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DWR Publication No. 18

DWR - Souvenir

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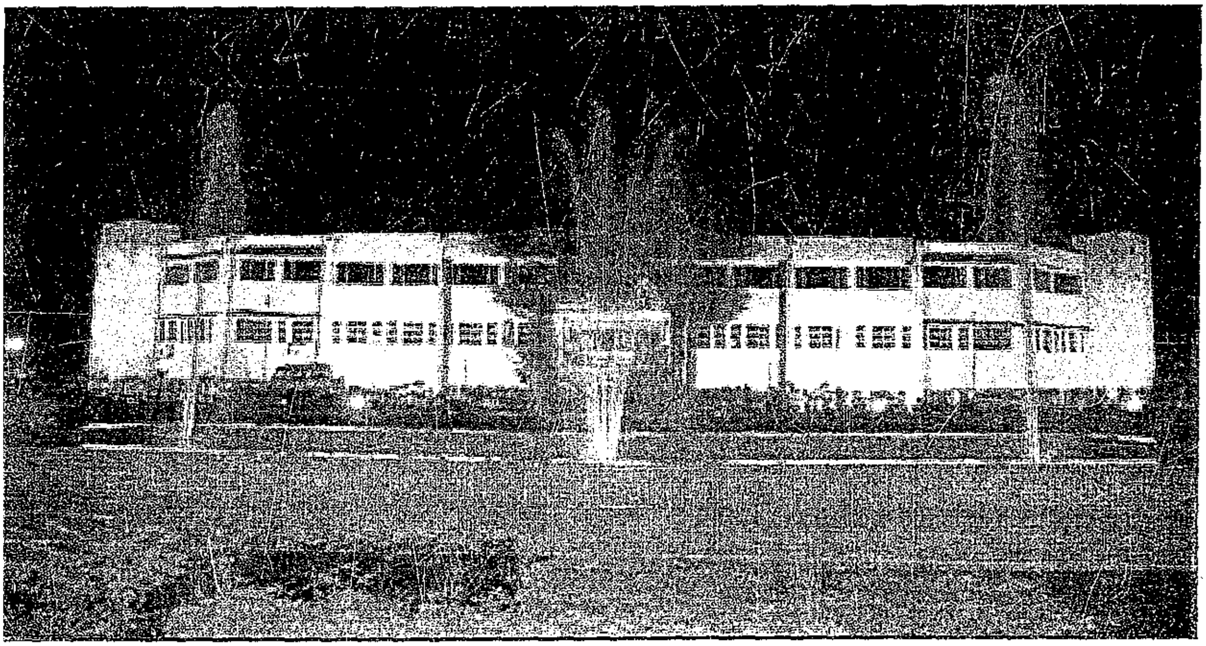

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D W R

Weed management research in India – an analysis of past and outlook for future

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Agriculture is a critical sector of the Indian economy. Though agriculture's contribution to the overall Gross Domestic Product (GDP) of the country has fallen from about 30% in 1990–91 to <15% in 2011–12, agriculture yet forms the backbone of development. Achieving an 8–9% rate of growth in overall GDP would help in poverty reduction and in providing food and nutritional security to all Indians, only when agricultural growth accelerates. In the last two Five Year Plans, it was mentioned that for the economy to grow at 9%, it is important that agriculture should grow at least by 4% per annum. The average growth in agriculture and allied sectors in the XI Plan is around 3.3–3.5% per year against a target of 4%. Despite a virtual ceiling on cultivable area of 140±2 M t, India's foodgrain production increased from 198 million tonnes (M t) in 2004–05 to 259 M t by 2011–12, at an average of about 6 M t per annum due to enhanced growth rates in yield of different crops. However, we need to produce more to meet the demands of 1.66 billion people (of 9.16 billion people of the world) to be inhabited in India by 2050. Further enhancement of crop productivity for the achievement of food and nutritional security and alleviation of poverty and unemployment on a sustainable basis depends on the efficient and judicious use of natural resources. Efficient use of natural resources, enhancing food and feed production to meet the demands (Table 1) of increasing population is possible only when biological constraints such as weeds are understood properly and alleviated by evolving and implementing appropriate management strategies.

Table 1. Production and future requirement of foodgrains in India

Crop	Production 2010–11 (M t)	Demand 2021 (M t)
Rice	103	120
Wheat	90	100
Coarse cereals	42	40
Pulses	17	25
Total	252	285

Source: www.epsoweb.org/file/853

Weeds are one of the major biological constraints that compete with crops for natural resources as well as added inputs, and are limiting agricultural production and productivity in India (Rao and Nagamani, 2010, 2013). Despite continuous research and extension efforts made in weed science, weeds continue to cause considerable losses to farming. As per the available estimates, weeds cause up to one-third of the total losses in yield, besides impairing produce quality and various kinds of health and environmental hazards (DWR, 2014). In their response to the survey carried out for the present chapter, Indian weed scientists estimated losses due to weeds from 10-80% (Table 2). Even the lowest estimate of 10% loss would amount to a loss of about 25 M t of foodgrains, currently valued at approximately US$ 13 billion (Yaduraju, 2012). Losses of similar magnitude may occur in plantation crops, fruits, vegetables, grass lands, forestry and aquatic environment. Thus, the total economic losses will be much higher if indirect effects of weeds on health, loss of biodiversity, nutrient depletion, grain quality etc. are taken into consideration.

