direct-seeded rice. The common herbicides recommended for weed control in rice do not provide effective control of weedy rice. Manual weeding is not effective because of its similarity with rice plant. In the absence of selective herbicides to control this weed in rice fields, use of clean seeds, proper land preparation, stale-seed-bed technique, rotation of rice-establishment techniques, use of purple colour rice varieties, flooding the fields, use of herbicide-tolerant rice varieties etc. may be practiced to manage this weed. Recently developed 'Weed wiper'by AICRP-WM, KAU, Thrissur, may also be used for management of weedy rice.

CONCLUSION AND FUTURE RESEARCH STRATEGIES

- Weed-management research in India is now more than 6 decades old, with major emphasis on screening and evaluation of herbicides. Use of herbicides has been increased at a faster rate in the last 1 decade due to labour shortage, ease in application, efficient weed control and cost-effectiveness. However, over reliance on herbicides may lead to development of herbicide resistance in weeds and residue hazards. Methodologies for early detection of herbicide resistance in weeds and their effective management strategies need to be developed. Similarly, protocols/ methodologies for quick detection and quantification of multiple herbicides residues in grains and other edible parts, soil, water, fishes, and other non-target organisms need to be developed. Breeding for herbicide-resistant crop varieties, nano-herbicides, herbicide mixtures and rotations, herbicide-soil moisture interactions etc. are the other important areas of research in herbicidal weed management. Hence, much-accelerated efforts on integrated weed management as a component of integrated crop management are needed.
- Climate change is a reality and being experienced worldwide. Research on impacts of climate-change factors on crop-weed interactions, weed-flora shifts and herbicide efficacy need to be intensified. There is an urgent need to strengthen basic and strategic research in order to make weed-management programme vibrant. Understanding the weed ecology and physiological, biochemical and molecular mechanisms of crop-weed interactions and herbicide resistance under changing climate need to be studied.
- Development of weed risk-assessment protocols for major alien-invasive weeds (AIWs), and their effective implementation is urgently required. Digitization of presence AIWs and biocontrol agents in the country is very much required. Efforts should be made to introduce more biocontrol agents against AIWs.
- In view of the emerging challenges in agriculture due to declining soil health, water shortage, energy crisis, climate change and global warming etc., CA is being promoted in India. Long-term impact of CA on weed-flora shift, weed seedbank and insect-pest dynamics, and their management strategies need to be worked out.
- In addition to manage the weeds, their potential for utilization as a source for vermicomposting material, biochar, essential oils, soil amendments, biofuel and bioenergy, bioremediation, feed/ food values, genetic variability for stress tolerance etc. should be explored and documented.
- There is a need to strengthen the research work on use of artificial intelligence (AI), decision support system, remote sensing and GIS, robotics, drones, spraying techniques, etc., for precision weed management.
- More focused basic and strategic research on biochemical and molecular basis of host-plant relationship of parasitic weeds and their effective management strategies are required.
- Impact assessment (economic, environmental and societal) of weed management technologies need to be given priority. The ICT tools need to be adopted for wider dissemination of weed-management technologies among farmers and other stakeholders.
- Multi-disciplinary and multi-institutional approach

along with collaboration with international institutions, laboratories and private industries need to be strengthened.

REFERENCES

DWR, 2017–18. *Annual Report*, Published by ICAR-Directorate of Weed Research, Jabalpur, Madhya Pradesh. pp. 80–81.

Baghel, J.K., Das, T.K., Mukherjee, I., Nath, C.P., Bhattacharyya, R., Ghosh, S. and Raj, R., 2020. Impacts of conservation agriculture and herbicides on weeds, nematodes, herbicide residue and productivity in direct-seeded rice. *Soil and Tillage Research* **201**: 104634.

Barman, S.C., Sahu, R.K., Bhargava, S.K. and Chatterjee, C. 2000: Distribution of heavy metals in wheat, mustard and weed grains irrigated with industrial effluents. *Bulletin of Environmental Contamination and Toxicology* **64**: 489–496.

Bhatt, R., Singh, P., Hossain, A. and Timsina, J. 2021. Rice–wheat system in the northwest IndoGangetic plains of South Asia: issues and technological interventions for increasing productivity and sustainability. *Paddy and Water Environment* **19**: 345–365.

Chandel, A.K., Tewari, V.K., Kumar, S.P., Nare, B. and Agarwal, A. 2018. On-the-go position sensing and controller predicated contact-type weed eradicator. *Current Science* **114**(7): 1,485–1,494.

