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Fifty Years of Weed Research in India

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A water channel severely infested with water hyacinth; *Phalaris minor* infestation in a wheat field; Invasion of *Mikania micrantha* on trees in forest

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Chapter 1

The historical and future perspective of Weed Science research in India

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Summary

The weeds menace is as old as agriculture. The total actual economic loss, due to weeds in 10 major crops of India, was estimated at US$ 11 billion. Weed management involves integrated efforts to manage weeds in crops to selectively minimize the weed competition so as to enable crops to optimally use resources such as soil fertility, water and sunlight, for attaining the optimal harvestable crop yield. During the last fifty years researchers have worked, evolved weed management technologies and passed on to farmers through different means by which farmers got benefited. However, weeds continue to be a major problem as weeds are dynamic. Hence, continuous efforts are needed to monitor the ever changing weeds and develop suitable weed management technologies for varying ecosystems. It is essential to review the research work so far conducted and plan for future weed management research for continuously keeping the crop weed balance in favor of crops. Hence in this paper a review of the research published in Indian Journal of Weed Science (IJWS) during the last fifty years was analyzed and synthesis is presented in this paper along with future weed management research needs.

Hand weeding and mechanical weed management were the major weed management tools used by the farmers prior to the initiation of research on herbicides in 1948 with 2,4-D in India. In the initial years of Indian weed management research, researchers focused on herbicide based weed management. Of 333 published papers in IJWS during 1980 to 1989, 69% of papers were on herbicides. The research on herbicides alone decreased with the time and the research on integrated weed management (IWM) increased from 9% (during 1980-89) to 36% (2010 to 2018). However, 39% of the papers are still on herbicides alone and comparing herbicides performance with hand weeding and other methods. Rice and wheat are the major crops researched in the past as well as at present. However, during recent years papers appeared on increased number of crops. The research papers published on cropping systems were 6% during 1980-89 and currently 8% only, of the total published. In recent years, a few papers are published on conservation agriculture and herbicide tolerant crops.Weed ecology papers were below 10% of the total papers published in IJWS and there is urgent need for increasing the efforts to understand the weeds through studying the ecology and biology for their better management. A few of the areas of weed management research that needs to be focused include: weeds monitoring; biocontrol; competitive crop cultivars; location specific mechanical tools to integrate with other methods; cropping systems and crop rotations as IWM components; preventive weed management; herbicide resistant weeds; weeds use; parasitic, problematic and aquatic weeds management; herbicides residues; developing simple decision making tools and apps for farmers to manage weeds.

The climate change is a reality now and it is a challenge for the Weed Scientists in India to understand impact of climate change on the weeds and weed management and evolve IWM strategies to manage weeds in the changing climate. Vast opportunity exists for Weed Science researchers to evolve effective, economical and ecologically safe integrated weed management strategies through interdisciplinary research involving disciplines such as biology; ecology; agronomy; physiology; microbiology; genetic engineering; soil science; toxicology; biochemistry; residue chemistry and agricultural engineering.

Introduction

Agriculture is a critical part of the India's economy. India ranks first in the world in net cropland area, with 179.8 Mha (9.6 percent of the global net cropland area) and India's agriculture sector makes up 16 per cent of the country's economy, while accounting for 49 per cent of employment (GOI, 2018). India has attained self sufficiency in food grain production and currently the largest exporter of rice in the world with about 12.7 MMT, valued at $7.7 billion during 2017-18. These achievements of progress in India were possible with the development and adoption of improved production technologies, including weed management technologies (Rao *et al.* 2014, 2015), in India. Inspite of progress made by India in producing adequate food grains, India faces a complex challenge of future food and nutritional security. It was estimated that about 15 per cent of the Indian population is undernourished (FAO 2018). By 2050, the global and Indian populations are projected to cross the 9 billion and 1.7 billion marks, respectively. Hence, India should address the nutrition security along with food securityof increasing global and Indian population in coming years. India is also aiming at doubling farmers' incomes by 2022when yield stagnation was observed in more than a third of India's maize, rice, wheat and soybean areas (Ray *et al.* 2012). Hence, it is essential to develop strategies and technologies based on actual farm needs for alleviating production constraints such as weeds and increasing agricultural production and income of farmers.

Weeds compete with crops for all the inputs and the total actual economic loss, due to weeds in 10 major crops of India, was estimated at US$ 11 billion (Gharde *et al*. 2018). Hence managing weeds is critical in attaing higher productivity of crops with improved resources use efficiency, to meet the food and nutritional demands of increasing Indian population as well as increasing income of the farmers (Rao and Chauhan 2015). Weed management involves integrated efforts to manage weeds in crops to selectively minimize the weed competition so as to enable crops to optimally use resources such as soil fertility, water and sunlight, for attaining the optimal harvestable crop yield (Rao and Nagamani2007, 2010). During the last fifty years researchers have worked, evolved weed management technologies and passed on to farmers through different means (Rao *et al.* 2014a) by which farmers got benefited (Rao *et al.* 2014). However, weeds continue to be a major problem as weeds are dynamic (Rao *et al.* 2018). Hence, continuous efforts are needed to monitor the ever changing weeds in different ecosystems and develop suitable weed management technologies for varying ecosystems.

It is essential to review the research work so far conducted and plan for future weed management research for continuously keeping the crop weed balance in favor of crops in India. Hence, in this paper review was done of the published Weed Science research during the last fifty years in India; the synthesized analysis of Indian Weed Science research during the past fifty years is presented and future weed management research needs of India are listed based.

