ISWS Golden Jubilee International Conference

Jabalpur, India

Fifty Years of Weed Research in India

Editors

Sushil Kumar

J.S. Mishra

Supported by

NABARD

Indian Society of Weed Science
ICAR - Directorate of Weed Research (DWR)
Maharajpur, Jabalpur - 482004, Madhya Pradesh, India

Editors:

Dr. Sushilkumar
Principal Scientist
ICAR-Directorate of Weed Research
&
Secretary, Indian Society of Weed Science
Jabalpur, Madhya Pradesh 482 004
Email: sknrcws@gmail.com

Dr. J.S. Mishra
Principal Scientist
Division of Crop Research,
ICAR Research Complex for Eastern Region,
Bihar Veterinary College, Patna - 800014 (Bihar)
&
Chief Editor - Indian Journal of Weed Science
Email: jsmishra31@gmail.com

Correct citation of book:

Sushilkumar and Mishra JS (Eds.). 2018. *Fifty Years of Weed Science Research in India.* Indian Society of Weed Science, Jabalpur, 349 p.

Correct citation of chapter in book:

Author(s). 2018. Title of chapter. Pp. 00-00. In: *Fifty Years of Weed Science Research in India.* (Eds. Sushilkumar and Mishra JS). Indian Society of Weeds Science, Jabalpur

ISBN - 978-81-931978-7-5

9 788193 197875

Publisher:
Indian Society of Weed Science (ISWS),
ICAR-Directorate of Weed Research (DWR)
Maharajpur, Jabalpur - 482 004 India; http://www.isws.org.in

***Cover Design*:**
Gyanendra Pratap Singh

***Printed at*:**
Amrit Offset Press
Jabalpur (M.P.), India. Ph.- 0761-2413943

Cover page Photographs (Left to Right)

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

ISWS Golden Jubilee
International Conference
Jabalpur, India

Fifty Years of Weed Research in India

50th Anniversary Celebratory Volume

Edited by:
Sushilkumar
J.S. Mishra

Publisher:
Indian Society of Weed Science

Sponsored by:
National Bank For Agriculture And Rural Development (NABARD)

Table of Contents

PREFACE

Weeds are a perennial problem with the farmers. They are omnipresent and reduce yield and quality of crops substantially. Farmers spend a lot of resources to reduce their impact, many a times quite unsuccessfully. In India, the highest loss (33%) is caused by weeds, followed by pathogens (26%), insects (20%), storage pests (7%), rodents (6%) and others (8%). It has been estimated that weeds cause a total economic loss in arable crops equivalent to approximately USD 11-13 billion per annum. Weed management is an integral component of crop production. Despite the development and adoption of modern weed management practices, weeds continue to be a constant threat to agricultural productivity and environment.

Research work on weed management is going on in India for the past 6 decades since the initiation of a coordinated scheme in principal crops like rice, wheat and sugarcane in 1952. This work was strengthened with the launching of All India Coordinated Research Project on Weed Control in 1978, which is now being implemented all over the country. The establishment of National Research Centre for Weed Science (NRCWS) in 1989 at Jabalpur and its upgradation as Directorate of Weed Science Research (DWSR) in 2009 (renamed as Directorate of Weed Research (DWR) in 2014) was a major step forward to undertake systematic research and development programmes on weed management in a holistic and comprehensive manner by adopting multi-disciplinary approach. The Indian Society of Weed Science (ISWS) was established in 1968 to promote research, education, and extension outreach activities related to weeds, to provide science-based information to the public and policy makers, and to create awareness of weeds and their impacts on managed and natural ecosystems in the country. During the last 5 decades, sound weed management technologies in major crops and cropping systems have been developed and promoted in the country, which have helped in reducing costs and drudgery involved in weed control, and increasing crop productivity.

It is a matter of great pleasure that on completion of its 50 years of journey, the Indian Society of Weed Science has organized the ISWS Golden Jubilee International Conference at Jabalpur, India during 21-24 November, 2018. The theme of the Conference is ‘Weed Science and Society: Challenges and Opportunities’. The present book entitled ‘Fifty Years of Weed Science Research in India’ incorporates the compilation of research work done in India during the last 50 years on various aspects of weed management in major crops, crop-weed competition and losses, herbicide residue, mechanization, herbicide use, biological weed control, weed management in conservation agriculture, nanotechnology application, parasitic weeds, weed utilization, *etc*. We state that the findings, views and opinions expressed in this book are solely those of authors of the chapters but do not reflect the official policy of ISWS and the editorial board. It is hoped that this publication will benefit researchers, teachers, students, extension personnel, policy makers and all others dealing with weeds and weed management across the country. It will help the budding science to identify the ness areas of weed research in India.

The financial grant received from Research and Development Fund of National Bank for Agriculture and Rural Development (NABARD) towards this publication is gratefully acknowledged.

Editors
Dr. Sushilkumar
Dr. J.S. Mishra

Chapter 1

The historical and future perspective of Weed Science research in India

A.N. Rao
IDC and International Rice Research Institute (IRRI); International Crops Research Institute for Semi Arid Tropics*; Building # 303, ICRISAT, Patancheru, Hyderabad, Telangana 502 324*
Email: anraojaya1@gmail.com

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

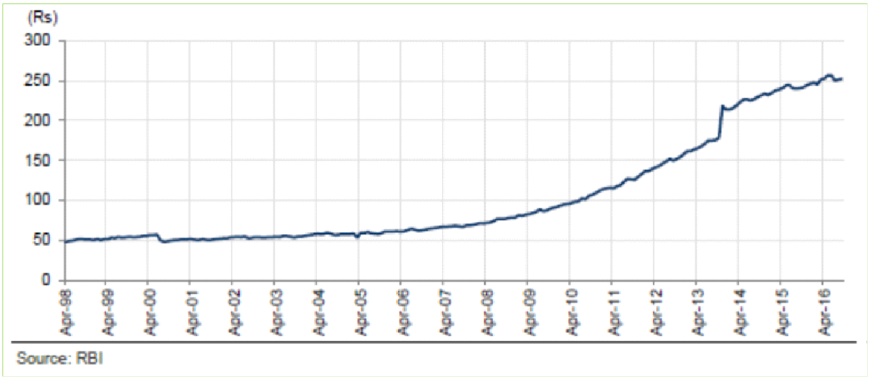
(Sushilkumar 2011); impact of climate change on weeds and weed management (Singh *et al.* 2011), biology and control measures of *Orobanche* (Punia 2014); weed management approaches for weed management in direct-seeded rice (Rao *et al.* 2007); dry-seeded rice (Chauhan and Yadav 2013), finger millet (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.



Source: RBI

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

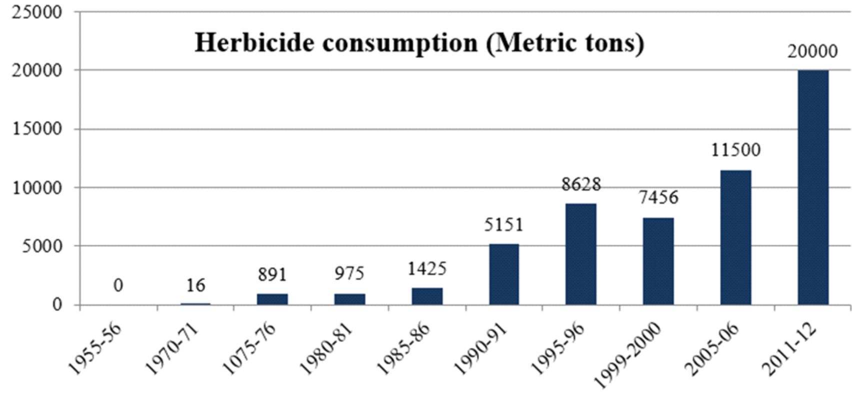


Figure 2. Herbicide consumption across yeas in India from 1955 to 2012 (Source: DWR 2015)

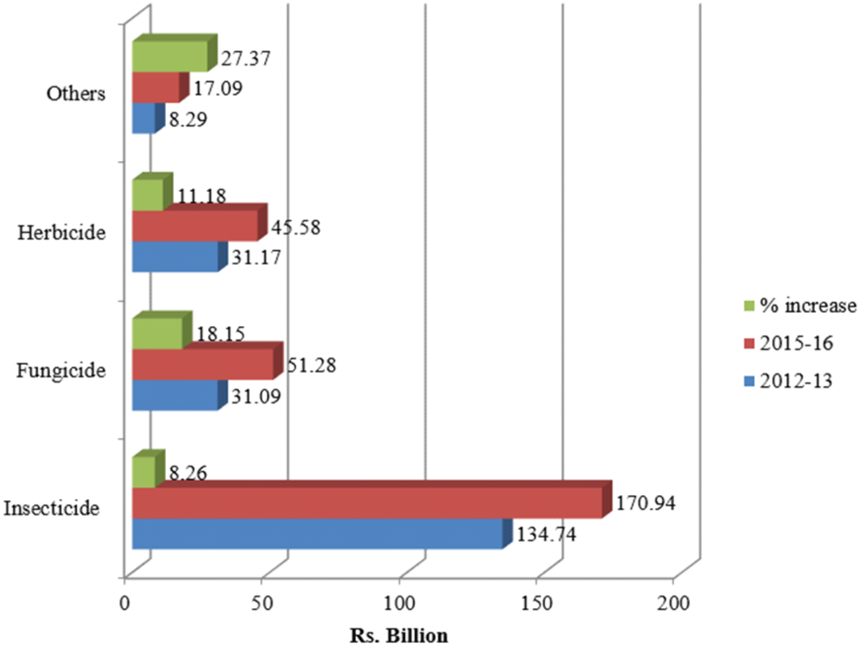


Figure 3. Plant protection market of India showing 11.18% increase in herbicide market in 2015-16 compared to 2012-13 (Data Source: FICCI, TATA Strategic management consultants)

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.

Acknowledgements

A.N. Rao wishes to thank Government of Karnataka for financial support (BhooSamrudhi). He also thanks IRRI, ICRISAT, Dr. Pooran Gaur, Dr. Arvind Kumar, Dr. Srinath Dixit, Dr. J.K. Ladha and Dr. Vikas, for their support.

References

Abraham CT and Nimmy Jose. 2015. Weedy rice invasion and its management. *Indian Journal of Weed Science* **47**: 216–223.

Amarjeet, Punia SS, Yadav Ashok and Malik RK. 2003. Effect of pH on degradation of chlorsulfuron in Soil. *Indian Journal of Weed Science* **35**: 97–99.

Ambasht RS. 1977. Ecology, education and research in India in relation to weed problems. Volume 2, 679-684. In: P*roceedings of the 6th Asian-Pacific Weed Science Society Conference,* Jakarta, Indonesia, 1977.

Arakeri HR. 1977. Weed Science technology: Retrospect and Prospect. Valedictory address. pp. 12-15. In: Proc. Weed Science Conference. Indian Society of Weed Science, Hyderabad, India.

Arora A and Tomar SS. 2012. Effect of soil solarization on weed seed bank in soil**.** *Indian Journal of Weed Science* **44**: 122–123.

Babu MBBP and Yaduraju NT. 2000. Decision support systems: A tool for sustainable weed management. *Indian Journal of Weed Science* **32**: 119–128.

Balyan RS, Yadav A, Pahwa SK and Malik RK. 1999. Response of fenoxaprop and other herbicides on isoproturon resistant and susceptible biotypes of little seed canary grass and other weeds in Wheat. *Indian Journal of Weed Science* **31**: 38–43.

Behera UK, Jha KP, Mahapatra IC. 1997. On-farm evaluation of different weed-management practices in early rice (*Oryza sativa*) in the rainfed uplands of eastern India. *Indian Journal of Agronomy* **42**: 446–451.

Bhan VM, Maurya RA, Negi PS. 1980. Characterization of critical stages of weed competition in drill seeded rice. *Indian Journal of Weed Science* **12**: 75–79.

Bhan VM, Singh M and Maurya RA. 1971. Crop weed competition studies in groundnut. *Indian Journal of Weed Science* **3**: 32-36.

Bhan VM. 1994. Herbicidcs resistance against weeds•-a growing menace in India. *Weed News* 1: 7–9.

Bhullar MS, Pandey M, Kumar S and Gill G. 2016. Weed management in conservation agriculture in India. *Indian Journal of Weed Science* **48**: 1-12.

Bhullar MS, Punia SS, Tomar SS, Singh VP and Sharma JD. 2014. Little seed canary grass resistance to clodinafop in Punjab: farmers' perspective. *Indian Journal of Weed Science* **46**: 237–240.

Brar SS, Kumar S, Brar LS and Walia SS. 1998. Effect of crop residue management systems on the grain yield and efficacy of herbicides in rice-wheat sequence. *Indian Journal of Weed Science* **30**: 39–43.

Chandrakwnar SS, Nanjappa HV, Ramachandrappa BK, Kumar H and Prasad M. 2002. Weed management through soil solarization in sunflower. *Indian Journal of Weed Science* **34**: 231–235.

Chauhan BS and Yadav A. 2013.Weed management approaches for dry-seeded rice in India: A review. *Indian Journal of Weed Science* **5**: 1–6.

Chinnusamy C, Senthil A, Bhuvaneswari J and Prabhakaran NK. 2010a. Studies on the threshold values of horse purslane in onion. *Indian Journal of Weed Science* **42**: 109–111.

Chinnusamy C, Senthil A, Kumar GP and Prabhakaran NK. 2010. Identification of threshold level of horse purslane in irrigated cowpea. *Indian Journal of Weed Science* **42**: 91–92.

Choudhari SD, Muzaffar S and Upadhyay UC. 1980. Integrated Striga control in sorghum. *Indian Journal of Weed Science* **12**: 15–20.

Choudhury PP, Singh R, Ghosh D and Sharma AR. 2016. *Herbicide use in Indian agriculture.* ICAR - Directorate of Weed Research, Jabalpur, Madhya Pradesh, 110 p.

Das VSR and Raghavendra AS. 1973. A screening of the dicotyledonous weed flora for the occurrence of C_4 dicarboxylic acid pathway of photosynthesis. *Proceedings of the Indian Academy of Sciences* **3**: 93–100.

Das TK and Yaduraju NT. 2007. Effect of irrigation and nitrogen levels on grassy weed competition in wheat and comparative eco-physiology of *Phalaris minor* Retz. and *Avena sterilis* ssp. ludoviciana Dur. in wheat. *Indian Journal of Weed Science* **39**: 178–184.

Das TK and Yaduraju NT. 2008. Effect of soil solarization and crop husbandry practices on weed species competition and dynamics in soybean-wheat cropping system. *Indian Journal of Weed Science* **40**: 1–5.

Datta TR 1977. Weed science at the Indian grassland and fodder research institute. *Proceedings of Weed Science Conference*, Indian Society of Weed Science, Hyderabad, A.P.

Deshmukh G. 2012. Rotary weeder for drudgery reduction of women during weeding in rice field.*Indian Journal of Weed Science* **44**: 132–134.

Dhawan RS, Dhawan AK, Kajla S. 2004. Protein profiles of some Isoproturon susceptible and resistant biotypes of *Phalaris minor* Retz. *Indian Journal of Weed Science* **36**: 38–40.

Dhawan RS, Singh R, Punia SS, Dhawan AK and Dudeja SS. 2008. Molecular diversity of little seed canary grass (*Phalaris minor* Retz.) populations from wheat growing belts of India. *Indian Journal of Weed Science* **40**: 101–108.

Dhawan RS, Singh S and Malik RK. 2003. Growth response of *Echinochloa crusgalli* in association with rice genotypes. *Indian Journal of Weed Science* **35**: 197–200.

Divakaran O, Arunachalam M, Murugan T and Nair NB. 1980. Studies on the life cycle and ecology of *Salvinia molesta* Mitche ll. *Proceedings of the Indian Academy of Sciences* (Plant Science). **89:** 519–528.

Datta TR. 1977a. Status report on a decade of weed science at Jhansi and perspectives for the future. Volume 2, 690-692. In: *Proceedings of the 6th Asian-Pacific Weed Science Society Conference*, Jakarta, Indonesia.

DWR. 2015. *Vision 2015*. Directorateof Weed Research (DWR), Jabalpur, India. 45 p.

FAO. 2018. *The State of Food Security and Nutrition in the World*. FAO, Rome, Italy.

Garg VK, Gupta R and Balyan RS. 1999. Biology and control of Carrot weed–A Review. *Indian Journal of Weed Science* **31**: 124–129.

Gharde Y, Ghosh D, Singh PK and Dubey RP. 2017. Fitting dose-response curve to identify herbicide efficacy and ED50 value in mixture. *Indian Journal of Weed Science* **49**: 165–169

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

GOI (Government of India). 2018. *Economic Survey 2017-2018*. Chapter 6. Climate, Climate Change, and Agriculture. Government of India, Ministry of Finance, Department of Economic Affairs, Economic Division.

Hosmani MM. 1978. *Striga (A Noxious Root Parasitic Weed)*. University of Agricultural Sciences. Bangalore. 165 pp.

ICFA. 2017. National round table of CEOs on Indian plant protection. 17 February 2017. Indian Council of Food and Agriculture (ICFA), New Delhi, India.

Joshi NC. 1973. Some problems and progress of weed control in India, 1948-1972. 170-176. In: *Proceedings of the 4th Asian-Pacific Weed Science Society Conference,* Rotorua.

Joshi NC. 1977. Weed problems and herbicide use in India. pp. 257. In: *Proceedings of Weed Science Conference, Weed Science Conference and Workshop*. Indian Society of Weed Science, A.P. Agriculture University, Hyderabad, India.

Joshi NC. 1974. *Manual of Weed Control*. Research co Publications, Delhi, India.

Kaur S, Kaur R, Chauhan BS. 2018. Understanding crop-weed-fertilizer-water interactions and their implications for weed management in agricultural systems. *Crop Protection* **103**: 65–72.

Kaur M, Kumar M, Sachdeva S and Puri SK. 2018a. Aquatic weeds as the next generation feedstock for sustainable bioenergy production. *Bioresource Technology* **251**: 390–402.

Kaushik SK and Mani VS. 1980. Effect of chemical weed control on the nutrition and seed yield of direct-sown rice. *Indian Journal of Agricultural Sciences* **50**: 41–44.

Khonglam A and Singh A. 1980. Studies on the weed species of Eupatorium found in Meghalaya, India. *Proceedings of the Indian Academy of Sciences* (Plant Sciences) **89**: 237–241.

Kondap SM, Rao AN and Rao YY. 1983. Weed suppressing ability of five crops intercropped with maize. p. 271–275. In: *Proceedings* 9th Asian Pacific Weed Sci. Soc. Conf., Manila, Philippines.

Kondap SM, Rao AN, Krishna KR and Reddy GP. 1982. Investigation on the competitive ability of certain crops against purple nut sedge. (*Cyperus rotundus* L.). *Indian Journal of Weed Science* **14**: 124–126.

Krishnamurthy K, Bommegowda A, Jagannath MK, Prasad, TVR, Venugopal N, Jayaram G, Raghunatha G and Rajashekarara BG. 1973. Studies on herbicidal tolerance in maize (*Zea mays* L.) 1. Differential he rbicidal response of genotypes. *Indian Journal of Weed Science* **5**: 114–119.

Krishnamurthy K, Prasad TVR, Muniyappa TV and Venkata Rao BV. 1977. *Parthenium, A New Pernicious Weed in India*. U.A.S. [University of Agricultural Sciences] Technical Series. No. 17. 46 pp. Univ. Agric. Sci., Hebbal, Bangalore-560 024, Karnataka, India.

Kumar P, Singh Y and Singh UP. 2013. Evaluation of cultivars and herbicides for control of barnyard grass and nutsedge in boro rice. *Indian Journal of Weed Science* **45**: 76-79.

Kumar R, Singh J and Uppal SK. 2017. Management of weeds in sugarcane-wheat intercropping system in sub-tropical India.*Indian Journal of Weed Science* **49**: 139–146.

Kumar RM, Subbaiah SV and Singh SP. 2000. Effect of weed competition and level of nitrogen on performance of rice hybrids.*Indian Journal of Weed Science* **32**: 51–54.

Leela D. 1976. Weed control in fruit crops - a review. *Haryana Journal of Horticultural Sciences* **5**: 31–42.

Mahajan G and Brar LS. 2001. Studies on herbicide resistance in *Phalaris minor* under Punjab conditions. *Indian Journal of Weed Science* **33**: 1–4.

Malik RK and Singh S. 1993. Evolving strategies for herbicides use in wheat: Resistance and integrated weed management. pp. 225–238. In *Proceedings International Symposium, Indian Society of Weed Science,* held in November 1993.

Malik RK and Singh S. 1995. Little seed canary grass (*Phalaris minor*) resistance to isoproturon in India. *Weed Technoloogy* **9**: 419–25.

Mani VS. 1977. Weed research in India: status, problems and strategies. In: *Proceedings of Weed Science Conference*, Indian Society of Weed Science, Hyderabad.

Mankotia BS, Thakur RC, Kumar J and Kumar S. 2006. Use of Lantana and Eupatorium as green manure in rainfed maize-wheat system in north-west Himalayas.*Indian Journal of Weed Science* **38**: 263–266.

Misra PK and Lenka D. 1972. A note on minimum tillage in rice cultivation. *Indian Journal of Weed Science* **5**: 57–59.

Misra PN, Chandra V and Kaul KN. 1972. Use of *Argemone mexicana* L. for improving paddy yield in Saline Alkali Soils. *Indian Journal of Weed Science* **4**: 33–41.

Misra R. 1969. *Final Technical Report*. PL480 research project on “Ecology of ten noxious weeds common to Gangetic plains, India and USA. Banarus Hindu University, Varanasi, U.P., India.

Moolani MK and Katyal MBR.1972. Time of weed control in tobacco (*Nicotiana rustica*). *Indian Journal of Weed Science* **4**: 113

Mukhopadhyay SK. 1980. Effects of herbicides and insecticides alone and their combinations on soil microflora. *Indian Journal of Weed Science* **12**: 53–60.

Muniyappa TV, Prasad TVR and Krishnamurthy K. 1980. Comparative effectiveness and economics of mechanical and chemical methods of control of *Parthenium hysterophorus* Linn. *Indian Journal of Weed Science*. **12**: 137–144.

Muniyappa TV, Prasad, TVR and Krishnamurthy K. 1983. Biology and chemical for control of *Oxalis latifolia* Linn. *Indian Journal of Weed Science* **15**: 182–187.

Murthy MM, Devendra M and Viswanath R. 1995. Identification of suitable crop species and plant density to suppress growth of *Cyperus rotundus*. *Indian Journal of Weed Science* **27**: 222–223.

NRCWS. 2007. NRCWS - Perspective Plan Vision 2025, National Research Centre for Weed Science, Jabalpur, Madhya Pradesh.

Naidu VSGR 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* & *Conservation* **14**: 9–12.

Oudhia P and Tripathi RS.1999.A useful weed *Blumea lacera* L.—A review. *Indian Journal of Weed Science* **31**: 108–109.

Punia SS. 2014. Biology and control measures of *Orobanche*. *Indian Journal of Weed Science* **46**: 36–51.

Rajkhowa DJ. 2008. Utilization of weed Biomass for nitrogen substitution in rice (*Oryza sativa*) - rice system. *Indian Journal of Weed Science* **40**: 27–32.

Ram P, Sreenivas G, Rani PL and Madhavi A. 2017. Weed management to improve productivity and nutrient uptake of Rabi maize. *Indian Journal of Weed Science* **49**: 90–92.

Ramachandra D, Ramamohan G, Bhan A and Suresh PJ. 2016. Weed management in cotton: The potential of GM crops. *Indian Journal of Weed Science* **48**: 136–143.

Rana NS, Kumar S and Saini SK. 2004. Weed management in spring sugarcane based intercropping systems. *Indian Journal of Weed Science* **36**: 68–72.

Rao VS. 2017. *Principles of Weed Science*. Second Edition CRC Press LLC., USA.

Rao VS. 2014. Paradigm shifts in weed science and challenges they pose to India and weed scientists. *Indian Journal of Weed Science* **46**: 111–116.

Rao AN. 1980. *Some Eco-Physiological Aspects of Weeds Management in Different Cropping Systems*. Postdoctoral report submitted to the International Crops Research Institute for Semi Arid Tropics, India. 119 p.

Rao AN and Matsumoto H. 2017. Weed management in rice in the *Asian-Pacific region. Asian-Pacific Weed Science Society* (APWSS); The Weed Science Society of Japan, Japan and Indian Society of Weed Science, India.

Rao AN and Chauhan BS. 2015. Weeds and weed management in India - A Review. pp. 87–118. In: *Weed Science in the Asian Pacific Region*. Indian Society of Weed Science, Jabalpur, India.

Rao AN and Yaduraju NT. 2015. Weed Science for Sustainable Agriculture, Environment and Biodiversity. Volume 1. ICAR Directorate of Weed Research, Jabalpur, Madhya Pradesh.

Rao AN and Ladha JK. 2013. Economic weed management approaches for rice in Asia, pp. 500–509. In: *Proceedings of the 24th Asian–Pacific Weed Science Society Conference*, (eds. BakiHj B, Kurniadie D and Tjitrosoedirdjo), Bandung Indonesia.

Rao AN and Nagamani A. 2010. Integrated weed management in India - Revisited. *Indian Journal of Weed Science* **42**: 1–10.

Rao AN and Nagamani A. 2007. Available technologies and future research challenges for managing weeds in dry-seeded rice in India. pp. 391–401. In: *Proceedings 21st Asian Pacific Weed Science Society Conference*, (Eds. Marambe B, Sangakkara UR, De Costa WAJM and Abeysekara ASK), 2-6 October 2007, Colombo, Sri Lanka

Rao MR and Shetty SVR. 1976. Some biological aspects of intercropping systems on crop-weed balance. *Indian Journal of Weed Science* **8**: 32–43.

Rao AN, Singh RG, Mahajan G, Wani SP. 2018. Weed research issues, challenges, and opportunities in India. https://doi.org/10.1016/j.cropro.2018.02.003.

Rao AN, Wani SP, Ramesha M and Ladha JK. 2015. Weeds and weed management of rice in Karnataka State, India. *Weed Technology* **29**: 1–17.

Rao VS, Yaduraju NT, Chandrasena NR, Hassan G and Sharma AR. 2015a. *Weed Science in the Asian-Pacific Region*. An Asian Pacific Weed Sci. Soc. Public. Indian Soc. Weed Sci., Jabalpur, India. 389 pp.

Rao A.N, Ladha JK, Wani SP. 2015b. Weeds and weed control in finger millet in India – a review. pp. 114. In: *Proceedings 25th Asian-Pacific Weed Science Society Conference*, on “Weed Science for Sustainable Agriculture, Environment and Biodiversity”, during 13-16 October, 2015, Hyderabad, India.

Rao AN, Wani SP and Ladha JK. 2014. Weed management research in India - an analysis of the past and outlook for future. pp. 1–26. In: Souvenir (1989-2014). DWR Publication No. 18.Directorateof Weed Research, Jabalpur, India.

Rao AN, Malik RK, Yadav A, Ladha JK.2014a. Strengthening farmers' knowledge for better weed management in developing countries. pp. 991–405. In: *Recent Advances in Weed Management*. (Eds. Chauhan BS and Mahajan G), Springer, USA.

Rao AN, Johnson DE, Sivaprasad B, Ladha JK, Mortimer A. 2007. Weed management in direct-seeded rice. *Advances in Agronomy* **93**: 153–255.

Ray DK, Ramankutty N, Mueller ND, West PC and Foley JA. 2012. Recent patterns of crop yield growth and stagnation. *Nature Communications*, 3, Article No 1293, doi:10.1038/ncomms2296.

Remesan R, Roopesh MS, Remya N and Preman PS. 2007. Wet Land Paddy Weeding- A Comprehensive Comparative Study from South India. Agricultural Engineering International: the CIGR Ejournal. Manuscript PM 07 011. Vol. IX. December, 2007

Sandhu KS and Gill GS. 1973. Studies on critical period of weed competition in maize. *Indian Journal of Weed Science* **5**: 1–5.

Sarma CK and Gautam RC. 2006. Effect of tillage; seed rate and weed control methods on weeds and maize (*Zea mays* L.).*Indian Journal of Weed Science* **38**: 58–61.

Sastry KSK, Boraiah G, Govindu HC, Khaleel TF. 1980. *Weeds of Karnataka*. University of Agricultural Sciences, Bangalore. 360 p.

Shetty SVR and Krantz BA. 1980. Weed research at ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). *Weed Science* **28**: 451–454.

Shetty SVR and Gill HS. 1974. Critical period of crop-weed competition in rice (Oryza sativa L.). *Indian Journal of Weed Science* **6**: 101–107.

Shivaraj B, Hosamani MM and Patil SV. 1969. Control of *Cynodon dactylon* by mechanical and chemical methods. *Indian Journal of Weed Science* **1**: 1–4.

Singh SR, Singh OP, Singh Y, Sharma HC and Singh M. 1976. Mechanical weeding in direct-sown rice. *Indian Journal of Agricultural Sciences* **46**: 507–509.

Singh B and Rana NS. 2003. Effect of weed management practices on weeds, soil micro flora and yield of sugarcane ratoon. *Indian Journal of Weed Science* **35**: 77–81.

Singh J, Gupta S, Chauhan SS and Mishra D. 2011. Evaluation of toxins of phytopathogenic fungus for eco-friendly management of Parthenium. *Indian Journal of Weed Science* **43**: 178–180.

Singh MK, Singh RP and Singh NP. 2002. Methods to study crop weed competition experiments - A review. *Indian Journal of Weed Science* **34**: 264–268.

Singh PK, Dhagat S and Gharde Y. 2017a. Weed manager (App for mobile): Harnessing innovations in Indian farming. *Indian Journal of Weed Science* **49**: 414–416.

Singh PK, Sondhia S, Dubey RP, Sushilkumar, Kumar B, Gharde Y and Choudhary VK. 2017. Adoption and impact assessment of weed management technologies in wheat and greengram under conservation agriculture system in central India. *Indian Journal of Weed Science* **49**: 23–28.

Singh PK, Yogita G and Choudhary VK. 2018. Adoption of integrated weed management practices correlates with farmers profile characteristics. *Indian Journal of Weed Science* **50**: 69–71

Singh RP, Ramesh KS and Singh MK. 2011.Impact of climate and carbon dioxide change on weeds and their management–A review.*Indian Journal of Weed Science* 43: 1–11

Singh VP, Kumar A and Banga B. 2010.Current status of zero tillage in weed management. *Indian Journal of Weed Science* **42**: Supplement, 1-9.

Singh DV, Gaur AK and Mishra DP. 2004. Biochemical and molecular mechanisms of resistance against isoproturon in *Phalaris minor*: Variations in protein and RAPD profiles of isoproturon resistant and sensitive *Phalaris minor* biotypes. *Indian Journal of Weed Science* **36**: 256–259.

Singh R and Singh B. 2004. Effect of irrigation time and weed management practices on weeds and wheat Yield. *Indian Journal of Weed Science* **36**: 25–27.

Singh S and Lall AC. 2001. Studies on technological gaps and constraints in adoption of weed management practices for rice-wheat cropping system. *Indian Journal of Weed Science* **33**: 116–119.

Singh AP, Chowdhury T, Kolhe SS, Bhambri MC and Chandrakar BL. 2010. Weed shift and grain yield as influenced by tillage and weed management methods in rice-wheat cropping system in Chattisgarh. *Indian Journal of Weed Science* **42**: 31–36.

Singh R. 2006. Effect of cropping sequence, seed rate and weed management on weed growth and yield of Indian mustard in Western Rajasthan. *Indian Journal of Weed Science* **38**: 69–72

Subramanian E and James MG. 2006. Effect of chemical, cultural and mechanical methods of weed control on wet seeded rice. *Indian Journal of Weed Science* **38**: 218–220.

Subudhi ECR. 2004. Evaluation of weeding devices for upland rice in the eastern Ghat of Orissa, India. *International Rice Research Notes* **29**(1): 78–80.

Sushilkumar. 2011. Aquatic weeds problems and management in India. *Indian Journal of Weed Science* **43**: 118–138.

Sushilkumr and Varshney JG. 2010. Parthenium infestation and its estimated cost management in India. *Indian Journal of Weed Science* **42**: Supplement, 73–77.

Tiwari JP and Bisen C.R. 1984.Ecology of *Parthenium* hysterophorus. *Indian Journal of Weed Science* **16**: 203-206.

Tripathi B, Barla A and Singh CM. 1991.Carrot weed *P. hysterophorus* (L.) - Overview of the problems and strategy for its control in India. *Indian Journal of Weed Science* **23**: 61–71.

Veerabhadraiah GP, Rama Rao S, Udaykumar M and Krishnasastry KS. 1980. Increase of penetration and translocation of foliar-applied 2, 4-D into the underground parts of nutsedge. *Indian Journal of Agricultural Sciences* **50**: 352–356.

Verma SK, Singh RP and Singh RK. 2007. Performance of varieties and herbicides on production potential of wheat (*Triticum aestivum* L.) and associated weeds. *Indian Journal of Weed Science* 39: 197–200.

Walia US, Gill G, Walia SS and Sidhu AS. 2010. Competitive ability of rice genotypes against weeds in direct seeding production system. *Indian Journal of Weed Science* **42**: 32–34.

Walia US and Brar LS. 1996. Performance of new herbicides for controlling wild canary grass (*Phalaris minor*) in wheat. *Indian Journal of Weed Science* **28**: 70–73.

Yadav RS, Sharma SK, Poonia BL and Dahama AK. 2004. Selectivity and phytotoxicity of oxadiargyl on cumin and weeds and its residual effect on succeeding moth bean and pearl millet. *Indian Journal of Weed Science* **36**: 83–85.

Yaduraju NT and Mishra JS. 2018. Smart weed management: A small step towards doubling farmers' income. *Indian Journal of Weed Science* **50**: 1–5.

Yaduraju NT, Ahuja KN, Das TK, Singh DK, Tomar S and Kumar S. 1999. Screening wheat cultivars against post-emergence herbicides used for controlling herbicide resistant population of *phalaris minor*. *Indian Journal of Weed Science* **31**: 93–94.

Chapter 2

Parasitic weed management

S.S. Punia[1], J.S. Mishra[2]*, T.V.R. Prasad[3], C. Chinnusamy[4] and M. Madhavi[5]
[1]CCS Haryana Agricultural University, Hisar, Haryana, 125 004
[2]ICAR Research Complex for Eastern Region Patna Bihar 800 014
[3]University of Agricultural Sciences, Bangalore 560 032
[4]Department of Agronomy, Tamil Nadu Agricultural University, Coimbatore
[5]Prof. Jayashankar Telangana State Agril. University, Hyderabad 500 030
**Email: jsmishra31@gmail.com*

Summary

Parasitic weeds are becoming major constraints to many crops in tropical agriculture and the efficacy of available means to control them is minimal. In India, parasitic weeds of genus *Orobanche*, *Cuscuta*, *Striga*, *Dendropthe* cause huge losses in field crops and fruit and wood trees. These plants have certain specific characteristics like prolific seed production potential, competitiveness and aggressiveness with the host plants, prolonged seed viability. They are troublesome weeds and very difficult to control by normal weed management measures. Control strategies have largely focused on agronomic practices, the use of resistant/tolerant cultivars and the use of herbicides, although success has been marginal. There is, thus, an urgent need to re-evaluate the control methods in the light of recent developments in herbicide molecules, crop breeding and molecular genetics and to place these within a framework that is compatible with current agronomic practices. In this chapter an attempt has been made to compile the research work done on various aspects of parasitic weed management in India during the last 50 years.

Key words: Cuscuta, Loranthus, Management, Orobanche, Parasitic weeds, Striga

Parasitic plants account for approximately 1% of angiosperm species and are present in 22 botanical families. Several of the parasitic species are important agricultural weeds, infest a wide range of crops around the globe, and pose a major threat to the food security of numerous communities. When one organism steals all of its food from another organism's body it is called a parasite. The organism, which who is being robbed of its food supply is called the host. The parasitic mode of existence can be found throughout the kingdom of life, from bacteria and fungi to insects, arachnids and worms. The transfer of host solutes in to a parasitic plant relies on the formation of a bridge between the two organisms. This organ, the haustorium (from the Latin, *haurire,* to drink) is thus the defining feature of all parasitic plants. True plant parasites can be hemiparasitic (semiparasitic) with photosynthetic leaves (such as mistletoe), or holoparasitic and completely dependent on their host (such as dodder). Some stem parasites are endoparasitic and live completely within the stems of their host. The only part of pilostyles that emerges from the host is a tiny bud that opens into a minute red flower. This is similar to a pimple appearing on our face that bursts into a tiny blossom. Of all the more than 2,30,000 species of flowering plants, the root and stem parasites certainly include some of the most bizarre and beautiful species; including the world's largest flower *(Rafflesia arnoldii)* that is three feet (one meter) in diameter.

The agriculturally important parasitic weeds fall into four main groups:

1. *Orobanchaceae* (broomrapes): Holoparasitic root parasites that invade dicot plants
2. *Cuscutacea*e (dodders): Holoparasitic twining stem parasites that attack dicot plants
3. *Scrophulariaceae* (figworts and witchweeds): Contains hemi-parasitic root parasites that invade roots of host plants
4. *Viscaceae* and *Loranthaceae* (mistletoes): Green hemiparasites that parasitize aerial parts of shrubs and trees

Orobanche spp.