Chander, S., Tyagi, V.C., Ghosh, D., Chethan, C. R., Mishra, S.K., Kumar, B. and Singh, P. K. 2019. Herbicide resistant Jungle rice Herbicide resistant Jungle rice in soybean growing belts of Madhya Pradesh. *Indian Farming* **69**(9): 24–26.

Chhokar, R.S., Sharma, R.K., Gill, S.C. andMeena, R.P. 2015. Herbicides for broad-leaved weeds management in wheat. *Indian Journal of Weed Science* **47:** 353–361.

Chinnamuthu, C.R. and Kokiladevi, E. 2007. Weed management through nanoherbicides (In) *Application of Nanotechnology in Agriculturem* pp. 23–36. Chinnamuthu. C.R., Chandrasekaran, B. and Ramasamy, C. (Eds), Tamil Nadu Agricultural University, Coimbatore, India.

Chinnusamy, C. 2012. Managemnt of parasitic weed Orobanche in tobacco in western zone of Tamil Nadu. *Annual Report, 2012*. AICRP–Weed Control, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India. pp 63–67.

DAC&FW. 2018. *Directory of Agriculture Machinery and Manufacturers*. Farmer's portal, Department of Agriculture and Cooperation and Farmers Welfare, Ministry of Agriculture and Farmers Welfare, Government of India. New Delhi.

Das, A., Manoj Kumar, Ramkrushna, G.I., Patel, D.P., Jayanta Layek, Naropongla, Panwar, A.S. and Ngachan, S.V. 2016. Weed management in maize under rainfed organic farming system. *Indian Journal of Weed Science* **48**(2): 168–172.

Dhanapal, G.N. 1996. Management of broomrape (*Orobanche cernua*) in tobacco (*Nicotiana tabacum*) Ph.D. Thesis, Wageningen Agricultural University, Wageningen, the Netherlands, 183 pp.

Dubey, R. P. 2008. Effect of weed control and nitrogen application rates on weed infestation and productivity in maize-cowpea intercropping system. *Indian Journal of Weed Science* **40** (3 and 4 supplementary): 155–158.

Dubey, R. P. 2018. Weed management in organic agriculture. (In) *Proceedings of ISWS Golden Jubilee International Conference on Weeds and Society: Challenges and Opportunities*, 21–24 November 2018, ICAR-DWR, Jabalpur, Indian Society of Weed Science, India. pp. 69.

Gharde, Y., Singh, P.K., Dubey, R.P., and Gupta, P.K. 2018. Assessment of yield and economic losses in agriculture due to weeds in India. *Crop Protection* **107:** 12–18.

Gnanasoundari, P. and Somasundaram, E. 2014. Non-chemical weed management in organic rice. *African Journal of Agricultural Research* **9**(26): 2,077–2,084.

Grover, Nitasha , Kumar, Aruna, Yadav, Ashutosh Kumar, Gopala Krishnan, S., Ellur, Ranjith Kumar, Bhowmick, Prolay Kumar, Vinod, K.K., Bollinedi, Haritha, Nagarajan, M., Viswanathan, C., Mithra, Amitha, Sevanthi, V., Singh, Nagendra Kumar, Mohapatra, Trilochan and Singh, Ashok Kumar. 2020. Marker assisted development and characterization of herbicide tolerant near isogenic lines of a mega Basmati rice variety, "Pusa Basmati 1121". *Rice (NY)* **13**: 68, doi: 10.1186/s12284-020-00423-2,

Heap, I. 2021. Current status of International herbicide resistant need data-base. www.weedscience.org.accessedon20october 2021.

IAS, 1996. International Allelopathy Society. https://allelopathy-society.osampytheas.tr

Kaur, M., Aggarwal, N.K., Kumar, V., and Dhiman, R. 2014. Effects and management of *Parthenium hysterophorus*: A weed of global significance [online]. Available: http://dx.doi.org/10.1155/2014/368647 [03 Dec 2020].

Khankhane, P.J., Sushilkumar and Bisen, H.S. 2014. Cadmium, nickel, copper and manganese extracting potential of water weeds of Jabalpur. *Indian Journal of Weed Science* **46**(4): 361–363.

Malik, R.K., Kumar, V., Yadav, A. and Mc.Donald, A. 2014. Conservation agriculture and weed management in south Asia: Prospective and development. *Indian Journal of Weed Science***46**: 31–35.

Mc Dade and Christians,N.E. 2000. Corn gluten meal – a natural pre-emergence herbicide: Effect on vegetable seedling survival and weed cover. *Weed Science* **48**(4): 112–116.

Mishra, J.S. 2009. Biology and management of *Cuscuta* species. *Indian Journal of Weed Science* **41**(1 and 2): 1–11.