Methodology

To synthesize the Weed Science research in India across years, research published by the Indian Weed Scientists, mostly, in the Indian Journal of Weed Science (IJWS) was considered. In addition, the research publications by Indian Weed Scientists in other journals were also referred in the synthesis, at appropriate places.We have considered:

A. For the past:

(i) **The beginning years**: IJWS publications from the year 1969 to 1979

(ii) **1980s**: IJWS publications from the year 1980 to 1989

(iii) **1990s**: IJWS publications from the year 1990 to 1999

(iv) **2000s**: IJWS publications from the year 2000 to 2009 and

B. for current decade: IJWS publications from the year 2010 to 2018 Volume : 50, Issue : 1.

The names of universities were changed over time and new universities and Institutions were established from time to time. These were considered while reviewing and recent names were used.

Weed Science research organizational setup in India

The Indian programs on agricultural research, higher education and frontline extension are spearheaded by the Indian Council of Agricultural Research (ICAR), since its inception in 1929 through a network of Research Institutes, Agricultural Universities (AUs), All India Coordinated Research Projects and Krishi Vigyan Kendras (KVKs). However the systematic scientific research work on weed management in India was initiated by ICAR in 1952 with the inception of All India Coordinated Research Scheme on major crops like rice, wheat and sugarcane in Tamil Nadu, Bose Research Institute, Calcutta, Punjab, Maharashtra, Andhra Pradesh, Rajasthan, Kerala, Assam, Madhya Pradesh, U.P. and J & K. (Mani 1977). In the same year (1952), the weed control section was started in the Division of Agronomy at the Indian Institute of Agriculture Sciences (IARI), New Delhi, India. In 1960, the first Agricultural University was started at Pantnagar, and later several agricultural universities were established across the country, in which currently Weed Science is a part of curriculum and Weed Science research is being carried on. The Government of India desired to set up a “Central Weed Control Laboratory” in Lucknow. Later, in view of some other constraints, a “Division of Weed Ecology and Control” was added to the India Grassland and Fodder Research Institute, Jhansi, in December 1967 (Datta 1977). It was envisaged that this Division would

initiate integrated research in Weed Science for the entire country (Datta 1977a). All India Coordinated Research Project on Weed Control was initiated in 1978 with funding from USDA-PL480 project funds. Initially, started with six centers and later increased to current 23 centers, located in different States of India and AUs. National Research Centre for Weed Science was established in India during 1989 at Jabalpur, Madhya Pradesh which was upgraded as Directorate of Weed Science Research in 2009 and renamed as Directorate of Weed Research (DWR) in 2014. Since its inception, the institute is engaged in research on weeds and weed management. It also coordinates location-specific weed management research carried out at coordinating units located at different parts of the country. DWR has been successfully contributing in conducting and coordinating research on weeds and weed management and in enhancing crop productivity and sustainability in India.

To develop effective and economic weed management technologies for the major crops and cropping systems of the semi-arid tropics, Weed Science research was carried out at ICRISAT, Hyderabad, India (Shetty and Krantz 1980) with emphasis on surveys, ecological studies, cultural weed control (Rao 1980) and herbicide screening with a view to improving productivity of sorghum, pearl millet, chickpea, pigeon pea and groundnut. However, the Weed Science research at ICRISAT was, unfortunately, discontinued. The small and marginal farmers of Semi-Arid Tropics farming community of the world, in addition to India, will be benefitted if ICRISAT reinitiates the Weed Science research.

Indian Society of Weed Science (ISWS) and Indian Journal of Weed Science (IJWS)

India was the first country to organize a Weed Science Society in Asia. "The Indian Society of Weed Science" was initiated in 1968 "to advance the development of Weed Science and weed control in India" by the coordinated efforts of the educational, research, and industrial sector of the country. Except for a brief period at Bangalore (1980-1992), the headquarters of ISWS was at Hissar until 2005. Later ISWS headquarters was permanently shifted to DWR, Jabalpur in 2006. Drs. M.K. Moolani, H.R. Arakari, H.S. Gill, V.S. Mani, K. Krishnamurthy, V.M. Bhan and others took active part and contributed towards the early development of Weed Science in India. ISWS has organized 8th Asian Pacific Weed Science Society (APWSS) conference at Bangalore in 1981 and the Silver Jubilee 25th APWSS Conference at Hyderabad, India in 2015.

In 1969, the Indian Journal of Weed Science (IJWS) was started as the technical publication of the Society to "chronicle the work of the members" so that the new weed control technology could be utilized in agriculture. IJWS is continuing successfully till to date with its Volume 50 in 2018. Drs. MK Moolani, HS Gill, VS Mani, VM Bhan and KC Gautam were the authors with higher number of papers published in IJWS in the beginning years (1969 to 1979). The first published paper (Shivaraj *et al.* 1969) in IJWS was on *Cynodon dactylon*, one of the world's worst weed. Herbicides in combination with mechanical method (plowing) were found effective in managing *C. dactylon*. Papers from 58, 69, 67, 56 and 140

institutions contributed to papers in IJWS during 1969 to 1979; 1980s; 1990s; 2000s and 2010s, respectively. Thus as the years pass by, there was an increase in the number of institutions participating in Weed Science research and publishing the results of research. A few papers were published in IJWS by the Weed Scientists from other countries like USA, Pakistan, Nepal, Australia, Philippines, Iran, Tunisia, Iraq, Libya, Saudi Arabia, Nigeria. Among different Universities, CCS HAU, Haryana in 1969 to 1980; 1990s and 2000s and PAU, Punjab during 1980s and current decade (2010 to 2018) were the institutions with highest number of publications in the IJWS (**Table 1**).