Table 2. Possible yield loss due to weeds in different major crops of India, as expressed by the Indian weed scientists in the survey

Crop	Yield loss (%)	Crop	Yield loss (%)
Chickpea	10–50	Pea	10–50
Cotton	40–60	Pearlmillet	16–65
Finger millet	50	Pigeonpea	20–30
Greengram	10–45	Potato	20–30
Groundnut	30–80	Rice*	10–100
Horsegram	30	Sorghum	45–69
Jute	30–70	Soybean	10–100
Lentil	30–35	Sugarcane	25–50
Maize	30–40	Vegetables	30–40
Mustard	20–30	Wheat	10–60
Niger	35		

*Yield losses could be up to 100% if weeds are not controlled

As weeds are dynamic, continuous monitoring and refinement in management strategies is essential for alleviating adverse effects of weeds on agricultural productivity and environmental health (Rao and Nagamani, 2013). Currently, weed scientists of India have the challenge of evolving effective weed management technologies that are economical and have least impact on environment and non-target organisms (Rao and Nagamani, 2010). For the research efforts to be more effective and target based, it is essential to review, from time to time, the research work carried out and identify the research needs based on: (a) impact of research results attained and extended to farming community, and (b) new emerging weed problems that farmers are facing in response to adoption of improved weed and crop management technologies.

The present paper aims at understanding and analyzing the weed management research carried out in India in the past, being carried out at present and suggests future research needs based on current farmers needs.

Methodology

The first assumption made for this study was that the research carried out in India is mostly published by the Indian weed scientists in the Indian Journal of Weed Science (IJWS). Hence, for the purpose of this paper, publications of Indian Journal of Weed Science have been considered as the criteria of research carried out in India during different periods of time. We have considered:

Past:

(i) Far–past: IJWS publications from the year 1980–1989

(ii) Past: IJWS publications from the year 1990–1999

(iii) Immediate past: IJWS publications from the year 2000–2009

Present: IJWS publications from the year 2010–2013

The publications were categorized into different sub-disciplines of weed science, analysed and discussed. Future research needs, as we felt important, are discussed in this paper. The short communications during the period of 2000–2009 were not considered in this analysis (due to time constraint). For the rest of the years, they too were included. The research findings as presented in "Proceedings of the Annual Group Meeting of All India Coordinated Research Project on Weed Control" from 2010–2013 were also referred and summarized.

A survey was conducted, using structured questionnaire, among Indian weed scientists on relevant aspects of weed management in India. Twenty-four scientists responded and the summary of their response was used at appropriate places with due acknowledgement.

Weed management research in India

In the past, hand weeding was synonymous to weed management due to abundant labour availability, cheaper cost of labor and the nature of agriculture as major occupation. Hence manual and mechanical methods were used by the farmers. During 1990s, the nominal farm wages grew at a rate of 11.6% per annum, while in 2000s the growth rate was 8.9% per annum. Within 2000s, the growth was only 1.8% during 2001–2002 to 2006–2007 and 17.8% during 2007–2008 and 2010–2011 (Source: Labour Bureau, Shimla, India). Increased labour wages lead to adoption of chemical weed control alone or as a component of integrated weed management by the farmers in India during recent times.

Earliest attempts in India to control weeds by herbicides were made in 1937 in Punjab for controlling *Carthamus oxycantha* by using sodium arsenite. After the discovery of 2,4-D as plant growth regulator (Zimmerman and Hitchcock, 1942), it was first tested in India in 1946 (Mukhopadhyay, 1993). Since then a number of herbicides have been imported and tested for their effectiveness in controlling many weed species. In 1952, ICAR initiated a scheme for testing the field performance of herbicides in rice, wheat and sugarcane in different states of

India. Maximum amount of herbicides (50-60%) were used in the tea plantation. ICAR recognized the need for strengthening weed research in India by setting up in 1978 an All India Co-coordinated Research Project on Weed Control (AICRP-WC) in collaboration with United States Department of Agriculture (USDA), which is continued and now being implemented through 22 centres all over the country. National Research Centre for Weed Science was set-up in 1989 at Jabalpur and was upgraded as Directorate of Weed Science Research in 2009. Prior to establishment of AICRP-WC, weed science was considered as sub-discipline of Agronomy and is still considered in many agricultural universities of India.

Rice and wheat were the major crops of weed management research in India during past as well as current period (Table 3). The research efforts on these crops increased from 1980 to 2009. However, during present period (2010 to 2013), percentage papers on rice and wheat decreased as relatively more results were reported on crops such as sugarcane, maize and other crops. Research papers with studies on weed management in cropping systems perspective remained less throughout.

Table 3. Research publications on different crops (% of total papers published) in IJWS across years

Crop	Percentage of published papers in IJWS			
	1980-1989	1990-1999	2000-2009	2010-2013
Rice	14	20	26	21
Wheat	13	14	20	16
Cropping systems	5	7	9	6
Maize	4	3	3	3
Soybean	3	7	5	6
Greengram	3	2	<1%	1
Blackgram	2	<1%	2	1
Groundnut	3	3	<1%	1
Potato	2	1	1	<1%
Tomato	2	1	<1%	-
Mustard	1	1	1	1
Sorghum	3	<1%	-	1
Sugarcane	2	1	2	3
Chickpea	2	1	3	1
Fingermillet	2	<1%	-	1
Onion	2	1	2	2
Cotton	1	2	2	<1%
Brinjal	1	-	<1%	<1%
Cauliflower	1	<1%	-	
Cowpea	1	1	-	<1%
Barley	1	1	<1%	<1%
Chillies	1	<1%	-	

Contd..