Fig. 1 Mustard cultivation in India

Orobanche or Broomrape (*Orobanche* spp.) locally known as Margoja, Rukhri, Khumbhi or Gulli is a phanerogamic, obligate, troublesome holo root parasite that lack chlorophyll and obtain carbon, nutrients, and water through haustoria which connect the parasites with the host vascular system. The attached parasite functions as a strong metabolic sink, often named "*super- sink*", strongly competing with the host plant for water, mineral nutrition and assimilate absorption and translocation. The diversion of these substances to the parasitic weed causes moisture and assimilates starvation, host plant stress and growth inhibition leading to extensive reduction in crop yield and distressed crop quality in infested fields. Depending upon the extent of infestation, environmental factors, soil fertility, and the crops' response. Damage from *Orobanche* can range from zero to complete crop failure.

Geographical distribution: Rapeseed-mustard (*Brassica* spp.) is a major group among oilseed crops in the world being cultivated in 53 countries across the six continents (Goyal *et al.* 2006), with India ranking third in area and production in the world. In India, *Orobanche* spp. has emerged as a major threat to rapeseed-mustard production in northern Rajasthan, Haryana, Punjab, and north-east Madhya Pradesh. In Andhra Pardesh, 50% area under tobacco (40,000 ha) is infested with broomrapes and causing 50% crop losses. In Karnataka state, 90% area under bidi tobacco is infested with this weed with 50-60% yield losses in some areas (Dhanapal *et al.* 1998). Yield losses due to *Orobanche* spp. in tobacco growing areas of Tamil Nadu, Gujarat and Maharastra is also reported to be very high. Tomato and brinjal crops are also infested with *Orobanche* spp. in Mewat and Bhiwani districts of Haryana state (Anonymous 2013). Even *Orobanche* infestation on cauliflower and cabbage was observed in Dadri areas of Bhiwani and

Mewat areas of Haryana (India). Farmers reported 40-75% loss in fruit yield due to its infestation in tomato crop depending on intensity of infestation (Anonymous 2014). A continuous increase in *Orobanche* infestation in these areas has forced farmers to abandon tomato cultivation and switch over to other profitable crops cultivation

Compared with non-parasitic weeds, the control of *Orobanche* control has been proved to be exceptionally difficult in agricultural crops due to its underground location, close association with host plant roots, complex mechanisms of seed dispersal, germination, and longevity. Because the parasite germinates only in response to host root exudates and then attaches and develops underground on the host plant for the major part of its life, it is inaccessible to conventional control methods such as tillage and herbicide treatments. Furthermore, when the plant becomes visible above ground, much of the damage has already been done and control would be futile. The late appearance of parasite shoots above the soil and the lack of a photosynthetic system as a potential herbicide target does not seems to be practically feasible. The characteristics of *Orobanche* extremely small seeds produced in vast numbers and seed longevity in fields for 13 years account for much of the difficulty in controlling this parasitic weed.

Biology: Broomrapes are dicotyledonous annual plants (10-60 cm tall, depending upon the species). The fruits are capsular and contain numerous tiny black seeds. Broomrapes reproduce only by seeds which are usually dark brown, oval shaped, measure 0.35 x 0.25 mm dust sized weighing 3 to 6 µg and very difficult to recognize without a magnifying microscope.

In an experiment on weed biology of *Orobanche* at Hisar, it was observed that *Orobanche* panicles appeared above soil on an average 45-54 days after sowing of mustard. Fresh weight. /shoot was in the range of 34.9-42.5 g/plant as against 4.02-5.20 g/plant dry wt. /shoot. Violet cream colored flowers started to appear 11-13 days after panicle emergence of *Orobanche*. The capsule number per shoot varied from 38-45 while capsule weight was observed to be in the range of 0.094-0.124 g. The number of seeds per capsule varied 3870-5840 per capsule (Anonymous 2014) and a single plant may produce more than one lakh seeds depending upon species. Seed generally remains viable in soil for 10 to 13 years but the viability can be up to 20 years.

Seeds of *Orobanche* generally remain dormant and require a post-harvest ripening period for their germination in response to chemical stimulation (alectrol/ orobanchol) from the host plant roots. These conditions ensure that only seeds with in the rhizosphere of an appropriate host root will germinate. Suitable temperatures of conditioning of *Orobanche* seeds are between 15-20 °C for at least 18 days for maximum germination. Optimum temperatures for conditioning and germination are 18 °C for *O. crenata* and about 23 °C for *O. ramosa.*

Following the conditioning phase, germinated seed produces a germ tube or radicle in close proximity to the host plant roots that elongates chemotropically and develops an organ of attachment ‘the haustorium’, which serves as a bridge between the parasitic weed and host plant to drive water, mineral nutrients and carbohydrates from the host plant.

The part of the broomrape seedling swells outside the root of host plant to form a tubercle. Within 1-2 weeks, a shoot bud develops on the tubercle producing a flowering spike which elongates, and emerges outside the surface soil surface soil. Within a period of 15-20 days, the parasitic weed completes its life cycle and shed lakhs of seeds per plant.

Control measures

Cultural methods

Crop rotation: A crop rotation system includes *Orobanche* host crops, trap crops and catch crops and non-host crops. Crop rotation of mustard with non-host crops like wheat, barley, chickpea etc. is the most effective and commonly used management strategy for reducing the weed seed bank in heavily infested areas. The major restriction in adopting crop rotation in long-run is the longer viability of its seeds. Thus, heavy infestations may remain in a field despite absence of host crops for several years. Weed seeds buried in the soil beneath the crop root zone can be brought up to surface soil as a result of subsequent ploughings, germinate and provide competition to the host crop in later years. Frequent planting of susceptible crops on the same field should be avoided and as far as possible grow mustard in alternate years with diverse growing habit genotypes.

Trap and catch crops: These crops exude stimulants that induce *Orobanche* seed germination but no viable attachment to the host plant roots is established and the weed seedlings withers away and die up and ultimately their seed bank in the soil gets reduced. In Indian conditions, at Agricultural Research Station, Nepani (Karnataka), sun hemp and green gram proved to be promising trap crops for *Orobanche cernua* control where bidi tobacco is grown in long growing(*Kharif and Rabi*) seasons (Dhanapal and Struik 1996). Acharya *et al.* (2002) noticed that a local cultivar of *Brassica campestris* has been used as a catch crop in Nepal, reducing the *O. aegyptiaca* seed bank by around 33.35 per cent. Experimental results in Tehran indicated that using trap crops namely sesame, brown Indian-hemp, and common flax and black-eyed pea decreased broomrape biomass by 86, 85.3, 75.2, and 74.4 per cent, respectively. Reducing broomrape biomass caused increases in the tomato yield. Meanwhile, sesame, brown Indianhemp, Egyptian clover and mungbean increased total biomass of tomato by 71.4, 67.5, 65.5, and 62.5 per cent, respectively. It was observed that these plants have a great potential to reduce broomrape damage and they can be used in rotation in broomrape infested fields. Krisnamurthy and Rao 1976, Krishnamurthy *et al.* 1977, listed some trap crops found effective and may help to reduce seed bank of *Orobanche* spp. The trap crops for O. *crenata* are: Sorghum *(Sorghum vulgare*), barley (*Hordeum vulgare*), vetch *(Vicia vilosa* var. *dasycarpa)* and purple vetch. (*V. atropurpurea),* clover (*Trifolium alexandrinum*), flax (*Linum usitatissimum*), and coriander

(*Coriandrum sativum*). Trap Crops for *O. cernua, O. aegyptiaca* and O. *ramosa* are; pepper (*Capsicum annuum*), sorghum (*Sorghum bicolor*, cowpea (*Vigna unguiculata*), hemp (*Hibiscus subdariffa*), mungbeans, (*Phaseolus aureus*) flax, alfalfa (lucerne) (*Medicago sativa*), soybean (*Glycine max*, vetches (*Vicia* spp.) and chickpea *(Cicer arietinum*).

An additional cultural means for reducing *Orobanche* seed bank in the soil is the use of 'catch crops' *i.e.*, planting an *Orobanche* host crop for inducing parasite seed germination and attachment and that will be destroyed later on by means of light tillage practices or residual soil herbicides. But the use of trap and catch crops to manage this weed is somewhat limited due to (a) enormous amount of *Orobanche* seeds dispersed in the soil and only a small proportion may be exposed to germination stimulants in the rhizosphere. b) Feasibility and economics of growing these crops in the existing situations is also a big question mark.

Sowing dates and cropping density: Delaying the planting date affects *Orobanche* more than its hosts. Late planting of mustard (last week of October-first fortnight of November) is observed to be helpful in reducing the parasitism of *Orobanche* a result of specific weed and host plant differential response to low temperatures (Yadav *et.al.*, 2005) in Indian conditions. Moreover, farmers' perception for late sowing is pessimistic owing to limitation of mustard cultivation to conserved moisture conditions and competition for water utilization for pre-sowing irrigation in wheat; therefore, alternation in sowing time seems to be uncommon and unrealistic approach under Indian context.

Increased seed rate may reduce competition and number of attachments to some extent but additional cost of seed and other inputs besides providing congenial crop growth environment should also be taken care of while deciding the fate of such interventions.

Water management: Less infestation of the parasitic weed has been observed in raya/mustard grown under flooded irrigation compared to sprinkler irrigation or on conserved moisture as the seeds of *Orobanche* do not survive an extended period of inundation. Availability of water and undulating topography are again the limiting factors to practice flooding.

Nutrient management

Higher *Orobanche* infestation and its parasitism on host plants is generally more in inherently poor fertility soils dominated by major mustard growing areas of the India Application of urea or ammonical form of nitrogen during conditioning and germinating phases has been reported to reduce the germination, radicle length and weed proliferation. Urea, ammonium nitrate, and ammonium sulfate and the goat manure at 20 and 30 t/ha were found to be most effective in reducing parasitism of *Orobanche* and enhancing growth of tomato plants.

To confirm the effect of nitrogen fertilization through different sources on *Orobanche* inhibition in mustard, localized field studies were carried out through farmers' participatory approach in Haryana state of India during 2004-2010. Erratic response over the years was observed with respect to weed infestation and population dynamics when nitrogen sources, *viz.* ammonium sulphate, calcium nitrate and urea were evaluated alone or in combination with FYM, poultry manure, castor cake, pressmud or vermicompost. Use of neem cake/vermi-compost/castor cake and increased N fertilization (120 kg/ha) increased/maintained the crop productivity with parasitism of *Orobanche* by sustaining the host plant growth even with depleted fertility status. Pre-emergence, pre plant incorporation or herbigation of pendimethalin along with hoeing, use of organic sources of manure viz. castor cake and neem cake proved ineffective in minimizing density of this weed. Seed coating of mustard seeds with 1.0 ppm of chlorsulfuron and triasulfuron gave 70-98% control of *Orobanche aegyptiaca* but efficacy of seed treatment with sulfosulfuron was poor (Punia 2016)

Mechanical and physical methods

Hand weeding / hand pulling: Hand weeding or hand pulling before flowering followed by burning can be an effective and practicable method of checking seed production. Hand weeding though useful under low weed infestation but it is time consuming, labour intensive and costly affair. Profuse emergence of new inflorescence from below ground plant parts has also been observed within a short span of 7-10 days of hand weeding or hoeing therefore, this warrant for frequent repetitive measures.

Tillage / intercultivation: Tillage/intercultural operations are not practically and economically feasible due to late emergence of growing shoots and the risk/ uncertainty of crop injury always remains there due to close proximity of the root parasite with the host plant. Deep tillage during summer months causes seed desiccation and places them below the root zone preventing seed germination to some extent, but again the longer viability (up to 20 years) of weed seeds raises a question mark in long run.

Soil solarization: Covering moist soil (with or without minimum disturbances at planting) with white or black polyethylene sheet for a month or so can increase the soil temperature by almost 10°C (48-57 °C) compared to uncovered soil resulting in killing of *Orobanche* seeds that are in the imbibed state; therefore soil must be wet at the time of treatment. Soil solarization has been proven to be the most effective methods in controlling broomrape in open crops fields but high cost of polyethylene, appropriate machinery and cloud-free sunny days may restrict its use on larger scale. Patel (1989) reported effectiveness of soil solarization to control *Orobanche* under Gujarat conditions.

Biological methods

Reports on managing *Orobanche* through biological perpetuation of a fly, *Phytomyza orobanchia* Kalt (Pathak and Kannan 2014). Flies breed from larvae on associated with its mass rearing, release, formulation and delivery systems are available.but are not practically feasible. Fungi such as *Trichoderma viridae* and *Psuedomonas inflorescence* were tested at farmers' fields of Bhiwani and CCS

HAU Hisar during 2010-14, but these were found ineffective against *0robanche* in mustard (Anonymous 2011). More research is needed to develop a reliable biological method under Indian conditions.

Chemical methods

Two groups of chemicals *i.e.* soil applied herbicides and post- emergence applied herbicides have been reported to possess potential to control *Orobanche*.

Residual soil applied herbicides: Seed treatments with imidazolinones and sulfonylureas have proven to be effective for controlling *Orobanhche*. The herbicide is incorporated as a coating on the seeds and distributed with them at the time of planting. This replaces a pre-emergence treatment and saves mechanical application costs. In addition, the application of herbicides through seed treatment reduces the herbicide rate required by two to three folds, hence being less harmful to the environment. However, under favourable environmental conditions for broomrape attack, the treatment must be supplemented to obtain high broomrape control. In pot culture (2004-05), seed coating with chlorsulfuron, triasulfuron or sulfosulfuron at 0.05-0.1 mg/kg seed proved safe for crop. Results of experiments conducted from 2008-10 under farmers' management practices revealed that seed treatment of mustard with triasulfuron, sulfosulfuron and chlorsulfuron have been found to reduce 55-98% population of *Orobanche,* but the results were inconsistent over the years. Moreover over-dosing of the herbicide seed treatment sometimes caused poor germination and suppression in crop growth (Punia *et al.* 2012, Punia 2016).

Foliar applied herbicides: Sulfosulfuron and triasulfuron are registered worldwide for pre- and post-emergence of grass and broad-leaf weeds in wheat. Ethoxysulfuron is recommended to control broad-leaf weeds and sedges in rice. These systemic and somewhat persistent herbicides are absorbed through foliage and roots of plants with rapid acropetal and basipetal translocation. Study conducted in Chickballapura district of Karnataka state (India) revealed effectiveness of pre-emergence sulfosulfuron at 75 g/ha in controlling *Orobanche* in tomato grown under irrigated conditions (Dinesha and Dhanpal 2014).

Based on two years study on *Orobanch*e control in tomato in Mewat area of Haryana, Punia *et al*. (2016) reported that post-emergence application of ethoxysulfuron/sulfosulfuron at 25 g/ha at 30 DAS followed by its use at 50 g/ha or sulfosulfuron at 50 g/ha at 30 and 60 DAS, respectively, provides 85-90% control of Egyptian broom rape in tomato without any adverse effect on crop with yield increase of 46-58% as compared to untreated check. No herbicide residues were found in tomato fruits and soil at maturity. However residual carry over effect of sulfosulfuron is observed on succeeding sorghum crop depending upon soil type, rainfall during the season and number of irrigations applied to tomato crop. Sulfosulfuron at 20 g/ha at 45 and 90 DAP of eggplant (brinjal) provides effective control of *Orobanche* but with 5-10% crop suppression (Singh *et al.* 2017).

The imidazolinones are ALS-inhibiting herbicides are used pre-emergence and post-emergence for control of annual and perennial grass and broadleaf weeds. Most of these herbicides have medium to long soil persistence.

This herbicide was the first of the imidazolinone group to be registered for *Orobanche* control. A post emergence application of 20 g/ha on garden and field pea *(Pisum sativum* and *Pisum arvense,* respectively) one month after planting, and an additional treatment of 20-40 g/ha two weeks later, was selective to pea and efficient in *Orobanche* control.

Some of the locally available common herbicides at different concentrations, *viz.* pendimethalin (PE) 1000 g/ha, linuron (PE) l000 g ha, trifluralin (PPI) 1000 g/ha, fluchloralin (PPI) 1000 g/ha, metribuzin (PE/PPI) 175-200 g/ha sulfosulfuron (PE) 5-10 g/ha, oxyfluorfen (PE) 125-175 g/ha, thiazopyr (PE) 240 g/ha, isoproturon (PE/PPI) 500-1000 g/ha, chlorsulfuron (PE/PPI) 2-6 g/ha and triasulfuron (PE/PPI) 5-10 g/ha were tested in field trials conducted at farmers' fields in Bhiwani district and KVK, Mahendergarh (Haryana) by CCS HAU scientists from 2000-2008, but were found inconsistent in their efficacy against the parasitic weed over the years and sometimes even showed phyto-toxicity to the mustard crop or both(Yadav *et al.* 2005)

Glyphosate use for control of *Orobanche* : Earlier workers reported the glyphosate use on limited areas for *Orobanche* control in broad bean, carrot and celery. All these reports favour the use of glyphosate as a potential herbicide for *Orobanche* management, but there is dire need to conduct research particularly under real time farm situations to determine the optimum period and dose of herbicide application during which the parasite is most sensitive and the mustard crop is most tolerant. Since glyphosate is a broad spectrum non-selective foliar applied herbicide, there is no doubt that its efficacy in managing *Orobanche* could be quite useful but at the same time the selectivity of this herbicide is limited and needs critical precautionary measures to have effective results.

A study undertaken at Hisar (Haryana) to evaluate the efficacy and to standardize the dose and time of glyphosate application against the parasitic weed *Orobanche* in mustard(*Brassica juncea* L.) from 2006-2010, indicated that higher dose of glyphosate at early crop stages sometimes caused localized phytotoxicity on mustard plant viewing marginal leaf chlorosis, slow leaf growth, interveinal leaf bleaching, and/or slight elongation of apical leaves but the crop recovered within 7-10 days after spray with no yield penalty. 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 harvest (without any crop injury) with yield improvement from 12 to 41% over the traditional farmers' practice in different years of the study (Punia *et al.* 2010, Punia 2014). Similar findings on the control of *Orobanche* in mustard through herbicide application were also reported by the scientists at Gwalior and Bikaner (DWR 2009, Kumar 2002, Hira lal *et al.* 2016).

These results were further validated in large scale multi-locational trials conducted at different locations through farmers' participatory approach in

Haryana State during the *Rabi* seasons of 2010-11 to 2016-17. A total of 758 demonstrations were conducted in mustard growing areas of Haryana state covering 1831 ha area and it was observed that overall 76.5% (range 40-95%) reduction in *Orobanche* weed infestation with 21.4% (range 13.9-38.7%) yield superiority was noticed with glyphosate treated plots (25 g/ha at 30 DAS followed by 50 g/ha at 55-60 DAS) when compared with the farmers' practice of one hoeing at 25-30 DAS. This technology has now spread to the most *Orobanche*-infested mustard-growing areas of Haryana and the farmers are fully convinced of the benefits of this low-cost technology.

There are reports on the effectiveness of glyphosate in tomato, tobacco, faba beans, and other crops under greenhouse conditions elsewhere, but have not been yet reported from India, particularly under field conditions. Foliar spray of glyphosate twice; 25 g/ha at 30 DAS followed by 50 g/ha at 55 DAS may be helpful in reducing the *Orobanche* infestation by checking the further increase in weed seed bank without any crop suppression, but at the same time requires certain precautionary measures in its use. Since most of the mustard cultivation in India is limited to light textured soil having inherent poor fertility status and water holding capacity, care should be taken that the crop should not suffer from any moisture stress at the time of foliar spray, therefore, the fields should be irrigated 2-3 days prior to herbicide application. The proper time and dose of herbicide should also be taken care of to have better efficacy of herbicide application as repetitive/higher/ lower than the recommended dose may lead to adverse impact on mustard crop or may result in development of herbicide-resistant weeds (Shoeran *et al*. 2014). The present study has shown that glyphosate, if used at desired concentrations can be very helpful in reducing the parasitic weed infestation while affording tolerance to the mustard crop. This would definitely obviate the *Orobanche* seed bank to further increase as well as improve the overall productivity and economic wellbeing of the mustard growing farmers' fraternity.

Management *Orobanche* in tobacco: Dhanapal (1996) assessed the efficacy of 15 herbicides for control of broomrape and results indicated that 0.5 kg/ha glyphosate 60 DAS and 0.01 kg imazaquin 30 DAS gave best weed reduction (75-80%) and increased the yield of tobacco by 43%. Dhanapal *et al*. (1998) assessed the effect of natural oils on the control of broomrape in a naturally infested tobacco field at Agricultural Research station, Nipani, Karnatka, India. Natural oils which were less expensive and biodegradable differed in their ability to kill young broomrape spikes. Neem, coconut, sunflower, castor niger and mustard oils killed the buds of *Orobanch*e within 3 to 5 days without phytotoxicity to tobacco. Dhanapal *et al*. (1998b) reported that glyphosate at 500 g/ha applied at 60 days after transplanting (DAT) and imazaquin at 10 g/ha applied at 30 DAT reduced the number of above-ground broomrape spikes by 75 to 80%, respectively, and increased tobacco yield by 80 to >100% compared to the untreated plots. Imazethapyr and EPTC were found to be less effective for broomrape control, but they still led to substantially higher tobacco yields. None of the herbicide treatments resulted in higher yields than those in the hand-weeded plots. Toxicity to tobacco of all herbicides was higher at the higher rates tested but it was lowest with imazaquin. In tobacco, plant hole application of neem cake (200 kg/ha) lower the *Orobanche* shoots (62%) and increase the dry leaf yield by 51% (Chinnusamy 2012). Directed spraying of glyphosate at 0.1-0.2% or 75-100 g/ha on the lower side of the host plants around 50-55 days after planting/sowing of host crops will lower the emergence of *Orobanche*. Repeat the spray after 15 days depending on the emergence of *Orobanche* shoots. Drenching of plant holes with $CuS0_4$ 5% solution reduce the *Orabanche* infestation by 37% and increase the dry leaf yield by 28% in tobacco (Chinnusamy 2012).

Cuscuta spp.

Cuscuta spp. (dodder) also known as 'Akashbel' or 'Amarbal', is a parasitic angiosperm belonging to the family Convolvulaceae in older references, and Cuscutaceae in the more recent publications. The genus *Cuscuta* is comprised of about 175 species worldwide. Out of 12 species are reported from India (Gaur 1999), *C. campestris* and *C. reflexa* are more common. In some Indian literatures *Cuscuta chinensis* (Tosh *et al.* 1977) and *C. trifolii* are also reported. The wide geographical distribution of dodder species, their wide host range, and the difficulties associated with their control place them among the most damaging parasites worldwide. The invasive characterstics of *Cuscuta* spp. could be detrimental to the cultivation of many economically important crops. It could also affect the natural ecological balance and floristic composition in natural ecosystems. Some *Cuscuta* spp. have important medicinal, pharmacological and edible values while others are a threat to the natural ecosystems and agricultural crops.

In India, *Cuscuta* poses a serious problem in oilseed (niger, linseed) and pulses (blackgram, greengram, lentil, chickpea especially in rice-fallows) and fodder crops (lucerne, berseem) in the states of Andhra Pradesh, Chhattisgarh, Gujarat, Orissa, West Bengal and parts of Madhya Pradesh under rainfed as well as in irrigated conditions. In the production of crop seeds, the *Cuscuta* impose a severe limitations because of difficulty of removal of their seeds when the crop is graded out, thus, reducing the yield and quality. To this must be added increased cost of harvesting and cleaning.

Cuscuta seeds usually germinate on or near the soil surface. Seedlings are rootless, leafless stem. After emergence, the seedlings twin around the leaf or stem of a suitable host plant. Haustoria from the *cuscuta* penetrate the host and establish a parasitic union. Once the *Cuscuta* is attached to a host plant, it remains parasitic until harvest. It reproduces mainly by seeds and to a lesser extent by shoot fragments. Although *Cuscuta* seedlings contain a small amount of chlorophyll, they are obligate parasites and can not complete their life cycle without attachment to host plants.

***Cassytha* spp.**: *Cassytha* also known as "laurel dodder" or "love vine" is a high-climbing parasitic vine belongs to family Lauraceae (sub family Cassythoideae). The genus *Cassytha* has 20 species of parasitic herbs, of which *Cassytha filiformis*

L. also known as amarbeli, is very common in India, especially near the sea coast. It is almost similar to *Cuscuta* and is often mistakenly identified as such even by botanists. However, the fruit is a drupe with the single seed enclosed in a white translucent, fleshy pericarp. Like dodder, *Cassytha* seeds will germinate without any host influence although they too must be scarified. The mature *Cassytha* vine is usually a greenish-orange and on the whole favors woody rather than herbaceous hosts. Extracts from the plants are used in curing skin diseases and cleaning ulcers besides being useful in chronic dysentery. The powdered stem, mixed with sesamum oil, is used as hair tonic. However, *Cassytha* contains laurotetanine, an alkaloid which produces severe cramps when used in large doses (Mondal and Mondal 2001).

***Cuscuta campestris* Yuncker: The most common *Cuscuta* species in India:** Out of the 12 species reported from India, *C. campestris* is severely infesting field crops like alfalfa, niger, blackgram, greengram, lentil, chickpea and linseed. However, there is always confusion in the correct identification of the species. In most of the Indian literature, it is mentioned as *Cuscuta* spp. and in few cases, as *Cuscuta chinensis* (Rath 1975, Rath and Mohanty 1986). To identify the species correctly, *Cuscuta* seeds were collected from niger (Orissa), lucerne (Gujarat), blackgram/greengram (Andhra Pradesh) and linseed (Madhya Pradesh) and grown in pots with host plants. Photographs of *Cuscuta* vines, flowers, fruits and seeds were taken and sent to Mr. Chris Parker, U.K. and Dr. L.J. Musselman, Parasitic Plant Laboratory, Virginia, USA for identification of the species of *Cuscuta*. Both of them unanimously identified the species as *Cuscuta campestris* Yuncker due to following reasons.

"Capsules not circumscissile, corolla lobes are not keeled; the withered corolla is at the base of most of the capsules, lobes of calyx and corolla not thickened at their tips, filaments broadest at base, tapering distally".

***Cuscuta reflexa* Roxb.**: *Cuscuta reflexa* is theanother most common species found on woody plants and shrubs in Hyderabad region (Rao 1986).

Hosts of *Cuscuta* and yield losses: *Cuscuta* spp. is a serious problem in forage legumes, principally alfalfa (*Medicago sativa*), clovers (*Trifolium* spp).), and niger (*Guizotia abyssinica*). Other crops plagued by *Cuscuta* include linseed (*Linum usitatissimum*), chickpea (*Cicer arietinum*), lentil (*Lens culinaris*), pea (*Pisum sativum*), blackgram (*Vigna mungo*), greengram (*Vigna radiata*), pigeonpea (*Cajanus cajan*) sesame (*Sesamum indicum*), soybean (*Glycine max*), tomato (*Lycopersicon esculentum*), potato (*Solanum tuberosum*), carrot (*Daucus carota*), sugarbeet (*Beta vulgaris*), cranberry (*Vaccinium macrocarpon*), blueberry (*Vaccinium* spp.), citrus (*Citrus* spp.), and numerous ornamental species. *Cuscuta* also parasitizes numerous species of dicotyledonous weeds and wild plants. *Cuscuta* can parasitize asparagus (*Asparagus officinalis*) and onion (*Allium cepa*), which are monocotyledonous crops, but grasses and grains (Poaceae) are usually not parasitized. In Assam, *Cuscuta* spp is reported to occur on 86 weed species (28 herbs. 27 shrubs, 20 trees and 11 climbers) (Barua *et al*. 2003).

Damage potential of *Cuscuta* in different field crops: The infestation of *Cuscuta* results in heavy loss in terms of quantity and quality of produce. Many times it may cause complete failure of the crops. The yield reductions due to *Cuscuta* are reported to the tune of 60-65% in chillies (Awatigeri *et al.* 1975), 31-34% in greengram and blackgram (Kumar and Kondap 1992), 60-65% in niger (Tosh *et al.* 1977), 87% in lentil and 85.7% in chickpea (Moorthy *et al.* 2003) and 60-95% in alfalfa (Narayana 1989, Mishra 2012) depending upon its intensity of infestation. The intensity of damage caused by *Cuscuta* depends upon its capacity to rapidly parasitize the host crop. Gidnavar (1979) found a reduction of yield in lucerne from 3145 grams to 1825 grams per square meter when infested with China dodder. Field experiments conducted at the NRCWS, Jabalpur revealed that frenchbean, mustard, wheat, rice and cowpea were not affected by the *C. campestris* infestation as evidenced by no yield reduction. The other crops, *viz.* chickpea, lentil, greengram, niger and sesame were highly affected while pea, linseed, soybean, blackgram, groundnut and pigeonpea were moderately affected.

Beg *et al.* (1968) reported the growth of cuscuta spp. caused a ma~ked reduction in total phosphate content of *medicago sativa* (L.). They also observed that destructive feature of parasite was the higher content· of phytic acid in comparison to the host plant. *Cuscuta compestris* absorbed one fourth of the total nitrogen content of balsam *(Impatiens balsamina)* Mishra and Saxena (1971). Rao *et al.* (1985) reported a reduction of 33.2 per c’ent in dry matter of greengram infested with cuscuta when compared to fluchloralin treated plot at the rate of 1.87 kg per hectare. Setty (1971) reported that the *Cuscuta* spp.reduced the protein content of *Petunia hybrida.* Similar study made by Singh (1971) revealed a reduction in starch concentration of *Petunia hybrida* when it was infested by *Cuscuta* spp.

Infestation of *Cuscuta* results in heavy loss in host crops. Experiments conducted at Jabalpur revealed that increasing densities of *Cuscuta* decreased the seed yields of all the crops. The loss in seed yield of the crop due to *Cuscuta* from 1 to 10/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, niger, lentil and chickpea (Mishra 2009).

Effect of time and concentration of sulfuric acid seed treatment on germination of *Cuscuta*: Rao (1986) observed that dormancy of *Cuscuta* seeds was broken by scarification in concentrated H2so4 for 30 minutes.Results of a laboratory experiment conducted at Jabalpur indicated that the germination of *Cuscuta* seeds started two days after treatment. Maximum germination was recorded when treated for a period of 60 minutes. The 100 per cent germination was recorded at 3 days after sowing when treated for 45 minutes, however 30 and 60 minutes timings were at par with 45 minutes. This shows that fresh *Cuscuta* seeds must be treated with concentrated sulfuric acid for a minimum of 30 minutes to obtain maximum germination (Mishra 2009).

Emergence of *Cuscuta* seedlings and contact with host plants: *Cuscuta* seeds are very small. They can not emerge when placed deep in the soil (Mishra *et al.* 2003a). The results showed the *Cuscuta* seedlings started emerging within 4 days from surface to 4 cm depth. Higher emergence was recorded at 8 days after sowing from surface to 4 cm depth and thereafter some *Cuscuta* seedlings showed mortality. Maximum seedling emergence was recorded at the surface sowing closely followed by 2 and 4 cm depths. Further increase in seeding depths significantly reduced its emergence and there was no emergence beyond 8 cm seeding depth. Delayed and decreased seedling emergence at deeper depth seems to be due to mechanical impedance, poor aeration and shorter length of coleoptiles of *Cuscuta* seeds. Bhattacharya (1969) observed that phosphate was found to accumulate in the zone of contact between the parasite and host. Redistribution of phosphate in the upper leaves of the infested host was considerably reduced as compared with that in un-infested plants. Rao and Gupta (1981) reported that *Cuscuta* spp. prevailing in coastal Andhra Pradesh would be yellow coloured twining stems which flowered in 25 to 30 days after germination and twining stems not only deprived the host. Plant nutrients but also inhibited formation of pods in I host plants.

Reproductive Characters of *Cuscuta*: A well- established single plant of *Cuscuta* produces seeds from 16,000 to more than one lakh seeds, which remain viable for many years (Sandip *et al*. 2014). Mishra (2009) studied the seed producing capacity of *C. campestris* in niger and reported that a single plant of this weed can produce more than one lakh seeds. Details are given below:

- Number of fruit bunches/plant: 3696
- Number of fruits/bunch: 17
- Number of fruits/plant: 38475
- Number of seeds/fruit: 3
- Number of seeds/bunch: 38
- Number of seeds/plant: 116973
- 1000 seed weight (g): 0.78
- Seed weight / plant (g): 83.81

Control measures

It is extremely difficult to achieve effective control of *Cuscuta* because its seeds have a hard seed coat, can remain viable in soil for many years and continue to germinate and emerge throughout the year. In addition, the nature of attachment and association between host and parasite requires a highly selective herbicide to destroy the parasite without crop damage.

Prevention

Seeds of *Cuscuta* are transported as a contaminant of seed of crops such as alfalfa and clover. Consequently, most *Cuscuta* problems have originated from human carelessness in transporting and planting contaminated crop seed. *Cuscuta* persists and spreads within infested fields through further agricultural activities, by periodic onsite seed production, and because the seed may remain viable for several years in the soil.

"Prevention is better than cure". The best method of controlling *Cuscuta* in cropland is to prevent its introduction onto a field. Planting crop seed contaminated by *Cuscuta* seed has been the major means of *Cuscuta* spread.

Therefore, the crop seeds should completely be free from *Cuscuta* seeds. Strict seed laws and programs of seed certification are required to reduce the crop seed contamination by *Cuscuta*. Great care must be exercised in moving machinery or livestock between fields, so that seed within harvesting machines, in mud on wheels of machinery, in mud or manure on animal hooves, or within the digestive systems of animals is not moved to clean fields.

Destruction of individual plants

Awareness and vigilance are important companions to prevention in managing *Cuscuta*. Farmers should be aware of the serious threat of *Cuscuta*. They should watch for *Cuscuta* so that any plants discovered can be destroyed. When an individual *Cuscuta* plant is found, it should be dried and burned before it produces any seed.

Cultural and mechanical methods

Various cultural practices will kill, suppress, or delay *Cuscuta*. Such control methods are inexpensive and can be combined with other methods to develop integrated management systems for *Cuscuta*.

Stale seedbed preparation: Under favourable conditions, *Cuscuta* seeds germinate without host plant and seedlings die after 8 days in absence of host. Shallow tillage or spraying of non-selective herbicides (glyphosate or paraquat) after seedling emergence but before sowing of crop reduces the *Cuscuta* infestation. Allowing *Cuscuta* to germinate and then destroying it by tillage gave some control and when combined with hand plucking, complete control was achieved (Sher and Shad 1989.)

Hand pulling: Hand-pulling is the simplest and most effective method of controlling *Cuscuta*. In this practice, it is necessary to pull the infested host plant together with the parasite. If flowering and seed set has already occurred, the pulled material must be removed from the field and eventually burnt. Sher and Shad (1989) however, reported that manual control (hand plucking) does not give effective control of *Cuscuta*.

Crop rotation: *Cuscuta* does not parasitize members of the Poaceae. Hence it can be controlled completely by crop rotation. Without a host plant nearby, *Cuscuta* seedlings emerge and die. Broad-leaf weeds must be controlled in such crops to deprive *Cuscuta* of all hosts, so that no new *Cuscuta* seed is produced. During each year without host plants, the reservoir of *Cuscuta* seed in the soil will be reduced. Nevertheless, some hard seed of *Cuscuta* usually remain viable and present a potential problem to susceptible crops for many years.

Time and method of planting: Unlike root parasites, *Cuscuta* seeds do not require a specific stimulant from hosts to induce germination. However, seedlings die after 8-10 days in the absence of host. Hence, delay in host planting by 8-10 days reduces the *Cuscuta* infestation. *Cuscuta* is very sensitive to shade. Therefore, the crop management practices that favour vigorous crop growth would suppress the growth of *Cuscuta*. However, if the main flush of *Cuscuta* germinates before the crop is well established, this will be ineffective. The shade from dense crop foliage suppresses the *Cuscuta* significantly to control it almost completely.

Mixed cropping: There is some possibility for control of *Cuscuta* by mixed cropping of host crop with non-host crops. The pulse crops can be partially protected from *Cuscuta* parasitism by growing the *Cuscuta* resistant clusterbean (*Cyamopsis tetragonoloba*) along with greengram or blackgram in a mixed cropping system (Rao and Reddy 1987, Reddy and Rao 1987).

Resistant crops and varieties: Crop species and cultivars are known to differ in their competitiveness with weeds. There are genotypic differences with regards to tolerance to *Cuscuta* infestation. The penetration of haustoria to the host plant depends on several factors such as reaction on the external attachment of the haustorium to the host surface, growth behaviour of the haustorial cells within the host tissue, reaction of the protoplasts of the parasitic cells and reaction of the host tissue. The vigorous growth of some cultivars, high pubescence and hardness of stems may restrict the entry of parasite into the cultivars. This offers opportunities to select and breed for competitive cultivars that can be adopted by the farmers as a part of integrated weed management programme. There has been only limited interest in developing *Cuscuta*-resistant crop varieties, and presently no resistant varieties of normally susceptible species have been developed. Lucerne variety '*T9*' was found to be highly sensitive whereas '*LLC 6*' and '*LLC 7*' were moderately tolerant to *Cuscuta* infestation (Narayana 1989). Greengram variety '*M2*' and blackgram variety '*T9*' were tolerant to *Cuscuta* as compared to other varieties (Kumar and Kondap 1992). Mishra *et al.* (2006) evaluated 14 linseed varieties, *viz.* '*Garima*', '*Parvati*', '*JLS-27*', '*NL-97*', '*R-17*', '*Padmini*', '*J-23*', '*Meera*', '*Shekhar*', '*T-397*', 'Sweta', '*Shubhra*', '*Sheela*' and '*JLS-9*' for their relative tolerance against *Cuscuta campestris* at Jabalpur and found that different varieties varied significantly in their response to *Cuscuta* infestation. Reduction in seed yield due to *C. campestris* in different varieties varied from 7.26% in '*Garima*' to 44.29% in '*J 23*' indicating that '*Garima*' as the most tolerant linseed variety against *C. campestris*.