Table 1. The top ten institutions* that contributed more research papers to IJWS across years

Ranking (1 = Highest contributed papers)	The beginning years (1969 to 1980)	1980s	1990s	2000s	Current decade (2010 to 2018)
1	CCSHAU	PAU	CCSHAU	CCSHAU	PAU
2	PAU	CCSHAU	CSKHPKV	PAU	GBPUAT
3	IARI	GBPUAT	PAU	GBPUAT	CCSHAU
4	UAS	CSKHPKV	JNKVV	CSKHPKV	DWR
5	OUAT	JNKVV	UAS	IARI	ANGRAU
6	GBPUAT	UAS	GBPUAT	ANGRAU	TNAU
7	BHU	ANGRAU	ANGRAU	AUT	KAU, CSKHPKV
8	TNAU	TNAU	TNAU	BHU	SKUAST
9	IGFRI, ANGRAU, MPUAT	GAU	IARI	DWR	JNKVV
10	JNKVV, RRL, CSAUAT	IARI	BHU	JNKVV	BHU, MPUAT

ANGRAU = Acharya N. G. Ranga Agricultural University, Andhra Pradesh; **AUT**= Annamalai University, Annamalai Nagar, Tamil Nadu**; BHU** = Banaras Hindu University, Varanasi, Uttar Pradesh; **CCSHAU** = **CCS** Haryana Agricultural University, Hissar, Haryana; **CSKHPKV** = **CSK** Himachal Pradesh Krishi Vishvavidyalaya, Palampur, Himachal Pradesh; **CSAUAT** = C. S. Azad University of Agriculture & Technology, Kanpur, Uttar Pradesh; **DWR** = Directorate of Weed Research, Jabalpur, Madhya Pradesh; **GAU** = Gujarat Agricultural University; Anand, Gujarat; **GBPUAT** = G.B. Pant University of Agriculture & Technology, Pantnagar, Uttarakhand; **IARI** = Indian Agricultural Research Institute, New De1hi; **IGFRI** = Indian Grassland & Fodder Research Institute, Jhansi, Uttar Pradesh; **JNKVV** = Jawaharlal Nehru Krishi Vishwa Vidyalaya, Jabalpur, Madhya Pradesh; **KAU** = Kerala Agricultural University, Kerala; **MPUAT** = Maharana Pratap University of Agriculture & Technology, Udaipur, Rajastan; **OUAT** = Orissa University of Agriculture & Technology, Bhuvaneswar, Orissa; **PAU**= Punjab Agricultural University, Ludhiana, Punjab; **RRL** = Regional Research Lab, Jammu & Kashmir; **SKUAST** = Sher-e-Kashmir University of Agricultural Sciences and Technology, Jammu, Jammu & Kashmir; **TNAU** = Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu; **UAS** = University of Agricultural Sciences, Bangalore, Karnataka (more than one institution at a place indicates publication of similar number of papers by them)

Weed Science Research in India across years

i. The beginning years (1969-1979)

In the late 1960s, Indian farmers began using high-yielding variety (HYV) seeds, launching the green revolution which saw dramatic increase in crop productivity and production.The Challenge for the Weed Scientists in India at that time was to reduce the reported (Mehta and Joshi 1965) losses of about 10% caused by weeds to principle agricultural products amount to approximately Rs. 4200 million per annum in 1965 and Rs. 15,500 million per annum in 1977 (Joshi 1977). Abrief account of the losses caused by weeds and of the progress of weed control in India from 1948-72 was summarized by Joshi (1973, 1974).

In 1948, 2,4- D was introduced in India. Since then a number of chemicals have been imported and tested. Some of them were quite effective in controlling certain weeds (Arakeri 1977). Hence, in the beginning years, research was mainly herbicides based (67%), as the Weed Scientists of India have seen an opportunity in using herbicides for selectively managing weeds in India. Weed ecology (14%) and integrated weed management (IWM) (9%) publications were less (**Table 2**). Rice, maize, potato, groundnut were major crops researched (**Table 3**). Critical period of crop weed competition for groundnut (Bhan *et al.* 1971), tobacco (Moolani and Katyal 1972), rice (Shetty and Gill 1974), maize (Sandhu and Gill 1973) and other crops were published during this period. PAU, HAU, UAS were major institutions that published most in IJWS during this period. There were publications from USA (5%) too. The potentiality of weeds (*Argemone mexicana* L.) use for improving rice yield in saline alkali soils was identified (Misra *et al.* 1972). Misra and Lenka (1972) published first paper on conservation agriculture (CA) in IJWS while reporting that paraquat at 1.2 kg/ha can substitute puddling in rice, without any yield reduction and with saving in water. Differential response of maize varieties to herbicides (herbicide tolerance) was also brought to light during this period (Krishnamurthy *et al.* 1973). Weed control in the horticultural crops (strawberries, raspberries, grapevines, apples, pears, peaches, cherries, plums, mandarins, lemons, bananas, pineapples, sapodillas, guavas and pawpaws was reviewed (Leela 1976).