Garlic	1	< 1%	< 1%	1
Jute	1	< 1%	–	< 1%
Mint	1	< 1%	–	
Pea	2	1	–	–
Pigeonpea	1	1	< 1%	1
Lentil	< 1%	1	1	2
Sunflower	–	1	1	1
Mulberry	–	1	< 1%	–
Rajmash	–	1	< 1%	
Sesame	–	1	1	< 1%
Coriander	–	–	1	–
Cumin	< 1%	–	1	< 1%
Okra	< 1%	< 1%	1	1
Sweet corn	–	–	–	1
Cluster bean	–	< 1%	< 1%	1
< 1%	Chickpea, radish, tobacco, bamboo, banana, bell pepper, *Brassica capsularis*, carrot, fenugreek, field peas, french bean, greengram, fodder, isabgul, orchards, peach, plum orchard, ramie, safflower, urd bean, winter vegetables, vegetable pea	Flax, ber, kinnow, linseed, pearlmillet, lemon, saffron, toria, bell pepper, carrot, cassava, citrus, faba bean, fenugreek, field bean, fodder maize, French bean, *Citronella*, mandarin, opium poppy, pointed gourd, roses, runner bean, safflower, tobacco, tomato, toria, urdbean, vegetable nurseries	Garden pea, pea, pearlmillet, shaftal, aswagandha, baby corn, blond psyllium, fenugreek, berseem as fodder, chicory, chamomile, cabbage, cocoa, rubber, coconut, teak, banana and pineapple, dwarf pea, fenugreek, niger, linseed, niger, onion, opium poppy, Persian clover, pointed gourd, seed potato, *Setaria*, sweet potato, tea.	*Jujube*, strawberry, baby corn, bhalia plantation, berseem, Egyptian clover, ginger grapes, *Gladiolus*, isabgul, Lucerne tapioca, urdbean, greengram, pearlimilllet, toria.

Analysis of the past

Far past period (1980–1989)

During far past period, major emphasis was on utilisation of herbicides for weed management. Out of 333 papers published, 69% were on herbicides (such as alachlor, atrazine, bifenox, butachlor, 2,4-D, dicamba, diquat, fluchloralin, fluroxypyr, glyphosate, methabenzthiazuron, metoxuron, nitrofen, paraquat, propanil, simazine, terbutryne, and sethoxydim) and on herbicide related aspects of weed science (Table 4). Efficacy of herbicides in managing weeds in different crops, herbicide efficacy interaction with irrigation, fertilisers, effect of herbicides sprayed in one crop on the succeeding crops, tolerance of crop cultivars to herbicides were certain aspects of herbicide based studies. Only 9% of research papers were on integrated weed management (IWM) and all these were herbicide based

Table 4. Broad research areas of publications in Indian Journal of Weed Science across thirty three years

Research area	Percentage of papers published in IJWS			
	1980-1989	1990-1999	2000-2009	2010-2013
Herbicides	69	57	53	41
IWM	9	20	30	35
Ecology	16	15	11	10
Cultural	2	3	3	4
Genomics	0	0	1	0
Physiology	1	1	1	3
Allelopathy	3	1	1	1
Biocontrol	1	< 1	1	1
Weed use	0	< 1	< 1	2
Economics	0	1	< 1	< 1
Review	1	1	< 1	2
Modelling	0	0	1	< 1
Decision support	0	0	< 1	0
Total publications referred to by author	333	560	424	277

A considerable number of papers were published on weed ecology (16%) during the period. Weed ecological research focussed on assessing critical period of crop weed competition (rice under different methods of establishment, brinjal, finger millet, groundnut, maize and sugarcane) and weed flora surveys (in the states of Andhra Pradesh, Punjab, Madhya Pradesh, Maharashtra, higher hills of Nilgiris, Kashmir, West Bengal, Western Himalayas and Tarai region) during the far past period. Results of research on ecology of *Parthenium hysterophorus* (Tiwari and Bisen, 1984) and biology and control of *Oxalis latifolia* were reported (Muniyappa *et al.*, 1983). Allelopathy studies were focussed on effects of weed leachates on germination of crop seeds. The concept of utilising competitive crops for managing *Cyperus rotundus* was put forward (Kondap *et al.*, 1982). Only one publication on the biocontrol was published on the role of *Teleonemia scrupulosa* in controlling *Lantana* (Gupta and Pawar, 1984).

Past period (1990-1999)

During the past period, a significant increase in research papers on integrated weed management was observed while papers on herbicides alone slightly decreased.

During this period, resistance of isoproturon against *Phalaris minor* had posed a severe threat in wheat production in India (Malik and Singh, 1993, 1995; Bhan, 1994). Until the early 1990s, *Phalaris minor* could be effectively controlled by isoproturon, a substituted urea herbicide first recommended in 1977–78 and widely used since the early 1980s. But continuous use of this single herbicide for 10–15 years coupled with mono cropping of rice–wheat led to the evolution of resistance in this weed. By 1993, the resistance affected area ranged between 0.8–1.0 M ha in North West India and it also affected other *tarai* areas. Screening for alternative herbicides (Walia and Brar, 1996; Balyan *et al.*, 1999) and varieties tolerant to those herbicides (Yaduraju *et al.*, 1999) were initiated and reported.

In this period, reviews on biology and control of *Parthenium* (Tripathi *et al.*, 1991; Garg *et al.*, 1999) and usefulness of the weed, *Blumea lacera* (Oudhia and Tripathi, 1999) were published. Several publications on critical period of crop weed competition also appeared during this period in addition to results on herbicide evaluations, IWM, and weed flora surveys. Interesting publications of this period include identification of suitable crop species and plant density to suppress growth of *Cyperus rotundus* (Murthy *et al.*, 1995) and efficacy of crop residue management on herbicide efficacy in the rice–wheat sequence (Brar *et al.*, 1998).