Mechanical methods

In any crop grown in rows, such as alfalfa grown for seed production, sugarbeets, carrots, or onions, timely cultivation can kill *Cuscuta* seedlings and their potential weed hosts. Once *Cuscuta* is attached to the host plant, mechanical removal of the part of the host bearing the *Cuscuta* will control the parasite. Such selective pruning may be practical in woody crops such as citrus or in woody or herbaceous ornamentals.

Cuscuta seeds do not germinate if placed deeply (Mishra *et al.* 2003a). Deep ploughing of *Cuscuta*-infested land should greatly reduce the chances of the parasite and establishing from the most recently shed seed but older seed in the soil may be brought to the surface by this practice. Rotation in tillage i.e. deep ploughing in one season followed by shallow or minimum tillage for some years may be done to avoid bringing seeds back to the surface.

Chemical control

Nonselective foliage-applied herbicides: Because *Cuscuta* is an obligate parasite and cannot live without a host plant, any herbicide that kills the host will also destroy the *Cuscuta*. Contact herbicides such as paraquat and diquat and translocated herbicides such as glyphosate kill *Cuscuta* effectively, but they also kill the host foliage on which it is growing. As the contact herbicides are not translocated, they kill only the parts of plants that they contact directly. Such nonselective destruction is useful for treating scattered patches of *Cuscuta* and thereby preventing seed production and expansion of an infestation.

Selective soil-applied herbicides: Several soil-applied herbicides were found to kill *Cuscuta* seedlings before or soon after they emerge from the soil. Such treatments keep the *Cuscuta* from becoming attached to the host plant. Various crop plants tolerate these herbicides. Consequently, *Cuscuta* can be controlled selectively when these herbicides are applied appropriately. Fluchloralin 1.5 kg/ha as pre-emergence (Kumar 2000) and 1.0-1.25 kg/ha as pre-plant soil incorporation (Mishra *et al.* 2004, Rao and Gupta 1981) controlled *Cuscuta* effectively in blackgram. Pendimethalin 0.5-1.5 kg/ha applied as pre-emergence controlled *Cuscuta* in niger (Mishra *et al.* 2005), blackgram (Mishra *et al.* 2004), linseed (Mahere *et al.* 2000), onion (Rao and Rao 1993), chickpea and lentil (Mishra *et al.* 2003). Misra *et al.* (1977) observed that pre-emergence application of pronamide at 1.0 to 1.5 kg/ha was successful in inhibiting the germination of dodder (*Cuscuta*) seeds. Tosh *et al.* (1977) reported that pronamide and chloropropham 1.5 kg/ha and 4 kg/ha, respectively, controlled *Cuscuta* effectively in niger.

Gupta and Lamba (1978) reported that application of pronamide at 0.1% controlled *Cuscuta* but the host foliage was damaged by spray. Tosh and Patro (1975) stated that application chloropropham at 4 kg/ha applied on the day following the initiation of dodder controlled the dodder without damaging niger. Nagar and Sanwal (1984) reported that *Cuscuta* already attached to a host plant was killed when sprayed with 0.1 M solution of calcium chloride. Promising control of dodder in niger crop by pronamide has been reported (Misra *et al.* 1981). Pre-emergence application of pronamide at 1.5 kg /ha although controlled the parasite but found phytotoxic to balackgram (Kumar 2000). Barevadia *et al.* (1998) reported that application of pendimethalin at 0.50 kg/ha as pre-emergence and at 4 days after sowing (DAS), and fluchloralin at 0.50 kg/ha as pre-plant incorporation and at 4 DAS showed severe phytotoxicity to lucerne seedlings.

Selective foliage-applied herbicides: *Cuscuta* can regenerate freely from isolated haustoria within the host stem. When glyphosate at 50 g/ha was applied as post-emergence to control *Cuscuta* in niger, chickpea and lentil, it killed the extended vines of *Cuscuta* and checked its growth for a period of 25-30 days. There after the parasite grew in bunches from imbedded haustoria and infested the crop plants at later stage of growth. In contrast, glyphosate applied to alfalfa foliage controlled *Cuscuta* better because it contacted the imbedded haustoria during translocation from host to parasite. Nevertheless, glyphosate seldom killed all of the attached *Cuscuta*. Some imbedded haustoria usually survived and new shoots regenerated from this surviving tissue. Pendimethalin at 0.50 kg/ha applied at 2 weeks after sowing effectively controlled the *C. campestris* in lucerne and berseem without damaging the crop (Trivedi *et al.* 2000, Mishra 2009). Its pre-emergence application was, however, phytotoxic to both the crops.

***Striga* spp.**

Striga, commonly known as witch weed, is a from family *Scrophulariaceae* that occur naturally in parts of Africa, Asia, and Australia, is a major biotic constraint in the subsistence agriculture and causes considerable crop damage in millets in the semi-arid tropics. In India, incidence of *Striga* alone causes 75% reduction in grain yield of sorghum (Nagur *et al.* 1962, Rao 1978). In India, Barber (1901) first reported the occurrence of *S. angustifolia* in sugarcane. It was also reported to parasitise pearl millet, maize, sorghum, sugarcane and rice. It is known to occur in almost all states where sugarcane is grown in India. Cane yield reduction of up to 36 per cent was reported by Khanna (1978). *Striga lutea* is a native of India and attack sorghum and sugarcane severely. It is dominant in lighter soils, dry climate and low rainfall areas. Sharma *et al.* (1956) reported heavy damage to sugarcane by *S. lutea* in Bihar. Hosmani (1978) reported that yellow flowered types of *S. asiatica* occur in main tract of Karnataka state in India.

Witch weed parasitizes maize, millet, sorghum, sugarcane, rice, legumes, and a range of weedy grasses. It is capable of significantly reducing yields, in some cases wiping out the entire crop. Three species cause the most damage: *Striga asiatica, S. gesnerioides,* and *S. hermonthica*. Witch weeds are characterized by bright-green stems and leaves and small, brightly colored and attractive flowers. They are obligate hemiparasites of roots and require a living host for germination and initial development, though they can then survive on their own. Although most species of *Striga* are not pathogens that affect human agriculture, some species have devastating effects upon crops, particularly those planted by subsistence farmers. Host plant symptoms, such as stunting, wilting, and chlorosis, are similar to those seen from severe drought damage, nutrient deficiency, and vascular disease.

Life cycle: Each plant is capable of producing between 90,000 and 500,000 seeds, which may remain viable in the soil for over 10 years. Most seeds produced are not viable. Its seeds germinate in the presence of host root exudate, and develop haustoria which penetrate host root cells. Host root exudate contain strigolactones, signaling molecules that promote striga seed germination. A bell-like swelling forms where the parasitic roots attach to the roots of the host. The pathogen develops underground, where it may spend the next four to seven weeks before emergence, when it rapidly flowers and produces seeds. Witch weed seeds spread readily via wind and water, and in soil via animal vectors. The chief means of dispersal, however, is through human activity, by means of machinery, tools, and clothing.

Haustorium development: Once germination is stimulated, the *Striga* seed sends out an initial root to probe the soil for the host root. The initial root secretes an oxidizing enzyme that digests the host root surface, releasing quinones. If the quinone product is within the appropriate concentrations, a haustorium will develop from the initial root. The haustorium grows toward the host root until it makes contact with the root surface, establishing parasitic contact in relatively short order. Within 12 hours of initial haustorium growth, the haustorium recognizes the host root and begins rapid cell division and elongation. The haustorium forms a wedge shape and uses mechanical force and chemical digestion to penetrate the host root, pushing the host cells out of the way. Within 48–72 hours, the haustorium has penetrated the host root cortex. Finger-like structures on the haustorium, called oscula (from Latin osculum, "little mouth") penetrate the host xylem through pits in the membrane. The oscula then swell to secure their position within the xylem membrane. Striga sieve tubes develop along with the oscula. Shortly after the host xylem is penetrated, Striga sieve tubes develop and approach the host phloem within eight cells. This eight cell layer allows for nonspecific nutrient transport from the host to the Striga seedling. Within 24 hours after tapping the host xylem and phloem, the Striga cotyledons emerge from the seed.

Environment

Temperatures ranging from 30 to 35 °C (86 to 95 °F) in a moist environment are ideal for germination. Witch weed will not develop in temperatures below 20 °C (68 °F). Agricultural soils with a light texture and low nitrogen levels tend to favor Striga's development. Still, witch weed has demonstrated a wide tolerance for soil types if soil temperatures are favorably high. Seeds have been shown to survive in frozen soil of temperatures as low as "15 °C (5 °F), attesting to their aptitude as overwintering structures. Soil temperature, air temperature, photoperiod, soil type, and soil nutrient and moisture levels do not greatly deter the development of witchweed.

Adaptation of *Striga* to parasitism includes not only dependence upon a host plant for metabolic inputs such as water, minerals, and energy, but also for developmental signals. In this way, parasite and host development are highly integrated. The early host derived chemical signals Striga requires, for seed germination and for nitiation of the haustorium by which it attaches to the host roots, are exuded from host roots into the soil. After Striga penetrates the host root, subsequent developmental signals are apparently exchanged directly, through vascular tissue. Germination stimulants for most Striga hosts have been identified as strigol-type compounds (strigolacetate).

Yield reduction caused by *Striga* sp.: Heavy crop losses are caused by *S. asiatica* on sorghum in Maharashtra (Joglekar *et al.* 1959), Karnataka (Kajjari *et al.* 1967) and Andhra Pradesh (Nagur *et al.* 1962). In Andhra Pradesh, both *S. asiatica* and *S. densiflora* were known to attack sorghum and the yield loss may range from 15 to 75% depending upon severity of infestation (Venkateshwara Rao *et al.* 1967).

Shanmugasundaram and Venkataraman (1964) from Tamil Nadu reported 50% loss in sorghum grain yield due to *Striga* infestation. He noted yield loss at a rate of 1 kg of grain/1500 *Striga* plant/ha. Thus, this root parasite reportedly caused about 70% yield loss in Sudan and 60% in Nigeria (Rana *et al.* 1980).

Management of striga spp.

Preventive methods: Quarantine the infested area, prevent the spread through seeds, planting materials, implements, manure, animals, human beings *etc*. Use of clean and certified seeds may be one preventive methods In soil previously infested with *Striga.* deep ploughing incorporates *Striga* seeds well below the root zone and prevents stimulants reaching the parasite's seeds. This method will lower the menace of *Striga* considerably.

Soil solarisation: with 0.05 mm thick white polyethylene sheets for 30-40 days during hot summer; though expensive can lower the *Striga* menace by 60-80% in the host crops grown after solarisation. This technology will effectively reduce several soil borne pathogens and pests.

Hand pulling: is valuable where *Striga,* plants in the crop fields are few, and it is a futile exercise in a heavily infested field and expensive. Use of trap crops *(Striga* germination stimulating crops with inherent attachment barriers i.e. produce stimulants to germinate *Striga* seeds, which will be a suicidal germination, as germ tube fail to have attachment with non-host crops) - cotton, linseed, cowpea, chickpea, pigeonpea, greengram, blackgram, groundnut, castor, sunflower, sesamum, melons. *Celosia argentea*. sunhemp *(Crotalaria* spp.) are often suggested as possible means to reduce *Striga* populations. Crop rotation of host crops with these trap crops will considerably lower the menace of *Striga* by depleting the seed bank through suicidal germination during fallow phase.

Catch crops susceptible host crops: *Setaria*, maize (more *Striga* susceptible), may be taken up in high density before the main crop. The catch crops are harvested or ploughed and incorporated after 6 to 8 weeks before the parasite reproduce and thus lower the seedbank in the soil considerably. One catch crop will exhaust the *Striga* seeds in the soil, but in severe infested soil, two or three catch crops may be necessary to reduce witchweed infestation. Subsequent taking up main crop will have reduced density of *Striga.*

Crop rotation: Infestation *of Striga* builds up to a severe level in mono-cropping area. Therefore rotation of trap crops (cotton, groundnut, linseed, cowpea, gram, redgram, sunhemp) with main host crops for at least 2-3 seasons will lower the seed n the soreservoir iil and favour higher yields in host crops. It is generally agreed that for the subsistence farmers of the tropics, the development of resistant varieties of sorghum (*N-13, No. 148/168 (CSV-5*). For instance, the new hybrids of pearl millet arc appeared to be free from *Striga* under Indian conditions.

Improving soil fertility through manures and fertilizers (application at higher dosage or at recommended level) enhance the growth of crops which offer better competition to *Striga* and lower its damage potential. Improved fallows by adopting agro forestry technology reduced *Striga* infestation through the trees in the fallow system act as false hosts and cause suicidal germination of *Striga* seeds, increased mineral nitrogen in the top soil at the end of fallows and nitrogen mineralization in the subsequent cropping phase; production *of Striga* stimulant in the process of leaf litter decomposition; enhanced microbial activity following the incorporation of organic residues in the soil affect *Striga* seed conditioning and seed viability and improved soil fertility enabling crops to better compete with *Striga* and reduce its damaging potential (Rao and Gachcru 1998). Intercropping with legumes (greengram, cowpea, soybean, red gram, silver leaf) along with main host crops also appeared to lower the competition of *Striga* due to improvement in the soil fertility and also suicidal germination *of Striga.* Thus, enhanced soil fertility low^{r}ers the menace *of Striga* due to reduced growth of the parasite with concomitant increased vigour of host plants. *Striga's* infestation is usually less in the wet season, in adequately N fertilised plots, and in densely sown crops.

Use of mulch: Mulching will reduce *Striga* infestation and enhance yield of host crops - maize, sugarcane, sorghum. Pre-emergence application of atrazine or metribuzin at 1.0 kg/ha followed by trash mulching at 3-5 t/ha in between rows of sugarcane at 60 DA P effectively lower the *Striga* emergence and enhance cane yields.

Use of herbicide: Directed applications of 2,4-D Na salt at 1.0-2.0 kg/ha is a very practical alternative to this for breaking future populations of *Striga* in sorghum, maize, sugarcane. 2,4-D amine salt is applied at 0.5-0.75 kg/ha, 2-3 times during the crop season to destroy flushes of *Striga* in its vegetative phase in sugarcane. However, sorghum is vulnerable to stalk twisting and lodging if 2,4-D is sprayed in to leaf whorl, hence proper precautions should be taken while spraying. Further directed application of paraquat (5 ml/liter of water) on the emerging *Striga* population at the base of the host plants will effectively kill *Striga* and reduce future population. Use of pre-emergence or early post-emergence of oxyfluorfen 0.09-0.12 kg/ha can lower the menace of *Striga* in maize and sorghum. Use of imazethapyr 10 SL 45 g/ha or pyrithiobac 21 g/ha as seed dressing, priming and coating to ALS resistant sole maize will lower *Striga* meance by 80% and improve the yield substantially. Singh *et al.* (2001) opined that pre-emergence application of metribuzin or atrazine both at 1.0 kg/ha followed by trash mulching at 3-5 t/ha in between the rows in sugarcane at 60 DAP provided effective control of *Striga* with higher cane yield compared to pre and post-emergence herbicide applications. 2,4-D or MCPA at 1 to 2 kg /ha at flowering to just before seed set was found effective in controlling *Striga* in India (Chopde *et al.* 1973, Yaduraju 1975).

Use of stimulants like strigol, GR 7, GR 45 and like compounds as pre-plant incorporation in sick soil at 0.1-1.0 kg/ha before sowing of main host crops was found to lower striga population by 50%. The stimulants will be effective on moist soil for at least 3-4 weeks and when the temperature is about 20°C. The probability of *Striga* making a successful attachment with host plant after ethylene stimulation is rare. Thus, a successful ethylene and methyl bromide fumigation treatments induce suicidal germination and thus achieve 90% reduction in *Striga* population of the plough layer of the soil, as practiced in US. However, this is not practicable for the arid farmers. Further research to develop chemical stimulants of varied strains of *Striga.* timing of soil treatment with the stimulants and the planting of crops needs to be worked out properly. Isolated infestations of *Striga* growing on some host weed species, outside the field boundaries, should also be destroyed with any non-slective herbicide (paraquat 2.5-5.0 ml/liter of water) or glyphosate 8.0-10.0 ml/liter of water) to prevent its seed production and further perpetuation to the main field.

Biological control: Natural enemies of *Striga* species include insects belonging to Coleoptera, Diptera, Hymenoptera and Lepidoptera, numerous fungi and few bacteria (Hosmani 1978). Many phytophagous insects have been collected on *Striga* sp. but most of them are polyphagous and the target weed species are often not their principal host plants. Sankaran and Rao (1966) and Sankaran *et al.* (1969) reported two *Eulocastra* spp. feeding on fruits of *S. hermonthica, S. asiatica* and *S. densiflora*.

***Loranthus* spp (Mistletoes)**: Mistletoes, Loranthaceae and Santalaccae - two principal families, are obligate, semi/hemi-stem parasite, most troublesome weeds of tree crops and bushes. Loranthaceae has 70-77 genera with 803-1000 species and Santalaceae has 7-11 genera with 450-577 species. Flowers in Santalaccae are small and inconspicuous, whereas those of Loranthaceae arc large, colourful and calyculus.

In India, mistletoes belonging to the genera *Dendrophthoe* and *Viscum* are most commonly observed causing damage on coffce, citrus, guava, tamarind. *Ficus* spp., *Annona sqamosa, Acacia nilotica, Alhigia lebheck, Moringa* spp and other fruits and ornamental trees.

The genus *Dendrophthoe* comprises about 31 species spread across tropical Africa, Asia, and Australia. In India, 7 species are found from sea level to 3500 m in Himalayan hills. *D. jalcata* bears grey barks, thick coriaceous leaves variable in shape with stout flowers. Two varieties are: *D. falcata* var. *coccinea* (red flowers), and *D. jalcata* var. *jalcata* (greenish white flowers). Mistletoes attack numerous trees and shrubs of forests and plantations bringing untimely death of the host plant. In forests, they are reported to reduce the productivity of both timber and related forest products.

Mistletoes affect host foliage, phenology and respiration: reduce growth, yield, quality and increase operational and protection cost of plantation. In trees, the parasite enters the entophytic system, invades the bole / heartwood and thus affects wood quality. Wood quality is also affected by production of larger knots and other altered physical properties. They also alter the pattern of plant succession, and disturb the vegetation pattern of the landscape. In many parts of India, it occurs on almost all forest trees, high value timbers (teak. rose. sandalwood. eucalyptus, casuarina, neem. copperpod. banyan. ficus, flame of the forest), fruit/commercial trees (mango, citrus, sapota. guava. pomegranate, cocoa, coffee). Occurrence of *Dendrophthoe* spp has not been observed on Tamarind in Karnataka. Mango, sapota and cashew plantations are some of the most seriously affected ones.

Seed dispersal and pollination is usually mediated by the birds that thrive on fruits from the parasite and or host. In southern India, Ticket's flowerpecker (also called the pale-billed flowerpecker) is reported to facilitate seed dispersal of *D. jalcata* among neem plants through fecal excretions or regurgitations (Karunaichamv *et al.* 1999). This method of dispersal is expected to occur even on other tree species also.

Management of loranthu sp.

- Lopping off or pruning of the shoots (stems and leaves) (the portion below the mistletoe contact with the shoot) infected with mistletoes to prevent further growth and spread in the initial stage itself (Prasad *et al.* 2002).
- The shoots of the mistletoe can also be removed, which if done before seeds are set, will help to reduce the number of new infections originating from this seed source.
- Mistletoe shoots will regrow from the improperly pruned infection area. It is also important to remember that this method is only a temporary solution and does not prevent the introduction of seeds from other infected neighbouring trees.
- Scraping the bark of the parasite at the point of attachment of the haustoria on the tree, then place cotton pad/foam containing 1 g 2.4-D Na salt 80 WP in 20 ml water or with 8.0 g copper sulphate and 1.0 g 2,4-D sodium salt and covering with tape to ensure entry of the chemicals into the host plant through haustoria in an effective method. Directed spraying of ethrcl (Ethephon 39 SL) 25 ml/litre or 10% on the parasite causes complete defoliation without harming the host plants and regrowth do not occur for at least 6 month. The second spray can be repeated on the regrown mistletoe to weaken its growth and gradually wardoff the mistletoe.
- Pruning of leafy mistletoe clumps to 2.5 cm and the spraying with 5-10 ml of diethanolamine salt of 2,4-D (1.33%) + dicamba (0.44%) (Super D Weedone) minimized sprouting of mistletoe for *a* year. Second spray becomes inevitable to check mistletoes' further spread.

Conclusion

The worldwide research on management of parasitic weeds has been in progress for at least 100 years. In India, systematic research works on these weeds was initiated in late seventies. There are many examples of dedicated work leading to useful control, based on resistant varieties, cultural, chemical, or integrated methods providing near-adequate suppression of problems on at least a local basis. However, in spite of all these efforts, it has been observed that the major problems have not been reduced to any significant degree, and in the case of

Orobanche and *Loranthus* there may even continue to be some spread and intensification of the problems in many crops. It is improbable that many of these species will be completely overcome in the foreseeable future, but there has to be continued effort on the most important, species. This short review emphasises the enormous scale of losses from the full range of parasitic weeds in India and the need for sustained, and where possible, increased effort to find economic solutions for the sake of the farmers and growers affected and for the sake of maintaining food, fruits and timber supplies.

References

Acharya BD, Khattri GB, Chettri MK, Srivastava SC. 2002. Effect of *Brassica campestris* var. *toria* as a catch crop on *Orobanche aegyptiaca* seed bank. *Crop Protection* **21**: 533–537.

Anonymous 2011. Use of fungi against *Orobanche* in mustard. Annual Report. AICRP Weed Control, CCS HAU Hisar

Anonymous 2013. Front line demonstration for the control of *O aegyptiaca* in mustard. pp. 109–114. In: *Annual Progress Report,* AICRP on Weed Control, CCS HAU Hisar.

Anonymous 2014. Biology of *Orobanche aegyptiaca* in mustard. In: *Annual Progress Report,* AICRP on Weed Control, CCS HAU Hisar.

Awatigeri MB, Hosmani MM, Shetty RA, and Vijaya KN. 1975. *Current Research* (Monthly Newsletter), *University of Agricultural Sciences, Bangalore* **4**: 47–48.

Barber C. 1901. Sugarcane disease in Godavari and Ganjam districts. *Madras Dept. Agrl. Bull.,* **2**: 181–193.

Barevadia TN, Moisuriya MT and Patel BH. 1998. Control of C*uscuta* in forage lucerne. *Indian Farming* **48**(5): 10–11.

Barua IC, Rajkhowa DJ, Deka NC and Kandali R. 2003. Host range study of *Cuscuta reflexa* Roxb. In Assam. *Indian Journal of Forestry* **26**(4): 414–417.

Beg MU *et al.* 1968. Biochemical aspects of parasitism by the engiosperm parasites, Part 3, Phytic acid and other forms of acid soluble phosphate in angiosperm parasites and hosts. *Indian Journal of Biochemistry* **5**(4): 157–160.

Bhattacharya MK. 1969. Evidences of bidirectional flow of inorganic nutrients between host and parasite during *Cuscuta* infection. *Phyton. B Aires* **26**(1): 23–6.

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

Chopde PR, Shinde VK and Sewlikar AL. 1973. Screening sorghum varieties for resistance to *Striga lutea* Lour. *Sorghum Newsletter* **16**: 57–58.

Dhanapal GN and Struik PC. 1996. Broomrape control in a cropping system containing bidi tobacco. *Journal of Crop Science* **177**(4): 225–236.

Dhanapal GN Ter Borg SJ and Struik PC. 1998b. Post–emergence chemical control of nodding broomrape (*Orobanche cernua*) in bidi tobacco (*Nicotiana tabacum*) in India. *Weed Technology* **12**(4): 652–659.

Dhanapal GN. 1996. Management of broomrape (*Orobanche cernua*) in tobacco (*Nicotiana tabacum*). 183 p.

Dinesha MS and Dhanapal GN. 2014. Broomrape parasitic weed biology and its management with herbicides in naturally infested tomato field. pp. 303. In: *Extended Summary, Biennial Conference of Indian Society of Weed Science on emerging Challenges of Weed Management*, DWSR, Jabalpur, February 15–16.

DWR. 2009. Proceedings of AICRPWC Biennial Workshop. Directorate of Weed Science Research, Feburary 28–March 1, 2009 *AAU, Anand* **99**: 5–6.

Gaur RD. 1999. *Flora of the District Garhwal,* North West Himalaya, Transmedia, Srinagar Garhwal, pp. 443–444.

Gidnavar VS. 1979. *Cuscuta* – a serious shoot parasite on lucerne. *Current Research Monthly Newsletter of University of Agricultural Sciences Bangalore*, **8**(12): 201–202.

Goyal KS, Das B, Singh R. and Mohanty A K. 2006. Influence of the thermal environment on phenology, growth and development of mustard varieties. *Journal of Oils & Crops*, **16**(2): 283–290.

Gupta and Lamba 1978 *Biology and control of special weeds*. Modern Weed Science. p. 335–336.

Hiralal, Singh D. and Jat B.L. 2016. *Orobanche* infestation in Indian *Brassica juncea* L. in Ajmer districts of Rajasthan and its management. *Asian Journal of Environmental Science* **12**(1): 1–22.

Hosmani MM. 1978. *Striga – a noxious root parasitic weed*. University of Agricultural Sciences, Dharwad. India, p.66.

Joglekar RG, Hardas MG and Deshmukh NY. 1959. A short note on control of weeds *Striga*. *Indian Journal of Agronomy*, **4**: 114–118.

Kajjari NB, Hiremath PS and Renukarya MK. 1967. Sorghum variety BH 4–1–4 tolerant to witchweed, downy mildew and rust. *Sorghum Newsletter* **10**: 51–53.

Karunaichamv KSTK, Paliwal K and Arp PA. 1999. Biomass and nutrient dynamics of mistletoe (*Dendrophthoe falcate*) and neem (*Azadirchta indica*) seedlings. *Current Science* **76**(6): 840–843.

Khanna KL. 1978. *Annual Report.* Central Sugarcane Research Station, Pusa, Bihar, p. 118.

Krishnamurthy GVG, Nagarajan K and Lal R. 1977. Further studies on the effect of various crops on germination of *Orobanche* seed. PANS **23**: 206–8.

Krishnamurthy S and Rao UM 1976. Control of *Orobanche* through crop rotation. *Indian Farming* **25**: 23.

Kumar S. 2002. Preliminary studies on the control of broomrape in mustard. *Indian Journal of Weed Science* **34**(3&4): 303–304.

Kumar RM. 2000. Effect of herbicides on the control of parasitic weed *Cuscuta* in blackgram (*Vigna mungo*). *Journal of Research*, *ANGRAU* **3**: 1–5.

Kumar RM and Kondap SM. 1992. Paper presented at the *National Seminar on Changing Scenario in Pest and Pest Management*, CPPTI, Hyderabad.

Mahere J, Yadav PK and Sharma RS. 2000. Chemical weed control in linseed with special reference to *Cuscuta*. *Indian Journal of Weed Science* **32**: 216–217.

Misra A, Tosh GC, Mohanty DC and Patro GK. 1977. Herbicidal and selective effect of pronamide for control of dodder in Niger. Abstract of Papers of, Weed Science Conference. Hyderabad pp. 13.

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

Mishra J S, Moorthy BTS and Bhan Manish. 2005. Relative tolerance of *kharif* crops to dodder and its management in niger. pp. 213–214. In: *Extended Summaries. National Biennial Conference, ISWS,* April 6–9, 2005. PAU, Ludhiana.

Mishra JS, Bhan Manish and Moorthy BTS. 2003b. Efficacy of herbicides against *Cuscuta* in winter pulses. pp. 190–191. In: *Abstract, National Symposium on Pulses for Crop Diversification and Natural Resource Manage.* December 20–22. ISPRD, IIPR, Kanpur.

Mishra JS, Bhan Manish, Moorthy BTS and Yaduraju NT. 2004. Bio–efficacy of herbicides against *Cuscuta* in blackgram [*Vigna mungo* (L.) Hepper]. *Indian Journal of Weed Science* **36**: 278–279.

Mishra JS, Bhan Manish, Moorthy BTS and Yaduraju NT. 2003a. Effect of seeding depth on emergence of *Cuscuta* with linseed and summer blackgram. *Indian Journal of Weed Science* **35**: 281–282.

Mishra JS. 2012. Management of dodder in Lucerne and Egyptian clover. *Indian Journal of Weed Science* **44**(1): 6–10.

Mishra JS, Moorthy BTS and Gogoi AK. 2006. *Biology and management of Cuscuta* spp. *NRCWS Technical Bulletin No.* 8. National Research Centre for Weed Science, Jabalpur (M.P.).

Misra A, Tosh GC, Mohanty DC and Patro GK.1977. Herbicidal and selective effect of pronamide for control of dodder in niger. pp. 13. In: *Abstracts of papers of Weed Science Conference, Hyderabad*.

Misra PC and Saxena VR. 1971 Nitrogen metabolism in angiosperm parasites: Total nitrogen and its forms. *Indian Journal of Experimental Biology* **9**(1): 172–74.

Misra A, Tosh GC, Mohanty DC and Patro GK. 1981. Herbicidal and selective effect of pronamide for control of dodder in niger. 255–257 pp. In: *Proceeding of 8th Asian–Pacific Weed Science Society Conference*, Bangalore, India.

Mondal AK and Mondal SP. 2001. Parasitic plants. *Science Reporter,* December, 2001. pp. 51–55.

Moorthy BTS, Mishra JS and Dubey RP. 2003. Certain investigations on the parasitic weed *Cuscuta* in field crops. *Indian Journal of Weed Science* **35**: 214–216.

Nagar R and Sanwal GG. 1984. Biochemical aspects of parasitism in *Cuscuta reflexa&* inhibition of cell wall degrading enzymes of *Cuscuta* by nonsusceptible plants. *Proceedings of third international national symposiums on parasitic weeds* ALEPPO, 175–183.

Nagur T, Sriramulu C and Sivaramakrishnai MA. 1962. Striga resistant culture No. 109. *Andhra Agricultural Journal* **9**: 145–148.

Narayana L. 1989. Management of *Cuscuta* in alfalfa. M.Sc. Thesis, Andhra Pradesh Agricultural University, Hyderabad, India.

Patel AG and Metha HM. 1989. Effect of solarization, summer ploughing and herbicide on weed control. *Indian Journal of Agronomy* **34**: 1151–153.

Pathak Aditi and Kannan C. 2014. A new cost-effective method for quantification of seed bank of Orobanche in soil. *Indian Journal of Weed Science* 46(2): 151-154.

Prasad TVR, Ashok Kumar TN, Denesh GR, Devendra R and Gowda RC. 2002. Loranthus (*Dendrophthoe*)–*a* parasitic weed of trees. *Weed News,* Jan–Mar, 2002.

Punia SS, Yadav A, Singh S, Sheoran P, Yadav DB and Yadav B. 2012. Broomrape: A threat to mustard cultivation in Haryana and its control measures, pp 105. In: *Proceedings of 1st Brassica Conference "Production Barriers & Technological options in Oilseeds Brassica"* March 2–3, 2012, CCS HAU, Hisar.

Punia SS, Yadav A, Yadav DB and Singh S. 2010. Management of *Orobanche aegyptiaca* in Indian mustard. pp. 174. In: *Proceedings of Biennial Conference of ISWS "Recent Advances in Weed Science-2010*" February 25–26, 2010, IGKVV, Raipur (Chhatisgarh).

Punia SS. 2016. Effectiveness of different measures on control of *Orobanche aegyptiaca* in Indian mustard. *Agriculture Research Journal* **53**(2): 276–279.

Punia SS, Duhan Anil, Yadav Dharam Bir and Sindhu VK. 2016. Use of herbicides against *Orobanche* in tomato and their residual effect on succeeding crop. *Indian Journal of Weed Science* **48**(4): 404–409.

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

Rana BS, Serink H.J.En, Rulto JK and Ochanda N. 1980. *Progress Report of 1980 LR Basic field document of UNDP/FAO*, Ministry of Agriculture, Nairobi, pp. 42.

Rao AN. 1978. Ecophysiological responses of crops and weeds against herbicides and their residues. PhD. Thesis, VikramUniversity, Ujjain, Madhya Pradesh, India

Rao KN, Rao AS and Reddy R.1985. Effect of different herbicides on control of Cuscuta in legumes. *Pesticides* **19**(6): 61–62.

Rao MR and Gacheru E.1998. Prospects of agroforestry *Striga* management. *Agroforestry Forum* **9**(2): 22–27.

Rao KN.1986.Weed management in *Rabi* pulses. APAU, RARS, Lam ARS, Guntur, AP.

Rao, K N and Gupta K M. 1981 Chemical control of *Cuscuta* in pulses and other crops. pp. 251. In: *Proceedings of 8th Asian Pacific Weed Science Society Conference*, 22-29 November, 1981. Bangalore.

Rao KN and Rao RSN. 1993. Control of *Cuscuta* with herbicides in onion. 3: 196–198. In: *Proceedings of International Symposium on Integrated Weed Management for Sustainable Agriculture*, 18-20 November, 1993. Indian Society of Weed Science, Hisar.

Rao PN and Reddy A. 1987. Effect of China dodder on two pulses: Greengram and clusterbean–the later a possible trap crop to manage china dodder. pp. 665–674. In*: Proceedings of the 4th International Symposium on Parasitic Flowering Plants*, Marburg.

Rath GC and Mohanty SS. 1986. Damage caused by *Cuscuta chinensis* to niger. *Indian Phytopathology* **39**: 309–310.

Rath GC. 1975. Host range of *Cuscuta chinensis*. *Science and Culture* **41**(7): 331–332.

Reddy ARS and Rao PN. 1987. Clusterbean–a possible herbicidal source for managing China dodder. pp. 265–270. In: *Proceedings of 11th Asian-Pacific Weed Science Society Conference* Taipei, Republic of China.

Sandip S Nikam, Santosh BP and Kanade MB. 2014. Study of *Cuscuta reflexa* with reference to host diversity, anatomy and biochemistry. *Central European Journal of Experimental Biology* **3**(2): 6–12.

Sankaran T and Rao VP. 1966. Insects attacking witch weed (*Striga*) in India, *Common Wealth International Institute of Biological Control* **7**: 63.

Sankaran T, Rajendran MK and Ranganath Bhat Y. 1969 The Biology of *Eulocastra argentispars* Hampson (Lep: Noctuidae) with special reference to the occurrence of dimorphism. *Common Wealth International Institute of Biological Control* **11**: 31.

Shanmugasundaram A and Venkataraman K. 1964. Co.20 Jowar stands up to *Striga*. *Indian Farming* **14**(4): 9.

Sharma SL, Rao D and Trivedi KN. 1956. Taxonomy of three species of *Striga* parasites on sugarcane. *Proceedings of the Indian Academy of Sciences* **43**: 63–71

Sheoran Parvender, Punia SS, Singh Samunder and Singh Dhiraj. 2014. *Orobanche* weed management in mustard: Opportunities, possibilities and limitations. *Journal of Oilseeds brassicas***.** **5**(2): 96–101.

Sher MA and Shad RA. 1989. Distribution, hosts and measures to control dodder. *Progressive Farming* **9**: 17–20.

Setty PN. 1971. Studies on parasitism simultaneously by Orobanche and Cuscuta: Tissue protein and phosphorus. *Indian Journal of Experimental Biology* **7**(2): 244–247.

Singh DV. 1971. Biochemical changes observed in the metabolism of petunia during infection singly and incombination by *Cuscuta* and *Orobanche*, Part–I, Starch Metabolism. *Indian Journal of Biochemistry and Biophysics* **8**(3): 183–186.

Singh Narender, Punia SS and Yadav Dharam Bir. 2017. *Chemical control of Orobanche aegyptiaca* L. in brinjal. Abstract published in proceedings of Biennial Conference of the Indian Society of Weed Science on "*Doubling Farmers' Income by 2022: The Role of Weed Science*", March 1-3, 2017, Udaipur, India.

Singh SN, Singh RK and Singh B. 2001. Herbicidal cum–integrated approach of weed management in spring planted sugarcane. *Indian Journal of Weed Science,* **33**(3&4): 136–138.

Tosh GC and Patro GK. 1975. Control of dodder (*Cuscuta chinensis* Damk.) in niger with chloropropham. *Weed Research* **15**: 207–209.

Tosh GC, Patro GK and Misra A. 1977. Effect of pronamide and chlorpropham on *Cuscuta* stem parasite in niger. *Abstracts of Papers of Weed Science Conference, Indian Society of Weed Science*, Hyderabad, India, 275–276 pp.

Trivedi GC, Patel RB, Patel BD, Meisuriya MI and Patel,VJ. 2000. Some problematic weeds and their management -A review. *Agricultural Reviews* **21**(4): 238–243.

Venkateshwara Rao L, Rama Rao V. and Pardhasardhy AV. 1967. N-13 - A high yielding *Striga* resistant strain of Jonna. *Andhra Agriculture Journal* **14**: 67–70.

Yadav Ashok, Malik RK, Punia SS, Malik RS, Kumar Rakesh, Yadav KK and Singh Sher. 2005. Broomrape (*Orobanche aegyptiaca* Pers.) Infestation in Oilseed–rapes and Management Options, pp. 18. In: *Technical Bulletin (6),* Department of Agronomy and Directorate of Extension Education, Chaudhary Charan Singh Haryana Agricultural University, Hisar.

Yaduraju NT. 1975. Studies on *Striga* (*Striga aslatica* (L.) Kuntze) control in sorghum (*Sorghum bicolor* (L.) MOENCH). M.Sc (Ag.) thesis, University of Agricultural Sciences, Bangalore.