From 1955 to 1975, ecology teaching and research on Weed Science expanded at the B.H.U. (Banaras Hindu University) (under the leadership of Prof. R. Mishra) and other Universities like Gorakhpur University; Punjab University; Vikram University; Saugar University; Saurashtra University; BITS, Pilani; Kasmir University among others (Ambasht 1977). Autecological research was focused on weeds and some of the weeds which autecology was studied in Botany Department, BHU were: *Achyranthes aspera*, *Achyranthes bidentate*, *Alhagi camelorum*, *Alysicarpus monilifer*, *Argemone mexicana*, *Asphodelus tenuifolius*, *Bacopa monnieri*, *Biophytum sensitivum*, *Boerhavia diffusa*, *Chrozophora rottleri*, *Croton sparsiflorus*, *Desmodium triflorum*, *Eichhornia crassipes*, *Euphorbia dracanculais*, *Euphorbia hirta*, *Euphorbia thymifolia*, *Gomphrena celosioides*, *Melilotus indicus*, *Nepeta ruderalis*, *Peristrophe bicalyculata*, *Rauvolfia tetraphylla*, *Rauvolfia serpentina*, *Rumex dentatus*, *Salvia plebeia*,

Table 2. Broad areas of research of the publications in Indian Journal of Weed science across years

Research area	Percentage of published papers in IJWS				
	The Beginning years (1969 to 1979)	1980 to 1989	1990 to 1999	2000 to 2009	Recent years (2010 to 2018)
Herbicides	67	69	57	53	41
IWM	9	9	20	30	36
Ecology	14	16	15	11	8
Cultural	1	2	3	3	3
Genomics	0	0	0	1	0
Physiology	0	1	1	1	1
Allelopathy	1	3	1	1	1
Biocontrol	1	1	< 1%	1	2
Weeds use	1	0	< 1%	< 1%	3
Economics	2	0	1	< 1%	< 1%
Review	4	1	1	< 1%	6
Modelling	0	0	0	1	< 1%
Decision support	0	0	0	< 1%	0
Total publications referred by author	213	333	560	424	706

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

Crops	Percentage of published papers in IJWS			
	1969 to 1979	1990 to 1999	2000 to 2009	2010 to 2018
Rice	14	20	26	27
Wheat	8	14	20	11
Cropping systems	5	7	9	8
Maize	9	3	3	5
Soybean	4	7	5	4
Mung bean	2	2	< 1%	3
Blackgram	0	< 1%-	2	4
Ground nut	7	3	< 1%	< 1%
Potato	5	1	1	< 1%
Tomato	0	-	< 1%	< 1%
Mustard	-	1	1	1
Sorghum	5	< 1%	-	1
Sugarcane	4	1	2	1
Chickpea	1	1	3	< 1%
Finger Millet	1	< 1%	-	1
Onion	2	1	2	1
Cotton	5	2	2	3

Scoparia dulcis, *Setaria glauca*, *Solanum nigrum*, *Solanum surattense*, *Spirodela polyrhiza*, *Tribulus terrestris*, *Trichodesma amplexicaula* and *Xanthium strumarium*. Weed ecological information is valuable as it provides insight on the weakest phase in the life cycle when weeds could be could be easily controlled. A PL 480 research project with USAID was undertaken (1964-1969) on

the ecology of ten common noxious weeds including: *Chenopodium album*, *Cyperus rotundus*, *Eichhornia crassipes*, *Anagallis arvensis*, *Spirodela polyrrhiza*, *Portulaca oleracea*, *Cassia tora*, *Eleusine india*, *Amaranthus spinosus* and *Eleocharis palustris* (Misra 1969). Ecological research on weeds in most cases is confined to ecological life cycle, mechanism of perennation and persist appearance in certain habits (Ambasht, 1977). Das and Raghavendra (1973) screened weed flora for the occurrence of C_4 photosynthesis. Based on the studies on influence of biological factors such as crop species, crop variety, plant population, crop geometry, relative proportions of the crops in the mixture and cropping pattern on the crop-weed balance, Rao and Shetty (1976) advocated that these should be taken into account when evolving integrated weed management systems.

ii. 1980s

During 1980 to 1989, major emphasis continued to be on utilization of herbicides (such as alachlor, atrazine, bifenox, butachlor, 2,4-D, dicamba, diquat, fluchloralin, fluroxypyr, glyphosate, methabenzthiazuron, metoxuron, nitrofen, paraquat, propanil, simazine, terbutryne, and sethoxydim) for weed management. Of 333 papers published in IJWS, 69% of papers were on herbicides and on herbicide related aspects of weed science (**Table 2**). 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 cop cultivars to herbicides were certain aspects of herbicide based studies. Mechanical weeders like hand-hoe, blade-hoe and paddy weeder were found equally effective in managing weeds and were found more economical than hand weeding (Singh *et al.* 1976). Only 9% of research papers were on integrated weed management (IWM) and all those were also herbicide based. The herbicides were reported to be more economical than mechanical methods in managing problematic weed like Parthenium (Muniyappa *et al.* 1980).