Immediate past (2000–2009)

During this period, research papers on herbicide evaluation in different crops and weed ecology studies decreased in comparison to past period and those of IWM increased considerably. Increase was also observed in reports of studies on cultural weed management.Use of biotechnology for understanding molecular diversity of *Phalaris minor* populations in wheat (Dhawan *et al.*, 2008) and mechanism of resistance of *Phalaris* to isoproturon (Dhawan *et al*, 2004; Singh *et al.*, 2004) were initiated during this period. Methodology to study crop weed competition was reviewed by Singh *et al.*, (2002). Possible utilisation of weeds such as *Lantana* and *Eupatorium* as green manure in rainfed maize–wheat system (Mankotia *et al.*, 2006) and weed biomass for nitrogen substitution in rice–rice system (Rajkhowa, 2008) were published. An attempt to understand the technological gap in adoption of weed management technology in rice–wheat system of Uttaranchal was made (Singh and Lall, 2001). Cultural practices like use of smother crops in sugarcane (Rana *et al.*, 2004); soil solarisation alone in sunflower (Chandrakumar *et al.*, 2002) and soil solarisation along with crop husbandry practices like tillage with and without irrigation, wheat straw incorporation (e.g. Das and Yaduraju, 2008); irrigation and nitrogen in wheat (Das and Yaduraju, 2007) etc. were evaluated for their weed management efficacy and reported in the journal. Evaluation of varieties and hybrids in rice (e.g. Dhawan *et al.*, 2003; Kumar *et al.*, 2000) for response to fertilizers and herbicides and reports on varieties and herbicides in wheat (Verma *et al.*, 2007) were published. Publications on integrated weed management included combination of herbicides with manual weeding (e.g. Singh and Singh, 2004), trash burning (e.g. Singh and Rana, 2003), intercultivation (e.g. Subramanian and James, 2006), tillage (Sharma and Gautam, 2006), rotation (Singh, 2006), and several other combinations in several crops. Herbicide studies involved herbicide evaluation in different crops, their degradation (Amarjeet *et al.*, 2003), resistance in weeds (Mahajan and Brar, 2001); and herbicide residue effect on crops grown in rotation (Yadav *et al.*, 2004). The importance of decision making tools was brought to light (Babu *et al.*, 2000).

Present (2010 - 2013)

During the present period 277 research papers have been published in IJWS as Volumes 42 to 45. Supplementary volumes published from Jabalpur during these years were also considered in this analysis. Majority of the studies published during present period were herbicide based (41%). Integrated weed management studies and its percentage increased from 30-35%. Studies on weed use and cultural weed management increased slightly. But the studies on weed ecology decreased. Reviews on aspects such as integrated weed management (Rao and Nagamani, 2010); aquatic weed problems and management in India (Sushil Kumar, 2011); impact of climate change on weeds and weed management (Singh *et al.*, 2011); weed management approaches for dry-seeded rice (Chauhan and Yadav, 2013); zero tillage in weed management (Singh *et al.*, 2010) and cost of *Parthenium* and its management (Sushilkumar and Varshney, 2010) were published. In addition to studies on weed management with recently available herbicides, some of the interesting papers that appeared during this period were on shifts in weed flora due to tillage and weed management practices (Singh *et al.*, 2010); threshold level of horse purslane in irrigated cowpea and onion (Chinnuswamy *et al.*, 2010, 2010a); non-chemical methods for managing weeds in rice (Deshmukh, 2012); screening rice genotypes against weeds in direct-seeded rice (Walia *et al.*, 2010); evaluation of cultivars and herbicides for control of barnyard grass and nutsedge in rice (Kumar *et al.* 2013); evaluation of toxins of phyto-pathogenic fungus for eco-friendly management of *Parthenium* (Singh *et al.*, 2011); management strategies for rehabilitation of *Lantana* infested forest pastures in Jammu & Kashmir (Sharma *et al.*, 2012); and solarization for reducing weed seed bank in soil (Arora and Tomer, 2012).

Present day weeds and weed management practices used by farmers (as revealed by Indian weed scientists)

Dominance in weed flora and increase / decrease of weed dominance across years varied at different locations in India (Table 5). Majority of the crops, the scientists observed that hand weeding prevailed as the method of weed management in past and currently, herbicides are being used to manage crops associated weeds (Table 6). Labour wages for weeding have increase from 20 (20 years back) to 100 (3 years back) of the past to 120 to 300 of the present day. The increased labour wages are forcing farmers to adopt herbicides as a component of integrated weed management. Reported percentage of farmers using integrated weed management ranged from 10-30% in wheat; 10-70% in rice; 10-60% in soybean; 15-60% in chickpea; 5-40% in mustard and 20-50% in maize. Variation in the herbicides used in the past and present has also been observed. In the past, herbicides largely used were isoproturon and 2,4-D. Currently, sulfosulfuron, clodinafop, metsulfuron, mesosulfuron + iodosulfuron and isoproturon + 2,4-D were reported to be used by the wheat farmers. In rice thiobencarb, butachlor and 2,4-D, anilophos were used in the past. Currently, bispyribac sodium, fenoxaprop, chlorimuron + metsulfuron, oxadiargyl, ethoxysulfuron, pyrazosulfuron, butachlor, pretilachlor and 2,4 D are being used by the farmers. However, in Haryana, it was reported that many grassy weeds like *Leptochloa chinensis*, *Eragrostis* spp. and *Dactyloctenium* were not controlled by any of the herbicides used (AICRP-WC, 2013).

Based on research work carried out in India, DWSR has published books on: i) AICRP-WC recommendations on weed management, ii) Herbicide use in field crops, iii) Hand book on herbicide recommendations (http://www.nrcws.org/Listpublication.html). Hence, details of herbicides and their recommendations are not summarised in this paper.