Chapter 3

Trends and developments of nanotechnology application in weed management in India

C.R. Chinnamuthu* and N. Viji
Department of Agronomy, Tamil Nadu Agricultural University,
Coimbatore, Tamil Nadu 641 003
**Email: crchinnamuthu@yahoo.com*

Summary

The new science, nanotechnology throws rays of hope for the development of nanoherbicides with highly specific, controlled release and increased efficiency to circumvent the weed competition under different ecosystem of crop production. Nanotechnology is a technology having the potential ability to study, design, create, synthesis, manipulation of functional materials, devices, and systems to fabricate structures with atomic precision by controlling the size of the matter at the scale 1–100 nanometers. The properties and effects of nanoscale particles and materials differs signiûcantly from larger particles of the same chemical composition. By controlling structure precisely at nanoscale dimensions, one can control and tailor the properties of nanostructures, such as nanocapsules, in a very accurate manner for slow release herbicide to achieve season long weed control. Degrading phenolic compounds responsible for dormancy of weeds with suitable functionalized nanoparticle would be an intelligent solution for the exhausting the weed seed bank. Nanobiosensor for quick detection and quantification of herbicide residue in soil and crops to avoid toxicity by inhalation, ingestion and dermal contact. Remediation of environmental contamination of the industrial waste and agricultural chemicals like pesticides and herbicide residues are possible through metal nanoparticles.

Key words: Encapsulation, Herbicide residue, Nanotechnology, Nanoparticle, Nanobiosenor Slow release, Weed control, Weed seed bank

Introduction

Although herbicides will continue to be the dominant technology in weed management programs, several problems have arisen from reliance on herbicides including herbicide movement to non-target areas, environmental contamination and development of herbicide-resistant weeds. Continuous exposure of plant community having mild susceptibility to an herbicide in one season and different herbicide in another season develops resistance to all the chemicals in due course and become uncontrollable through chemicals. The performance of herbicides in tropical environments can sometimes be erratic and inefficient. This is particularly true for soil-applied herbicides where high temperatures, intense rainfall, low soil organic matter and microbial activity results in rapid breakdown and loss through leaching. Further the irrigation process decreases the herbicide concentration lead to reduced weed control efficiency coupled with leaching and potential ground water pollution. Thus, the half-life period for many soil applied herbicides remains very short period of time ranging from few hours to couple of weeks. Whereas some of the herbicides parent material persist in soil for long time and results in residual toxicity problems. Among the herbicides, atrazine is almost a non-volatile and its half-life in neutral condition varies from 4-57 weeks depending on various environmental factors like pH, moisture content, temperature and microbial activity. Though, there are several different methods (by activated carbon adsorption, microbes or air stripping) for removal of atrazine residues from aquatic system, there are no established methods for the vast soil phase. Furthermore the herbicides available in the market are designed to control or kill the germinating or growing above ground part of the weed plants. None of the herbicides are inhibiting the viable underground propagating materials. It is time to think laterally to knock down the problems encountered in the management of weeds and herbicide residues with the new science nanotechnology. In India, the Tamil Nadu Agricultural University, Coimbatore pioneered in the areas of developing controlled release nanoherbicide formulations, season long weed control with slow release herbicide, exhausting weed seed bank with nanoparticles and faster degradation of herbicide residue with metal nanoparticles for soil clean up. The detailed concepts of application of nanotechnology in weed management and results obtained already in these areas are reviewed in this paper.

Existing management options of weeds

Manual method

Traditionally physical power of human being has been utilized to remove weeds. On an average 320 man hours are required to remove weeds from one hectare of land. Imagine for 164 million hectares of cultivated lands in India? Further manual method of weed management is laborious, time consuming and inefficient due to adverse soil conditions.

Mechanical method

Introduction of mechanical methods relieved some extent from drudgery. Ploughing with help of animal power or mechanical implements has been one of the most widely used practices to prepare land for planting. Although effective for clearing fields of existing vegetation and preparing a seedbed, tillage also predisposes many weed species to germination. Tillage causes a breakup of *Cyperus rotundus* tubers bringing them close to the soil surface where they are subjected to carbohydrate starvation, desiccation and cold injury (Glaze 1987). Intercultivation in the wide row spaced crops is effective only between rows and the weeds untouched within rows. In some instances, tillage worsen the weed problem. Commonly known silver night shade *Solanum elaeagnifolium* spread by rhizomes or root fragments. Frequent tilling of soil leads to multiplication of this weed through root fragments.

Chemical method

Chemical weed control is a better supplement to conventional methods and forms an integral part of the modern crop production. Before the discovery and rapid expansion of phenoxy herbicides in the late 1940's, weeds were controlled by cultural practices with limited use of non-selective herbicides. With the invention of selective herbicides, there has been a major reliance on these synthetic chemicals in weed management. Search for new methods to kill the weeds selectively, continuous till the discovery of 2,4-D during 1940's. The chemical at lower concentration act as a growth regulator, selectively kills the broad-leaved weeds at higher concentration leaving no or less effect on crop, revolutionized the weed control.

At present thousands of herbicide formulations are available in the market to combat weed plants under diverse situation. Although, herbicides will continue to be the dominant technology in weed management programs, several problems have arisen including herbicide movement to non-target areas, environmental contamination and development of herbicide-resistant weeds. Continuous use of same herbicides or herbicides belonging to a similar group is believed to be the chief reason for development of herbicide resistance in weeds and may cause weed shift problem.

International survey of herbicide resistant weeds (Heap 2018) recorded 495 unique cases of herbicide resistant weeds globally, with 255 species (148 dicots and 107 monocots) in 2018. Weeds have evolved resistance to 23 of the 26 known herbicide sites of action and to 163 different herbicides. Herbicide resistant weeds have been reported in 92 crops in 70 countries. In India extensive use of isoproturon for over 20 years in rice-wheat ecosystem led to development of resistance in *Phalaris minor*, a grass weed resembles wheat crop. Development of herbicide resistant crops like "Roundup Ready" in soybean poses a threat of becoming a *"Super Weed"* in the subsequent crops. Various non-chemical approaches such as cover crops, mechanical cultivation, competitive cultivars and biological control agents have been found to provide various levels of weed suppression but often they are inadequate to provide acceptable and consistent control of weeds by themselves.

Present weed management technologies aim to control only the emerging weeds or emerged weeds. Mostly they target only the above ground growing part of the weeds. None of the available herbicides are inhibiting activity of viable underground plant parts like rhizome or tubers which act as a source for new plants in the current season. Due to the unavailability such kind of molecules, one must wait either germination of weed seeds or appearance of weeds for foliar application of herbicides. Especially in *Cyperus* species, the foliar applied herbicides mainly destroy the plants above ground parts, but no effect on the root system and the tubers. In addition, the tubers can survive in harsh weather conditions, further contributing to the difficulty of eradication.

Since lack of selective herbicides for perennial weeds, herbicides should be applied in the fallow land by compromising the growing season. Tilling operation many a times worsen problem of perennial weed population buildup. Effective weed control by using herbicides depends largely on the soil types, soil moisture, humidity and atmospheric temperature at the time of application of herbicides. Herbicides may leach down if the soil moisture is in excess or gets photo decomposed when exposed to sunlight (Dick 2010). The method, rate and amount of irrigation will affect the herbicide spatial distribution and its dispersion in the field. Furthermore, chemical weed control involves safety risks and may enhance environmental pollution.

The CEC is a measure of the quantity of adsorptive sites present in a soil and is based primarily on the clay and organic matter content. As CEC increases, more herbicide is bound to soil colloids and less is available in the soil solution. Sandy loam soils with low organic matter requires less quantity of herbicides than clay loams. This is the reason why recommended rates for most soil-applied herbicides are based on soil type. By increasing herbicide rates on soils with a high CEC, the concentration of herbicide in solution can be maintained at toxic concentrations (Hartzler 2002).

Nanotechnology application in weed management

Application of nanotechnology to manage problematic weeds

Nanotechnology has the potential ability to study, design, create, synthesis, manipulation of functional materials, devices, and systems to fabricate structures with atomic precision by controlling the size of the matter at the scale 1–100 nanometers. The properties and effects of nanoscale particles and materials differ considerably from larger particles of the same chemical composition. By controlling structure accurately at nanoscale dimensions, one can control and tailor properties of nanostructures, such as nanocapsules, in a very precise manner for slow release herbicide to achieve season-long weed control (Dhillon and Mukhopadhyay 2015).

Nanotechnology is working with the smallest possible particles which raise hopes for improving agricultural productivity through encountering problems unsolved conventionally (Chinnamuthu and Murugesa Boopathi 2009). In general, weed scientists are aimed to control the weeds belongs to communities with a single herbicide molecules. The multi-species approach in the cropped environment resulted in poor control and lead to development of herbicide resistance. Continuous exposure of plant community having mild susceptibility to herbicide in one season and different herbicide in another season develops resistance to all the chemicals in due course and become uncontrollable through chemicals.

The target domains of the present day herbicides in a plant cell are destruction of structure and function of the plant-specific chloroplast, inhibition of lipid biosynthesis, interference with cell-division by disrupting the mitotic sequence or inhibiting the mitotic entry, inhibition of cellulose biosynthesis and deregulation of auxin-induced cell growth (Ko Wakabayashi and Peter Boger 2004).

Although molecular mechanisms of action are not yet completely understood even for some commercially available herbicides, about 60% of conventional herbicides interfere with the PET system of the chloroplast. The PET is embedded in thylakoids of chloroplast and it converts light energy into chemical energy, namely NADPH and ATP. The PET consists of photosystems I (PS-I) and II (PS-II), being combined by the cytochrome-b/f complex. The PS-II is connected with the O_2-evolving complex. At present, no commercial herbicides exist that interfere with CO_2-fixation and sugar production. Some of the herbicides affecting photosynthesis inhibit the biosynthesis of photosynthetic pigments (i.e. chlorophylls or carotenoids), causing bleaching (1) interfere with the photosynthetic electron flow as electron-transport inhibitors by binding to the D1-protein of PS-II (2) produce superoxide by dragging off electrons at the end of PS-I like paraquat, inducing radical formation that results in peroxidation.

Molecular characterization of underground plant parts for a new target domain and developing a receptor based herbicide molecule expected to kill the viable underground propagules. Selectivity of such herbicides can be increased by smart delivery mechanism with the help of nanoparticles. Several pesticide manufacturers are developing agrochemicals encapsulated in nanoparticles (OECD and Allianz 2008). If the active ingredient is combined with a smart delivery system, herbicide will be applied only when necessary according to the conditions present in the field. These chemicals may be shown time bound release or release upon the occurrence of an environmental trigger (Example: Temperature, humidity and light).

The regulatory structure in developed countries is driving development of nanoscale pesticides and herbicides in the direction of nanoscale adjuvant rather than nanoscale-active ingredients. Whether the application is due to a nano-sized active ingredient or the creation of a nano-sized formulation through the use of an adjuvant, the benefits of applications are similar. Nano-capsules would help to avoid phytotoxicity on the crop by using systemic herbicides against parasitic weeds. Nano-encapsulation can also improve herbicide application, providing better penetration through cuticles and tissues and allowing slow and constant release of the active substances. Nanoparticles have a great potential as ‘magic bullets’, loaded with herbicides, chemicals or nucleic acids and targeting specific plant tissues or areas to release their charge. Improvements in the efficacy of herbicides through the use of nanotechnology could result in greater production of crops and reduced dosage.

With the advancement of science in nano-scale level, vast scope is ahead for the weed scientist to identify and selectively control the unwanted plants without hampering the natural ecosystem.

Nano-herbicides to exhaust the weed seed bank

Soil weed seed banks are reserves of viable seeds present in the soil. The seed bank is an indicator of past and present weed populations. There is enormous number of viable weed seeds in the soil. For example, the seeds of *Striga* spp. produce thousands of seeds per plant per season and remain viable in the soil for more than 20 years. The seeds will germinate when the weather factors are favourable. The tubers and rhizomes of the sedges are dormant and viable during unfavourable seasons.

The easiest way of reducing the weed incidence is exhausting the weed seed bank which act as the source for weeds over generations. Existing stale seedbed technique, a fallow period cultural weed management method often practiced during summer to reduce the weed seed bank. It involves frequent tilling and irrigation, so it adds weed management cost.

Molecular characterization of problematic weed seed coat will help us to identify the receptor having specific binding property with nanoherbicide molecules. Developing receptor based herbicides tagged with nanoparticles like carbon nanotubes will destroy the specific weed species completely from the soil. Chinnamuthu and Kokiladevi (2007) reported that smart delivery of herbicide will be highly useful to exhaust the weed seed bank and is a great accomplishment for the farming community.

Cyperus rotundus (purple nutsedge) is one of the world worst weeds causes hundred per cent yield loss at times. Tubers of purple nutsedge have many buds over that. But only few buds will sprout and others remain dormant due to the presence of the phenolic compounds. Growth regulators were used to break dormancy and inducing germination of purple nutsedge tubers. Laboratory experiments conducted at Tamil Nadu Agricultural University, Coimbatore (TNAU) reported that 0.01 per cent of cytokinin recorded the maximum percentage of germination by breaking dormancy. Besides tuber sprouting, cytokinin treated tubers produced more number of sprouts per tuber, dry matter, root, shoot length and vigour index (Ravisankar and Chinnamuthu 2013). The combination of growth promoting substances and herbicides on the viability of *C. rotundus* tubers reported that combined application of 0.01% cytokinin and metolachlor at 2 kg/ha as tank mix completely reduced the viability of tubers. In the case of followed by application, cytokinin at 0.01% induced all the buds to sprout and were killed by the followed by application of glyphosate at 2.5 kg/ha on the third day after sprouting (Ravisankar and Chinnamuthu 2017).

Nanoparticles play a vital role in exhausting the weed seed bank of a problematic weed *C. rotundus*. Sprouting of dormant buds may induced by degrading the phenols present in the tubers. Exhausting the food reserves of the tubers may reduce the multiplication of tubers. In this connection, experiments conducted by Brindha and Chinnamuthu (2012) found that the ZnO nanoparticles were effectively regraded the phenolic compounds. The tubers treated with ZnO nanoparticles at 1500 mg kg^{-1} under dry method (powder form) and 2250 mg/kg under wet method (liquid form) respectively, influenced the tuber germination by means of phenol degradation and biochemical components significantly.

The novel magnetic iron oxide nanoparticles (nano-adsorbent) are quite efficient for degrading phenols present in the purple nutsedge tubers. A laboratory experiment was carried out to break the dormancy of purple nutsedge tubers using iron oxide nanoparticles by degrading the phenols. Iron oxide nanoparticles at 3.0 g kg/tubers recorded higher percentage of phenol degradation (89% over control) (Viji and Chinnamuthu 2015a). Advanced oxidation processes (AOP) are widely used for the removal of recalcitrant organic constituents such as phenols. In the case of the AOPs, the generation of hydroxyl radicals takes place through a catalytic mechanism in which the iron oxide nanoparticles played an important role in phenol degradation. By the way of breaking dormancy factor, the germination percentage of the iron oxide nanoparticles treated purple nutsedge tubers was increased (Viji and Chinnamuthu 2015a). In addition, the zinc oxide nanoparticles at 3.0 g/kg of tubers recorded 74.5% higher rate of germination over untreated control due to degradation of phenol. Since, nanoparticles lead to production of more OH^- radical results in the oxidation of phenol, by means germination percentage of tubers was increased (Viji and Chinnamuthu, 2015b).

Besides, titanium dioxide nanoparticles at 2.5 g/kg of tubers recorded higher percentage of phenol degradation i.e., 69.7% compared to control. It was on par with titanium dioxide nanoparticles at 2.0 and 1.5 g/kg of tubers recorded 68.8 and 67.2% phenol degradation, respectively compared to control. Phenol degradation is due to AOPs catalyst by titanium dioxide nanoparticles (Viji and Chinnamuthu 2018). Titanium dioxide nanoparticles at 2.5 g/kg of tubers recorded 41.7 percentage of germination over control. The germinated weed can be controlled by different means of control measures. By this way an effective seed bank exhaustion of purple nutsedge could be achieved.

Hydrolytic enzyme namely alpha-amylase was also used to exhaust the food reserve in the purple nutsedge tubers leading to death of tubers before emerging out. It was found that, treating the tubers of purple nutsedge with alpha-amylase at 200 ppm recorded the minimum content of starch and maximum content of amylose after 24 hours of soaking. Alpha-amylase acts on starch and breaks into glucose molecules, which may be due to the hydrolysis of starch to glucose and maltose. Soaking of tubers in alpha-amylase at 1250 ppm was recorded the reduced content of starch in the whole as well as cut tubers treatment (Brindha and Chinnamuthu 2015).

Silver nanoparticles are used to exhaust the food reserves present in the *C. rotundus* tubers. Treating the tubers with silver nanoparticles at the concentration of 2.5 g/kg of tubers recorded higher starch degradation (7.3%) over control. The presence of silver nanoparticles accelerates the rate of enzymatic degradation of soluble starch. The combination of alpha-amylase enzyme and silver nanoparticles are used for higher rate of starch degradation present in the tubers. Alpha-amylase + silver nanoparticles at the concentration of 500 ppm + 2.5 g/kg of tubers, respectively recorded higher rate of starch degradation (25.3%) over control. The interaction of alpha-amylase with the silver nanoparticles accelerates the degradation of starch into reducing sugars. The reaction speed was high and the breakdown of starch to smaller molecules like monosaccharides and disaccharides was faster (Viji *et al.* 2016).

Exhausting the weed seed bank reduces the crop weed competition and improves the growth and yield of crops. Hydrogen peroxide is a biocide commonly used for sterilizing soil borne pathogens. An experiment was conducted to study the effect of herbicides in combination with nanoparticles and hydrogen peroxide on weed emergence and weed seed bank besides growth and nodulation of blackgram variety. Application of H_2O_2 at 300 ml/m^2 *fb* pendimethalin at 0.75 kg/ha + ZnO nanoparticles at 500 ppm/m^2 registered significant reduction in the emergence pattern of weeds due death of weed seeds before emergence as well killing of emerged weeds and increased yield of crop (Vimalrajiv *et al.* 2018).

Nano-herbicides to eradicate the perennial weed

The task sounds simple but it remains unsolved over several decades. A perennial weed propagates survive through underground structures like rhizomes and stolon (*Cynodan dactylon*), tubers (*Cyperus* spp.) and deep root (*Solanum elaeagnifolium*). Cultural practices like ploughing, hand weeding and hoeing through implements increase the infestation of these perennial weeds rather than control. Tillage may have harmful effect, instead of controlling it will help to spread through stem cuttings. Further the perennial weeds are difficult to control with herbicides because the root system is widespread and connects to adjacent above-ground growth. Studies indicated that repeated application of herbicide like glyphosate and picloram helps to reduce the intensity for a current season. Alterative soil fumigation by methyl bromide which is too banned because of its mammalian toxicity but can be employed certain extent to eradicate small infestations.

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

Nanotechnology has potential for efficient delivery of chemicals using nanomaterials based agrochemical formulations. Nanotechnology approach will reduce the need for toxic herbicides, which many weed species have grown resilient to. By using nanoherbicide which is 1-100 nm range will try to mingle with the soil particle and destroy the entire weeds from their roots by not affecting other food crops. Due to incredibly small proportions of nano-scale herbicides, then can easily blend with soil and reach the seeds that are buried below the reach of tillers and conventional herbicides. This approach will destroy the weeds even when the seeds are buried in soil and will prevent them from growing under most favourable conditions (Food quality news 2006). As the nanoparticles are target specific they can be used to kill the weeds and to get better yield. Herbicides like atrazine and triazine could be encapsulated to get efficient release to the plants (Agri nanobiotech 2016).

Developing nanoherbicides molecule targeting the new domain

Heavy use of herbicides has given rise to serious environmental and public health problems. It is therefore important to develop new herbicide formulations that are highly effective, safer and that involve a low cost/production ratio. In this sense, controlled release formulations of herbicides have become necessary in recent years, since they often increase herbicide efficacy at reduced doses.

Developing a target specific herbicide molecule encapsulated with nanoparticles is necessary. Nanoparticles have high surface area, sorption capacity, and controlled-release kinetics to the targeted sites making them smart delivery system. The nanoparticles with herbicide molecule when get in contact with specific receptor present in the roots of target weeds enter into the system and translocated to the parts and inhibit the glycolysis of food reserve in the root system. This will make the specific weed plant for starve for food and gets killed (Chinnamuthu and Kokiladevei 2007). It could be achieved with the advancement of science in nano-scale level. A vast scope is ahead for the weed scientist to identify and selectively control the unwanted plants without hampering the natural ecosystem. Single species approach helps us to obviate an unwanted plant in the cropping without impairing the ecosystem.

Developing or modifying the herbicide molecule in nanoscale or encapsulated in a biodegradable polymer nanoparticles matching the receptor identified in the underground plant parts to kill a specific weed species is needed. Pendimethalin herbicide nano formulation was fabricated by Pradeesh Kumar and Chinnamuthu (2014) using direct encapsulation technique. The mono dispersed pendimethalin molecules were loaded on to the $MnCO_3$ nano core template with layer by layer (LBL) adsorption of opposite charge polyelectrolyte. Thus encapsulated soil applied herbicide formulations, escapes from the chemical and biological degradation process and reach the active absorption part of the roots of weeds. When the encapsulated materials are selected in such way that the molecules desired by the plant will enter through the protein channels of bilayer by mimicking as that of the nutrients in demand.

Developing smart delivery mechanism to the targeted site

The controlled release formulations of herbicides have become necessary in recent years. It is important to develop new herbicide formulations that are highly effective, safer, low cost ratio and high herbicide efficacy at reduce dose. Nano-capsules could be designed for improving penetration through leaves and cuticles. Liposomes and lipid vesicles can cross through the plant cuticle easily owing to their amphiphilic composition. Micro and nano-spheres fabricated from a biodegradable polymer for drug delivery systems have become increasingly important owing to their controlled release at desired sites. For controlled release system, micron-scale core materials are encapsulated with an outer shell. The core must be insoluble under some condition, such as low pH and soluble under the conditions at which controlled release is to take place. The release rate generally depends on the thickness of the encapsulating shell and the material used in the coating. Thicker shells lead to longer release times (Arida and Al-Tabakha 2007).

In recent years, starch is used as matrix forming polymer for encapsulation of agriculture chemicals such as herbicide and pesticide. It has been developed for better targeting to reduce the environmental impact. The loss of chemicals by volatilization, decomposing by sunlight and leaching by water were greatly reduced due to encapsulation. The encapsulated chemical dissolves in the imbibed water and diffuses out of the starch matrix. The herbicide alachlor encapsulated with ethylcellulose microsphere by solvent evaporation method (Urrusuno *et al.* 2000). Ethylcellulose microspheres may prove useful for the prolonged release of alachlor. Pradeesh Kumar and Chinnamuthu (2017) fabricated nanostructure using solvent evaporation was found to be longer in releasing the encapsulated herbicide molecules consistently upto the study period of 40 days under controlled environmental condition. This confirms that the herbicide entrapped inside the polymer was well protected from the environmental factors and released in slow manner based on the moisture availability**.**

Nanoherbicides for rainfed agriculture

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

In rainfed areas, lands are prepared for sowing immediately after rainfall. Sowing of seeds will be done in the optimum moisture. Seeds of weeds and crops plants starts to germinate with the available moisture. Slow growing nature of most crops in rainfed condition during initial stages weeds take advantage and suppress the crop growth further. However weeds can be effectively managed in rainfed areas by employing either manual or mechanical methods, which involves more cost and takes long time to cover larger area by that time damage might have reached unrecoverable stage. Generally, farmers under rainfed areas are poor in nature and unable to invest any additional investment for weed management.

The next best option to manage the weed menace in rainfed areas is by chemical method. Control of weeds through herbicides are highly economical and resource depletion could be minimized. However chemical weed management in rainfed areas depends on the moisture availability at the time of herbicide application. Pre-emergence herbicides have to be applied immediately after sowing of crops to control the emerging weeds along with crop. Pre-emergence herbicides work well when the soil with sufficient moisture. Since crop seeds are placed in deeper layer will germinate with the available soil moisture and establishes. Weed seeds present in the top layer of soil unable to germinate due lack of moisture during initial growth stages of crop. However, if there is rain in the subsequent days which favour the germination of weed seeds and it become too late to go for herbicide application. Application of herbicides with insufficient soil moisture may lead to loss as vapour. Hence an alternate approach have to identified to manage the weeds in rainfed areas

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

Nanoherbicides for season long weed control

The half-life period for many soil applied herbicides remains very short period ranging from few hours to couple of weeks. Once the concentration of soil applied herbicides reduced to 50% of its original strength, correspondingly it loses its weed control efficiency (Khan *et al.* 2011). An effective herbicide should control weeds with reasonable doses selectively, non-toxic to crops, remain in the area where applied, persist throughout the growing season taking care of frequently germinating weeds and leaving no residue at the end of the season permitting subsequent crops in the sequence.

The technologies, *viz.* smart delivery, encapsulation and slow release have revolutionized the medicine and pharmacology for drug delivery by possessing the timely control, spatially targeted and remotely regulated. As tried in the other field of science, the nano-encapsulation for slow release can also be attempted to fabricate the slow release herbicide for season long weed management under irrigated ecosystem (Agnihotri *et al.* 2012). The replacement of conventional agrochemical formulations by slow release systems not only helps to avoid treatment with excess amounts of active substances, but also offers ecological and economic advantages in the system. Development of a slow release nano-encapsulated herbicide formulation will help the agronomist to increase the productivity of crops by taking care of new flushes of weeds appearing at all stages of crop growth.

The synthetic cationic surfactants, organic polymers and natural plant materials like lignin and starch materials have been found to have the adsorbing property for the slow release formulations of agrochemicals thus causes the efficient release to the crop based cultivation system. Micro-encapsulated alachlor formulations using ethylcellulose (EC) was efficient in reducing the herbicide losses due to volatilization (Dailey 2004).

Paraquat is a contact herbicide which has a broad spectrum of activity. A study was conducted to encapsulate paraquat herbicide with nanoparticles to find the release profile (Silva *et al.* 2011). The herbicide showed good association with the nanoparticles, which altered its release profile. Sorption tests, using either free or associated paraquat, showed that the soil sorption profile was reduced when paraquat was associated with the nanoparticles, hence improving the herbicidal action. The formulation of paraquat with alginate/chitosan nanoparticles shows promising potential for future use in agricultural applications, reducing negative impacts caused by herbicide, offering increased duration of action of the chemical on specific targets, while reducing problems of environmental toxicity.

The chlorophenoxy herbicide MCPA (4-chloro-2-methylphenoxyacetic acid), widely used for the control of broad-leaf weeds primarily in cereal and grasses. As the formation of inclusion complexes with cyclodextrins can improve its solubility properties, the interaction between the herbicide MCPA and â-cyclodextrin was investigated (Garrio *et al.* 2012). The formation of an inclusion complex between MCPA and â-CD increased the aqueous solubility of this herbicide which could be a particularly advantageous property for some specific applications, namely to improve commercial formulation and for environmental protection.

Encapsulation of any active ingredients could be achieved by direct, indirect, solvent evaporation and spray drying methods. Each one is having its own merits and demerits. Among the methods tried in TNAU, the solvent evaporation was able to encapsulate the pre-emergence herbicide pendimethalin effectively and released slowly throughout the study period of 40 days (Pradeesh Kumar and Chinnamuthu 2014). Besides the steady release of herbicides from the polymer matrix and season long weed control, the nano-encapsulated herbicides with the recommended dose offers several advantages compared to commercial form. It prevents the enlarging of weed seed bank, avoids harbouring of pest and diseases, conserve the soil nutrients and moisture, facilitate easy harvest operation and improve the quality of harvested material.

The herbicides imazapic and imazapyr are the members of the imidazolinone group of compounds mainly used to control weeds in plantations of maize, soybean and groundnut. Alginate/chitosan and chitosan/tripolyphosphate nanoparticles were used to encapsulate the herbicides imazapic and imazapyr (Maruyama *et al.* 2016). Nanoparticle encapsulated herbicides recorded higher weed control efficiency of 60% and they were released more slowly than the free form. Encapsulation of the herbicides with the nanoparticles improved their mode of action and reduced their toxicity, indicating their suitability for use in future practical applications.

The herbicide terbuthylazine (TBA) is widely used to control of many grass and broad-leaf weeds. But, it has poor aqueous solubility profile that results in reduced bioavailability. Cyclodextrins (5ØýÞ-CD) and modified cyclodextrins (HP-5ØýÞ-CD) were considered as an appropriate agent for improving pesticide water solubility. A study was conducted to form inclusion complex of TBA with 5ØýÞ-CD and HP-5ØýÞ-CD to attain its aqueous solubility enhancement. The development of TBA-CD formulations would enable, through their inclusion into the hydrophobic cavity of CDs, enhancement of solubility, bioavailability, stability of the herbicide and providing the same effect using a lower dose (Garrido *et al.* 2017).

Slow release formulations reduced the herbicide movement within the soil column by keeping enormous portion of the herbicide active ingredient in the upper soil layer, where the weed seeds are exist, could be checked effectively. Release of herbicide in to soil solution slowly over a long period of crop growth lead to reduction in the frequency of herbicide application and manual removal of weeds. An experiment was conducted to study the effect of entrapped slow release pre-emergence herbicide oxadiargyl on weed control duration and yield of transplanted rice. The herbicide molecule was entrapped with zeolite, biochar, starch and water soluble polymer. Application of oxadiargyl loaded with zeolite on 3 DAT recorded significantly less total weed dry weight at all stages of crop growth compared to commercial formulations (Bommayasamy *et al.* 2018a).

Intensification of agriculture has amble scope to increase vegetable production in rice fallow system, because of preparatory cultivation is more arduous, require conducive condition, time consuming and more expensive. Weeding operation is also difficult and uneconomical practice in this system because of dense stubbles and non-availability of labour in time. Application of either pre-sowing or pre-emergence herbicides is also difficult due to lack of field preparation and limited period of their application. Slow release formulation of pre-emergence herbicide applied to previous season rice crop recorded lower weed density as well weed dry weight throughout the crop growth of the vegetable bhendi crop grown as second crop in the sequence (Bommayasamy *et al.* 2018b).

Herbicide residue management

Nano biosensors for herbicide residue detection

Herbicide residues and its metabolites left in the field as well in the produce need to be detected to avoid any toxic effect to human beings and animals upon ingestion, inhalation or contact. Detection and quantification of residues by analytical methods are time consuming besides limitation in the precision levels. Hence alternate methods being evaluated using sensors for the quick detection and quantification residues to parts per billion levels. Compared to a standard sensors biosensor are further highly precised in detection and quantification. A biosensor is composed of a biological component, such as a cell, enzyme or antibody, linked to a tiny transducer, a device powered by one system which supplies power to a second system. The biosensors detect changes in cells and molecules that are then used to measure and identify the test substance, even if there is a very low concentration of the tested material. When the substance binds with the biological component, the transducer produces a signal proportional to the quantity of the substance. With this technology, large number of samples can be tested readily *in situ* itself with low cost and high sensitivity.

Nanotechnology plays an important role in the development of biosensors (Haruyama 2003, Jain 2003). Sensitivity and other attributes of biosensors can be improved by using nanomaterials. Development of nanobiosensor will be revolutionized with the advancement in nanotechnology. Nanomaterials are extensively used to design new types of biosensors. In future, nanotechnology-based biosensors will be integrated with biochips with on-board electronics and analytical techniques. This will greatly improve functionality, by providing devices that are small, portable, easy to use, low cost, disposable, and highly versatile diagnostic instruments in every field of agriculture and allied activities.

Trifluralin herbicide residue was detected using an electrochemical sensor consisting of a carbon electrode modified with copper nanowires (Mirabi-Semnakolaii *et al.* 2011). The presence of copper nanowires improved the conductivity, resulting in increased of rate of electron transfer. This sensor showed a linear response in concentration range from 100 to 0.2 nmol./L with 0.008 nmol./L of detection limit and quantitation limit of 0.15 nmol./L for trifluralin and the supporting electrolyte phosphate buffer solution of 0.05 mol./L and pH 4.0.

An immunosensor has been developed to detect the atrazine, a long persistent triazine group of soil applied pre-emergence herbicide using a printed carbon electrode modified with styrene sulphonic acid doped with polyaniline by Deep *et al.* (2014). The mechanism used was the interaction of atrazine with the anti-atrazine antibody, immobilized on the sensor surface. The detection was specific and highly sensitive (0.01 ng.m/L atrazine) in concentrations from 0.01 to 50 ng.m/L. For detection of atrazine in water samples, Tortolini *et al.* (2016) used biosensor amperometric based on mushroom tyrosinase. Atrazine could be detected due to inhibition of enzyme activity in the presence of the catechol substrate, where it catalyzes the oxidation of catechol o-quinone.

Among the enzymatic disruptor herbicides, mesotrione is able to inhibit 4-hydroxy phenyl pyruvate dioxygenase (HPPD), which plays a key role in the carotenoid synthesis. Therefore, enzyme based a nanobiosensor was developed by Pâmela Soto Garcia *et al* (2015) based on HPPD for mesotrione detection. Theoretically, the molecular docking and molecular dynamics simulation estimated the interacting regions of HPPD with mesotrione. Here the atomic force microscope tip was functionalized by immobilizing with HPPD was successfully able to the detect mesotrione molecules.

Detoxification of herbicide residue

Residue management can be done by adopting optimum dose of herbicide, FYM application, ploughing, leaching, crop rotation, non-phytotoxic oils, activated carbon and biodegradation by Agrobacterium radiobacter *etc*. (Struthers *et al.* 1998). But all these management practices are time consuming. Hence, alternate technology may be developed to remediate the problem within a short period of time to clear the land for the next crop in the system.

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

Residual problems due to the application of atrazine herbicide pose a threat to widespread use of the herbicide and limit the choice of crops in rotation. Atrazine has high persistence (half life-125 days in sandy soils, (Cox 2001) and mobility in some types of soils because it is not easily absorbed by soil (IPSC 1990) and often causes contamination of soil and groundwater. It is a s-triazine ring herbicide used globally (Sattin *et al.* 1995) for the pre and post-emergence control of broad-leaf and grass weeds in major crops like maize, sorghum, sugarcane, timber plantations, lucerne, grass and potatoes. Worldwide, it is second highly consumed herbicide and in India annual consumption of atrazine (technical grade) amounts to 340 MT (Kadian *et al.* 2008).

In USA, atrazine has been classified as a Restricted Use Pesticide (RUP) due to its potential for groundwater contamination (Ware 1986). It was reported that atrazine in quantities as minute as 0.1 parts per billion are causing sex reversal in frogs in India. Atrazine was found to be one of the environmental toxicants responsible for the genotoxicity of the Ganges water at Narora (U.P.), India (Vasudevan 2002). In soils, atrazine undergo abiotic hydrolysis to hydroxyatrazine, but this occurs very slowly unless dissolved organic matter is present or the soils are extremely acidic. Photolytic degradation of atrazine is slow with an estimated half-life in water about a year. It is generally biodegraded by soil microorganisms to hydroxyatrazine, desethylatrazine, or deisopropylatrazine, with subsequent metabolism to cyanuric acid. This may be followed by relatively complete degradation to CO_2 (mineralization) within 20 weeks. Complete biodegradation (mineralization) of atrazine was not observed in either saturated or unsaturated soils, at different depths over a period of 120 days. Based on the *in vitro* study, Susha and Chinnamuthu (2009) found that silver modified ferric oxide (Fe_3O_4)-CMC nanoparticles was superior in degrading the atrazine. They showed 82-88 % atrazine was degradation within 24 hours of treatment. Further studies are required to standardize the synthesis of iron based metal nanoparticle and nanocomposite for higher surface reactivity, stabilizing with suitable capping agent for sustaining the reaction under different agro ecosystem.

A study was conducted to degrade the 2,4-D residues using photocatalytic behavior of nanopartilces. Titanium dioxide (TiO_2) nanoparticles doped with platinum (Pt) particles was synthesized by sol-gel method. The electrons generated on the TiO_2 surface by UV light illumination quickly move to Pt particle to facilitate the effective separation of the photogenerated electron and holes, resulting in the significant enhancement of photocatalytic activity. Pt plays a positive role as electron acceptor, more acceptor centers are provided with increasing Pt-doping, therefore the degradation rate for 2,4-D increases with the increase of Pt content (Abdennouri *et al.* 2015).

Future focus

Methods adopted already to manage weeds are labour intensive, time consuming and inefficient. Methods in practice are aiming only the germinated weeds. The weed seed bank responsible for the next generation weeds are untouched. Lack of moisture in rainfed agriculture limits the modern method of weed management. There is an urgent need for lateral approach and alternate methods to exhaust the weed seed bank in soil with new molecule and new methods of delivery. Developing new herbicide molecule with emerging technology, the nano science and technology, will address the issues discussed.

Conclusion

Weeds are considered as one of the important factors limits the crop production and productivity. From time immemorial, methods are being developed and refined to manage the weeds to reduce their interference in crop growth. Weeds are managed through culturally, manually and chemically depend upon the specific situation and needs. Among the methods, chemical plays a major role. Germinated as well germinating weeds are killed by spraying pre-emergence and post-emergence herbicides. However, the soil as well foliage applied herbicides are failed to check weed seeds stored in the soil. Soil applied herbicides having long persistence limits the choice of crops in the next season. Hence an urgent technological intervention is required to manage problematic weeds and weed seed bank.

References

Abdennouri M, Furnace EM, Tounsadi H, Mahjoubi FZ, Elmoubarki R, Saiq M, Khamar L, Galadi A, Baalala M, Bensitel M, Elhafiane Y, Smith A and Barka N. 2015. Photocatalytic degradation of 2,4-D and 2,4-DP herbicides on Pt/TiO_2 nanoparticles. *Journal of Saudi Chemical Society* **19**(5): 485-493.