Considerable number of research papers published on weed ecology (16%) during that period. Weed ecological research was focused on assessing critical period of crop weed competition (rice under different methods of establishment, brinjal, finger millet, groundnut, maize, 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). Research results were published related to: critical stages of weed competition in drill-seeded rice (Bhan *et al.* 1980); weed management in dry direct-seeded rice (Kaushik and Mani 1980); physiological studies on perennial weeds that indicated that could thus enhance the effectiveness of 2,4-D in their control with lowering the pH and addition of sucrose and detergent (Veerabhadraiah *et al.* 1980); cytogenetic aspects of problematic weeds which indicated that polyploidy, agamospermy, vegetative reproduction and genic heterozygosity of *Eupatorium adenophorum* (2n = 51), *E. riparium* (2n = 51) and *E. odoratum* (2n = 60) confer an advantage in competition (Khonglam and Singh 1980); enhanced rate of proliferation of due to

mechanical disturbance (Divakaran *et al.*, 1980); ecology of *Parthenium hysterophorus* (Tiwari and Bisen1984); influence of herbicides on soil microflora (Mukhopadhyay, 1980); integrated Striga control in sorghum (Choudhari *et al.* 1980); biology and control of *Oxalis latifolia* were reported (Muniyappa *et al.* 1983). Allelopathy studies were mainly focused on effects weed leachates on the germination of crop seeds. The concept of utilizing competitive crops for managing *Cyperus rotundus* (Kondap *et al.* 1982) and other weeds (Kondap *et al.* 1983) was put forward.

iii) 1990s (1990 to 1999)

During this period, interest on integrated weed management increased significantly as indicated by significant increase in research papers published on integrated weed management and slight decrease in papers on herbicides alone. During this period, resistance of isoproturon against *Phalaris minor* has 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 evolution of resistance in this weed. By 1993, the resistance affected area ranged between 0.8 and 1.0 million hectares 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 for 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 appeared during this period also 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 rice-wheat sequence (Brar *et al.* 1998).

iv) 2000s (2000 to 2009)

In this period, the research papers on herbicides evaluation in different crops and weed ecology studies decreased than the past period and those of IWM increased considerably. Increase was also observed of reports of studies on cultural weed management. Use of bio-technology tools for understanding molecular diversity of *Phalaris minor* populations in wheat (Dhawan *et al.*2008) and mechanism of resistance of Phalaris to isoproturn (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) was assessed. 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 smother crops in sugarcane (Rana *et al.* 2004); soil solarisation alone in sunflower (Chandrakwnar *et al.* 2002) and soil solarisation along with crop husbandry practices like tillage with and without irrigation; wheat straw incorporation (Das and Yaduraju 2008); irrigation and nitrogen in wheat (Das and Yaduraju 2007), were evaluated for their weed management efficacy. In upland crops, farmers use the animal drawn blade harrow by males for managing inter row weeds and hand weeding for intra row weeds by hired or family female labour, even now. The mechanical weeders (rotary weeder) usage was observed to saves nearly 57% labour compared with hand weeding (Subudhi 2004). The cost of weeding for female labours could be reduced by 4.85 times and 5.2 times and male labour by 6.6 times and 7.6 times, by using rotary weeder and conoweeder respectively, compared to hand weeding (Remesan *et al.* 2007). Climate change is confirmed during this period. The enhanced growth, biomass production and increased flower production of *Parthenium hysterophorus* (C_3) and *Amaranthus viridis* (C_4) was observed under elevated CO_2 (Naidu and Paroha 2008). Evaluation of varieties in rice (Dhawan *et al.* 2003); hybrids and fertilizers in rice (Kumar *et al.* 2000) and varieties and herbicides in wheat (Verma *et al.* 2007) were reported. Publications on integrated weed management included combination of herbicides with manual weeding (Singh and Singh 2004), trash burning (Singh and Rana 2006), intercultivation (Subramanian and James 2006), tillage (Sarma and Gautam 2006), rotation (Singh, 2006), and several other combinations in several crops. Herbicide studies involved herbicides evaluation in different crops, their degradation (Amarjeet *et al.* 2003), weeds resistance (Mahajan and Brar 2001), and herbicide residue effects on crops grown in rotation (Yadav *et al.* 2004). The importance of decision making tools was brought to light (Babu *et al.* 2000).

B. Current decade (2010 to 2018)

During the current decade, 432 research papers were published in IJWS (including supplementary volumes). Herbicide based weed management research publications continued to predominate (41%). But, integrated weed management studies published during this period increased from 30 to 36%. Publications on weeds use increased and those of weed ecology decreased. Publications on rice crop continued to be high during this period. Publications on blackgram and greengram increased which indicates the interest in using these short duration legumes rice crops in rice fallows for crop intensification and increasing the farmers income. Rice, wheat, maize, blackgram, soybean, greengram, cotton, groundnut, chickpea, lentil, onion, sesame, turmeric, barley, finger millet, wheat, cluster bean, mustard, sorghum, sugarcane, groundnut, pigeonpea, chrysanthemum, bottle gourd, castor, chilli, fenugreek, french bean and garlic were the crops with more than 1% of publications.Reviews on aspects such as integrated weed management (Rao and Nagamani 2010); conservation agriculture and weed management (Bhullar *et al.* 2016); aquatic weeds problems and management in India

(Sushilkumar 2011); impact of climate change on weeds and weed management (Singh *et al.* 2011), biology and control measures of *Orobanche* (Punia 2014); weed management approaches for weed management in direct-seeded rice (Rao *et al.* 2007); dry-seeded rice (Chauhan and Yadav 2013), finger millet (Rao *et al.* 2015b); zero tillage in weed management (Singh *et al.* 2010); cost of *Parthenium* and its management (Sushilkumar and Varshney 2010); paradigm shifts in weed science and challenges they pose to India and Weed Scientists (Rao 2014); weedy rice problem and management (Abraham and Nimmy Jose 2015); understanding crop-weed-fertilizer-water interactions and their implications for weed management in agricultural systems (Kaur *et al.* 2018); aquatic weeds as the feedstock for sustainable bioenergy production (Kaur *et al.* 2018a) and smart weed management for doubling income (Yaduraju and Misra 2018) and other aspects were published.