Table 5. Summary of major weeds, new weeds, decrease and increase in weed species occurrence in India at different locations as reported in recent AICRP-WC meetings

Location	Weeds with decreased incidence	Weeds with increased incidence	Major weed problem / new weeds	References
Andhra Pradesh			*Vicoa indica* and *Cassytha filiformus* (parasitic weed) (new weeds in Ananthapur district)	AICRP-WC (2013)
Assam			*Eichhornia crassipes* followed by *Ipomoea carnea* (In aquatic situations of Dibrugarh district)	AICRP-WC (2013)
Assam (Jhum cultivation)	*Biophytum reinwardtii*, *Desmodium gangaticum*, *Mollugo pentaphylla*, *Passiflora foetida*, *Smilax perfoliata*, *Sonchus asper*, *Stephania japonica*, *Digitaria setigera*, *Echinochloa colona* and *Phragmites karka*			AICRP-WC (2012)
Bihar			Dominant weeds: *Cyperus rotundus*, *Cynodon dactylon*, *Echinochloa colona* and *Eleusine indica*, in initial stages and at later stages, *Caesulia axillaris* (in rice);	AICRP-WC (2013)

			weedy rice (New weed in direct-seeded deep water rice in Darbhanga and Madhubani districts)	
Chhattisgarh		*Alternanthera triandra* (DSR); *Malwa pusila* (replacing *Parthenium* on road sides);	Major weed: *Phalaris minor* (in wheat)	AICRP-WC (2013)
		Alternanthera triandra (in direct-seeded rice)		AICRP-WC (2011)
			Malwa pusilla is replacing *Parthenium hysterophorus* (in crop fields); *Alternanthera triandra*	AICRP-WC (2012)
Haryana (North-eastern)		*Medicago denticulata, Chenopodium album, Rumex dentatus* (in Hisar- wheat field due to continuous use of clodinafop)		AICRP-WC (2010)
		Solanum nigrum and *Malwa parviflora* (zero tilled wheat fields)		AICRP-WC (2011)
	Avena ludoviciana (disappeared in wheat)	*Ammania baccifera* (in transplanted rice)		AICRP-WC (2012)
			Avena ludoviciana (in wheat of southern Haryana); *Orobanche* spp. (in tomato)	AICRP-WC (2013)

Himachal Pradesh		*Commelina benghalensis* and *Brachiaria ramose* (due to continuous use of atrazine)	*Syndrella viallis* (new weed in maize at Palampur)	AICRP-WC (2010)
		Ageratum conyzoides, *Commelina benghalensis* and *Brachiaria ramosa*		AICRP-WC (2012)
			Ageratum conyzoides, *Commelina benghalensis* and *Brachiaria ramosa* (in Kangra district); *Parthenium hysterophorus* (started invading the upland *kharif* crops in the mid-hill conditions)	AICRP-WC (2013)
Jharkhand			*Hyptis suaveolens*	AICRP-WC (2012)
Karnataka			*Tithonia diversifolia* ; *Mikania micrantha* and *Ipomoea triloba* (new weeds); *Ambrosia psilostachya* (new quarantine weed recorded at Turevekare taluk of Tumkur district)	AICRP-WC (2013)
			Solanum carolinense, *Solanum trilobatum* (Solanaceae), *Cenchrus tribuloides/ biflorus*, (Poaceae), *Verbesina encelioides* Cav., *Echinops echinatus* Roxb. (Asteraceae), *Ipomoea hederifolia*, *Ipomoea quamoclit* (Convolvulaceae), *Anoda cristata* (Malvaceae) (New weeds noticed on cropped fields and road sides	AICRP-WC (2011)

Kerala		*Alternanthera philoxeroides* (Alligator weed) (spreading in the low lands in the Kuttanad and Koleland regions, where one crop is rice is taken during summer)		AICRP-WC (2012)
		Weedy rice (*Oryza* spp.) (rice growing tracts of Kerala, viz. Kuttanad, Thrissur Kole and Palakad regions)		AICRP-WC (2012)
			Leptochloa chinensis (rice in the Kole lands and Kuttanad)	AICRP-WC (2012)
Madhya Pradesh			Dominant weeds: *Orobanche aegyptica* (in mustard of Bhind, Datia, Shivpuri and Sheopur districts) *Orobanche aegyptiaca* and *Asphodelus tenuifolius* (in Gwalior and Morena districts)	AICRP-WC (2013)
			Alternanthera sessilis	AICRP-WC (2012)
Odisha			Major weeds: *Mikania micrantha, Parthenium hysterophorus, Eichhornia crassipes, Alternanthera philoxeroides, Orobanche aegyptica* (In East and South Eastern Coastal Plain Zone); *Celosia*	AICRP-WC (2013)
Punjab		*Poa annua* (increasing in Ludhiana		AICRP-WC (2010)

		wheat field due to continuous use of clodinafop and sulfosulfuron)		
		Eleusine spp. and *Leptochloa* (as they escape bispyribac in rice)		AICRP-WC (2012)
		Phalaris minor (showed signs of cross resistance to pinoxaden, sulfosulfuron, mesosulfuron + iodosulfuron and clodinafop)	Likely to be dominant: *Poa annua* (in wheat, berseem and oats); *Ipomoea* (in berseem); weedy rice (in transplanted rice), and *Dactyloctenium spp., Leptochloa spp* , and *Eragrostis spp.,* (in direct-seeded rice)	AICRP-WC (2013)
Tamil Nadu	*Tridax procumbens*	*Parthenium hysterophorus* (in cropped and non-cropped area)		AICRP-WC (2013)
Uttar Pradesh (Eastern)	*Avena fatua*		*Poa annua, Stellaria media; Solanum nigrum* and *Rumex acetosella* (new weeds)	AICRP-WC (2012)
			Polypogon monspliensis and *Poa annua, Rumex* spp. and *Medicago denticulata* (new weeds in wheat) and weedy rice (New weed in lowlying rice)	AICRP-WC (2013)
		Solanum sysimbrifolium (in potato, cabbage and cauliflower)		AICRP-WC (2013)