Ali Mirabi-Semnakolaii, Parandis Daneshgar, Ali Akbar Moosavi-Movahedi, Mehdi Rezayat, Parviz Norouzi, Ali Nemati and Mohammad Farhadi. 2011. Sensitive determination of herbicide trifluralin on the surface of copper nanowire electrochemical sensor. *Journal of Solid State Electrochemistry* **15**(9): 1953-1961.

Agnihotri N, Mishra Ravinesh, Goda Chirag, and Arora Manu. 2012. Microencapsulation-A novel approach in drug delivery: A review. *Indo Global Journal of Pharmaceutical Sciences* **2**(1): 1-20.

Agrinanobiotech. 2016. *http://agrinanobiotech.blogspot.tw*

Arida AI and Tabakha MMA. 2007. Encapsulation of ketoprofen for controlled drug release. *European Journal of Pharmaceutics and Biopharmaceutics* **66**: 48-54.

Bommayasamy N, Chinnamuthu CR, Venkataraman NS, Balakrishnan K, Rathinasamy A and Gangaiah B. 2018a. Effect of entrapped slow release pre-emergence herbicide oxadiargyl with zeolite, biochar, starch and water soluble polymer formulations on weed control duration and yield of transplanted rice. *International Journal of Chemical Studies* **6**(3): 1519-1523.

Bommayasamy N, Chinnamuthu CR, Venkataraman NS, Balakrishnan K, Rathinasamy A and Gangaiah B. 2018b. Effect of entrapped preceding rice crop herbicide oxadiargyl on growth and yield of succeeding bhendi. *International Journal of Current Microbiology and Applied Sciences* **7**(6): 1915-1921.

Brindha K and Chinnamuthu CR. 2012. New domain approach to manage the world's worst weed the *Cyperus rotundus* with engineered nanoparticles, herbicides and hydrolytic enzyme. Thesis submitted to the Department of Agronomy, Tamil Nadu Agricultural University, Coimbatore, India.

Brindha K and Chinnamuthu CR. 2015. Degrading phenolic compounds and exhausting food reserves stored in the tubers of *Cyperus rotundus* L. with hydrolytic enzyme. *Journal of Innovative Agriculture* **2**(1): 1-4.

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

Chinnamuthu CR and Murugesa Boopathi P. 2009. Nanotechnology and agroecosystem. *Madras Agricultural Journal* **96**(1-6): 17-31.

Cox C. 2001. Atrazine, global pesticide. *Campaigner* **11**(3): 18-25.

Dailey O. 2004. Volatilization of alachlor from polymeric formulations. *Journal of Agricultural and Food Chemistry* **54**: 6742-6746.

Deep A, Saraf M, Neha SK, Bharadwaj Sharma AL. 2014. Styrene sulphonic acid doped polyaniline based immunosensor for highly sensitive impedimetric sensing of atrazine. *Electrochimica Acta* **146**: 301–306.

Dhillon NK and Mukhopadhyay SS. 2015. Nanotechnology and allelopathy: Synergism in action. *Journal Crop and Weed* **11**(2):187-191.

Dick C. 2010. How soil pH affects soil – applied herbicides. Calcium products incorporated. (http://blog.calciumproducts.com/posts/how-soil-ph-affects-soil-applied herbicides.cfm). Food quality news, 2006: *http://www.foodqualitynews.com/R-D/Nano-herbicide-in-the-works*.

Garrido EM, Santosi M, Silva P, Cagide F, Cagide J and Borges F. 2012. Host-guest complexes of phenoxy alkyl acid herbicides and cyclodextrins. MCPA and â-cyclodextrin. *Journal of Environmental Science and Health*, Part B **47**: 869–875.

Garrido EM, Rodrigues D, Milhazes N, Borges F and Garrido J. 2017. Molecular encapsulation of herbicide terbuthylazine in native and modified 5øýþ-cyclodextrin. *Electronic Journal of Chemistry.* DOI: *https://doi.org/10.1155/2017/8120367*.

Glaze NC. 1987. Cultural and mechanical manipulations of *Cyperus spp. Weed Technology* **1**: 82-83.

Haruyama T. 2003. Micro and nanobiotechnology for biosensing cellular responses. *Advanced Drug Delivery Reviews* **55**: 393–401

Hartzler B. 2002. Absorption of soil applied herbicide. Weed Science. Extension weed management specialist. *http://www.weeds.iastate.edu/mgmt/2002/soilabsorption.htm*.

Heap, I. 2018. The international survey of herbicide resistant weeds. *http://www.weedscience.org/*

IPSC. 1990. *International Programme on Chemical Safety, Atrazine Health and Safety Guide No. 47,* WHO Geneva.

Jain KK. 2003. Nanodiagnostics: application of nanotechnology in molecular diagnostics. *Expert Review of Molecular Diagnostics* **3**: 153–61.

Joo SH and Zhao D. 2008. Destruction of lindane and atrazine using stabilized iron nanoparticles under aerobic and anaerobic conditions: Effects of catalyst and stabilizer. *Chemosphere* **70**(3): 418-425.

Kadian N, Gupta A, Satya S, Mehta RK and Malik A. 2008. Biodegradation of herbicide (atrazine) in contaminated soil using various bioprocessed materials. *Bioresource Technology* **99**(11): 4642-4647.

Kanimozhi V and Chinnamuthu CR. 2012. Engineering core/hallow shell nanomaterials to load herbicide active ingredient for controlled release. *Journal of Nanoscience and Nanotechnology* **2**: 58-69.

Khan Rahmat, Ullah Rashid, Abdul Khan and Muhammad Sohail. 2011. Impact of various rates of pendimethalin herbicide on weed control, seed yield and economic returns in mungbean under rainfed conditions. *Journal of Agricultural Research* **49**(4): 491-498.

Ko Wakabayashi and Peter Böger. 2004. Phytotoxic sites of action for molecular design of modern herbicides (Part 1): The photosynthetic electron transport system. *Weed Biology and Management* **4**: 8–18.

OECD and Allianz. 2008. *https://www.oecd.org/science/nanosafety/44108334.pdf*

Maruyama CR, Guilger M, Pascoli M, Jose NB, Abhilash PC, Fraceto LF and Lima R. 2016. Nanoparticles based on chitosan as carriers for the combined herbicides imazapic and imazapyr. *https://dx.doi.org/10.1038%2Fsrep19768*.

Pâmela Soto Garcia, Alberto Luís Dario Moreau, Jéssica Cristiane Magalhães Ierich, Ana Carolina Araujo Vig, Akemi Martins Higa, Guedmiller S. Oliveira, Fábio Camargo Abdalla, Moema Hausen, and Fábio L. Leite A. 2015. Nanobiosensor based on 4-hydroxyphenylpyruvate dioxygenase enzyme for mesotrione detection. *IEEE Sensors Journal* **15**(4): 2106- 2113.

Pradeesh Kumar T and Chinnamuthu CR. 2014. An attempt to synthesis a new nanoformulation of pendimethalin herbicide for slow release using direct encapsulation technique. *Trends in Bioscience* **7**(14): 1987-1692.

Pradeesh Kumar T and Chinnamuthu CR. 2017. Assembly of nanoencapsulated pendimethalin herbicide using solvent evaporation method for season long weed control under irrigated ecosystem. *International journal of pure and applied bioscience* **5**(1): 349-357.

Ravisankar, D and Chinnamuthu CR. 2013. Effect of selected growth promoting substances in combination with herbicides on sprouting and viability of purple nutsedge (*Cyperus rotundus* L.) tuber. *Acme International Journal of Multidisciplinary Research* **1**(10): 66-68.

Ravisankar, D and Chinnamuthu CR. 2017. Study on purple nutsedge (*Cyperus rotundus*) tuber dormancy and its control through combined application of growth regulator and herbicides. *Chemical Science Review and Letters* **6**(22): 727-731.

Sattin M, Berti A and Zanin G. 1995. Agronomic aspects of herbicide use. pp 45-70. *In*: Pesticide Risk in Groundwater (Eds. VighiI M, Funari E). Boca Raton: CRC.

Silva M, Cocenza DS, Grillo R, Melo NF, Tonello PS, Oliveira LC and Fraceto LF. 2011. Paraquat-loaded alginate/chitosan nanoparticles: Preparation, characterization and soil sorption studies. *Journal of Hazardous Materials* **190**(1-3): 366–374.

Struthers JK, Jayachandran K and Moorman TB. 1998. Biodegradation of atrazine by agrobacterium radiobacter J14a and use of this strain in bioremediation of contaminated soil. *Applied and Environmental Microbiology* **64**(9): 3368-3375.

Susha VS, Chinnamuthu CR, Stella J, Winnarasi and Pandian K. 2008. Mitigating atrazine, 2-chloro-4-(ethyl amine)-6-(isopropylamine)-s-triazine herbicide residue in soil using palladium and silver nanoparticles doped iron oxide nanoparticles with different stabilizing agents. International Conference on *Magnetic Materials and their Applications for 21st Century* (MMA-21) October 21-23, 2008. National Physical Laboratory, New Delhi and Magnetic Society of India (MSI).

Tortolini C, Bollella P, Antiochia R, Favero G and Mazzei F. 2016. Inhibition-based biosensor for atrazine detection, Sensors and Actuators B: *Chemical* **224**: 552–558.

Urrusuno RF, Gines JM and Morillo E. 2000. Development of controlled release formulations of alachlor in ethylcellulose. *Journal of Microencapsulation* **17**(3): 331-342.

Vasudevan K. 2002. *News l*. Declining Amphibian Populations Task Force–South Asia.

Viji N and Chinnamuthu CR. 2015a. Iron oxide nanoparticles to break the tubers dormancy of the world's worst weed the *Cyperus rotundus*. *International Journal of Agricultural Science and Research* **5**(3): 259-266.

Viji N and Chinnamuthu CR. 2015b. Breaking dormancy and inducing germination of the world worst weed the *Cyperus rotundus* using nanoparticles. *Annals of Plant and Soil Research* **17**(Special Issue): 361-363.

Viji N, and Chinnamuthu CR. 2018. Titanium dioxide nanoparticles to break the tubers dormancy of the world's worst weed the *Cyperus rotundus* L. *Multilogic in science* **7**(special issue): 322-325.

Viji N, Chinnamuthu CR and Chinnusamy C. 2016. Depriving the purple nutsedge by degrading the starch present in the tubers using immobilized amylase on the surface of organically synthesized silver nanoparticles. *Green Farming* **7**(1): 107-110.

Vimalrajiv B, Chinnamuthu CR, Subramanian E and Senthil K. 2018. Effect of nanoparticles in combination with pendimethalin and hydrogen peroxide on growth parameters and nodulation of blackgram (*Vigna mungo* L.). *International Journal of Chemical Studies* **6**(3): 2816-2819.

Ware GW. 1986. *Fundamentals of Pesticides: A Self-Instruction Guide*. Thomson Publications.

Chapter 4

Crop-weed competition and yield loss due to weeds in India

Yogita Gharde*, P.K. Singh and P.K. Gupta[1]
ICAR – Directorate of Weed Research, Jabalpur, Madhya Pradesh 482 004
[1]JNKVV, Jabalpur, Madhya Pradesh 482 004
**Email:yogitagharde@gmail.com*

Summary

Crop-weed competition is a natural phenomenon whereby crop and weed plants incline to attain a maximum combined growth and yield at the expense of the other. It takes place when the demands of the plants for moisture, nutrients, light, and also the carbon dioxide exceed the available supply and thus, this may lead to crop-weed competition. Due to this, crop suffers with many damages and losses, among which most important is reduction in the crop yield as its direct effect on crop. Depending upon the type of weed, its intensity of infestation, period of infestation, crop competition and climatic conditions, the loss caused by weeds may be different. In past, many studies have been conducted to estimate the yield losses due to weeds in many crops in India. However, these estimates are mainly based on experimental data. Further, yield loss estimation from experimental condition is provisional on local effects and sometimes it is valid only for some cropping situation and it may be challenging to generalize the results obtained from experiments for yield losses in farmers' fields. Some researchers also estimate the yield losses due to weeds using data from farmers' fields. Yield losses are very important statistics for assessment of usefulness of existing plant protection measures. These data provide a basis for making decisions on the relative importance of weeds with respect to agriculture and the environment. Similarly, economic losses are also important statistics for policy makers and others including researchers to comprehend the impact of weeds in economic terms. This review presents work done in India on estimation of yield and economic losses caused by weeds in major crops.

Key words: Crop, Economic loss, Estimates, Weed, Yield loss

Weeds own many development and adaptations characteristics which allow them to use successfully the various ecological niches left uninhabited by other crop plants. Among these, few more important relevant to competitive advantage are well synchronized germination habit, quick establishment and growth of saplings, tolerance to shading effects by the crop or by other weeds during the establishment, quick reaction to available moisture and nutrients in the soil, adaptation to the unfavourable climatic conditions of the habitat, relative resistance to post seeding soil disturbance, practices and resistance to some herbicides that are used.

Crop-weed competition is a natural phenomenon whereby crop and weed plants incline to attain a maximum combined growth and yield at the expense of the other. It takes place when the demands of the plants for moisture, nutrients, light, and also the carbon dioxide surpass the available supply. This may lead to crop-weed competition. When no appropriate control measure is applied to control the weeds, crop and weeds subsequently may grow and reach to the maturity stage in the state of mutual suppression. Owing to its quick growth and development characteristics, weed suppresses the crop and result in reduction of yield. In some situation, such as in row crop cultures, crop also suppresses the weeds.

Crop–weed competition studies can provide valuable information to the farmers and farm managers on whether weed control is necessary, and if so, what is the optimum timing to implement weed control practices to reduce the yield loss to a greater extent. For instance, the development of economic thresholds for weed helps farmers in making decisions about the requirement of weed control and the cost effectiveness of various weed control options. Knowledge of critical periods for weed control assists growers in determining when, or when not, to pursue further weed control measures to protect crop yield.

Further, crop–weed competition studies can provide information on the merits of various components of a cropping system. Crop rotation, intercropping, seeding rates, row spacing, and fertilizer placement are components of a cropping system that invariably influence the competitiveness of the crop or the weed, or both. Competitive cropping systems that enhance crop establishment, rate of leaf appearance, and canopy cover reduce weed competition and costs associated with weed control.

Competition for nutrients

Weeds have much more adaptation characteristics to our agro-ecosystems than crop plants. Hence, they absorb nutrients from soil faster than crop plants and accumulate them in their tissues in greater amount. For example, during the experimentation, after comparing the nutrient uptake of the plants and the weeds one month after the sowing of the maize, it was observed that nutrient quantity taken up by the weeds was much higher at least 5 times higher than that of the maize (Lehoczky and Reisinger 2003). In another study, N, P and K contents in weed species tissue were found to be 1.8 to 2 times higher those that of black seed (Seyyedi *et al*. 2016). Mehriya *et al*. (2007) also observed a high uptake of N, P and K by weeds under weed-cumin (*Cuminum cyminum*) competition.

Competition for moisture

Weeds directly compete with crops for moisture leading to moisture stress condition for crops, and are potentially responsible for 34% of crop loss globally (Oerke 2006). Weeds absorb moisture available for crops, cause water loss by seepage through root channels, transpire water, and cut water flow in irrigation ditches, leading to more consumption of water by weeds and more evaporative water loss (Zimdahl 2013). Some common annual weeds present in the cropped areas transpires about four times more water than a crop plant and use up to three times as much water to produce a unit of dry matter as do the crops. For example, the consumptive use of water for *Chenopodium album* was estimated by 550 mm against 479 mm for wheat crop (Hasanuzzaman 2008). Further, under water stress condition, weeds are able to reduce crop yields by more than 50% through moisture competition alone. However, the competition between weeds and crops are depending on weed density, the plant's physical characteristics rather than the aboveground biomass. Thus, perennial weeds can be less affected by drought than annual weeds (Abouziena *et al*. 2014-15).

Competition for light

Competition for light may be considered as one of the most important factors in reducing yields, especially with weeds that grow taller than the crop. It becomes important factor of crop-weed interaction when moisture and nutrients are abundant.

Competition for space

Competition for space is the actual requirement for CO_2 for the plants and it may occur when extremely crowded plant density is present in the cropped situation. Weed competition for space lead to reduction in photosynthetic rate of plants and finally the yield. Weeds outgrow the crop in the seedling stage and will not allow sunlight to the crop. Hence, the crop is smothered due to poor sunlight leading to competition for space which has a final say on crop yield.

Losses caused by weeds

Due to crop-weed competition, crop suffers with many damages and losses. Among these, some important are reduction in the crop yield, increase in the cost of production, reduced quality of the produce, reduced quality of livestock produce, harbor insect-pests and disease pathogens, water flow check in irrigation channels, harmful effect on human beings and animals, reduction in the value of the land etc. Among all, reduction in the crop yield are of great concern for farmers, which is necessary to deal with.

Reduction in crop yield

If weeds are left uncontrolled, potential yield losses from 20 to 100%, on an average 40-60% are commonly occurred (Joshi *et al*. 2001). Depending upon the type of weed, its intensity of infestation, period of infestation, crop competition and climatic conditions, the loss caused by weeds may be different. In India, many studies have been conducted in past to estimate the yield losses due to weeds in many crops. However, these estimates are mainly based on experimental data. According to Mani *et al*. (1968), weeds caused a loss of 31.5% in foodgrain crops of which maximum loss occurred in the *Kharif* season. Yield loss due to weeds is maximum in sugarbeets (70.3%), followed by onion (68%), sugarcane (34.2%), linseed (34.2%), groundnut (33.8%), and peas (32.9%) (Mandal 2007).

In India, about 33% of the total losses due to pests in agricultural produce is due to weeds alone. As per the study conducted by ICRISAT (International Crop Research Institute for Semi-Arid Tropics), Hyderabad, the per cent yield reduction due to weed competition was observed upto 70% in sorghum, 60% in pearlmillet and 40% in chickpea. The data collected from several field experiments conducted during 1978 to 1987 (10 years) both under AICRP-Weed Management and else on

Table 1. Average yield and yield loss under different weed management practices in major cereal crops

Crops	Yield under weed free (t/ha)	Yield loss under chemical control (%)	Yield loss under manual weeding (once or twice) (%)	Yield loss under weedy check (%)
Rice (transplanted)	4.50	2.8	2.0	16.9
Rice (direct-seeded)	1.78	31.5	15.4	47.2
Wheat	3.76	7.5	5.85	26.0
Maize	4.13	2.6	1.5	40.7
Sorghum	1.85	10.3	7.0	44.8
Pearl millet	1.12	1.1	0.4	56.5

Source: Saraswat 2009

different aspects of weed management were used to estimate losses in yield in cereals, pulses, oilseeds, fibres and other commercial crops. The results from this study indicated that yield losses were maximum in unweeded crops which varied from 16.9% in transplanted rice to 56.5% in pearlmillet, where very less control measures like manual weeding and herbicides were applied, compared to completely weed free crop (**Table 1**). The losses in other crops like oilseeds were upto 71.2%, 38.8% in pulse and 50.4% in commercial crops in unweeded crops (Saraswat 2009).

Globally, the food loss due to weeds is reported to be about 287 million tons, accounting for 11.5% of the total food production. However, farmers adopt some kind of weeding operations on their field, therefore, conservative estimates showed at least 10% reduction in crop yields. Further, such losses in advanced countries are 5% while in the under developed countries, it is about 25% (Kumar and Jagannathan 2003).Yield losses due to weeds are presented in **Table 2**.

Table 2. Yield losses due to weeds in some important crops

Crop	Yield loss range (%)
Rice	9.1-51.4
Wheat	6.3-34.8
Maize	29.5-74.0
Millets	6.2-81.9
Groundnut	29.7-32.9
Sugarcane	14.1-71.7
Cotton	20.7-61.0
Carrot	70.2-78.0
Peas	25.3-35.5

Source: Kumar and Jagannathan (2003)

Bhan *et al.* (1999) estimated that weeds decrease the crop yields by 31.5% (22.7% in winter and 36.5% in summer and *Kharif* seasons) in India. Many researchers reported yield loss data obtained from experiments conducted in different crops. Extensive scientific data based on experiments are available and summarized, which show yield loss of about 15.9% in blackgram to 76.8% in

Table 3. Losses in crop yield caused due to weeds in some important crops

Crop	Yield (t/ha)			Source
	Weed free	Weedy	Loss (%)	
Food crops				
Direct-seeded Rice (*Oryza sativa* L.)	5.19	2.35	54.7	Sanodiya *et al.* (2017)
	5.34	2.01	62.4	Singh *et al.* (2017)
	3.88	1.48	61.9	Pinjari *et al.* (2016)
Transplanted rice (*Oryza sativa* L.)	6.33	3.76	40.6	Mohapatra *et al.* (2017)
Wheat (*Triticum aestivum*L.)	5.91	4.04	31.6	Yadav *et al.* (2018)
Maize (*Zea mays* L.)	10.10	3.86	61.8	Mukherjee *et al.* (2016)
Greengram [*Vigna radiata* (L.) Wilczek]	1.14	0.29	74.6	Punia *et al.* (2017)
	1.65	0.55	66.7	Singh *et al.* (2015)
	1.50	0.51	66.0	Singh *et al.* (2017)
Barley (*Hordeumvulgare* L.)	3.70	2.40	35.1	Jena*et al.* (2018)
Black gram (*Vigna mungo*L.)	1.25	0.63	49.6	Patel *et al.* (2017)
	4.48	3.77	15.9	Balyan *et al.* (2016)
Pearl millet (*Pennisetum glaucum* L.)	3.22	1.91	40.7	Girase *et al.* (2017)
Lentil (*Lens culinaris* Medik.)	2.01	1.05	47.8	Panwar *et al.* (2017)
Pigeonpea (*Cajanus cajan* (L.)Millsp)	1.71	0.78	54.4	Malik *et al.* (2014)
Chickpea (*Cicer arietinum*L.)	2.16	0.68	68.3	Khope *et al.* (2011)
Fatty Oil crops				
Sesame (*Sesamum indicum* L.),	1.38	0.32	76.8	Mathukia *et al.* (2015)
Groundnut (*Arachis hypogaea* L.)	8.53	4.93	42.2	Singh *et al.* (2017)
Soybean (*Glycine max* (L.) Merr.)	3.73	1.90	49.1	Jadhav (2013)
Fibre Crops				
Cotton (*Gossypium hirsutum* L.)	2.39	0.95	60.3	Veeraputhiran *et al.* (2015)
Sugar crops				
Sugarcane (*Saccharumofficinarum* L.)	50.45	38.00	24.7	Singh *et al.* (2016)
Vegetable Crops				
French bean (*Phaseolus vulgaris* L.)	1.59	1.06	33.3	Kumar *et al.* (2014)
Garlic (*Allium sativum* L.)	6.28	2.70	57.0	Sampat *et al.* (2014)
Chilli (*Capsicum annuum* L.)	1.68	0.56	66.7	Gare *et al.* (2015)
Onion (*Allium cepa* L.)	3.62	2.44	32.6	Singh *et al.* (2016)
Okra *[Abelmoschus esculentus* (L.) *Moench]*	16.8	5.50	67.3	Patel *et al.* (2017)
Garden pea (*Pisum sativum* L.)	7.29	4.54	37.7	Mawalia *et al.* (2016)
Clusterbean *[Cyamopsis tetragonoloba* (L.) Taub.]	1.49	0.77	48.3	Gupta *et al.* (2015)
Other Crops				
Turmeric (*Curcuma longa* L.)	8.35	3.05	63.5	Sachdeva *et al.* (2015)

sesame. Yield losses in different crops compiled from the research articles published in Indian Journal of Weed Science during 2011 - 2018 are given **Table 3**.

In the studies conducted by ICAR-Directorate of Weed Research (2013), it was reported that weeds cause up to one-third of the total losses in the yield, besides deteriorating quality of produce and causing health and environmental hazards. reported yield losses from 10% to 100% (**Table 4**) .

However, yield loss estimation from experimental condition is provisional on local effects and sometimes it is valid only for some cropping situation and it may be challenging to generalize the results obtained from experiments for yield losses

Table 4. Potential yield loss due to weeds in different major crops of India

Crop	Yield losses (%)	Crop	Yield losses (%)
Chickpea	10-50	Pea	10-50
Cotton	40-60	Pearlmillet	16-65
Fingermillet	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
Niger	20-30	Wheat	10-60

Source: Rao *et al.* (2014)

in farmers' fields. The reason may be the different experimental conditions for the different experiment (Walker 1987, Savary *et al.* 1998). Further, it is more convincing to establish results from field trials comparing the different treatments in the farmers' field (Walker 1983, Zanin *et al.* 1992, Oerke *et al*. 1994, Oerke and Dehne 1997, Tamado *et al*. 2002). Therefore, recently a study at ICAR-Directorate of Weed Research, Jabalpur was commenced to reassess the yield losses (potential as well as actual) estimates along with economic losses due to weeds in major field crops of India based on data from farmers' fields. Yield losses were estimated using the data obtained from on-farm research trials conducted by All India Coordinated Research Project on Weed Management coordinating centres located at 18 states during 2003 to 2014. This was done for 16 major field crops of India. Actual and potential yield losses (%) are shown in **Table 5**.

Table 5. Actual and potential yield losses (%) in major field crops of India

Crop	Actual Yield loss (%)	Potential yield loss (%)
Transplanted rice	3.4 - 30	15 – 66.2
Direct-seeded rice	5.6 - 49.7	-
Wheat	7.5 - 41	16.5 - 43
Maize	8.6 - 51	17.6 - 65
Mustard	9.6 - 38	-
Soybean	20.2 - 47.7	50 – 76.4
Sunflower	25 - 41	-
Pigeonpea	5.1 - 42	33.6
Groundnut	25 - 50.7	45 – 70.7
Chickpea	35	-
Sugarcane	6.6 - 43.2	67.8
Sorghum	23.5 - 27.4	35 – 49.5
Blackgram	30.7	50.9
Greengram	13 - 43.3	56.5
Sesame	14.4 - 32.9	58
Cotton	13.9 - 24.4	-
Pearl millet	27.6	41

It is clear from the table that variation is high in the case of direct-seeded rice (5.6-49.7%) followed by maize (8.6-51%). Actual yield loss was less in transplanted rice as compared to direct-seeded rice. Gharde *et al.* (2018) observed that state, crop and soil type were significantly different from each other and thus contributed significantly in explaining the variability in yield loss data.

Economic losses

The total losses due to weeds to different parts have been estimated Rs. 5000 crores during 1973-74, of which 33% contributed by weeds alone in India (Financial Express, 7th April, 1975). The economic losses due to disease (26%), due by insect (20%), due by rodents (6%) and due by storage (6-8%) other than weeds. Results also showed that out of total (Rs. 5000 crores) weeds found to cause around Rs. 1650 crores loss alone (Joshi *et al.* 2001).

The economic losses due to weeds in India was estimated as ` 20 to 28 billion about two decades ago (Sahoo and Saraswat 1988, Sachan 1989). Even a conservative estimate of about 10% loss (Bhan *et al.* 1999) would amount to a loss of food grains valued at approximately US$ 13 billion (Yaduraju 2012). In another study, it was reported that loss in agricultural production due to weeds amounts to INR 1050 billion per annum (NRCWS 2007, Varshney and Prasad Babu 2008, Gharde *et al.* 2018).

In the study conducted at ICAR-Directorate of Weed Research, Jabalpur, monetary losses due to weeds were also calculated (**Figure 1**).Results revealed that actual economic losses is highest as 36% (` 28291crore) of total loss in case of rice (total) followed by wheat (` 21606 crore) and soybean (` 9979 crore), respectively (**Figure 1**). Rice is found as the most economically affected crop than others, however, only 14% actual average yield loss in transplanted and 21% in direct seeded condition was observed. Further, potential yield loss upto 66% was observed in case of rice where weeds were not controlled and left to grow with crops. It indicates that many weed management methods are being used at farmer's level to control weeds in rice and also in wheat. Further, study revealed that foodgrains (cereals, pulses and millets) experienced more economic losses due to weeds (76.5%) followed by oilseed crops (16.5%) and cash crops, *viz.* sugarcane and cotton (7%). All together total actual economic loss in 16 major crops in 18 states were estimated as ` 78591 crores due to weeds alone. However, the total economic losses will be much higher, if indirect effects of weeds on health, losses of biodiversity, nutrient depletion, grain quality, etc. are taken into consideration.

Yield losses due to weeds are very important statistics for assessment of usefulness of current plant protection measures (Oerke and Dehne 2004). These data provide a base for making decisions on the relative importance of weeds with respect to agriculture and the environment (Walker 1983). Economic losses due to weeds are also very important statistics for policy makers and others including researchers to comprehend the impact of weeds in economic terms. All studies discussed here include only the direct losses in crop yield due to weed competition.

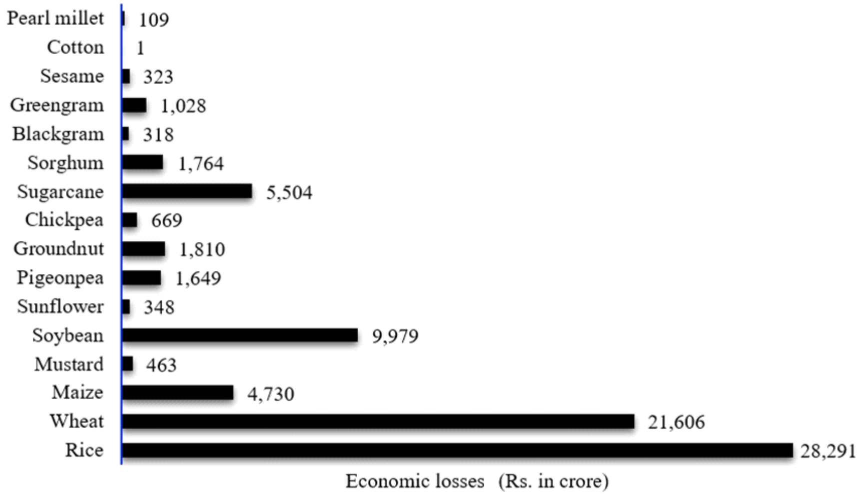


Figure 1. Economic losses due to weeds in India

However, there are some other indirect losses including the weed control measures that contribute to increased cost of production and also contribute in increasing economic loss due to weeds (Oliveira *et al*. 2014). Use of herbicides has been increasing during past decades and is still going up (Choudhury *et al.* 2016) for controlling weeds at farmers' fields due to shortage of labourers and high cost involved in the manual weeding. At the same time, herbicides are able to control the weeds up to certain time but flushes of weeds in the further growing stage of crops pose new challenges to the farmers during cropping season. Further, high cost of herbicides, their timely unavailability and lack of technical know-how also make weed control difficult for marginal farmers despite its harmful effects on environment. So, there is need to integrate different methods of weed management including cultural, mechanical and chemical under integrated weed management (IWM) strategy.

References

Abouziena HF, El-Saeid HM and Amin AAES. 2014-15. Water loss by weeds: a review. *International Journal of Chem Tech Research* **07**(1): 323–336.

Balyan JK, Choudhary RS, Kumpawat BS and Choudhary R. 2016. Weed management in blackgram under rainfed conditions. *Indian Journal of Weed Science* **48**(2): 173–177.

Bhan VM, Sushilkumar, Raghuwanshi MS. 1999. Weed Management in India. *Indian Journal of Plant Protection* **17**: 171–202.

Chopra SS, Kumar A and Samnotra RK. 2014. Chemical weed management in garlic. *Indian Journal of Weed Science* **46**(2): 146–150.

Choudhury PP, Singh R, Ghosh D and Sharma AR. 2016. *Herbicide Use in Indian Agriculture*. ICAR-Directorate of Weed Research, Jabalpur, Madhya Pradesh, India. 110 p.

Gare BN, Raundal PU and Burli AV. 2015. Integrated weed management in chilli under rainfed condition. *Indian Journal of Weed Science* **47**(4): 390–392.

Gharde Y, Singh PK, Dubey RP and Gupta PK. 2018. Assessment of yield and economic losses in agriculture due to weeds in India. *Crop Protection* **107**(12–18).

Girase PP, Suryawanshi RT, Pawar PP and Wadile SC. 2017. Integrated weed management in pearl millet. *Indian Journal of Weed Science* **49**(1): 41–43.

Gupta OP. 2008. *Weed Menace*. (In) *Modern Weed Management*. 589 p.

Gupta V, Singh SP and Yadav RS. 2015. Yield performance and nutrient uptake as influenced by integrated weed management in clusterbean. *Indian Journal of Weed Science* **47**(1): 82–84.

Hasanuzzaman M. 2008 Crop-Weed Competition. 6 pp. http://hasanuzzaman.weebly.com/uploads/ 9/3/4/0/934025/crop-weed_competetion.pdf

Jadhav VT. 2013. Yield and economics of soybean under integrated weed management practices. *Indian Journal of Weed Science* **45**(1): 39–41.

Jena T, Singh RK and Bisen N. 2018. Surfactant influence on efficacy of herbicides in barley. *Indian Journal of Weed Science* **50**(1): 56–58.

Joshi NC. 2001. Introduction to weed Science and classification of weeds; pp. 538. In: *Manual of Weed Control*.

Khope D, Kumar S and Pannu RK. 2011. Evaluation of post-emergence herbicides in chickpea (*Cicerarietinum*). *Indian Journal of Weed Science* **43**(1&2): 92–93.

Kumar JR, Jagannathan R. 2003. Weed science principles. In: *Weed Science Principles*. pp 338.

Kumar A, Saxena A and Singh PK. 2014. Chemical and mechanical weed management for increased yield of French bean. *Indian Journal of Weed Science* **46**(4): 350–352.

Lehoczky E and Reisinger P. 2003. Study on the weed-crop competition for nutrients in maize. *Comm. Appl. Biol. Sci.*, Ghent University, **68**(4a): 373–380.

Malik RS and Yadav A. 2014. Effect of sowing time and weed management on performance of pigeonpea. *Indian Journal of Weed Science* **46**(2): 132–134.

Mandal RC. 2007 Definition of some basic concepts; pp 306. In: *Weed, Weedicides and Weed Control Principles and Practices*.

Mani VC, Gautam KC and Chakraberty TK. 1968. Losses in crop yield in India due to weed growth, *Proceedings of the National Academy of Sciences* **42**: 142-158.

Mathukia RK, Sagarka BK and Jadav CN. 2015. Integrated weed management in summer sesame. *Indian Journal of Weed Science* **47**(2): 150–152.

Mawalia AK, Kumar S and Rana SS. 2016. Herbicide combinations for control of complex weed flora in garden pea. *Indian Journal of Weed Science* **48**(1): 48–52.

Mehriya ML, Yadav RS, Jangir RP and Poonia BL. 2007. Critical period of crop-weed competition and its effect on nutrients uptake by cumin (*Cuminum cyminum*) and weeds. *Indian Journal of Agricultural Sciences* **77:** 849–852.

Mohapatra S, Tripathy SK, Nayak BR and Mohanty AK. 2017. Efficacy of pre-emergence herbicides for control of complex weed flora in transplanted rice. *Indian Journal of Weed Science* **49**(3): 216–218.

Mukherjee PK and Rai A. 2016. Weed management in no-tilled dribbling maize for small land holder. *Indian Journal of Weed Science* **48**(3): 290–293.

Oerke EC. 2006. Crop losses to pests. *Journal of Agriculture Science* **144**: 31–43.

Oerke EC, Dehne HW, Scho¨nbeck F and Weber A. 1994. Crop production and Crop protection—Estimated Losses in Major Food and Cash Crops. Elsevier, Amsterdam, 808 p.

Oerke EC and Dehne HW. 1997. Global crop production and the efficacy of crop protection—current situation and future trends. *European Journal of Plant Pathology* **103**: 203–215.

Oerke E and Dehne HW. 2004. Safeguarding production - Losses in major crops and the role of crop protection. *Crop Protection* **23**: 275–285.

Oliveira CM, Auad AM, Mendes SM and Frizzas MR. 2014. Crop losses and the economic impact of insect pests on Brazilian agriculture. *Crop Protection* **56**: 50–54.

Panwar GS, Choudhury SR, Kumar S, Kumar A, Yadav A, Singh RG and Singh S. 2017. Herbicides for weed management in lentil under rainfed drought prone ecology of Bihar. *Indian Journal of Weed Science* **49**(4): 350–355.

Patel TU, Zinzala MJ, Patel DD, Patel HH and Italiya AP. 2017. Weed management influence on weed dynamics and yield of summer lady's finger. *Indian Journal of Weed Science* **49**(3): 263–265.

Patel CV, Poonia TC and Pithia MS. 2017. Integrated weed management in *Kharif* blackgram. *Indian Journal of Weed Science* **49**(1): 44–46.

Pinjari SS, Gangawane SB, Mhaskar NV, Chavan SA, Chavan VG and Jagtap DN. 2016. Integrated use of herbicides to enhance yield and economics of direct-seeded rice. *Indian Journal of Weed Science* **48**(3): 279–283.

Punia R, Punia SS, Sangwan M and Thakral SK. 2017. Efficacy of imazethapyr applied alone and its mixture with other herbicides in green gram and their residual effect on mustard. *Indian Journal of Weed Science* **49**(2): 151–155.

Sachan GC. 1989. Pesticides in agriculture. *Indian Farmers Digest* **22**: 9–13.

Sachdeva N, Kumar S and Rana SS. 2015. Integrated weed management in turmeric. *Indian Journal of Weed Science* **47**(1): 50–54.

Sahoo KM and Saraswat VN. 1988. Magnitude of losses in the yields of major crops due to weed competition in India. *Pesticide Information* **14**: 2–9.