Several review papers from USA which were presented at 25th APWSS conference on herbicide resistant weeds were published in IJWS, 2016, Vol 48, issue 2. 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 (rotary weeder use) for managing weeds in rice (Deshmukh 2012); use of black polythene mulch (25 µm thickness UV resistant) for managing weeds in maize (Ram *et al.* 2017); reported reduced efficacy of clodinafop on *Phalaris minor* by >30% farmers in spite of using 1.5 times of field dose (Bhullar *et al.* 2014); screening rice genotypes against weeds in direct-seeded rice (Walia *et al.* 2010); antagonistic effect of fenoxaprop on metsulfuron when used in mixture and reduced herbicides efficacy (Gharde *et al.* 2017); a weed manager app for mobile (Singh *et al.* 2017a), weed management in Bt cotton (Ramachandra *et al.*, 2016); efficacy of readymade blends of sulfosulfuron + metsulfuron (30 g/ha) and mesosulfuron + iodosulfuron (21.6 g/ha) in managing weeds in sugarcane-wheat intercropping system (Kumar *et al.* 2017); 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). Harnessing of CA, using happy seeder and herbicides, with rice-wheat-greengram cropping system in black-cotton soils was envisaged (Singh *et al.* 2017) to facilitate timely sowing in standing stubbles, minimize weed infestation, lower cost of production, improve fertilizer/water-use efficiency and improve soil health.

The more detailed synthesis of weeds predominant in India in different ecosystems, current weed management research and technologies developed and adopted by farmers in India were presented in other publications (Rao and Chauhan 2015, Rao *et al.* 2018).

Adoption of the technology developed by Weed Science research by farmers in India

The Weed Science research done and the technology developed varied across years in India and so does the technology adoption by the farmers. The hand weeding, which was considered cheaper and used by majority of the farmers in India until 1990's, is a non-economic method during 2010s, when used alone, as the labour wages increased due to their scarcity and increased labour wages (Rao and Ladha 2013). The daily average wage rates (DAWR) of India have increased five folds in 2016 compared to 1999 (**Figure 1**). Rice and wheat crops are the major crops of herbicide use in India. Area under zero-tillage is increasing in India (DWR 2015), leading to increased use of non-selective herbicides (glyphosate, glufosinate and paraquat) as a pre-plant application (Choudhury *et al.* 2016). Herbicides are currently the largest growing market segment in the market of plant protection chemicals. The herbicide consumption in India stands at ` 45.58 billion 2015-16 and is expected t grow at a CAGR of 15% over the next five years (ICFA 2017). The labor wage rates increase year after year (**Figure 1**) explains the increasing use of herbicides (**Figure 2**) and growth in herbicide market across years in India (**Figure 3**). Herbicide based research carried out in India, helped farmers in using the herbicides, that were found effective by researchers across the years, for managing weeds in 2010s.

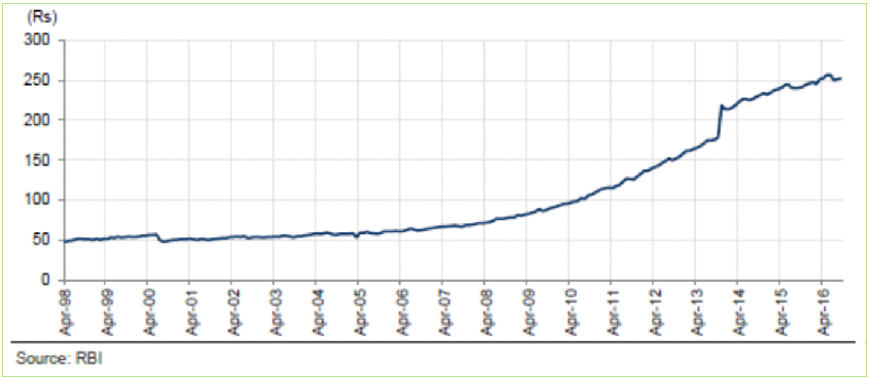

Figure 1. The real daily wage rates in India across years

On-farm farmers' participatory evaluation revealed that the resource-rich, medium and large farmers preferred the highest yielding option (herbicide fb hand weeding), while the resource-poor, small and marginal farmers preferred the less management- and resource-intensive weed control method running traditional country plough between crop rows at 14-16 days after germination (DAG) followed by hand-picking of leftover weeds at 25-30 DAG (Behera *et al.* 1997).These observations hold true even today. Integrated weed management involving the use of power weeder in row transplanted rice or direct-seeded rice in combination with herbicides was found to be economical by farmers (Rao, unpublished data). A survey on the adoption of IWM by farmers revealed that majority of the respondent farmers had medium extent of adoption of IWM practices with