Mishra, J.S., Poonia, S.P., Choudhary, J.S., Kumar R., Monobrullah, Md., Verma, M., Malik, R.K. and Bhatt, B.P. 2019. Rice mealybug (*Brevennia rehi*): a potential threat to rice in a long-term rice-based conservation agriculture system in the middle Indo-Gangetic Plain. *Current Science* **117**(4): 566–568.

Moolchand, Rajak, R.K., Radhey, Shyam, Reddy, O.R., Vijaykuma, C.S.K. and Indira, M. 2000. Interception of weed seeds in wheat imported from Australia. *Indian Journal of Weed Science* **32**(3 and 4): 210–212.

Naidu, V.S.G.R. and Paroha, S. 2008. Growth and biomass partitioning in two weed species *Parthenium hysterophorus* (C_3) and (C_4) under elevated CO_2. *Ecology, Environment and Conservation* **14**: 9–12.

Olofsdotter, M. and Navarez, D.C. 1996. Allelopathic rice for *Echinochloa crus-galli* control. In: *Proceedings of the 2nd International Weed Control Congress*, Copenhagen, Denmark, pp. 1,175–1,181.

Patil, B., Reddy, V.C., Ramachandra Prasad, T.V., Shankaralingappa, B.C., Devendra, R. and Kalyanamurthy, K.N. 2013. Weed management practices in irrigated organic fingermillet. *Indian Journal of Weed Science* **45**(2): 143–145.

Punia, S.S. 2014. *Orobanche*: Weed biology and control measures. *Indian Journal of Weed Science* **46**(1): 36–51.

Sarathambal, C., Rathore, M., Jaggi, D. and Kumar, B. 2016. Response of soil enzymes to elevated CO_2 and temperature in weeds associated with rice–wheat cropping system. *Indian Journal of Weed Science* **48**(1): 29–32.

Sharma, M. 2021. The future of Indian agriculture. *Down to Earth*, 04 February 2021. *https://www.downtoearth.org.in* Accessed on 10th August 2021.

Shobha, D., Raveendran, M., Manonmani, S., Utharasu, S., Dhivyapriya, D., Subhasini, G., Ramchandar, S., Valarmathi, R., Grover, Nitasha, Gopala Krishnan, S., Singh, A.K., Jayaswal, Pawan, Kale, Prashant, Ramkumar, M.K., Amitha Mithra, S.V., Mohapatra, T., Singh, Kuldeep, Singh, N. K., Sarla, N., Sheshshayee, M.S., Kar, M.K., Robin, S. and Sharma, R.P. 2017. Development and genetic characterization of a novel herbicide (Imazethapyr) tolerant mutant in rice (*Oryza sativa* L.). *Rice* **10**(1), doi: 10.1186/s12284-017-0151-8

Singh, M.C., Dubey, S.C. and Kumar, S. 2018. Interception of weed species in quarantine and wed risk analysis. (In) *Fifty Years of Weed Science Research in India*. pp: 150–160. Sushilkumar and Mishra, J.S. (Eds. Indian Society of Weeds Science, Jabalpur, Madhya Pradesh.

Singh, S.N., Singh, R.K. and Singh, B. 2001. Herbicidal cum integrated approach of weed management in spring planted sugarcane. *Indian Journal of Weed Science* **33**: 136–138.

Sreerama, Kumar,Prakya, Kumar, M.S., Shylesha, A.N., Ballal, C.R., Dhileepan, K., Shi Boyang and Callender, J.T. 2018. Importation and quarantining of seed feeding weevil *Smicronyxlutulentus* for prospective control of *Parthenium hysterophorus* in India. p. 209. (In) *Proceedings of 1st International Biological Control 'Approaches and applications,* pp. 27–29 September 2018, Bengaluru, Karnataka, India.

Sushilkumar. 2015. History, progress and prospects of classical biological control in India. *Indian Journal of Weed Science* **47**(3): 306–320.

Tewari, V.K. and Chethan, C.R. 2018. Mechanization in weed management: Global review. (In) *Fifty Years of Weed Research in India.* Sushilkumar and Mishra, J.S. (Eds). Indian Society of Weed Science, Jabalpur, Madhya Pradesh, India. pp. 215–237.

Wu, H., Pratley, J., Lemerle, D., Haig, T. and Verbeek, B. 1998. Differential allelopathic potential among wheat accessions to annual ryegrass. (In) *Proceedings of the 9th Australian Agronomy Conference*, WaggaWagga, NSW, Australia, pp. 567-571.

Yaduraju, N.T. and Mishra, J.S. 2018. Smart weed management: A small step towards doubling farmers' income. *Indian Journal of Weed Science* **50**(1): 1–5.