Sanodiya P and Singh MK. 2017. Integrated weed management in direct-seeded rice. *Indian Journal of Weed Science* **49(1):** 10–14.

Saraswat VN. 2009. Weeds: their ecology and control. (Eds. Mukerji KG, Upadhyay RH, Chamola OBP and Dubey P), Integrated Pest and Disease Management.

Savary S, Elazegui FA and Teng PS. 1998. Assessing the representativeness of data on yield losses due to rice disease in tropical Asia. *Plant Disease.* **82**: 705–709.

Seyyedi SM, Moghaddam PR and Mahallati MN. 2016. Weed competition periods affect grain yield and nutrient uptake of black seed (*Nigella Sativa* L.). *Horticultural Plant Journal* **2**(3): 172–180.

Singh A, SinghY, Singh R and Jat AL. 2017. Weed dynamics and production potential of direct-seeded rice cultivars as influenced by weed management. *Indian Journal of Weed Science* **49**(2): 108–112.

Singh G, Virk HP and Sharma P. 2017. Efficacy of pre- and post-emergence herbicides for weed control in greengram. *Indian Journal of Weed Science* **49**(3): 252–255.

Singh G, Kaur H, Aggarwal N and Sharma P. 2015. Effect of herbicides on weeds growth and yield of greengram. *Indian Journal of Weed Science* **47**(1): 38–42.

Singh R, Neelam, Singh DK, Singh AP, Chaturvedi S, Pal R and Singh M. 2016. Management of complex weeds in sugarcane by ametryn + trifloxysulfuron. *Indian Journal of Weed Science* **48**(2): 195–198.

Singh SP, Yadav RS, Kumawat A, Bairwa RC and Reager ML. 2017. Groundnut productivity and profitability as influenced by weed control measures. *Indian Journal of Weed Science* **49**(4): 360–363.

Singh SK, Shyam R, Chaudhary S and Yadav LM. 2016. Weed management in onion. *Indian Journal of Weed Science* **48**(2): 199–201.

Tamado T, Ohlander L and Milberg P. 2002. Interference by the weed *Parthenium hysterophorus* L. with grain sorghum: Influence of weed density and duration of competition. *International Journal of Pest Management* **48**: 183–188.

Varshney JG, PrasadBabu MBB. 2008. Future scenario of weed management in India. *Indian Journal of Weed Science* **40**(1&2): 1–9.

Veeraputhiran R and Srinivasan G. 2015. Post-emergence herbicides effect on weeds, yield and economics of *Bt* cotton. *Indian Journal of Weed Science* **47**(4): 379–382.

Walker PT. 1983. Crop losses: the need to quantify the effects of pests, diseases and weeds on agricultural production. *Agriculture Ecosystem and Environment*. **9**: 119–158.

Walker PT. 1987. Losses in yield due to pests in tropical crops and their value in policy decision-making. *Insect Science and its Application* **8**: 665–671.

Yadav DB, Yadav A and Punia SS. 2018. Ready mix of pinoxaden and clodinafop-propargyl for control of *Phalaris minor* in wheat and its residual effects on succeeding rice crop. *Indian Journal of Weed Science* **50**(1): 42–45.

Yaduraju NT. 2012. Weed management perspectives for India in the changing agriculture scenario in the country. *Pakistan Journal of Weed Science Research* **18**: 703–710.

Zanin G, Berti A and Giannini M. 1992. Economics of herbicide use on arable crops in North-Central Italy. *Crop Protection* **11**: 174–180.

Zimdahl RL. 2013. *Fundamentals of Weed Science*, 4th ed. Academic Press, San Diego, San Diego, California, USA.

Chapter 5

Herbicide residue, persistence and degradation: An Indian viewpoint

Shobha Sondhia*
ICAR - Directorate of Weed Research, Maharajpur
Jabalpur, Madhya Pradesh 482004
**Email: shobhasondia@yahoo.com*

Summary

Herbicides use is greater than ever throughout the globe due to increasing labour cost, choice of application of herbicides, quick weed control in cropped and non-cropped situations. As herbicides are basically synthetic chemicals in nature and thus excessive and repeated use may create residue problems, phytotoxicity to crop plants, residual effects on susceptible intercrops or succeeding crops, adverse effects on non-target organisms and ultimately health hazards to human beings and animals. Thus, herbicide residue, persistence and degradation in soil, water, plants, and other important ecological component are very important. Herbicide persistence and degradation is largely determined by several bio-chemical processes such as adsorption, absorption, volatilization, leaching, runoff, photodecomposition, degradation by microbial and chemical processes. Numerous instrumentation techniques for residue determination are becoming quite sensitive with time thus creating more awareness among public. Herbicide residues are monitored through multi-location supervised field trials at various institutes of ICAR, SAUs, independent laboratories, Directorate of Weed Research, Jabalpur along with its centres under All India Coordinated Project on Weed Management (AICRP-WM). Currently, the use of herbicides is higher in wheat and rice, followed by plantation crops. 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 80.0% samples with residues below the detection limit (BDL), 13.4% below maximum residue limit (MRL), and 6.6% samples were found to be above MRL values. Field experiments have been conducted for risk assessment of herbicide residues in agricultural commodities. Data of such trials are used for maximum residue limit (MRL) fixation. It can be predicted that herbicide residues in plants and natural waters were found to be infrequent and at low levels in the soils of central India. Information presents a holistic view of herbicide residue research in India.

Key words: Cyhalofop-P-butyl, Herbicide residue, Soil, Toxicity

Introduction

Agriculture is the backbone of the Indian economy and contributes to about 15% of the country's gross domestic product (GDP). In India, 15–25% of food produced by the farmers is lost due to pests and diseases. It is estimated that crop losses due to weeds far exceed the losses from insects, nematodes, diseases, and rodents combined. Such losses may account for up to 45% on the national and global scale (Rao 2000, Oerke 2006). Since weeds compete with crops for nutrients, moisture, sunlight and space, the agricultural productivity is hampered due to diversion of fertilizer nutrients to weed growth. Further, emergence of weeds reduces the photosynthetic efficiency leading to poor grain yield (Hawaldar and Agasimani 2012). Herbicides are used to control unwanted weeds in growing crops and to clear unwanted vegetation in grounds, parks, industrial sites and railway embankments. Smaller quantities of herbicides also find use in forestry, pasture systems, and management of areas set aside as wildlife habitat. While judicious use of herbicide is vital for higher productivity at lower cost, their non-judicious use may result in higher residues in food crops, soil, surface and ground water.

Over the years herbicides have emerged as an important tool in management of weeds. Herbicides use is increasing throughout the globe due to several reasons, such as increasing labour cost, choice of application of herbicides, quick weed control in crop and non-crop areas etc. After the discovery and use of 2, 4-D as a herbicide following IInd World War, there has been a phenomenal growth in development of new molecules as herbicides. Due to intensive research in herbicide discovery and mode of action of herbicides, many new molecules are available to cater the farmers need.

In India, herbicide use has increased to 30% during the last 10 years in managing weeds in the country. As herbicides are chemical in nature and thus excessive and repeated use may pose residue problems, phytotoxicity to crop plants, residual effect on susceptible inter-crops or succeeding crops or non-targets organisms and ultimately health hazards due to accumulation of herbicide residues in the soil, crop produce and ground water. Many herbicides are found as bound residues which make them not only unavailable to the targets but also polluting the soil ecosystem in a number of ways. There is a need to monitor herbicide residues in various commodities to assess buildup, biomagnifications and bioaccumulation of residues and adverse effects if any. An exhaustive study on fate, degradation and monitoring of herbicide residues in soil, water, crop plants, fishes etc have been conducted by Sondhia between 1999-2018 at Directorate of Weed Research, Jabalpur. Residue data was further strengthen by incorporating data from other studies conducted across the country.

Herbicide use pattern

Globally, herbicides constitute about 47% of the crop protection market followed by fungicides (17%), insecticides (29%) and others (7%). India is currently the fourth largest global producer of agrochemicals after the US, Japan and China, and herbicide usage is 30% (Sondhia 2014, Sondia *et al.* 2018). In many advanced countries, the average annual herbicide consumption is 675–1350 g/ha as compared to hardly 40 g/ha in India. As compared to other countries, India consumes less of herbicide due to availability of relatively cheap labor for manual weeding. However, with increase in farm wages and non-availability of labour, the use of herbicides in weed control is steadily increasing (Panchal and Kapoor 2016). The herbicide consumption in India stood at 0.4 billion USD in 2015 and is expected to grow at a Compound Annual Growth rate (CAGR) of 15% over the next five years to reach ~0.8 USD billion by 2020. Presently, approximately 75% of the available herbicides in India are used in plantation crops and the rest in the field crops like sugarcane, wheat, rice, maize, chili and other vegetables. While rice and wheat crops are the important crops in which the herbicides are applied, the maximum amount of herbicides (50–60%) is used in the tea plantation

Herbicides may be classified according to their chemical class, activity, mode of action, selectivity, method of application and time of application. They may be selective or non-selective. Selective herbicides control or suppress certain plants without affecting the growth of other plant species. Selectivity may be due to translocation, differential absorption, physical (morphological) or physiological differences between plant species. Non-selective herbicides, on the other hand, are not specific against certain plant species and control all plant types with which they come into contact. Some such non-selective herbicides like paraquat, glufosinate and glyphosate are mainly used to clear industrial sites, waste lands, railway tracts/embankments.

Repeated use of one or more herbicides with a similar mode of action can result in build-up of resistance in weed populations. Such weeds that have evolved resistance to a specific herbicide may also develop resistance to other herbicides with same mode of action as they share the same binding site (FAO 2003). Since herbicide use is predominant in the developed countries, majority of cases of herbicide resistance have been reported from the developed countries. The continuous use of isoproturon, coupled with monocropping of rice-wheat in Haryana and Punjab has led to resistance in *P. minor* (Walia *et al.* 1997, Sanbagavalli *et al.* 2000, Chhonkar and Sharma 2008).

In India currently 68 herbicides are registered for use in various crops Out of 2, belongs to category I of pesticide class (Extremely hazardous), 8 belongs to highly hazardous, 37 belongs to moderately hazardous and 23 belongs to fourth category that is unlikely to cause any harmful effects with LD_{50} value > 5000 mg/kg (**Figure 1**).

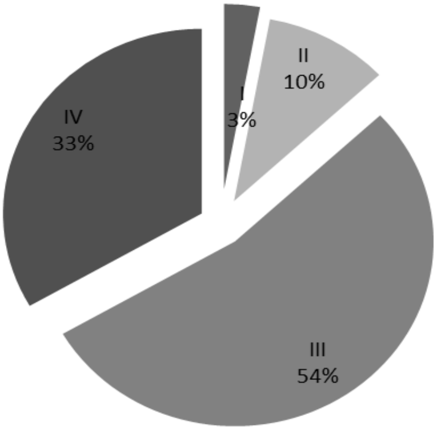


Figure 1. Toxicity rating of herbicides registered under/section 9 (3) of the insecticide Act 1968 as on January 2018 (*Source, Central Insecticidal Board* and registration committee)

*I: Extremely hazardous, II: Highly hazardous, III: Moderately hazardous, IV: unlikely to pose any hazard (Source: Central Insecticidal Board *and Registration Committee (2017),* http://cibrc.nic.in/)

Out of the total consumption of pesticides, 80% are in the form of insecticides, 15% are herbicides, 1.46% is fungicide and less than 3% are others. Herbicide application is more common in wheat crop (44%), followed by rice (31%), plantation crop (10%), soybean (4%), and other crops (11%).

Good agricultural practices and pesticide risk assessment

Risk assessment of the impact of herbicides on human health and the environment is dependent on the pesticide type, the extent of exposure, and the environmental characteristics of the areas where the pesticide is applied. Such risk factors can be minimized following good agricultural practices (GAP) during crop growth. To ensure food safety, regulatory agencies throughout the world advocate use of GAP for raising crops and producing safe food for human consumption. The main benefits of adoption of GAP is production of safe food at primary production level by eliminating chances of entering of contaminants like pesticide residues, veterinary (antibiotic) drug residues, metallic residues, aflatoxin residues, microbiological contaminants from entering the food chain (FAO 2004). Following GAP, the herbicides can be recommended at pre-emergent, post-plant pre-emergent and pre-harvest stage of various crops for the control of annual, perennial and biennial weeds.

Residues are estimated in the harvested produce to determine pre-harvest interval (PHI) in an edible food commodity following application at a recommended dose. Pre-harvest waiting periods determine the safe period for harvesting an edible commodity, subsequent to application of pesticides, especially in vegetables and fruits for ensuring Maximum Residue Limits (MRL) standards, set by FSSAI for India and Codex Alimentations Commission (Codex). The MRL of a pesticide is the largest amount detected in a commodity which any regulatory body expects to find in the crop when it has been treated following good agricultural practice. When MRLs are fixed, the compounds are assessed for effects on human health. So, if a food has a higher level of residue than the MRL, it does not mean that the food is not safe to eat. A residue above the MRL may show that the farmer has not used the pesticide properly or the high level of residues may be the result of drifting through wind, water and other environmental factors.

Analytical procedures

Several techniques have been used for the analysis of herbicide residues in crops, crop soils and water. The foremost steps in their analysis include sample preparation, extraction-cleanup and analysis by chromatographic techniques. Sample preparation involves extraction of herbicide from crops, crop soil and water, which depends on the polarities of the herbicides as well as nature of the sample matrix. The sample is homogenized and extracted with organic solvent(s) of high, medium or low polarity. Some efficient extraction techniques include supercritical fluid extraction (SFE), matrix solid-phase dispersion (MSPD), solid-phase micro-extraction (SPME), microwave assisted extraction (MAE) and accelerated solvent extraction (ASE). Clean-up procedure is required prior to the determination of herbicide residues in the samples. Extracts are usually cleaned-up by liquid-liquid partition (LLP) chromatography on columns packed with different adsorbents.

Solid-phase extraction (SPE) and gel permeation chromatography (GPC) have become preferred techniques for clean-up due to their less solvent consumption and substantially lower time for analysis. QuEChERS (Quick, Easy, Cheap, Effective, Rugged and Safe) method developed using primary and secondary amine (PSA) exchange material has become popular as a standard sample preparation method with excellent results of recovery for a wide range of pesticides in many types of samples. The method provides satisfactory results for determination of multi-pesticide residues in vegetables and fruits. Another sample preparation procedure for residue analysis is derivatization of pesticides, which is sometimes necessary for analyte stability or delectability by specific detector.

Gas chromatography (GC) is a technique widely used in the analysis of herbicide residues. Earlier packed columns and mega-bore columns were popular for resolving the active ingredients of herbicides from contaminants present in the matrix. The increase in resolution achieved with capillary columns has led to complete replacement of packed column by capillary for multi-residue analysis. Various selective and sensitive detectors are used for the trace analysis of herbicides present at nano-or pico-gram level. Two most popular among these are: electron-capture detector (ECD) and nitrogen-phosphorus detector (NPD) or thermionic specific detector (TSD). The later has been modified to thermionic ionization detector (TID) and is commonly used for the analysis of nitrogen-containing herbicides. Mass-spectrometry (MS) can be easily coupled with capillary GC for the identification of herbicides and their toxic degradation products or metabolites present in the samples. Capillary GC with tandem mass spectrometric (MS–MS) detection is a technique lately used for determination of non-polar pesticide residues in food and environmental samples with good selectivity and high sensitivity.

High-performance liquid chromatography (HPLC) is a technique used for the analysis of thermally unstable herbicides that cannot be analysed directly by GC due to their breakdown in the GC injection port or the hot column. Most HPLC methods perform analysis by reversed-phase chromatography using C_8 or C_{18} columns and relatively polar solvents, like acetonitrile, water and methanol as mobile phase. Ultraviolet (UV) detection with fixed or variable wavelength has been the most commonly used detection method for determination of herbicide residues by HPLC. Recent developments have led to universal Corona Aerosol Discharge (CAD) detector with improved sensitivity than old Refractive Index (RI) detector and finally HPLC–MS have the advantage, of not requiring a derivatization step while providing a high degree of structural information that allows their identification. Besides GC and HPLC other techniques, such as thin-layer chromatography (TLC), capillary electrophoresis (CE), and the enzyme linked immuno-sorbent assay (ELISA) are also employed.

A total of 10 herbicides were detected in 112 samples. The most predominant pendimethalin was present in 45 (30.2%) samples of 12 commodities *viz.* bitter gourd, cauliflower, cabbage, coriander leaves, curry leaves, green chili, red chili, tomato, grapes, rice, wheat, and cumin. Another herbicide, atrazine was present in 17.6% of the samples of 9 commodities, *viz.* cauliflower, cabbage, okra, gourd, grapes, curry leaves, coriander leaves, fennel, green chili, and water. Butachlor and chlorpropham were detected in 8% samples each. Other 6 herbicides out of 26 were still lesser in frequency of detection and remaining 16 were not detected at all during this exercise, which was conducted religiously across the country throughout the year (Sharma *et al.* 2018).

Herbicide residues, their persistence and degradation in the soil

As soon as a herbicide is applied, a number of processes immediately begin to remove the compound from the original site of application. After application, herbicide may get adsorbed on soil, taken up by the plant, get volatilized into air, leached into the groundwater, or undergo chemical, photochemical or microbial degradation on plant or soil surface to the toxicologically significant or non-significant degradation products/ metabolites (Sondhia *et al.* 2018, Singh *et al.* 2015, 2017, 2018). Some amount of herbicide residues in ppm or ppb levels may stay and persist in food commodities and the environment for some time. If herbicide residues still persistent in the environment, but cannot be recorded by instruments, radio-labeled compounds are used to know their fate in the environment. Certain sensitive crops have been used to sense the presence of herbicide residues below detectable level (Paul *et al.* 2009, Patel *et al.* 2010). Herbicides persistence in the soil is expressed as half life or time required to degrade fifty per cent of the original molecule (**Table 1**). However the half life is not absolute because it depends on the soil type, temperature, and concentration of the herbicide applied (Cornish 1992, Brandenboger 2007, Sondhia 2009 a,b, 2013, 2016). Beside herbicides structure, soil conditions prevailing during and after the application of a herbicide as well as herbicide application methods influence the fate of the herbicides in the soil (Eleftherohorinos 1987, Webster and Shaw 1976, Latchana 1987, Sondhia 2005, Sondhia and Singh 2008). Heavy rainfall will cause greater leaching and runoff. Sandy soil would have a higher leaching potential than a clay soil due to larger pore spaces and lower CEC (Sondhia and Yaduraju 2005, Sondhia 2007a,b, Sondhia 2008a,c, 2009a,b,c). Chemical degradation by redox reactions is common with anilines, phenols and dinitroanilines. Hydrolysis, ester formation, oligomerization/ polymerization reactions catalyzed by clay surfaces and photolysis are common with fluchloralin, bentazon, and olefins.

Several studies have been reported on the occurrence of herbicide residues in/on crops, crop soil, water and the food chain. For example, the occurrence of fluazifop-P-butyl in soybean (Kulshrestha *et al.* 1995, Sondhia 2007), alachlor in cotton (Ramesh and Maheshwari 2004), benthiocarb in transplanted rice (Aktar *et al.* 2007), imazosulfuron in rice (Sondhia 2008a), metsulfuron-methyl in wheat (Sondhia 2008b) and transplanted rice (Sondhia 2009), trifluralin in/on black gram (Aktar *et al.* 2009), anilophos in rice and rice soil (Sondhia 2007, 2014, Tandon 2012), anilophos and fluchloralin in cucumber and onion (Srivastava *et al.* 2011), pendimethalin and trifluralin in celery seeds (Kaur and Gill 2012), metamitron in

Table 1. Half-lives of some herbicides in soil (Source: Sondhia and Varsheny 2010)

Herbicides name	Half lives (Days)	Toxicty class based on LD_{50}	Herbicides name	Half lives (Days)	Toxicty class based on LD_{50}
Atrazine	13-58	III	Metribuzin	23-49	III
Butachlor	5-24	III	Metolachlor	8-27	III
Fluazifop-p-ethyl	8-24	III	Oxyfluorfen	12-29	III
Fluchloralin	12-46	IV	Pendimethalin	15-77	IV
Dithiopyr	11-25	IV	Pretilachlor	10-11	IV
Imazethapyr	57-71	IV	Sulfosulfuron	3-27	IV
Isoproturon	13-21	III	2,4-D	7-22	II-III
Chlorosulfuron	31-93	IV	Metsulfuron-methyl	70-147	IV
Chlorimuron	60	IV	Thiobencarb	19-24	III
Flufenaccet	9-22.5	V	Pyrazosulfuron-ethyl	16-21	IV

sugarbeet crop (Janaki *et al.* 2013b), ethoxysulfuron in rice soil (Sondhia and Dixit 2012), pyrazosulfuron in rice-field and soil (Singh *et al.* 2012, Sondhia *et al.* 2013), napropamide (Biswas *et al.* 2013) and glyphosate (Bandana *et al.* 2015) on tea, and pendimetalin in potato, cauliflower and raddish (Sondhia 2013b) have been reported under Indian tropical conditions and in most cases the residues were found to be safe at harvest.

A herbicide is said to be persistent when it may be found to exist in soil in its original or a closely related but phytotoxic form longer than one crop season after its original application (Sondhia 2005, 2011). Herbicide residues in crop produce above the safe level can cause health hazards to man and animal. Half lives for pyrazosulfuron-ethyl in soil under various water holding ranged from 42.9-85.5 days (Kumar *et al.* 2011, Mukherjee *et al.* 2010, Singh *et al.* 2012). Chlorsulfuron degraded faster in low pH soil rather than in high pH soil and showed higher GR_{50} value in low pH soil as compare to high pH soil (Amarjeet *et al.* 2003). Half-life of some herbicides under Indian tropical conditions in soil is presented in Table 2.

The addition of organic manure affects the biological, chemical and physical properties of soil that control the fate of herbicides. FYM incorporation at a rate of 10 t /ha decreased herbicide persistence and relatively lower half-lives of 44.93 to 39.09 days, each at the rate of 0.5 and 1.0 kg /ha for pendimethalin, trifluralin and fluchloralin were recorded with FYM incorporation. On the other hand, the half-life in absence of FYM was higher for all three dinitroaniline herbicides (Rathod *et al.* 2010). Triasulfuron residues dissipated from field soil with half-life of 5.8 - 6 days at two rates of application following a first-order-rate kinetics through biphasic degradation with faster rate initially ($t_{1/2}$ = 3.7 days), followed by a slower dissipation rate at the end ($t_{1/2}$ = 9.4 days). Similar trend was observed with non-sterile soil in laboratory with a longer half-life. Acidic pH and microbial activity contributed toward the degradation of triasulfuron in soil (Singh and Kulsherestha 2006).

Metsulfuron-methyl dissipated more rapidly in acidic silty loam soil as compared to high pH soil and light did not play any role in altering the persistence. A bioassay technique could detect the residue of metsulfuron-methyl up to 30 days in surface soil, while, with HPLC, residues detectable upto 15 day only. The half-lives of metsulfuron-methyl was found 6.3-17.5 days respectively (Paul *et al.* 2009). However residues of metsulfuron-methyl rice soil at 30 days was found 0.008 -0.016 µg/g at 2-8 g/ha application rates. Whereas residue in soil, rice grains and straw at harvest was found below 0.001 µg/g (Sondhia 2009b). Sushilkumar *et al.* (2003) and Sushilkumar and Sondhia (2017) reported that metsulfuron- methyl residues were not detected after 60 days at 16 g/ha application rate, but at higher application rates 20-24 g/ha, 0.002 and 0.011 mg/kg residues were found in back soils of Jabalpur. However Sondhia and Singhai (2006) and Sondhia (2008b, 2009b) found residues below the detection limit at 3–5 g/ha application rates and 0.002 µg/g at 8 g/ha, respectively in wheat plants at harvest. The oxyfluorfen residue dissipated faster in wheat plants than in soil respectively, with a mean half-life of 6.1 and 11.2 days. Dissipation followed first-order kinetics. A sorption study revealed that the adsorption of oxyfluorfen to the soil was highly influenced by the soil organic carbon with the K_{oc} value of 5450 and dissipation of oxyfluorfen in soil and onion was dependent on the physico-chemical properties of the soil and environmental conditions (Janaki *et al.* 2013a). Ethoxysulfuron residues were found below <0.001 µg/g in rice soil at harvest at 15 to 20 g/ha doses, respectively (Sondhia and Dixit 2012).

Atrazine in soil showed a gradual degradation with advancement in maize crop growth and residue were not found at harvest whereas 0.056 mg/kg of residue in the post harvest soil were found at double the recommended dose (Janaki *et al.* 2012). Bromacil and diuron residues at 3 kg/ha persisted on top 2.5 cm of the soil profile even after eight months (Leela 1984). Sondhia, (2001, 2002), and Nag and Das (2009) and Janaki *et al.* (2012) reported that more than 95% of atrazine dissipated from the field at the time of crop harvest. The half-life values were found to be 9.38-21.54 days in soil. Pre-emergence applications of atrazine and simazine at 1.5 kg/ha application rates persisted up to 47 and 83 days, respectively (Sharma and Angiras 1997). Kausik and Moolani (1974) reported about 97% of the atrazine dissipated from the soil within 4 months in which maize plants were growing whereas about 83 % dissipated from un-cropped soil. The persistence of fluazifop-p-butyl at two rates of application and at three temperature level revealed fast degradation in soil to corresponding acid, fluazifop-p as only 2% fluazifop-p-butyl was recovered after 24 h. The acid form of the herbicide had a half life of 19.8-23.9 days. Persistence was inversely related to soil temperature (Raut and Kulshrestha 1991). The residue level of fluazifop-p in soil was found to be 0.051 to 0.079 µg/g at 125- 500 g/ha application rates in soybean field (Sondhia 2007b).

Sondhia *et al.* (2006) reported rapid dissipation of butachlor in rice field as compared to laboratory conditions with half-life of 18.11-23.0 days at 1.0 -2.0 kg/ha. The butachlor degradation in soils were mainly influenced by soil organic matter and moisture and rapid disappearance was noticed at field capacity followed by submergence and air dry conditions in all soils. 2,4-D at 0.4 kg/ha alone and in combination with anilofos persisted up to harvest with half-life of 18-22 days (Jayakumar and SreeRamulu, 1993). Clodinafop propargyl ester generally convert to acid a major metabolites and also responsible for herbicidal action. It was found that dissipation of clodinafop was not affected by specific soil pH and soil type. Residue of clodinafop in soil was found 0.093 to 0.081 in alluvial, red and black soil (Roy and Singh 2006, Sondhia and Mishra 2005). Fentazamide residues at 240 g/ha application rate were found 0.03 to 0.04 mg/kg in soil of rice field in a three year study with a half life of 20 days, however residues were below the detection limit in rice husk and straw (Tandon *et al.* 2012). Chlorophenyltetrazoline and cyclohexyl ethylamine have been identified as major and minor metabolites of fentazamide in soil (Mukherjee and Gopal 2005). In a monitoring study of four herbicides, butachlor residues alone contributed 61% followed by pendimethalin (36%), and fluchloralin (3%). Alachlor was not detected in all the locations. The total range of herbicides was <0.01 to 1.46 ng/g with a mean of 0.21 ng/g. The individual concentration of herbicides ranged 0.03-1.28 ng/g (pendimethalin), 0.02-1.22 ng/g (butachlor), 0.01-0.25 ng/g (Kumar 2011**)**. The residues of pretilachlor dissipated to below detection limit within 30 days after application when applied with green manure, while at 0.75 to 1.5 kg/ha rates, it persisted up to 45 days with a half-life of 3.9 to 10.0 days (Dharumarajan *et al.* 2008).

Sorghum and cucumber plants were found very sensitive bioassay plants for metribuzin and could detect residues even at 0.010 and 0.046 mg/kg in the post-harvest soil of potato crop (Sondhia 2005). At harvest no detectable residues of fenoxaprop-ethyl or acid were detected in soil, wheat grain and straw samples at recommended doses (Sondhia 2007a, Singh *et al.* 2013). In paddy field benthiocarb residue dissipated to 90% within 30 days in soil and no residues were detected in soil layer as well as in straw, grain and husk samples at harvest when applied at 1500 to 3000 g/ha in transplanted paddy field (Aktar *et al.* 2007). However, Kumar, *et al.*(1993) reported lower temperature and higher concentration resulted in greater persistence (Jayakumar and Ramulu, 1993). Adsorption of alachlor increased with increase in concentration, time of incubation, rise in activation temperature, lowering of pH and increase in the organic matter content. (Sethi and Chopra, 1975). Sondhia (2002a,b) reported that alachlor and fluchloralin residues were not detected in the soil at harvest at 1.0 kg/ha rate in the soil of soybean field but at 1.2 and 1.5 kg/ha rates, 0.01 and 0.02 ìg/g residues were detected at harvest in soybean. Whereas in sandy loam soil of Karnataka, alachlor persisted for 60 days at 1.5 kg/ha application rate applied as pre-emergence in vegetable crops (Leela 1993).

Fluchloralin degraded at faster rate in flooded anaerobic soil than in aerobic soil and amendment of fluchloralin with organic matter enhanced degradation of flooded anaerobic soil and dealkylated fluchloralin, partially reduced fluchloralin and its cyclic product were detected as major degradation products Singh and Kulshrestha, (1995). Patel *et al.* (1996) found that persistence of the pre-plant incorporated fluchloralin at 0.67- 1.35 kg/ha application rates was longer in the loamy soil as compared to sandy loam soil with the half-life values in both the soils ranged between 42.4 to 45.6 days. Fluchloralin translocated to leaves and roots of chicory crop and was detected on the 60th day of application and did not found at harvest.

Dissipation of pendimethalin in the field peas (*Pisum sativum* L.) and chickpea soil followed first-order kinetics showing a half-life of 11.23-19.83 days averaged over all doses (Sondhia 2012, 2013). Kulshrestha and Yaduraju (1987) reported that repeated application of pendimethalin on the same soil led to rapid degradation of pendimethalin in each successive year with each successive crop. Pahwa and Bajaj, (1997) found that persistence of pendimethalin and trifluralin was directly correlated with temperature and application rate. Pendimethalin in a sandy loam soil applied at 1, to 4 kg/ha rates in wheat crop showed persistence up to 200 days and caused phytotoxicity to the succeeding sensitive sorghum crop at higher dose (Yadav *et al.* 1995). Pendimethalin was found to be persistent in soil of cabbage field however residues did not translocated to plant parts (Arora and Gopal 2004). Persistence of some herbicides under Indian tropical conditions in soil is given in **Table 2**.

Table 2. Persistence of some herbicides under Indian tropical conditions in soil

Herbicide	Persistence in soil (days)	Reference
Atrazine	45-90	Sandhu *et al.* 1994, Nag and Das 2009,
Alachlor	60-80	Leela, 1993, Sharma 2002
2, 4-D	45-90	Sushilkumar *et al.* 2003, Kumari *et al.* 2004
Butachlor	60-100	Sondhia *et al.* 2006, Rao *et al.* 2012
Dithiopyr	90-150	Guptaand Gajbhiye 2002, Saikia and Kulsherestha (2002)
Fluzifop p-butyl	30-90	Leela, 1993, Sondhia 2007
Isoproturon	90-120	Yaduraju *et al.* 1993, Sondhia and Singh 2006
Imazosulfuron	60	Sondhia 2006, 2008
Metoxuron	80	Randhawa and Sandhu 1997
Metribuzin	20-100	Sondhia 2002b,c , Gopal *et al.* 2004
Oxadiazon	56-125	Leela 1993, Raj *et al.* 1999
Pyrazosulfuron-ethyl	35-60	Mukherjee *et al.* 2010, Sondhia *et al.* 2013, 2016, Naveen *et al.* 2012
Pretilachlor	30-60	Dharumarajan *et al.* 2008, Kumar 2011, Sondhia 2012
Pendimethalin	60-200	Yadav *et al.* 1995, Rai *et al.* 2000 Gowda *et al.* 2002, Sondhia 2012, 2013
Tralkoxydim	28-45	Srivastava *et al.* 1995
Thiobencarb (benthiocarb)	28-60	Jayakumar and Ramulu, 1993, Aktar *et al.* 2007
Oxyflourfen	60-80	Devi *et al.* 1998
Imazethapyr	90-240	Rana and Angiras, 1993, Sondhia 2007d, 2008c,d, 2012b Patel *et al.* 2014, Nagwanshi *et al.* 2016
Metolachlor	40-190	Devi *et al.* 2000, Sanyal *et al.* 2003

Whereas, Goyal *et al.* (2003) reported that intermittent wetting and drying resulted in a very high persistence (90-99%) of trifluralin whereas with continuous ponding, the persistence of trifluralin decreased to 22-40 % in alluvial soil. Selvamani and Sankaran (1989) found that imazethapyr dissipated at higher rate under higher temperature and brighter sunshine condition. Sondhia (2006) and Kumar *et al.* (2017) reported dissipation of imazethapyr in soil with an amount of 0.008 µg/g imazethapyr residues at harvest in the soil of soybean crop at 100 g/ha application rate. Sondhia (2006, 2008b) reported 0.002, 0.006, 0.0075 and 0.010 µg/g residue of imazosulfuron in soil of transplanted rice field after 60 days at 30-60 g/ha application rates, however no residues were found after 90 and 120 days.

Sulfosulfuron followed first order dissipation kinetics in soil at 25-50 g/ha application rates and residues were not detected in the soil at harvest under wheat cropping system (Ramesh and Maheshwari, 2003, Sondhia and Singh 2008). However after150 days residues were found below 0.001 µg/g in soil samples collected from 25 to 50 g/ha treated plots (Sondhia and Singhai 2006).

The adsorption–desorption revealed strong adsorption of dithiopyr in alluvial soil with K_d values ranging from 3.97–5.78 and Freundlich capacity factor (K_F) value of 2.41. The leaching studies carried out under saturated flow condition revealed that dithiopyr was highly immobile in alluvial soil. Strong adsorption of dithiopyr may cause a greater persistence in the soil (Gupta *et al.* 2000, 2001, Gupta and Gajbhiye 2002). Singh and Kulshrestha (2006) reported dissipation of triasulfuron at 15 and 20 g/ha in soil under wheat crop with half-life of 5.8 and 5.9 days. Isoproturon degraded to non-detectable level within 60 days at 0.94 kg/ha rate in Ludhiana, it took 75 days in Badrukha, Kum Kalan and Chakkar district for its complete degradation (Walia *et al.* 2000). Isoproturon applied at 1.0 kg/ha rate in wheat crop degraded completely at harvest in black soil of Jabalpur (Randhawa and Sandhu 1997, Sondhia 2002a, Sondhia and Singh 2006). Isoproturon residues at 0.5 and 1.0 kg/ha application rates were found 0.0213 mg/kg after 70 days and 0.0201 mg/kg after 120 days in soil of potato crop (Yaduraju *et al.* 1993). Gupta *et al.* (2001) found that flufenacet dissipated to about 98% in soil after 60 days and no residues were detected after 90 days under submerged conditions than field capacity. Sondhia (2002) reported that metribuzin applied at 0.85 and 1.20 kg/ha persisted up to harvest in black soil in potato crop in Jabalpur. Rai *et al.* (2000) found rapid degradation (40-61%) of anilofos after 30 days of incubation under flooded than non-flooded conditions. Anilofos at 0.4 kg/ha application rate persisted up to 56 days in direct seeded rice field (Radhamani *et al.* 1997).

Metolachlor applied as pre-emergence at 1-2 kg/ha application rates was dissipated almost 100 % in the soil at harvest under field condition (Singh *et al.* 1997). Dissipation of metolachlor occurred in two distinct phases. The initial slow rate could be due to degradation and adsorption on soil. After one month herbicide dissipated rather rapidly. Sanyal and Kulserestha (2003) demonstrated moderate persistence of metolachlor with a half-life of 27 days in the field condition and leached to a depth of 15-30 cm in soil. It was found that fungi *Aspergillus flavus* and *Aspergillus terricola* rapidly degraded metolachlor applied at 10 kg/ha up to 92% and 87% after 20 days in sterile and non-sterile soils, respectively (Sanyal and Kulshrestha, 2003). Following the first order kinetics, the diclosulam dissipates in soybean crop soil with half-life values ranging between 5.28-8.36 days in three consecutive seasons, irrespective of the doses (Bhattacharyya *et al.* 2012).

Herbicide residues in agricultural commodities

The analytical results of herbicide residues in various crops indicated global presence of residues but below the alarming level. Using the latest hi-tech analytical devices the presence of herbicide residues can be easily detected at ppb level. Based on extensive herbicide residue work conducted at Directorate of Weed

Research, Jabalpur, All India Coordinated project on Weed Management (AICRP-WM) and various sources in India, in approximate 80% samples residues were found below detection limit (BDL), 13.4% below maximum residue limit (MRL) and 6.6% residues were found above MRL values.

Rice: Sondhia and Dixit (2012) demonstrated that ethoxysulfuron dissipated at faster rate in soil and plants and residues were found below 0.001 µg/g in grains and straw at harvest at 15-20 g/ha application rates, respectively. Imazosulfuron residues were found to be 0.009 and 0.039 µg/g at 50 and 60 g/ha rates, respectively in rice and residues were not detected at 30-40 g/ha in rice grains and straw, (Sondhia 2007a, 2008a,b). The residue level of butachlor in rice grain and straw samples were found 0.029 ìg/g and 0.042 µg/g (Sondhia *et al.* 2006). Harvest time samples of paddy grains, rice bran and straw, treated with butachlor showed residues below the detectable levels in rice, 0.002 mg/kg in bran, 0.009 mg/kg in straw and 0.006 mg/kg in rice grains at 1.0 kg/ha and at 2 kg /ha, the residue were 0.001, 0.005, 0.010 and 0.025 mg/kg in rice, bran, straw and paddy grains, respectively (Reddy *et al.* 1998). Similarly, Deka and Gogoi (1993) found 0.012 and 0.007 mg/kg residues in rice grains and straw after treatment with butachlor at 2.0 kg/ha rate.