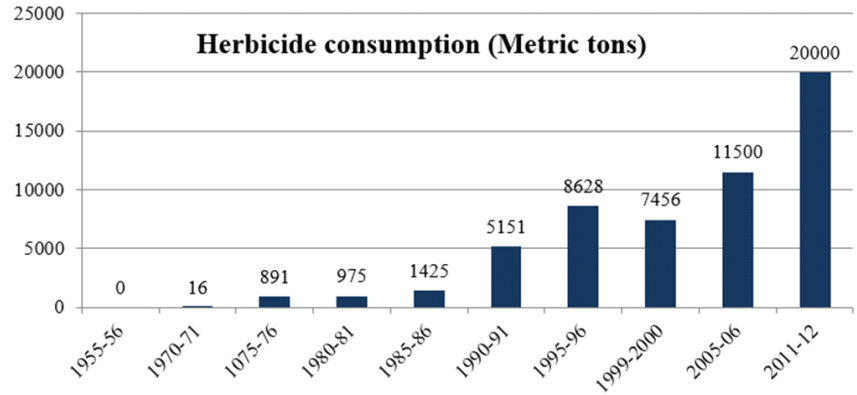

Figure 2. Herbicide consumption across yeas in India from 1955 to 2012 (Source: DWR 2015)

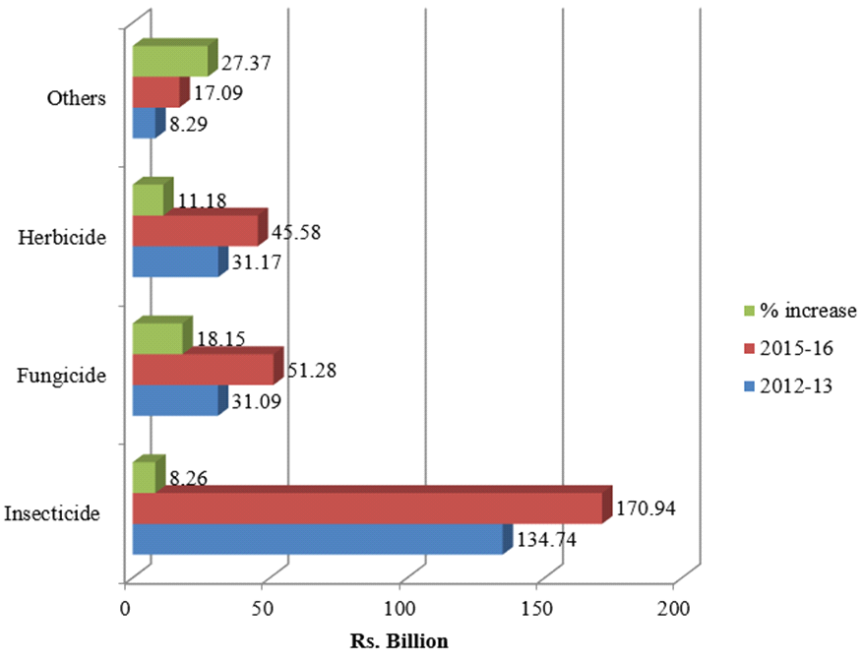

Figure 3. Plant protection market of India showing 11.18% increase in herbicide market in 2015-16 compared to 2012-13 (Data Source: FICCI, TATA Strategic management consultants)

reference to rice (56%), soybean (49%), greengram (50%) and wheat (55%) and a positive and significant correlation was observed between level of adoption of IWM practices with other variables, *viz.* age, education, farm size, training, extension contact, mass media exposure, input availability and innovativeness were noticed (Singh *et al.* 2018). At any point of time, the farmers' adopt weed

control practices that are adequate to obtain optimum yields under his current farming systems and socio-economic conditions.The cost of cultivation of crops and the weed management became major limiting factors for the farmers to realise higher system productivity and net returns.The herbicide use is more by farmers who put more effort to crops on more productive irrigated areas and to crops with high values per unit area. The weed management technology developed by IWM research, which is being increased during recent years, will be of help to farming community in coming years for managing weeds effectively and preventing herbicide resistant weeds predominance. Weed management research should be focused on and associated with research efforts aimed at achieving optimal net returns to farmers keeping in view of overall changes in the farming and farming systems.

Publications on Weed Science in India

During the earlier years, books on weeds were published on weed flora, (Sastry *et al.* 1980), Striga (Hosmani 1978), *Parthenium* (Krishnamurthy *et al.* 1977). A weed Atlas for major weeds in major crops in 435 districts spread across 19 states of the country was published by DWR. 826 weeds species were reported to cause yield losses in India of which 80 and 198 were considered very serious and serious weeds, respectively ((NRCWS 2007)). Major weed species of India in different situations were given in the vision document of DWR (DWR 2015).'Principles of Weed Science' is most read book of Weed Science in India with its second edition published (Rao 2017). ISWS together with APWSS has published books on weed management (Rao *et al.* 2015, 2015a, Rao and Yaduraju 2015, Rao and Matsumoto 2017). DWR has many useful publications (http://www.dwr.org.in/Research%20and%20Publication.aspx), since its inception. Several Weed Scientists from different AUs have published books on Weed Science and space constraint prevented in listing all of them here.

Future outlook based on history of Indian Weed Science

Significant advancement has been achieved in weed management since research began in India and improved weed management methods have allowed farmers to attain increases in crops productivity. In spite of this, the weeds menace is increasing in cropped and non-cropped lands of India, as the weeds are dynamic. This may be attributed partly to weeds response to high-input and intensive cropping systems adoption with lesser adoption of traditional practices like intercropping, mulching and crop rotations; herbicide resistance development in weeds like *Phalaris minor*; changing climate and occurrence and predominance of more aggressive and adopted weed species; growing menace of : i) weedy rice in many states, particularly where direct-seeding of rice is adopted; ii) *Orobanche* in mustard growing areas; iii) alien weeds (*Parthenium hysterophorus*, *Lantana camara*, *Ageratum conyzoides*, *Chromolaena odorata* and *Mikania micrantha*) invasion in many states of India. Hence, continuous weeds monitoring and weed management strategies and technologies development is needed to reduce the

adverse effects weeds on farm productivity and maintain positive ecological balance. Indian Weed Science research focus in future should be more on:

i. Better understanding of weeds: Management of weeds to limit their impact on crops productivity requires an understanding of the weed's life cycle, weed's growth habits, its susceptible growth stages, and its reproductive abilities. Hence intensification is needed on basic research pertaining to weed ecology and biology.The traditional universities with strong basic sciences foundation also be encouraged to undertake basic Weed Science research in understanding ecology and biology of weeds for utilizing that knowledge in managing weeds.