West Bengal			*Echinochloa glabrescens*, *Echinochloa crusgalli* both (in *boro* and *Kharif* rice) and *Oryza nivara*, *Oryza minuta*, *Oryza barthii* and *Oryza rufipogon* (in *Kharif* rice)	AICRP-WC (2012)

Table 6. Weeds of economic significance (in order of significance) in certain crops as reported by Indian weed scientists

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*

Majority of the scientists reported *Parthenium hysterophorus* as the most invasive weed species as it invaded soybean, vegetable, wheat, upland rice, sorghum and fruit orchards 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. *Lantana camara* was reported as most invasive weed of non-cropped areas. Other weeds that were reported to invade cropped and non-cropped areas during recent years include: *Ageratum* sp., *Alternanthera triandra*, *Argemone mexicana*, *Avena* sp., *Cenchrus ciliaris*, *Elatine triandra*, *Celosia argentia* and *Tithonia rotundifolia* in upland crops; *Hyptis suaveolens* in moist land; *Leptochloa chinensis* in paddy; *Medicago denticulata*, *Malva* spp., *Mikania micrantha*, *Hyptis suaveolens*, *Lantana camara*, *Chromolaena odorata* in off fields; *Rumex* spp., *Solanum* sp., parasitic weeds and water hyacinth.

Outlook for the future

Adoption of integrated weed management (IWM) is essential for economic management of weeds, management of herbicide resistance, and it also helps in minimising the size of weed seed banks over time, and has clear benefits for managing the risk of weed control failure due to adverse seasonal conditions that may prevail in the era of climate change. Using different components in an IWM plan is essential for the effective, long-term management of weeds. Some components of IWM that require emphasis on future research include:

Preventive control measures: Majority of the serious weeds are not native, but exotic and naturalised species. Trends of trade globalisation and global warming have potential to increase invasive plants dominance in agro-ecosystems of India. International cooperative efforts among weed scientists can be useful to prevent negative impact of invasive weeds. Considerable weed management can be achieved by adopting preventive weed control measures (Rao and Moody, 1988). Stricter introduction and implementation of seed laws (Rao and Moody, 1988a) and stricter enforcement of quarantine measures to prevent introduction would help in preventing new weed species into our country. Identification and popularisation of the preventive control measures for their use in arable and non-arable lands would be a low monitory input.

Mechanical weed management methods: Efforts to improve the efficacy of traditional implements and introduction of power operated mechanical implements to save labour hours and reduce drudgery to labour are essential.

Biocontrol: The first success in biological suppression of weeds was achieved in India with *Dactylopius ceyloniclus*, which was introduced from Brazil in 1795 for producing dye from a cactus species. It eradicated the problematic cactus species *Opuntia vulgaris* Mill. from India (Sushilkumar, 1993). Research on biological control of weeds was initially carried out at the erstwhile Commonwealth Institute of Biological Control at Bangalore which was known as Project Directorate of Biological Control and is now the National Bureau of Agriculturally Important Insects and the All India Co-ordinated Research Programme on Biological Control of Crop Pests and Weeds (AICRP-BCCPW).

Insect species such as *Neochetina* spp., *Cyrtobagolls salvallaie* and *Zygogramma bicolorata* were imported to India in earlier eighties, for controlling water hyacinth, water fern and *Parthenium*, respectively. Efforts have been successful and considerable control of respective weeds has been achieved by these insects. However few incidences of *Zygogramma bicolorata* feeding on sunflower were reported. Efforts in use of pathogens in managing weeds still remain in experimental stage.

Biocontrol may serve as a component of integrated weed management in future, inspite of several practical difficulties.

Habitat management: Research efforts in weed management through creation of unfavourable environment for weeds through habitat management has a lot of scope and greater future research efforts are needed here. Use of soil solarisation, manipulation in cultural practices such as change in time of seeding, seed rate, row spacing, tillage, time and dose of fertilizer application of different cropping systems adoption, selection of competitive crop varieties, allelopathic crops and their varieties and intercropping systems can serve as components of habitat management that can be integrated with other methods of weed management. Understanding weed ecology and biology is a prerequisite to effectively use habitat management of weeds and very little work has been done on weed ecology in India (Table 7). Greater efforts are needed to understand weed ecology particularly for the weeds such as weedy rice, *Parthenium* and others that were reported by Indian weed scientists as major weeds of economic significance (Table 5 and 6).