In paddy straw, 0.01-0.03 µg/g oxyfluorfen residues were detected at 240- 500 g/ha rates. Residues were 0.028-0.03 µg/g in soil when oxyfluorfen was applied at 240-500 g/ha rates. However, in rice grains, 0.018-0.106 µg/g of oxyfluorfen residues were detected in 240-500 g/ha treated plots (Sondhia 2009b). Residues of metsulfuron-methyl and pretilachlor in rice grains and straw at harvest were found below 0.001 µg/g (Dharumarajan *et al.* 2008, Sondhia 2009a). In plant foliage collected at harvest traces of atrazine residues were detected in few samples in first year but in the second year's residues were not detected (Nag and Das 2009). Fentazamide residues were below the detection limit in rice husk and straw at 240-420 application rates. Chlorophenyltetrazoline and cyclohexyl ethylamine have been identified as major and minor metabolites of fentazamide in soil (Mukherjee and Gopal 2005). Butachlor dissipated with half life varying from 12.5 to 21.5 days at 1.0 and 2.0 kg/ha application rates under with and without organic manures conditions. Low levels of residues were detected in rice grain (Rao *et al.* 2012). However, Devi *et al.* (1997) and Jayakumar and Sankaran, (1995) reported that butachlor and anilofos residues in rice crop were found below the maximum permissible residue limit (0.25 mg/kg) in soil. Sondhia (2014a,c) reported that butachlor residues were not detected after 120 days in clay loam soil applied at 1.0 kg/ha in transplanted rice crop. The pre-emergence application of anilofos and thiobencarb applied at recommended doses continuously for four seasons in rice crop showed residues in soil, rice grains and plant parts below the maximum allowable level (Balasubramanian *et al.* 1999).

Wheat: In a field experiment residues of isoproturon were found to be 0.006, 0.041 and 0.022 µg/g in post harvest soil, wheat grain and straw, respectively, while 0.021 and 0.096 µg/g residues of clodinafop were present in soil and grain at higher level of application (Arora *et al.* 2013). At harvest, no residues of metsulfuron-methyl were detected in wheat grains at 3–4 g/ha rates. However, 0.002 µg/g residues were detected in wheat straw at 5-8 g/ha application rates (Sondhia 2008 a,b). In wheat field soil, residues persisted beyond 30 days with a first order rate kinetics biphasic dissipation with initial faster dissipation followed by a slower dissipation during later period. Wheat grains, straw and soil at harvest (112 days) contained residues below detectable limits (Singh and Kulshrestha 2006). In a three year field trials revealed no detectable amount of tralkoxydim in treated samples of soil, whet grain and straw at harvest of wheat (Srivastava *et al.* 1994, Srivastava *et al.* 1995).

Clodinafop residues were not detected in the wheat grain and straw at doses 60-120, g/ha however 0.0089 mg/kg residues were detected in wheat grains at 240 g/ha treatment (Sondhia and Mishra 2005). Sulfosulfuron residues were not found in wheat grains, straw and subsequent vegetables in natural ecosystem as well as in model ecosystem at recommended rates in wheat crop (Ramesh and Maheshwari, 2004, Sondhia *et al.* 2007, Sondhia and Singhai 2008). Isoproturon dissipated by 120 days in the soil of wheat crop applied at 1.0 kg/ha and residues were not detected in wheat grains and straw at harvest (Sondhia and Singh 2006). Persistence of clodinofop-methyl evaluated at Ludhiana showed that it degraded to safe level by 60 days at 0.03 to 0.04 g/ha application rates and at higher doses *viz.* 11 and 22 g/ha, residues persisted for more than 80 days. Whereas Shobha *et al.* (2014 a) reported that clodinofop at 60 and 120 g/ha rates in wheat crop degraded completely by harvest and hence residues of clodinofop were not detected in wheat grains and soil at harvest. Metribuzin residues were not found in the soil, grains and straw following an application at 210 -420 g/ha in wheat crop at Pantnagar (Dubey *et al.* 1998). Fenoxaprop residue in the soil of wheat field was found 0.0004-0.0011 µg/g at 70-400 g/ha application rates (Sondhia 2006). Herbicide residues in crop plants at harvest are given in **Table 3**.

Pulses: Terminal residues of pendimethalin were monitored in the green field peas (*Pisum sativum* L.) and chickpea (*Cicer arietinum* L.) applied as pre-emergence herbicide at 750-185 g/ha rates. Low pendimethalin residues were found in mature pea grain (0.004-BDL µg/g), and straw (0.007-0.001 µg/g) at 750- 185 g/ha treatments, respectively (Sondhia 2013). Pendimethalin residues were 0.025, 0.015, <0.001 µg/g in chickpea grains at 750 to 185 g/ha treatments. Much lower pendimethalin residues, *viz.* 0.015 to <0.001 µg/g were found in straw at 750, 350 and 185 g/ha treatments, respectively (Sondhia 2012). Mandal *et al.* (2014) and Mukhopadhyay *et al.* (2012) demonstrated that at harvest, the residues of quizalofop ethyl on black gram seed, foliage and soil were found to be below the detection limit of 0.01 mg/kg following a single application of the herbicide at 50-100 g/ha for both the periods. In another field study, persistence and degradation kinetics of trifluralin applied as pre-emergence in black gram at 1.0 to 2.0 kg/ha for the control of broad-leaf weeds was conducted. The dissipation at 90 days was found approximately 97% and followed first order kinetics with the half life values 23.3 to 26.2 days. Irrespective of any dose, no residues of trifluralin were detected in black gram crop soil and plant samples at harvest (Aktar *et al.* 2009).

Table 3. Residues of some of the herbicides in the soil, food grain and straw

Herbicide	Crop	Dose (g/ha)	Residues (µg/g)			References
			Soil	Grains	Straw	
Ethoxysulfuron	Rice	15-20	<0.001	<0.001	<0.001	Sondhia and Dixit 2012
Butachlor	Rice	1000	0.005	0.025-0.002	0.029-0.006	Reddy *et al.* 1998, Deka and Gogoi 1993, Sondhia *et al.* 2006
Sulfosulfuron	Wheat	25	BDL	0.010-BDL	0.004-BDL	Ramesh and Maheshwari, 2003, Sondhia *et al.* 2007
Metsulfuron-methyl	Rice	4-4	BDL	BDL	0.002	Sondhia 2008a
	Wheat	4-8	BDL	BDL	BDL	
Isoproturon	Wheat	1000	0.006-0.032	0.035-0.041	0.065-0.022	Sondhia and Singh 2006, Arora *et al.* 2013
Oxyfluorfen	Rice	150-250	BDL	0.018	0.106	Sondhia 2009b
Imazethapyr	Soybean	100	0.016	0.210	BDL	Sondhia 2007, 2008e,b, Patel *et al.* 2009, Sondhia *et al.* 2015b,c
Imazosulfuron	Rice	30-40	BDL	BDL	BDL	Sondhia 2008b, 2007d , 2016
		50-60	BDL	0.006-0.009	0.009-0.039	
Fentazamide	Rice	240-420	BDL	BDL	BDL	Mukherjee and Gopal 2005
Anilofos	Rice	500	<MRL	<MRL	<MRL	Jayakumar and Sankaran, 1995
Clodinafop	Wheat	240	0.021-BDL	0.096-BDL	BDL	Sondhia and Mishra 2005, Arora *et al.* 2013
Tralkoxydim	Wheat	250-800	BDL	BDL	BDL	Srivastava *et al.* 1994

***Source**: (Sondhia 2007 2010)

**BDL-Below detection limit

Oilseed crops: In a three seasons field trial conducted under West Bengal conditions, diclosulam residues were found to be below detectable level (BDL) in soybean plant samples irrespective of the treatment doses and the days in all seasons (Bhattacharyya *et al.* 2012). The residues of imazethapyr in soil, soybean grains and straw were found 0.008, 0.102 and 0.301 µg/g, respectively at 100 g/ha application rate (Sondhia 2008b). Fluazifop-p-butyl, applied to soybeans, at 0.25 and 0.50 kg/ha at New Delhi, dissipated to 0.1 mg/kg in 30 days from both the dosages and was below detectable limits (0.08 mg/kg) in 60 days (Singh *et al.* 1999). Fluazifop-p-butyl can leach up to 15 cm soil and at harvest 0.012-0.036 mg/kg residues were found in the soil of soybean crop with 0.250-0.500 kg/ha rates, respectively and fluazifop-p-butyl at 0.5 kg/ha rate resulted in the translocation of 0.005 and 0.001 mg/kg residues to soybean grains and cake, respectively (Kulshrestha *et al.* 1995). The residue level of fluazifop-p in soil was found to be 0.051 to 0.079 µg/g at 125 to 500 g/ha applied rates. Residues of fluazifop p-butyl were 0.472, 0.554 and 0.702 µg/gin soybean straw and 0.297, 0.300 and 0.312 µg/g in soybean grains at 125, 250 and 500 g /ha , respectively (Sondhia 2007c,d, Sondhia and Dixit 2008)

Vegetables: Terminal residues of pendimethalin applied as pre-emergence at 1.0 kg/ha in tomato, cauliflower, and radishes were studies under field conditions. At harvest, 0.008, 0.001, and 0.014 µg/g residues of pendimethalin were found in tomato, cauliflower, and radishes, respectively (Sondhia 2013, Sondhia and Singh 2018). Terminal residues of oxyfluorfen applied at 150 to 300 g/ha in direct seeded onion crop at 90 days (green onion) and at 130 days (mature onion bulbs) were monitored in green onion, dry onion bulbs and soil samples under field condition at Jabalpur. The residues of oxyfluorfen in the green onion and mature onion bulbs were 0.041-0.063 and 0.0034-0.0460 µg/g at 150–300/ha rates. Residues of oxyfluorfen applied in mature onion were below the maximum residue limit (0.05 µg/g) (Sondhia and Dixit 2007a,b). A pre-harvest interval of 118 days for onion crop after the herbicide application was suggested (Sondhia 2010). Residues of pendimethalin, fluchloralin, and oxadiazon were found below the maximum residue limit in onion bulbs at harvest (125 days after spraying) at Anand. At harvest, 0.009 and 0.006 mg/kg terminal residues of fluchloralin applied at 0.75 and 1.50 kg/ha, respectively were found in stover and grains (Saikia and Pandey 1999). Sondhia and Dubey (2006) did not found pendimethalin residues at mature stage, however 0.007 µg/g pendimethalin residues were detected in green onion at 1.0 kg/ha application rate. Similarly, 0.005 and 0.003 µg/g haloxyfop residues were detected in the green and mature onion bulbs collected at 50 days and at harvest (129 days), respectively (Sondhia 2006). Oxyfluorfen residues applied to cabbages at 0.1 to 0.4 kg/ha application rates were not found in soil at harvest (Sundararajan *et al.* 1993). The half-life of pendimethalin in onion plants and soil varied from 11.8- 15.5 days and 14.9-15.1 days, respectively (Sinha *et al.* 1996).

Field experiment was conducted to study the persistence of pendimethalin and oxyfluorfen in soil and its residues in edible parts of radish. At harvest in both the seasons, more than 98% of initial deposit of pendimethalin was dissipated and observed half life in radish field was 6.45 days and 10.03 days at 0.5 and 0.75 kg/ha applied rates respectively. More than 60 % of the initial deposit of oxyfluorfen was dissipated at the time of harvest of crop and 6.96 days and 12.26 days of half life was observed at 0.1 and 0.15 kg/ha of oxyfluorfen application, respectively. In radish tubers the residues of pendimethalin and oxyfluorfen were below maximum residue limits (Sirestha *et al.* 2011). Samples of onion bulbs collected at 30, 60 and 90 days after spray and at uprooting stage showed no residues of oxyfluorfen and pendimethalin in onion bulbs (Kaur *et al.* 2010). Dissipation of haloxyfop in onion leaf and soil followed first order kinetics with The DT_{50} values in onion leaf ranged from 3.24-6.71 days whereas 3.78-6.96 days for soil following application 100-400 g/ha. No residue could be detected in bulb at harvest irrespective of doses (Chakraborty *et al.* 2005). At harvest the level of pendimethalin, fluchloralin and oxadiazon residue applied pre-emergence 1.0 - 0.5 kg/ha in onion bulbs ranged from 0.003 to 0.021, 0.004 to 0.036 and 0.080 to 0.104 µg/g, respectively. Marginal increase in the residue was observed with increased FYM application (Raj *et al.* 1999).

Maize: Atrazine applied at 1.0 kg/ha rate in maize crop degraded by harvest and residues were not detected in maize grains but at 2.0 kg/ha rate, 0.088 mg/kg of residues were detected (Sondhia and Saraswat 2000a,b, Sondhia 2001, 2002a,b). Atrazine was degraded to undetectable levels at all doses by the time the maize crop was harvested (90 days). The average half-life of atrazine varied from 23 to 25 days in the first year and 26 to 31 days in the second year. The residual effect of atrazine (1.0- 2.0 kg/ha), was studied on the succeeding crops of chickpea and Indian mustard, where fluchloralin was applied at 0.75 kg/ha. In chickpea and Indian mustard, low levels of fluchloralin residues were detected in soil at 150 days (64-85% and 69-82% losses, respectively). However, the magnitude of flucloralin persistence was not affected by preceding atrazine treatments applied to maize. The maize yield declined with an increase in atrazine dose and was lowest at 2.0 kg/ha (24.8 and 16.3 q/ha in 1994 and 1995, respectively, compared to 32.0 and 25.2 q/ha in the hand-weeded treatment). However, atrazine had no significant residual effect on chickpea or Indian mustard yields (Saikia *et al.* 2000).

Tea/plantation crops: India is the highest producer of tea in the world. Tea (*Camellia sinensis*) is a perennial crop grown on wide variety of soil types and climatic conditions. It is the healthiest drinks and second most consumed beverage after water. Glyphosate residues were found to be 0.003, 0.003 and 0.004 µg/g, respectively at 0.5, 1.0 and 2.0 kg/ha application rates. Thirty days after herbicide application, residues were below detectable levels in all glyphosate treatments indicate the complete degradation/disappearance of glyphosate in tea leaves under under northwestern mid-hill conditions of India (Bandana *et al.* 2015). It was found that the rate of the disappearance of glyphosate in plants was rapid during the initial periods which could be due to metabolization by the plants *via* oxidative cleavage of the carbon–nitrogen (C–N) bond to yield aminomethyl phosphoric acid (AMPA) and the breaking of carbon–phosphorus (C–P) by carbon phosphorus lyase to produce sarcosine (Beltman et a. 2001). Napropamide was rapidly dissipated in soil following the first-order kinetics with half-lives in the range of 12.54–27.87 days. The initial deposit of napropamide in tea cropped soil was found in the range of 1.18–1.49 and 2.08–2.90 µg/g at recommended dose (1.125 kg/ha) and double the recommended dose (2.25 kg/ha) respectively irrespective of any season and doses. At 30 days after application of the herbicide, more than 50% of the residue was dissipated. The residue declined below detectable limit in tea soil on day 60–90 day in x and 2x doses irrespective of season. The dissipation of napropamide in tea cropped soil followed the first-order kinetics with the half-life values varying from 12.54 to 27.87 days irrespective of doses and seasons in south India. In made tea, the initial concentration of napropamide was found in the range of 0.14–0.20 µg/g in recommended dose and 0.35–0.44 µg/g in double the recommended dose in three seasons (Biswas *et al.* 2013).

Other crops: Pendimethalin residues at 0.5 kg/ha application rate were not detected in the soil of lucerne crop at Anand. Alachlor residues were found at trace level in cotton plant, cotton lint and oil, water and fish at 2.5 and 5.0 kg/ha application rates under field condition at Chennai (Ramesh and Maheshwari 2004). It was found that 2,4-D residues at 0.06 mg/kg level caused malformation in leaves (Kathpal *et al.* 1980). Metamitron persist in sugar beet crop plant up to 15 days while up to 30 days in soil. On day 90, metamitron was detected in the soil at 7.0 kg/ha treated plots (Janaki *et al.* 2013). Application of pendimethalin, trifluralin and resulted in below detectable limit residues(0.02 mg/kg) in celery seeds (Kaur and Gill 2012). In cucumber, anilophos (ND–0.042 mg/kg*)* were detected, in onion, fluchloralin (0.012–0.065 mg/kg*)*, and anilophos (ND–0.033 mg/kg*)*, were detected (Srivastava *et al.* 2011). At Anand, pendimethalin applied at 0.6-0.9 % to tobacco recorded 0.198 to 0.376 mg/kg residues in tobacco leaves and 0.72 mg/kg residues in leaves treated with 0.5 % pendimethalin and 0.04-0.079 mg/kg residues treated with 0.25% pendimethalin (Parmar *et al.* 1998). Glufosinate ammonium at 0.45- 0.90 kg/ha application rates applied as post-emergence to cotton degraded to safe level by 20 day at Ludhiana.

Herbicide residues in water system

With the increasing use of herbicides for weed control, the applied herbicide may find it way into streams and underground water sources by runoff, drift and leaching mechanism. Many herbicides are routinely detected from the surface and ground water sources in developed countries like, USA, New Zealand, Australia, Canada, Japan and European countries. The most often detected herbicides above the prescribed maximum residues limits are 2,4-D, atrazine, cyanazine, carbaryl, simazine, bromacil, diuron, Diazinon, prometon, metolachlor, dinoseb, picloram, metribuzin, metsulfuron, glyphosate, metolachlor, propanil, butachlor, pendimethalin, oxyfluorfen etc. Many herbicides are strictly banned or restricted such as butachlor, atrazine, pendimethalin, and paraquat in USA, and European countries due to their high concentration in the ground and surface water and potential health hazards to aquatic, animal and human lives (Sondhia and Varshney 2010, Sondhia *et al.* 2012).

In India, reports on monitoring and detection of herbicide residues in water are limited as compared to developed countries. A pyrazosulfuron ethyl residue level of 0.0154 mg/kg on 21st day and of 0.0023 mg/kg on 35th day were detected in the underground water (Naveen *et al.* 2012). Persistence and mobility of 2,4-D was found to be dependent on soil water content (Gupta *et al.* 2012).The water samples collected from Singoor reservoir, Hyderabad were found contaminated with residues of atrazine (NO-1.056 µg/L). The concentration of atrazine residues in Osmansagar water was 0.056 µg/L during postmonsoon November 2005 and total pesticide residues together 3.369 µg/L (Reddy and Reddy 2010). Residues of alachlor were detected up to 60 days in acidic, neutral and basic buffer solution fortified with 0.5 and 1 µg /g. and residue were below the detection limit after 140 days in water different soils and no residues were detected after 80 days.

The studies conducted at AICRP weed control in water system revealed that butachlor residues were ranged between 0.001 to 0.093 mg/L in the water of rice field at Bangalore. Residues of paraquat were not detected after 20 days at 0.80 kg/ha application rate to control *Eichornia* but application of 1.8 kg/ha showed 0.069 and 0.028 mg/L residues in pond and canal water, respectively. 2,4-D increased pH, EC, carbonates and free CO_2 increased after treatment at 1.0-2.0 mg/kg dose but the dissolved oxygen decreased and the 2, 4 -D residues become non-detectable after 42 days. 2, 4-D residues at lower level than the acceptable daily intake (0.01 mg per kg body weight) were detected in fish samples at Thrissur at recommended rate of application at all the sampling interval and at higher dose viz 2.0 or 4.0 kg/ha waiting period of more than 4 month is suggested. Paraquat residues in the fish samples were also detected below the acceptable daily intake of 0.002 mg per kg body weight. It is reported that only 0.80 to 1.11 % of the applied paraquat remained in the sediment fraction however paraquat at 0.8- 3.2 kg/ha application rates increased the pH and electrical conductivity of water. It is reported that isoproturon residues were not present in the ground water in all the water samples collected from different districts of Hisar.

Leaching results indicated that imazethapyr could leach in clay loam soil up to the depth of 70 cm applied at 100 and 200 g/ha (Sondhia 2007c, 2013). Sondhia (2009) demonstrated that residues of sulfosulfuron were significantly higher in surface soil at higher dose compared to sub-surface soil at lower dose up to 150 day at 25-100 g/ha in wheat under field conditions. Initial concentration of sulfosulfuron residues in the surface soil (0-15 cm) were 0.229, 0.967 and 1.038 µg/g, which dissipated to 0.003- 0.005 µg/g at 25- 100 g/ha doses by100 days. However, at 0 days sulfosulfuron residues in sub-surface soil were 0.136-0.065 µg/g in 25-100 g/ha doses. Sulfosulfuron residues were not detected after 200 days in surface and sub-surface soils in all the doses. Pendimethalin could leach in clay loam soil up to the depth of 55 cm in 200 mm rainfall condition (Sondhia 2007a,b). High mobility of metsulfuron-methyl under continuous saturated moisture condition was found (Sondhia 2009a).

A laboratory experiment was conducted to study the persistence of pretilachlor in water at acidic, neutral and alkaline pH by incubating for 60 days. Irrespective of pH, pretilachlor residues were detected up to 15 days after application and were below detectable limit on 30th day. The half -life of pretitachlor in different pH water varied from 3.05 to 3.30 days and there was not much difference in half- life due to increase or decrease in pH of irrigation water (Deepa and Jayakumar 2006). The total mean concentration of atrazine ranged from 0.72 to 17.3 µg/L whereas 0.91 to 40.97 µg/L are recorded as the mean concentration of simazine in groundwater samples collected from Delhi (Aslam *et al.* 2013).

Herbicide degradation products

In an experiment, the sulfosulfuron degraded within 50 days on topsoil but the residual concentrations were localized at depth 30–45 cm depths this might due to leaching property of the sulfosulfuron(Saha and Kulshrestha 2002). The absence of sunlight, considerably lesser availability of microbial population and organic carbon content also participates in the stability in subsoil. Desmethyl sulfosulfuron, rearranged amine, sulfonamide and guanidine were identified as breakdown product of sulfosulfuron in the subsurface soil. From the results the calculated DT_{50} value for sulfisulfuron were around 105 to 147 days and the DT_{90} values around 349 to 488 days (Ramesh *et al.* 2007, Sondhia 2008c). Metabolites of pyrazosulfuron were detected from soil, pond water and rice field as ethyl-5-[(4,6-dimethoxypyrimidin-2-ylcarbamoyl)sulfamoyl]-1-methylpyrazole-4-carboxylic acid; ethyl 1-methyl-5-sulfamyl-1H-pyazole-4-carboxylate and 4,6-dimethoxypyrimidin-2-amine, 1-methyl-5-sulfamyl-1H-pyazole-4-carboxylic acid (Sondhia and Wseem 2012, Sondhia and Rajput 2012, Sondhia *et al.* 2013, Wassem and Sondhia 2014). *Penicillium chrysogenum* and *Aspergillus niger*, were found as potent pyrazosulfuron-ethyl degrading fungi (Sondhia *et al.* 2013).

Major degradation products of penoxsulam in field soil were identified as 1,2,4 triazolo-[1,5-c]pyrimidin-2 amine, 5,8 dicarboxylic acid; 2-(2,2-difluoroethoxy) -6 (trifluromethyl)benzenesulfonamide; 3-[[[2-(2,2-difluoroethoxy)-N-[1,2,4] triazole [1,5c]-6-trifluromethyl) benzene sulfonamide carboxylate m/z (Rajput and Sondhia 2014). Major metabolites of cyhalofop-butyl in soil and leachates were detected by LC/MS/MS as (R) -2-4(4-cyanao 2-fluroophenoxy) phenoxypropanoic acid (cyhalofop acid) and (R) -2-4(4-caboxyl-2-flurophenoxy) phenoxypropanoic acid (cyhalofop-diacid), and cyhalofop-phenol [(Sondhia and Raj 2014, Sondhia and Khare, **2017) (Figure 2**)]. The major photoproducts of metsulfuron methyl were identified as methyl-2-sulfonyl-amino-benzoate, 2-amino-6-methoxy-4-methyltriazine and saccharin (O-sulfobenzoimide). Stability test for pinoxaden and its metabolite NOA 407854(8– (2,6-diethyl-4-methyl-phenyl) -tetrahydropyrazolo[1,2-d][1,4,5]oxadiazepine-7,9-dione) in wheat for a period of 30days showed that the compound remained stable and the degradation observed was only 6.5% at the end of storage period. This shows slow dissipation of pinoxaden metabolites at 20±1° C. Residues of Pinoxaden and its metabolites were found below the detectable limit (<0.01 mg/kg) (Dixit *et al.* 2011).

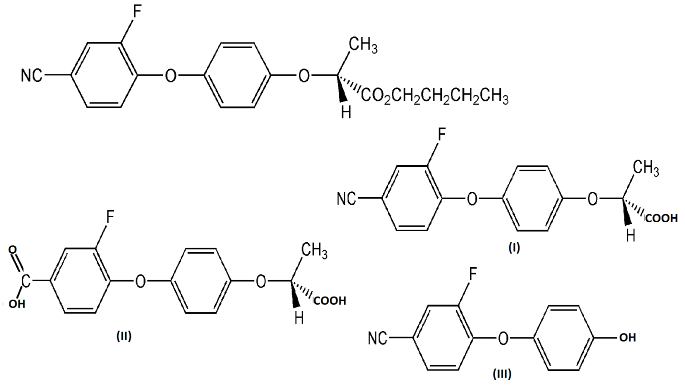


Figure 2 Degradation of cyhalofop-P-butyl in the soil and water. Cyhalofop-P-butyl and its three major secondary metabolites identified from soil of at 25-75 cm depths and leachates (Khare and Sondhia 2014, Sondhia 2015).

Toxicity and hazards associated with herbicide use

Herbicides have variable toxicity in addition to acute toxicity from occupational exposure to humans, domestic animals and the wildlife. They are extensively tested prior to approval for sale and labeling by the US-EPA and registration committees of various countries or Codex Alimentarius Commission for United Nations. Intentional/ unintentional consumption, inhalation of aerial sprays, direct contact of the herbicide with the applicator, and consumption of food prior to pre-harvest interval are some other ways of herbicide exposure. In addition to health effects caused by herbicides themselves, commercial formulations often contain other chemicals, including inactive ingredients, which may also have negative impacts on human health. Incidences of intentional acute poisoning by herbicide like butachlor, fluchloralin, paraquat, 2,4-D, pendimethalin, and glyphosate have been reported even when the level of contamination of soil, plant and water was considerably low (Senarathna *et al.* 2009). In the past, herbicide toxicity issues came to limelight when some manufacturers made misleading claims about the safety of their products. Dow AgroSciences, the manufacturer of picloram claimed that the herbicide has no adverse effects on animals in spite of evidence of strong carcinogenic activity of the active ingredient on rats (Reuber 1981). Monsanto, the manufacturer of glyphosate had to change its advertising after US agencies objected to their misleading claim of their product being practically non-toxic to mammals, birds, and fish. It was vouched to be even safer than the common salt (Talbot *et al.* 1991). Glyphosate has also been correlated with several diseases, including diabetes, obesity, asthma, Alzheimer’s disease, amyotrophic lateral sclerosis (ALS) and Parkinson’s disease (Samsel and Seneff 2016).

Cancer and other ill-effects of some herbicides are reported, but the scientific community often disagrees on the risk due to relatively higher LD_{50} of herbicides observed against mammals in comparison to common insecticides (Morrison *et al.* 1992). Some phenoxy herbicides are often contaminated with dioxins, such as TCDD, which increase cancer risk after their occupational exposure (Kogevinas *et al.* 1997). Triazines exposure has been implicated to increased risk of breast cancer, although a causal relationship remains unclear (Buchholtz 1965). While the risk of Parkinson’s disease has been shown to increase with occupational exposure to pesticides (Gorell *et al.* 1998), paraquat exposure is suspected to be an etiological factor of Parkinson’s disease (Dinis-Oliveira *et al.* 2006). Very recently, a proposal of the European Commission to put limits on the use of glyphosate and to ban one co-formulant surfactant namely polyethoxylated tallow amine (POEA) that enhanced the activity of glycophosate was delebrated (Michalopoulos 2016).

Heavy use of certain commercial herbicides has adversely affected wintering migratory birds and other bird populations (Blus and Charles 1997). Even herbicides having low toxicity to birds decrease the abundance of vegetation on which the birds rely (MacKinnon and Freedman 1993). In another study, herbicide use in Britain was linked to a decline in seed-eating bird species which rely on the weeds killed by the herbicides (Newton 2004). Exposure to low concentration of atrazine has reportedly caused demasculanization of frogs (Hayes 2002). Though some reports of herbicide poisoning are reported, nevertheless data on the occurrence of herbicide-related illnesses among humans and cattle is still vague and non-conclusive. Human health implications of herbicide residues with relevant references were reported by herbicide residues in cereals, pulses, oilseeds, vegetables, maize, plantation crops and fish in India. Their adverse effects on non-target plants, organisms and human health, and their mitigation have been comprehensively reviewed (Sondhia 2014a,b, Sondhia *et al.* 2015a, Sushilkumar and Sondhia 2017).

Earthworms: Earthworms are one of the important components in decomposer communities and contribute significantly to the organic matter decomposition, nutrient cycling and soil formation. Continuous application of pesticides may present risk to lead to soil pollution and affect soil fauna. Acetochlor increased the chromatid exchange frequency of human lymphocytes (Hill *et al.* 1997). It also decreased soil microbial community diversity (Luo *et al.* 2004). However, little is known about the effect of acetochlor on soil non-target animals like earthworms. LD_{50} of acetochlor to *Eisinea fetida* was 0.307 mg/kg as determined by filter paper test (Liang and Zhou 2003a).

Fishes: In a study, Yadav *et al.* (2010, 2013) revealed the genotoxic potential of butachlor even at low dose level (1.0 mg/kg) and suggested that butachlor interferes with cellular activities in fishes at genetic level inducing chromosomal aberrations and suggested a serious concern towards the potential danger of butachlor for aquatic organisms. On comparing the effect of different herbicides, it was observed that the fish mortality was more with 2,4-DEE and paraquat than with glyphosate (Muniappa *et al.* 1995). To evaluate the possible bio-accumulation of sulfosulfuron in the fish, an experiment was conducted in glass aquarium for 90 days. Sulfosulfuron was applied to the aquariums at 25–100 g/ha. Residues of sulfosulfuron in the fishes were found 1.09–3.52 µg/g after 10 days and by 90 days residues in the fish body were below the MRL (Sondhia 2008a, 2008d and 2008g). In another study on indirect effect of herbicides on fishes mortality was more with butachlor, followed by anilofos and oxyfluorfen (Sondhia 2012 and 2013). In another study, fishes (*Channa punctata*) were exposed for 10 days to sub lethal concentration (1/5th of static LC_{50}) of butachlor. Residue of butachlor after 10 days were 0.1255 mg/kg in gills, 0.3515 (Bloch) liver in (Bloch) liver, 0.3145 mg/kg in kidney and 0.2350 mg/kg in brain traces muscle of *Channa punctata*. The results revealed that prolonged exposure to sub lethal concentrations led to increase in the accumulation of residues. The residues are accumulated in different tissues, causing toxicity to the fish which ultimately results in biomagnifications through the food chain (Tilak 2007). *Tilapia mossambica* were exposed to sub lethal concentration (66 mg/L) for 24, 48, and 72 hrs, respectively to assess toxic effect of the metribuzin on the biochemical aspects such as total protein, carbohydrate and cholesterol in liver, muscle, kidney and gills. All parameters were found to be decreased in tissues in comparison to control (Saradhamani and Selvarani 2009).

Similarly dissipation of sulfosulfuron in natural water and its bioaccumulation in fish was conducted at two different concentration levels (1 and 2 mg/l). The dissipation data in water showed the fifty and ninety percent dissipation time (DT_{50} and DT_{90} values) 67–76 and 222–253 days and followed first order kinetics. Bioaccumulation of sulfosulfuron in fish was conducted under static conditions exposing the fish at one-tenth of sub-lethal concentration 9 mg/L and at double the concentration 18ml/g, for a period of 56 days. Accumulation of sulfosulfuron in fish in the range 0.009-0.496 µg/g was found. Both in water and fish samples, metabolites of aminopyrimidine, desmethyl sulfosulfuron, guanidine, sulfonamide, ethyl sulfone and rearranged amine were found. One of the metabolite aminopyrimidine was identified at higher concentration levels (0.01–0.1µg/mL) in comparison to other metabolites (Ramesh *et al.* 2007, Sondhia 2008). The calculated fifty and ninety percent dissipation time (DT_{50} and DT_{90} values) for aminopyrimidine dissipation in water were found to be 66–68 days and 218-226 days, respectively with a complete demineralization after three hundred days (Sondhia *et al.* 2015a).

In the fishes, 0.007, 0.0691 and 0.0376 µg/g residues of metsulfuron-methyl, bispyribac and pendimethalin were found after 30 days in fishes following an application of these herbicides in rice crop at 4, 25 and 750 g/ha, respectively. Herbicides treatments did not alter water quality significantly. An amount of 0.063 to 0.0085 µg/g and 0.51, to 0.161 µg/g oxyfluorfen and anilofos residues were detected from fishes collected at 10–90 days. Residues were found in the fishes up to 90 days. In the soil, 0.083–0.035 µg/g and 0.079– <0.001µg/g butachlor and anilofos residues were detected in rainy season during 1–90 days after herbicide application, whereas, 0.074, 0.0014 and 0.0230 µg/g residues of oxyfluorfen, butachlor and anilofos were detected from fishes collected at 90 days in Rainy season. Nearly 0.020, 0.0067, 0.0014 µg/g residues of sulfosulfuron, clodinafop and metsulfuron were detected at 60 days in fishes in winter season (Sondhia 2014c).

Human heath: Indirect effects of herbicides on human are not common in India. However increasing incidences of acute herbicide self-poisoning by butachlor, fluchloralin, paraquat, 2,4-D, pendimethalin, glyphosate etc are a significant problem in parts of Asia (Singh *et al.* 2003, Senarathna *et al.* 2009, Kumar and Verma 2012, Ghosh *et al.* 2012). Due to paraquat low vapour pressure and the formation of large droplets, inhalation of paraquat spray used in the open environment has not been shown to cause any significant systemic toxicity; however, inhalational exposure to paraquat in confined spaces, such as a greenhouse, is known to be associated with fatal pulmonary disease. Irrespective of its route of administration in mammalian systems, paraquat is rapidly distributed in most tissues, with the highest concentration found in the lungs and kidneys. The compound accumulates slowly in the lungs via an energy dependent process. Excretion of paraquat, in its unchanged form, is biphasic, owing to lung accumulation and occurs largely in the urine and, to a limited extent, in the bile (Suntres 2002). Poisoning with paraquat leads to both local and systemic effects.

Paraquat poisoning is an uncommon entity in India, and is associated with a high mortality rate (Agarwal *et al.* 2005, Kondle *et al.* 2013). These cases are reported in India to highlight the high mortality rate associated with paraquat poisoning in spite of advances in treatment and supportive care (Khosya and Gothwal 2012). The oxidative role of butachlor in intracellular ROS production, and consequent mitochondrial dysfunction, oxidative DNA damage, and chromosomal breakage, which eventually triggers necrosis in human PBMN cells is also reported (Dwivedi *et al.* 2012).

In an experiment, cultured human lymphocytes were exposed to three different concentrations (2.5, 5.0 and 10.0 ìg/ml) of fluchloralin for 24 and 48 h to assess chromosomal aberrations. A significant dose-dependent increase of chromatid type aberration was observed in these cells. Multiple aberrations (MA) were scored at all concentrations after 48 h treatment. Higher concentrations of fluchloralin (20, 40 and 50 ìg/mL) resulted in a significant dependent increase in number of micronucleated cells and showed genotoxic effects of fluchloralin in human cells (Panneerselvam *et al.* 1995). Nair *et al.* (2006) demonstrated that 2,4-D is capable of inducing higher DNA damage as well as chromosomal aberrations in human lymphocytes. In an Indian series of 17 patients of herbicide poisoning, the most common symptoms were vomiting (100%), followed by altered sensorium (59%), oral ulceration or dysphagia (53%), dyspnea (41%), or loose stools (24%) (Sandhu *et al.* 2003). Acute respiratory distress syndrome because of paraquat usually appears 24–48 h after ingestion (Singh *et al.* 1999). Similarly there are several cases of intentional poisoning due to ingestion of paraquat (Agarwal *et al.* 2006, Rana *et al.* 2008, Attar *et al.* 2009, Khosya and Gothwal, 2012, Gosh *et al.* 2012, Kondle *et al.* 2013, Saravu *et al.* 2013), pendimethalin (Kumar and Verma 2012), glyphosate (Das *et al.* 2012) and 2,4-DEE (Singh *et al.* 2008) in various places in India.

Herbicide poisoning: A diagnostic challenge

Hemoperfusion using activated charcoal has been shown to decrease paraquat level, but data to support survival benefit in humans is insufficient. It is only effective if initiated within 4 h of ingestion, as peak paraquat concentration in the lung is achieved in 5–7 h (Sandhu *et al.* 2003). Hemodialysis is used as a support of acute renal failure, but it does not increase clearance of the substance as it is rapidly distributed to the lungs and other organs (Sandhu *et al.* 2003). Immunosuppression with combination of cyclophosphamide and methylprednisolone was shown to be beneficial in moderate-to-severe cases by prevention of ongoing inflammation (Agarwal *et al.* 2005, Chandra *et al.* 2013). Unfortunately, none of the studied treatments, including controlled hypoxia, superoxide dismutase, vitamins C and E, N-acetylcysteine, desferrioxamine, and nitrous oxide, has been proven to be effective (Suntres 2001, Eddleston *et al.* 2003).