ii. Continuous monitoring of weed dynamics: The weeds are dynamic and the weeds must be monitored continuously, systematically to assess the emerging weeds of concern and manage them in time.

iii. Conservation agriculture (CA) and perennial weeds management: In recent years, the CA is given importance for sustainable crop production. A shift in weed population annual to perennial weed dominance within conservation tillage systems is expected due to less soil disturbance. Perennial weeds are more difficult to manage. Basic and applied research is needed to evolve perennial weed management strategies in CA systems.

iv. Herbicide resistant weeds monitoring and prevention: The herbicide use is increasing in India due to labor non availability and cost. The possibility of development of herbicide resistant weeds is higher under increasing herbicide use in India. Herbicide resistant weeds became a great concern in the global agricultural arena in recent decades and their management has become important for sustainable agriculture. To prevent herbicide resistant weeds predominance and spread in India, it is essential to take all preventive measures to delay the development of herbicide resistant weeds and direct part of Weed Science research to evolve resistance management practices while continuously monitoring for the herbicide resistant weeds to effectively manage them so that agricultural systems can remain profitable and sustainable.

v. Climate resilient integrated weed management strategies and technologies development: The impact of climate change on the weeds and management is to be quantified. The climate resilient weed management strategies and technologies that are effective and economical are to be developed and popularized from time to time in different ecosystems.

vi. Mechanization of weed management: Agriculture engineers need to play a critical role in developing mechanical tools/power weeders that suits to the needs of Indian small and marginal farmers. Weed-sensing detect spray system are to be developed indigenously for optimizing herbicide use by the farmers.

vii. Practical use of allelopathy and biocontrol: Allelopathy is still in research phase in India. Indian Weed Science research efforts must be directed to develop allelopathic crop varieties to use them as component of IWM, identify the

allelopathic compounds and discover, synthesize, formulate and register commercial allelochemical herbicide products. Systematic research on developing practical methods for biological control of weeds is to be intensified.

viii. Herbicide residue management: It is essential to monitor and evolve effective methods to prevent possible herbicide residues accumulation in soil, water and food chain due to increasing herbicide use in India.

ix. Invasive weeds management: With the globalization, invasive weeds menace may increase, if adequate measures are not taken. Rigorous monitoring through extensive surveys to detect invasive weeds, taking strict quarantine measures, evolving effective management strategies for containing the entrance and spread and preventing the losses caused by the invasive exotic weeds (eg: *Ambrosia trifida*, *Cenchrus tribuloides*, *Cynoglossum officinale*, *Chromolaena odorata*, *Eichhornia crassipes*, *Lantana camara*, *Parthenium hysterophorus*, *Mikania micrantha*, *Phalaris minor*, *Savlinia molesta*, *Solanum carolinense*, *Viola arvensis* and others) are essential.

x. Adopting cautious approach on herbicide tolerant crops: Herbicide tolerant crops cultivation requires strong stewardship, including the rotation of crops and herbicides with different modes of action, use of certified seeds, and avoiding growing herbicide tolerant crop in the same field during consecutive seasons, to mitigate the development of resistant weeds. Keeping in view of the recent experiences of USA related to dicamba and 2,4-D herbicide tolerant crop varieties adoption of Malaysia related to herbicide tolerant rice varieties and increase in herbicide tolerant weedy rice menace, India should adopt cautious approach, as the government of India is adopting, in developing and using herbicide tolerant crop varieties and their use. The technology is adoptable but only with adoption of all stewardship strategies and measures by all concerned and especially the farmers. Educating the farming community on safe and proper use of knowledge intensive technology is a prerequisite for their adoption.

xi. International collaborative efforts needed: With global interactions increasing, the boundaries of weeds are getting minimized and many weeds are becoming global weeds through varying dissemination methods and causing menace across the globe. International collaborative efforts by Indian Weed Scientists will help in evolving the management methods for minimizing their spread and impact.

xii. International Institutions need to play in major role strategic research on weeds and weed management: CGIAR institutions like IRRI, ICRISAT, CIMMYT have a bigger role to play in doing strategic research on basic and applied aspects of weeds and weed management by collaborating with Indian Research Institutions, DWR, Agricultural and traditional Universities in India.

Herbicides will continue to play a critical role in weed management in future too. As the herbicide use increases, improper use and lack of education about proper use of available herbicides on farms will result in the progression toward greater incidence of herbicide resistant weeds in India too. Hence the herbicide

industry and weed scientists have to play a greater role in educating the farmers and the extension staff on judicious and sustainable use of herbicides.There is a need for greater emphasis on developing multidisciplinary approaches through IWM systems with optimized combinations of physical, chemical, biological and ecological methods. Weed Scientists in India must focus more on evolving and extending to farmers the integrated weed management strategies that manage weeds effectively and economically in an ecologically sustainable manner.

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