Table 7. Weeds whose ecological aspects were published in the IJWS

Weed	Aspect studied	State of India	References
Ageratum houstonianum	Seed germination	Himachal Pradesh	Angiras and Kumar (1995)
Avena ludoviciana	Germination and emergence	Himachal Pradesh	Singh and Ghosh (1992)
Celosia argentea	Germination and emergence	Asia	Chauhan and Johnson (2007)
Cleome viscosa	Seed viability	Tamil Nadu	Sivasubramaniam and Vijayalakshmi (2012)
Convolvulus arvensis	Germination	Haryana	Kumari *et al.* (2010)
Cuscuta species	Biology and management – review	Madhya Pradesh	Mishra (2009)
Cyperus rotundus	Autecology	Andhra Pradesh	Raju and Reddy (1999)
E. colona, E. glabrescens and *E. crusgalli*	Autecology and biology	Andhra Pradesh	Raju and Reddy (1999a)
Eclipta alba	Germination and growth	Haryana	Dhawan (2007)
Eupatorium adenophorum	Biology and control	Himachal Pradesh	Singh *et al.* (1992)
Euphorbia geniculata	Seed biology	J&K	Araf Mohd. *et al.* (2009)
Ischaemum rugosum	Growth, competition	Punjab	Singh and Singh (1992)
Ischaemum rugosum	Emergence	Punjab	Singh *et al.* (1991)
Lathyrus aphaca	Germination	Haryana	Kumari *et al.* (2010)
Leptochloa chinensis	Germination	Punjab	Aulakh *et al.* (2006)
Malva neglecta	Biology	Punjab	Kaur *et al.* (2008)
Malva parviflora, Rumex dentatus and *R. spinosus*	Emergence	Haryana	Singh and Punia (2008)
Melilotus indica	Germination, emergence and establishment	Haryana	Dhawan (2009)
Oxalis lalifolia	Biology	Karnataka	Pratibha *et al.* (1994)
Oxalis latifolia	Biology and control	Karnataka	Muniyappa *et al.* (1983)
Oxalis latifolia and *Ageratum conyzoides*		Himachal Pradesh	Kumar and Singh (1990)
Parthenium hysterophorus	Ecology	Madhya Pradesh	Tiwari and Bisen (1984)
Parthenium hysterophorus	Ecology and control	Tamil Nadu	Kathiresan (2008)
Parthenium hysterophorus	Germination	Uttar Pradesh	Maurya and Sharma (2010)
Phalaris minor	Germination	Haryana	Chhokar and Malik (1999); Chhokar *et al.* (1999)
Phalaris minor	Emergence	Haryana	Yadav and Singh (2005)
Sidarhombifolia	Dormancy, germination and emergence	Asia	Chauhan and Johnson (2008)
Trianthema	Soil seed bank	Tamil Nadu	Sivasubramaniam (1996)
Trianthema portulacastrum	Dormancy and germination	Tamil Nadu	Umarani and Selvaraj (1994)

Weed use: Many weed species have been utilized by mankind as food, medicinal plants, animal feed, housing material, handicraft material, ornaments, manure, etc. Systematic studies on possible economical use of weeds may be conducted to include weed usage as a component of IWM, where ever feasible.

Herbicides: About three-fourth of the available herbicides in India are used in plantation crops. It has been estimated that herbicides are currently being used on >20 M ha, which constitute about 10% of the total cropped area in the country (Yaduraju *et al.*, 2006). Herbicides are also used in field crops like sugarcane, wheat, rice, maize, chillies, vegetable etc.

They will play a major role as component of IWM, especially when labour wages are increasing, labour availability is decreasing, hard work in fields is not preferred and zero tillage is gaining momentum in India. Research emphasis is needed to identify economic ways of herbicide use to reduce the cost of herbicide without affecting its efficacy and possible ways of integrating herbicides with other weed management practices. Educating farmers and popularizing safe and effective use of herbicides among farming community is essential (Rao *et al.*, 2014). With growing concern and the increased public interest in environmental conservation, efforts to popularize methods of minimizing adverse environmental effects of herbicides and development of herbicide resistance among weeds in India are to be strengthened. Monitoring herbicide residues in environment (soil; air, water) and food chain should be strengthened.

Biotechnological tools: Genetically engineered (GE) varieties with pest management traits became commercially available for major crops in 1996. Despite the rapid increase in adoption of corn, soybean, and cotton GE varieties by farmers of the world and cotton farmers in India, questions persist regarding their economic and environmental impacts, evolution of weed resistance, and consumer acceptance (Rao *et al.*, 2007; Rao and Ladha, 2013).

Herbicide-tolerant (HT) crops have traits that allow them to tolerate more effective herbicides, such as glyphosate, helping adopters to control pervasive weeds more effectively. HT seed-based production programs allow growers to use one product to control a wide range of both broadleaf and grass weeds instead of using several herbicides to achieve adequate weed control. Herbicide-tolerant crops also complement ongoing trends toward post-emergence weed control, adoption of conservation tillage practices, and use of narrow row spacing. The simplicity and flexibility of weed control programs for HT seeds requires less management attention, freeing valuable management time for other activities. In certain countries, adoption of HT crops has enabled farmers to substitute glyphosate for more toxic and persistent herbicides (Fernandez-Cornejo and McBride, 2002). However, over reliance on glyphosate and a reduction in diversity of weed management practices adopted by crop producers have contributed to the evolution of glyphosate resistance in weed species and biotypes. Thus weed resistance may be reducing use of the economic and environmental advantages of HT crop adoption regarding herbicide use.

In India the HT crops are yet to be tested and released. In our survey, majority (83%) of respondent Indian weed scientists were of the opinion that it is very unlikely (33%) and likely (50%) that HT crops have a role to play in future weed management in India (Figure 2). Genetic engineering and HT crops would be an important option in the future efforts towards sustainable weed management and agricultural production in India.

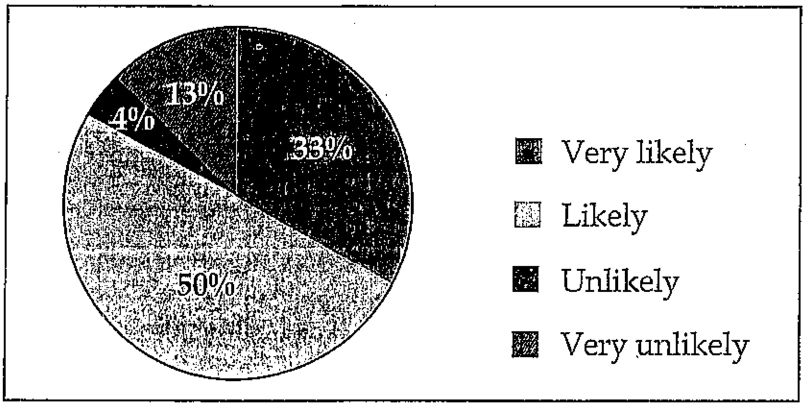

Figure 2. Response of current day Indian weed scientists on the role of genetically modified herbicide tolerant crops in future weed management in India

Climate resilient weed management options

Climate change is now a reality and bound to influence the ecology of weeds with possible implications for their management. It is important to have tools with which to assess likely impacts of climate change on potential future distribution and relative abundance of different weed species.

Fourteen of the world's worst weeds are C_4 plants. Seventy six per cent of the harvested crop area is with C_3 crops. The research carried out so far indicates that: (a) C_3 crops would benefit more from elevated CO_2 than C_4 weeds, losses due to C_4 weeds might decrease; (b) temperature increase /drought in combination with elevated CO_2 trends are not clear; (c) optimal temperatures for growth in C_4 plants are generally higher than optimal temperatures for C_3 plants, but with higher CO_2 the optimum temperature of many C_3 plants also increases; (d) in drought situations C_4 weeds might also have advantages over C_3 crops under elevated CO_2 (Yaduraju and Rao, 2013). However, in India, very little efforts been made to study the impact of climate change on weeds, weed ecology and their response to weed management practices including herbicides. Future research efforts must be intensified on these aspects to evolve climate resilient weed management approaches.

In the survey, 88% of Indian weed scientists have responded that in coming 25 years the change in weed flora is very likely (Figure 3).

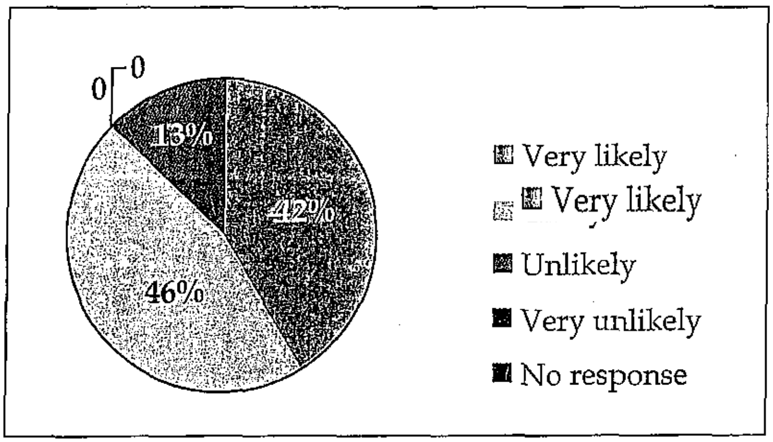

Figure 3. Response of weed scientists on the possibility of change in weed flora in coming 25 years

For managing weeds effectively in future, it is essential to adopt best management practices (BMPs) which include applying multiple herbicides with different modes of action, rotating crops, adopting best cultural weed management practices, planting weed-free seed, scouting fields routinely, cleaning equipment to reduce the transmission of weeds to other fields, and maintaining field borders. BMPs to control weeds may help delay the evolution of herbicide resistance. Location specific BMPs for different agro-ecological regions of India need to be developed and popularized. 88% Indian weed scientists expressed that funding for research is inadequate (Figure 4), any future effort to evolve best weed management options for different agro-ecological zones needs adequate funding.

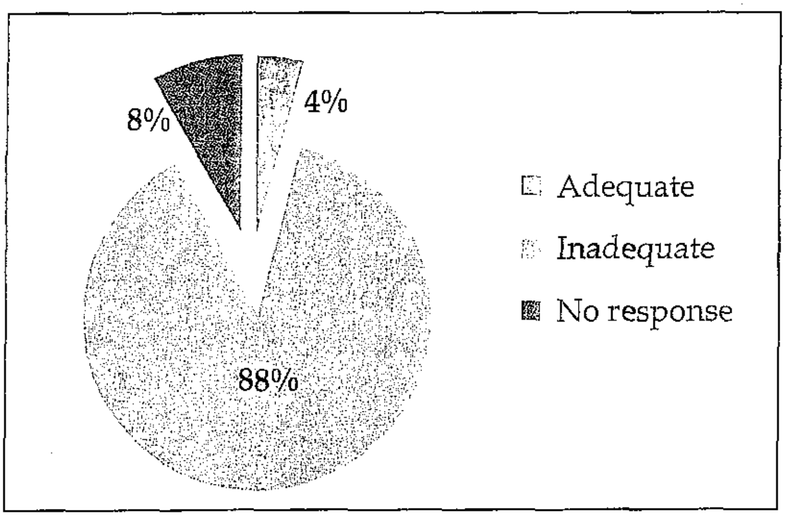

Figure 4. Response of Indian weed scientists on the adequacy of funds to weed science research in India

The present centers of All India Coordinated Research Project on Weed Control in different states of India must be upgraded as respective, "State Directorates of Weed Management Research" in the same pattern as DWSR to effectively evolve location-specific BMP for managing weeds effectively, economically and in an environmentally safe manner.

Acknowledgement

Dr. A.N. Rao is thankful to Government of Karnataka for the financial support. Thanks are due to Dr. A.R. Sharma, who took personal interest in getting the questionnaire answered by staff of DWSR. Dr. A.N. Rao extends his thanks to the weed scientists: Dr. A.R. Sharma, Dr. Bhumesh Kumar, Er. H.S. Bisen, Dr. D.K. Pandey, Dr. V.P. Singh, Mr. Dibakar Ghosh, Dr. Partha Pratim Choudhury, Dr. K.K. Barman, Dr. P.K. Singh, Dr. Meenal Rathore, Dr. C. Kannan, Dr. Raghwendra Singh, Dr. Yogita Gharde, Dr. C. Sarathambal, Dr. P.J. Khankhane, Dr. A.K. Ghosh, Dr. B.D. Patel, Dr. Adikant Pradhan, Prof. R.K. Ghosh, Dr. R.R. Dash, Dr. R.P. Dubey, Dr. A.P. Singh, Dr. J.S. Mishra and Dr. R.K. Singh for their response to the communicated questionnaire.

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