Conclusion

Herbicide residues even after recommended use for control of weeds are relatively high initially; however, the levels are reduced rapidly, and residues are often not detectable after a few days or weeks or at harvest. The soil acts as an important buffer governing the persistence and fate of most herbicides in the environment. As long as soil system remains healthy, possible adverse effect from herbicides in the environment probably can be minimized. Herbicides in most instances when applied at recommended doses have not been detected in food chain or in soil at level that should cause concern. Data on the occurrence of herbicide-related sickness among animal and humanbeing in developing countries are scanty. The persistence and half-life period of many herbicides were found to be less in Indian tropical conditions. This could be one of the reasons for the detection of low level of residues. It can be concluded that in India herbicide contamination of soil, plants and natural waters occurs infrequently and at low levels. With few exceptions aquatic herbicides do not accumulate and persist in fish.

References

Agarwal R, Srinivas R, Aggarwal AN and Gupta D. 2006. Experience with parquet poisoning in a respiratory intensive care unit in North India. *Singapore Medical Journal* **47**(12): 1033–1037.

Aktar MW, Gupta A, Gade V and Bhattacharyya. 2007. Fate and behavior of benthiocarb a herbicide in transplanted paddy under East–Indian Climatic Condition. *Bulletin of Environmental Contamination and Toxicol*ogy **79**: 646–649.

Aktar MW, Gupta D, Alam S and Chowdhury A. 2009. Degradation dynamics of a di–nitro aniline herbicide (trifluralin) in/on Black gram (Vigna mungo) under East–Indian climatic condition. *Electronic Journal of Environmental, Agricultural and Food Chemistry* **8**(11): 1172–1177.

Amarjeet S, Punia S, Yadav A and Malik RK 2003. Effect of pH on degradation of chlorsulfuron in soil. *Indian Journal of Weed Science* **35**(1&2): 97–99.

Nagwanshi A, Dwivedi A K, Sondhia S and Pandey R. 2016. Persistence of pretilachlor, penoxsulam and pyrazosulfuron herbicides in soil. *International Journal of Agricultural Science* **8**(8): 1087–1089.

Arora A, and Sondhia S. 2013. Persistence of imazethapyr in soybean and soil. *Indian Journal of Weed Science* **45**(3): 226–227.

Arora A, Tomar SS and Sondhia S. 2013. Efficacy of herbicides on wheat and their terminal residues in soil, grain and straw. *Indian Journal of Weed Science* **45**(2): 109–112.

Arora S and Gopal M. 2004. Residues of pendimethalin after weed control in cabbage crop (*Brassica oleracea* var L. *Capitata*). *Bulletin of Environmental Contamination and Toxicol*ogy **73**: 106–110.

Aslam M, Alam M and Rais S. 2013. Detection of atrazine and simazine in ground water of delhi using high performance liquid chromatography with ultraviolet detector current. *World Environment* **8**(2): 323–329.

Attar N R, Arsekar S, and Pawar MN. 2009. Paraquat poisoning – A deadly poison: A case report. *Vilas Chavan Medico–Legal Update* **9**(2): 43–47.

Balasubramanian R, Veerabadran V and Kannathasan M. 1999. Influence of continuous use of herbicides in rice based system on residue accumulation and on performance of succeeding pulse crop. *Pesticide Research Journal* **11**(2): 200–203.

Bandana, Neelam Sharma, Robin Joshi, Ashu Gulati and Shobha S. 2015. Dissipation kinetics of glyphosate in tea under North Western mid hills conditions of India’. *Journal of Pesticide Science* **40**(3): 82–86.

Basavarajappa DN and Nanjappa HV. 1994. Residual effect of herbicides applied to sunflower on succeeding crops. *Indian Journal of Weed Science* **26**: 97–98.

Beltman WHJ, Wieggers HJJ, ML, Rooy de and Matser AM. 2001. Afspoeling van amitrol, atrazin en glyfosaat vanaf een Beton klinkerverharding, Veldproeven en modelsimulaties Rijksinstituut voor Integraal Zoetwaterbeheer en AfvalwaterbehandelingAlterra–rapport 319p.

Bhattacharyya A, Ganguly P, Barik SR and Kundu C. 2012. Studies on thepersistence of Diclosulam in soybean crop. *Pakistan Journal of Weed Science Research* **18**: 29–37.

Biswas PK, Kumar S, Mitra SR and Bhattacharyya A. 2007. Persistence of napropamide in/on tea under North–East Indian climatic condition. *Bulletin of Environmental Contamination and Toxico*logy **79**: 566–569.

Brandenberger LP. 2007. Injury potential from carryover of watermelon herbicide residues. *Weed Technology* **21**: 473–476.

Buchholtz KP. 1965. Factors influencing oat injury from traizine residues in soil. *Weeds* **13**: 362–367.

Blus JL and Charles JH. 1997 Field studies on pesticides and birds: Unexpected and unique relations. *Ecological Applied* **7**(4): 1125–1132.

Chakraborty A, Ghosh M, Banerjee H and Bhattacharyya A. 2005. Persistence behaviour of haloxyfop – a new herbicide in/on onion. *Journal of Crop and Weed* **1**(1): 41–44.

Chandra N, Jain NK, Sondhia S, and Srivastava AB. 2013. Deltamethrin induced toxicity and ameliorative effect of alpha–tocopherol in broilers. *Bulletin of Environmental Contamination and Toxicology* **90**(6): 673–678.

Chhonkar RS, Sharma RK. 2008. Multiple herbicide resistance in littleseed canary grass (*Phalaris minor*): A threat to wheat production in India. *Weed Biol Manage* **8**(2): 112–123.

Cornish PS. 1992. Glyphosate residues in a sandy soil affect tomato transplants. *Australian Journal of Experimental Agriculture* **32**: 395–399.

Das SK, Anand PR, Vijaya Kumar V and Ponnusankar S. 2012. Case report on glyphosate surfactant herbicide (Gly SH) poisoning: A systemic method for management. *NSHM Journal of Pharmacy and Healthcare Management* **3**: 112–115

Deepa and Jayakumar 2006. Persistence of pretilachlor in water at different pH level. *Pesticide Research Journal* **18**(2): 199–200.

Deka SK and Gogoi AK. 1993. Studies on the persistence of butachlor in soil and residue in straw and grain of rice (*Oryza sativa* L.) Integrated Weed Management for Sustainable Agriculture. Vol. II, pp. 96–98. In: *Proceedings of an Indian Society of Weed Science International Symposium,* Hisar, India, 18–20 November 1993.

Devi MP, Reddy CN and Reddy NV. 1998. Crop tolerance studies to oxyfluorfen and its persistence in soil. *Indian Journal of Weed Science* **30**(3&4): 214–215.

Devi MP, Reddy CN, Reddy NV, Reddy DJ and Babu TR. 2000. Metolachlor and pendimethalin dissipation in red sandy loam soil and their movement in Alfisols and Vertisols. *Journal of* Research ANGRAU **29**(4): 95–99.

Devi MP, Reddy CN, Reddy NV, Reddy KN and Rao BN. 1997. Degradation of butachlor in transplanted rice and residues in soil, straw and grain of rice (Oryza sativa). *Journal of Research ANGRAU* **25**: 4, 13–15.

Dharumarajan S, Sankar R, Basakar A and Kumar K. 2008. Persistence of pretilachlor in coastal rice ecosystem. *Pesticide Research Journal* **20**(2): 273–274.

Dixit A, Sondhia S and Varshney J. 2011. Bio–efficacy of pinoxaden in wheat (*Triticum aestivum*) and its residual effect in succeeding rice (*Oryza sativa*) crop. *Indian journal of agricultural sciences* **81**(7): 659–61.

Dinis–Oliveira RJ, Remião F, Carmo H, Duarte JA, Navarro A Sánchez, Bastos ML, Carvalho F. 2006. Paraquat exposure as an etiological factor of Parkinson’s disease. *Neuro Toxicology* **27**(6): 110–112.

Dubey PK, Srivastava A Sand NK and Gupta KC. 1998. Analysis of metribuzin in soil, and grain and straw of wheat by HPLC. *Pesticide Research Journal* **10**: 101–104.

Dwivedi S, Saquib Q, Abdulaziz A, Al–Khedhairy, Musarrat J. 2012. Butachlor induced dissipation of mitochondrial membrane potential oxidative DNA damage and necrosis in human peripheral blood mononuclear cells. *Toxicology* **302**(1): 77–87.

Eddleston M, Wilks MF and Buckley NA. 2003. Prospects for treatment of paraquat–induced lung fibrosis with immunosuppressive drugs and the need for better prediction of outcome a systematic review. *QJM* **96**(11): 809–824.

Eleftherohorinos IG. 1987. Phytotoxicity and persistence of chlorsulfuron as affected by activated charcoal. *Weed Research* **27**(6): 443–452.

FAO. 2003. Herbicide–resistance management in developing countries (Bernal E. Valverde.). (Ed. Labrada R). In: *Weed Management for Developing Countries Addendum 1 FAO plant production and protection paper* 120 Add. 1. http: //www.fao.org/docrep/006/Y5031E/y5031e0h.htm

FAO. 2004. Good Agricultural Practices – a working concept. Background paper for the FAO Internal Workshop on Good Agricultural Practices. Accessed from ftp: //ftp.fao.org/docrep/fao/010/ag856e/ag856e00.pdf

Ghosh S, Singh S, Dewan S, Walia G and Bansal A. 2012. Herbicide poionmosing an diagonistic challenge. *Indian Journal of Critical Care Medicine* **16**(1): 52–54.

Gogoi AK, Yaduraju NT and Sondhia S. 2005. Monitoring of herbicide residues in food chain, soil and ground water in rice based cropping system. w. e. f. 6–8 April 2005 pp 302–304. In: *Proceedings of Biennial Conference of Indian Society of Weed Science*, held at Ludhiana, India.

Gowda RC, Devi LS and Prasad TVR. 2002. Bio–efficacy of herbicides in groundnut and residues of pendimethalin in soil under finger millet groundnut cropping system. *Pesticide Research Journal* **14**(2): 263–267.

Gorell JM, Johnson CC, Rybicki, BA, Peterson El, Richardson RJ. 1998. The risk of Parkinson’s disease with exposure to pesticides, farming, well water, and rural living. *Neurology* **50**(5): 1346–1350.

Goyal M VK and Phogat V K 2003. Persistence of trifluralin in soils under intermittent and continuous ponding condition. *Pesticide Research Journal* **15**(2): 181–184

Gupta M, Garg NK, Joshi H and Sharma MP. 2012. Persistence and mobility of 2,4–D in unsaturated soil zone under winter wheat crop in sub–tropical region of India. *Agriculture, Ecosystems and Environment* **146**(1): 60–72.

Gupta S and Gajbhiye VT. 2002. Adsorption–desorption, persistence and leaching behavior of dithiopyr in an alluvial soil of India. *Journal of Environmental Science and Health, Part B: Pesticides, Food Contaminants, and Agricultural Wastes* **37**(6): 573–586.

Gupta S, Gajbhiye VT and Agnihotri NP. 2001. Adsorption–desorption, persistence, and leaching behavior of flufenacet in alluvial soil of India. *Bulletin of Environmental Contamination and Toxicol*ogy **66**: 9–16.

Gupta S, Gajbhiye VT and Gupta S. 2000. Simple methods for dithiapyr residue analysis in soil, water and plant materials. *Annals of Plant Protection Sciences* **8**: 79–83.

Hawaldar S, Agasimani CA. 2012 Effect of herbicides on weed control and productivity of maize (*Zea mays* L.). *Karnataka Journal of Agricultural Sciences* **25**(1): 137–139.

Hayes TB, Collins A, Lee M, *et al.* 2002. Hermaphroditic, demasculinized frogs after exposure to the herbicide atrazine at low ecologically relevant doses. *Proceedings of NationalAcademy of Sciences* **99**(8): 5476–5480.

Hill AB, Jefferies PR, Quistad GB and Casida JE. 1997. Dialkylquinoneimine metabolites of chloroacetanilide herbicides induce sister chromatid exchanges in culture human lymphocytes. *Mutation Research - Genetic Toxicology and Environmental* **395**: 159-171.

Janaki P, Meena S, Chinnusamy C, Arthanari PM and Nalini K. 2012. Field persistence of repeated use of atrazine in sandy clay loam soil under maize. *Madras Agricultural Journal* **99**(7/9): 533–537.

Janaki P, Rathika S, Chinnusamy C and Prabhakaran NK. 2013a. Field dissipation of metamitron in soil and sugar beet crop. *Bulletin of Environmental Contamination and Toxicol*ogy **90**: 116–119.

Janaki P, Sathya R, Priya and Chinnusamy. 2013b. Field dissipation of oxyfluorfen in onion and its dynamics in soil under Indian tropical conditions. *Journal of Environmental Science and Health, Part B: Pesticides, Food Contaminants, and Agricultural Waste* **48**(11): 941–947.

Jayakumar R and Sankaran S 1995. Evaluation of anilofos 50 EC residues in transplanted rice. *Madras Agricultural Journal* **82**(4): 296–298.

Jayakumar R and Sree Ramulu US. 1993. Degradation and persistence of herbicides in transplanted rice "Integrated Weed Management for Sustainable Agriculture". pp 101-105. In: *Proceedings of an Indian Society of Weed Science International Symposium,* Hisar, Haryana, 18–20 November 1993.

Kathpal TS, Gupta K, Kamboj RK and Kairon MS. 1980. Contamination of cotton leaves with 2,4–D herbicide residues. *Haryana Agricultural University Journal of Research* **10**(2): 258–260.

Kaur R and Gill BS. 2012. Analysis of herbicide residues in celery seeds. *Indian Journal of Ecology* **39**(2): 258–260.

Kaur SM, Randhawa SK and Walia US. 2010. Analysis of herbicide residues in onion bulbs and soil under different planting patterns and straw management techniques. *Indian Journal of Weed Science* **42**(1&2): 77–81.

Kaushik SN and Moolani MK. 1974. Persistence of atrazine in soil cropped with corn (*Zea mays* L.). *Indian Journal of Weed Science* **6**(1): 53–60.

Khare RR and Sondhia S. 2014. Cyhalofop-p-butyl mobility and distribution of residues in soil at various depths. *Journal of Environmental Science and Health*, Part B **46**(6): 391-399.

Khosya S and Gothwal S. 2012. Two cases of paraquat poisoning from kota, Rajasthan, India case reports in critical care. ID 652146.DOI. 10.1155/2012/652146.

Kondle Raghu, Vidavalur Mahesh, Parri Sasidhar, Polam R Reddy, Vajja Venkataramaniah, and Agrawal A 2013. Paraquat poisoning: A case report and review of literature. *Case Report* **20**(3):198–200.

Kogevinas M, Becher H, Benn T, Bertazzi PA, Boffetta P, Bueno–de–Mesquita HB, Coggon D, Colin D, Flesch–Janys D, Fingerhut M, Green L, Kauppinen T, Littorin M, and Lynge E, Mathews JD, Neuberger M, Pearce N, Saracci R. 1997. Cancer mortality in workers exposed to phenoxy herbicides, chlorophenols, and dioxins. An expanded and updated international cohort study. *American Journal of Epidemiology* **145**(12): 1061–1051.

Kulshrestha G and Yaduraju NT. 1987. Persistence of pendimethalin in soil following pre–emergence application to wheat. *Indian Journal of Agronomy* **32**: 271–274.

Kulshrestha G, Singh SB and Gautam KC 1995. Residues of fluazifop–p–butyl following application to soybean. *Bulletin of Environmental Contamination and Toxicology* **55**(2) 276–282.

Kumar B, Sharma R and Singh SB. 2012. Evaluation of harvest residues of cyhalofop–butyl in paddy soil. *Bulletin of Environmental Contamination and Toxico*logy **89**: 344–347.

Kumar B. 2011. Residues of Pesticides and Herbicides in Soils from Agriculture Areas of Delhi Region, India. *Journal of Environment and Earth Science* **12**(1): 8.

Kumar DKS, Hanumantharaju TH, Shree KGS, Ashoka KR, Nalina CN and Rani SS. 2011. Persistence and degradation of pyrazosulfuron–ethyl in soils of Karnataka. *Asian Journal of Soil Science* **6**(2): 234–236.

Kumar J, JaiPrakash, Kumar J and Prakash J. 1993.Persistence of thiobencarb and butachlor in soil incubated at different temperatures. Integrated weed management for sustainable agriculture. Proceedings of an Indian Society of Weed Science International Symposium, Hisar, India, 18–20 November 1993, Vol. II, 123–124.

Kumar Lalit, Kumar Narendra, Sondhia Shobha, Basu PS and Srivastava GK 2017. Residues, persistence and dissipation pattern of imazethapyr in *Typic Usrtochrept* soil of Indo–Gangetic Plains. *Journal of Food Legume* **30**(4): 267–272.

Kumar, A and Verma A 2012. Acute severe suicidal poisoning by herbicide pendimethalin; a rare case report from rural India. *Sri Lanka Journal of Forensic Medicine, Science & Law* **3**(2): 1–5

Kumari D, Kumari B, Kathpal TS, Yadav A and Malik RK. 2004. Determination of 2,4-D sodium salt residues in soil and wheat using HPLC. *Annals of Agri–Bio Research* **9**(1): 59–61.

Latchanna A. 1987. Persistence of phytotoxic residues of atrazine in soils of rainfed sorghum. *Indian Journal of Weed Science* **19**: 166–170.

Leela D. 1993. Weedicides for vegetables *Indian–Horticulture.* **38**(2): 13–15.

Leela D. 1984. Studies on the persistence of herbicides in sandy loam soils. *Indian Journal of Horticulture* **41**(1&2): 123–126.

Liang J, Zhou Q. 2003a. Single and binary-combined toxicity of methamidophos, acetochlor and copper acting on earthworms *Esisenia foelide. Bulletin of Environmental Contamination and Toxicology* **71**(6): 1158-1166.

Luo H F, Qi H Y, Zhang H X, 2004. The impact of acetochlor on the bacterial diversity in soil. *Acta Microbiologica Sinica,* **44**: 519–522.

Mandal K, Sahoo SK, Battu RS and Singh B. 2014. Estimation of quizalofop ethyl residues in black gram (*Vigna mungo* L.) by gas liquid chromatography. *Bulletin of Environmental Contamination and Toxicology* **92**(1): 115–118.

MacKinnon DS, Freedman B. 1993. Effects of silvicultural use of the herbicide glyphosate on breeding birds of regenerating clear cuts in Nova Scotia, Canada. Journal of Applied Ecology **30**(3): 395–406.

Melwille DP and Oakes JY. 1976. Residual effect of herbicides in cotton, corn and soybean solahin. *Louisiana Agriculture* **19**: 8-9.

Morrison HI, Wilkins K, Semenciw R, Mao Y, Wigle D. 1992. Herbicides and cancer. J*ournal of Natural Cancer Institute* **84**(24): 1866–1874.

Michalopoulos S. 2016. EurActiv.com (updated: Jul 12, 2016). http: //www.euractiv.com/section/agriculture–food/news/eu–agrees–ban–on–glyphosate–co–formulant.

Mukherjee A, Dutta S, Karmakar PR, Kole RK and Bhattacharyya A. 2010. Dissipation pattern of the herbicide pyrazosulfuron–ethyl in alluvial and red lateritic soils of West Bengal. *Journal of Crop and Weed* **2**(2): 65–69.

Mukherjee I and Gopal M. 2005. Evaluation of fentrazamide for weed control and estimation of its residues in rice. *Bull. Environ. Contam. Toxicol* **74**: 667–672.

Mukhopadhyay S, Bhattacharyya A and Das S. 2012. Fate and persistence of herbicide quizalofop–p–tefuryl on black gram. *Journal of Crop and Weed* **8**(1): 190–192.

Muniappa VT, Manjunatha V, Babu VS and Shivkumar HR. 1995. Efficacy of post emergent herbicides on control of water hyacinth (Eichhornia crassipes Mart.) and their effect on fishes. *World Weeds* **2**: 117–121.

Nag SK and Das SK. 2009. Persistence of atrazine in soil under fodder sorghum. *Journal of Crop and Weed* **5**(2): 131–135.

Nair RS, Paulmurugan R and Wilsanand V. 2005. Genotoxix effects of coomonly used pesticides of south india in human lymphocytes. *Pollution resarch* **24**(1): 7–12.

Naveen DV, Gowda RC and Mamatha B. 2012. Field studies on persistence of pyrazosulfuron–ethyl in soil, ground water and residues in transplanted rice. *Asian Journal of Soil Science* **89**(5): 1032–1036.

Newton I. 2004. The recent declines of farmland bird populations in Britain: An appraisal of causal factors and conservation actions. *International Journal of Avian Science* **146**(4): 579–600.

Oerke EC.2006 Crop losses to pests. *Journal of Agricultural Sciences* **144**(1): 31–43.

Pahwa SK and Bajaj K 1997. Persistence of trifluralin and pendimethalin in soils incubated at different temperature. *Indian Journal of Weed Science* **29**(3&4): 187–182.

Panchal M and Kapoor C. 2016. Indian agrochemicals market to reach $6.8 bn by FY17. Tata Strategic Management Group study. http: //www.business–standard.com/content/b2b–chemicals/indian–agrochemicals–market–to–reach–6–8–bn–by–fy17–tata–strategic–management–group–113081200449_1.html.

Panneerselvam N, Sinha S and Shanmugam G. 1995. Genotoxicity of the herbicide fluchloralin on human lymphocytes in vitro,chromosomal aberration and micronucleus tests. *Mutation Research Genetic Toxicology* **344**(1&2): 69–72.

Parmar NB, Maraviya GV, Shah PG, Patel BK, Ghelani LM and Patel AM. 1998. Pendimethalin residues in tobacco plant. *Tobacco Research.* **24**: 1, 57–59.

Patel R, Sondhia S, Diwedi AK. 2014. Effect of imazethapyr and varying level of fertilizer on soybean crop quality. *J Res Environ Sci Toxicol* **3**(2): 21–24. http: //dx.doi.org/10.14303/jrest.2013.059.

Patel RK, Sondhia S and Dwivedi AK. 2009. Residues of imazethapyr in soybean grain, straw and soil under application of long term fertilizers in Typic Haplustert . *Indian Journal of Weed Science* **41**(1&2): 90–92.

Patel RK, Sondhia S, Dwivedi AK. 2010a. Dissipation and persistence of imazethapyr in soybean soil under application of long term fertilizers in Typic Hapuustert p.139. In: *Abstract in Biennial Conference on Recent Advances in Weed Science Research,* 25-26 February, 2010.

Patel RB, Patel BK, Shah PG, Raj MF and Patel JA. 1996. Dissipation of fluchloralin in soils and its residues in chicory. *Pesticide Research Journal* **8**(2): 182–185.

Paul R, Sharma R, Kulshrestha G and Singh SB. 2009. Analysis of metsulfuron–methyl residues in wheat field soil a comparison of HPLC and bioassay technique. *Pest Management Science* **65**(9): 963–968.

Radhamani S, Sankaran S and Jayakumar R. 1997. Degradation and persistence of herbicides in direct seeded puddled rice. *Madras Agricultural Journal* **84**(4) 194–196.

Rai AK, Chhonkar PK and Agnihotri NP 2000. Persistence and degradation of pendimethalin and anilofos in flooded versus non–flooded soils. *Journal of the Indian Society of Soil Science* **48**(1): 57–62.

Raina S, VKumar V, Kaushal SS and D Gupta 2008. Two cases of paraquat poisoning from Himachal Pradesh. JIACM 2008, **9**(2): 130–132.

Raj MF, Patel BK, Shah PG and Barevadia TN. 1999. Pendimethalin, fluchloralin and oxadiazon residue in onion. *Pesticide Research Journal* **11**(1): 68–70.

Rajput S and Sondhia S. 2014. Effect of penoxsulam on fungal population in rhizosphereic soil. p. 162. In: *Procedings of Biennial Conference of Indian Society of Weed Science on "Emerging Challenges in Weed Management"* February 15-17, 2014. Directorate of Weed Science Research, Jabalpur.

Ramesh A and Maheswari, S T.2004. Dissipation of alachlor in cotton plant soil and water and its bioaccumulation in fish, *Chemosphere* **54**: 547–652.

Ramesh A, Sathiyanarayanan S and Chandran L. 2007. Dissipation of sulfosulfuron in water – bioaccumulation of residues in fish LC–MS/MS–ESI identification and quantification of metabolites. *Chemosphere* **68**(3): 495–500.

Rana MC and Angiras N N 1993. Studies on persistence of imazethapyr applied in soybean and its residual effect on wheat + pea cropping system Integrated weed management for sustainable agriculture. pp. 106–108. *In: Proceedings of an Indian Society of Weed Science International Symposium,* Hisar, India, 18–20 November 1993.

Randhawa SK and Sandhu KS. 1997. Persistence of metoxuron in soil. *Journal of Research Punjab Agricultural University* **34**(2): 136–137.

Rao PC, Lakshmi CS, Madhavi M, Swapna G and Butachlor AS. 2012. Dissipation in rice grown soil and its residues in grain. *Indian Journal of Weed Science* **44**(2): 84–87.

Rao S. 2000 *Principles of Weed Science, 2nd ed*. New York: Science Publishers, 526p.

Rathod PH, Patel RB and Jhala A. 2010. Persistence and management of dinitroaniline herbicides residues in sandy loam soil. *International Journal of Environment and Sustainable Development* **9**(1): 58–73.

Raut AK and Kulshrestha G. 1991. Persistence of fluazifop–p–butyl in an inceptisol. *Pesticide Research Journal* **3**(1): 67–72.

Reuber MD. 1981. Carcinogenicity of picloram. *Journal of Toxicology and Environmental Health* **7**(2): 207–222.

Reddy KN and Reddy H. 2010. Pesticide residues in surface water of lakes around Hyderabad, India. *Pesticide Research Journal* **22**(2): 111–115.

Reddy KN, Rao B N, Sultan MA, Reddy D J and Babu TR. 1998. Residues of butachlor in paddy. *Journal of Research ANGRAU* **26(**3&4): 48–49.

Roy S and Singh SB. 2006. Effect of Soil Type, Soil pH, and microbial activity on persistence of clodinafop herbicide. *Bulletin of Environmental Contamination and Toxico*logy **77**: 260–266.

Saha S and Kulshrestha G. 2002. Degradation of sulfosulfuron, a sulfonylurea herbicide, as influenced by abiotic factors. *Journal of Agriculture and Food Chemistry* **50**(16): 4572–4575.

Saikia TP and Pandey J. 1999. Dissipation of fluchloralin in chickpea (*Cicer arietinum* L.). *Journal of the Agricultural Science Society of North East India* **12**(2): 236–238.

Saikia TP, Pandey J and Kulshrestha G. 2000. Investigation on residue of atrazine and fluchloralin in maize (*Zea mays*)–chickpea (*Cicer arietinum*) and maize (*Zea mays*)–Indian mustard (*Brassica juncea*) cropping sequences. *Indian Journal of Agronomy* **45**(4): 653–657.

Sanbagavalli S, Kandasamy OS, Ganesan K. 2000. Herbicide resistance in weeds: A review. *Agriculture Review* **21**(2): 80–88.

Sandhu JS, Dhiman A, Mahajan R and Sandhu P. 2003. Outcome of paraquat poisoning a five year study. *Indian Journal of Nephrology* **13**: 64–68.

Sandhu KS, Randhawa SK, and Bhatia RK. 1994. Atrazine persistence studies in berseem for fodder. *Journal of Research Punjab Agricultural University* **1**(4): 399–401.

Sanyal D and Kulshrestha,G. 2003. Degradation of metolachlor in soil inoculated with a mixed fungal culture. *Biology and Fertility of Soils* **38**(4) 253–256.

Sanyal D, Yaduraju NT and Kulshrestha G. 2003. Metolachlor persistence in laboratory and field soils under Indian tropical conditions. *Journal of Environmental Science and Health. Part–B, Pesticides, Food Contaminants and Agricultural Wastes* 35(5): 571–583.

Saradhamani N and Selvarani, BJ. 2009. A study on the effect of herbicide metribuzin on the biochemical constituents of the freshwater fish, *Tilapia mossambica* Peters (Pisces: Cichlidae). *Current Bioti*ca **3**(2): 220-231.

Samsel A, Seneff S. 2016. Glyphosate pathways to modern diseases V: Amino acid analogue of glycine in diverse proteins. *Journal of Biology Physics and Chemistry* **16**: 9–46.

Saravu K, Sekhar S, Pai A, Barkar AS, Rajesh V, and Earla JR. 2013. PAraquat–a deadly poision: report of a case and review.Indian *Journal of Critical Care Medicine* **17**: 182–184.

Senarathna L and Eddleston MF. 2009. Prediction of outcome after paraquat poisoning by measurement of the plasma paraquat concentration *QJM* **102**(4): 251–259.

Sethi, RK and Chopra SL.1975. Desorption, degradation and leaching of alachlor in some soils. *Journal of the Indian Society of Soil Science* **23**(2) 184–194.

Sharma KK, Tripathy Vandana, Gopal M and Wali S. 2018 Good agricultural practices and monitoring of herbicide Residues in India. pp 438. In: *Herbicide Residue Research in India*. (eds: Sondhia S, Chodhury P and Sharma AR).

Sharma KK. 2002. Degradation of alachlor in water and tropical soil of India. *Bulletin Environmental Contamination and Toxico*logy **68**: 394–399.

Sharma N and Angiras N N. 1997. Studies on persistence of herbicides applied in maize by bioassay technique. *World Weeds* **4**(1&2): 37–39.

Singh A, Kewat ML, Sondhia S. 2017. Effect of day time application of mesosulfuron–methyl on fungal population of wheat rhizosphere. p 278. In: *Abstract of the Biennial Conference of the Indian society of Weed Science on Doubling Farmers Income by 2022*: *The Role of Weed Science,* Udaipur, India, 1–3 March.

Singh A, Kewat ML, Sondhia S, Singh P. 2015. Effect of day time application of mesosulfuron–methyl on weeds and yield of wheat. p. 154. In: *Asian–Pacific Weed Science Society Conference on Weed Science for Sustainable Agriculture, Environment and biodiversity*, Hyderabad, India during 13–16 October, 2015, Vol 3. (eds: Shetty SVR, Prasad TVR, Chinnusamy C, Sanjay MT, Sondhia S and Sushilkumar).

Singh A, Kewat ML and Sondhia S. 2018. Studies on the effect of day time application of herbicide mesosulfuronmethyl on soil microbial communities of wheat rhizosphere. *Journal of Environmental Biology* **39**: 59–65.

Singh and Kulsherestha G. 2006. Soil persistence of triasulfuron herbicide as affected by biotic and abiotic factors. *Journal of Environmental Science and Health, Part B: Pesticides, Food Contaminants, and Agricultural Wastes* **41**(5): 635–645.

Singh DK, Singh G, Srivastava A., S and NK. 2008. Harvest time residue of isoproturon in soil, wheat grain and straw. *Pantnagar Journal of Research* **1**: 125–127.

Singh PK, Sondhia S, Dubey RP, Sushilkumar, Kumar B, Gharde Y and Choudhary VK. 2017. Adoption and impact assessment of weed management technologies in wheat and greengram under conservation agriculture system in central India. *Indian Journal of Weed Science* **49**(1): 23–28.

Singh S and Kulsherestha G. 2006. Persistence and harvest time residues of triasulfuron in soil and wheat crop. *Pesticide Research Journal* **18**: 2196–198.

Singh S, Bambery P, Chaudhry D, Makharia G, Kakkar N and Singh D. 1999. Fatal paraquat poisoning: report of two cases. *Journal of Association of Physicians of India* **47**(8): 831–832,

Singh S, Yadav S, Sharma N and Malhotra P. Bambe. 2003. Fatal 2,4–D (ethyl ester) ingestion. *Journal of Association of Physicians of India* **51**, 609–610.

Singh SB and Kulshrestha G. 1995. Degradation of fluchloralin in soil under predominating anaerobic conditions *Journal of Environmental Science and Health. Part–B, Pesticides, Food Contaminants, and Agricultural Wastes* **30**(3): 307–319.

Singh SB, Yaduraju NT and Kulshrestha G. 1997. Residues of metolachlor herbicide in soil and potato tubers under indian tropical conditions. *Bulletin of Environmental Contamination and Toxicology* **59**(2): 216–221.

Singh SB, Sharma R and Singh N. 2012. Persistence of pyrazosulfuron in rice–field and laboratory soil under Indian tropical conditions. *Pest Management Science* **68**(6): 828–833.

Singh SB, Tapas K, Das and Kulshrestha G. 2013. Persistence of herbicide fenoxaprop ethyl and its acid metabolite in soil and wheat crop under Indian tropical conditions. *Journal of Environmental Science and Health, Part B: Pesticides, Food Contaminants, and Agricultural Wastes* **48**(5): 324–330.

Singh SB, Yaduraju NT and Kulshrestha G 1999. Terminal residues of fluazifop–p–butyl in soybean. *Annals of Plant Protection Sciences* **7**(1): 87–90.

Sinha SN, Agnihotri NP and Gajbhiye VT 1996. Field evaluation of pendimethalin for weed control in onion and persistence in plant and soil. *Annals of Plant Protection Science* **4(**1): 71–75.

Sireesha A, Rao P C, Rao, PV, Swapna G and Ramalakshmi CS. 2011. Persistence of pendimethalin and oxyfluorfen at different temperature and moisture levels in an alfisol and vertisol. *Indian Journal of Weed Science* **43**(3&4): 181–187.

Sondhia S. 2008d. Evaluation of potential risk of herbicides bioaccumulation in fishes. *Proceedings of Taal 2007*: (eds: Sengupta, M. and Dalwani, R.) The 12 World Lake Conference: 149–151.

Sondhia S and Dixit A. 2007a. Determination of terminal residues of oxyfluorfen in onion. *Annals of Plant Protection Sciences* **15**(1): 232–234.

Sondhia S and Dixit A. 2007b. Persistence of oxyfluorfen residues in the soil of paddy field and detection of its residues in crop produce. *Indian Journal of Agricultural Science* **80**(10): 926–929.

Sondhia S and Dixit A. 2008. Persistence of flumioxazin residues in soybean (*Glycine max*) crop and soil. *Indian Journal of Agricultural Science* **78**(8): 716–718.

Sondhia S and Dixit A. 2012. Bioefficacy and persistence of ethoxysulfuron in rice. *ORYZA– An International Journal on Rice* **49**(3): 178–182.

Sondhia S and Khare RR 2017. Leaching of rice herbicide, cyhalofop–butyl in vertisols following an application in lysimeters under tropical rainfall conditions. *Asian Journal of Chemistry* **29**(4): 829–834.

Sondhia S and Mishra JS. 2005. “Determination of terminal residue of clodinafop propargyl in soil, wheat grains and straw.” *Indian Journal of Weed Science* **37**(3&4): 296–297.

Sondhia S and Saraswat, VN. 2000b. Dissipation and assessment of atrazine residues. pp 58. In: *Proceeding of the National seminar on Bio–Diversity Conservation, Management and Utilization for Sustainable Development*, India.

Sondhia S and Singh VP. 2006. Persistence of isoproturon in soil and detection of its residues in wheat grains and straw. *Geobios* **33**(2&3): 209.

Sondhia S and Singhai B. 2008. Persistence of sulfosulfuron under wheat cropping system. *Bulletin of Environmental Contamination and Toxicology* **80**(5): 423–427.

Sondhia S and Yaduraju NT. 2005. Evaluation of leaching of atrazine and metribuzin in tropical soil. *Indian Journal of Weed Science* **37**: 298–300.

Sondhia S, Khankhane PJ, Choudhary PP. 2015a. Herbicide residue monitoring and degradation. In: Sushilkumar and Singh VP (eds), DWR–25 years in service of nation. Published by ICAR–DWR, Jabalpur, p 185–218.

Sondhia S, Khankhane PJ, Singh PK, Sharma AR. 2015b. Detection of imazethapyr residues in field soil and plants under soybean grown area following an application to soybean. Journal of Pesticide Science **40**(3): 106–110.

Sondhia S, Choudhury PP and Sharma AR. 2018, *Herbicide Residue Research in India*. Published by Springer, ISBN 978–981–13–1037–9, p 438.

Sondhia S, Sharma N, Janaki P, and Parvinder K. 2015c. Herbicide residue hazards and their mitigation. *Indian Farming* **65**(7): 34–39.

Sondhia S, Singh PK. 2018. Bioefficacy and fate of pendimethalin residues in soil and mature plants in chickpea Field. *Journal of Research in Weed Science* **1**: 28–39.

Sondhia S, Singh S, Varma RK, Kumar A. 2016 Biodegradation of the herbicide penoxsulam (triazolopyrimidine sulphonamide) by fungal strains of *Aspergillus* in soil. *Applied Soil Ecology* **105**: 196–205.

Sondhia S, Singh VP and Yaduraju NT. 2005. Dissipation of butachlor in sandy clay loam soil and detection of its residues in rice grains and straw. pp 298–299. In: *Biennial Conference of Indian Society of Weed Science,* held at Ludhiana, India, w. e. f. 6–8 April 2005.

Sondhia S, Waseem U and Varma RK. 2013. Fungal degradation of an acetolactate synthase (ALS) inhibitor pyrazosulfuron–ethyl in soil. *Chemosphere* **93**(9): 2140–2147.

Sondhia S. 2007a. Herbicides residues in soil, water and food chain. pp. 17-24. In: *Annual Report National Research Centre for Weed Science Jabalpur.*

Sondhia S. 2008a. Assessment of herbicide leaching risk under natural rainfall conditions. pp 115-221. In: *Proceedings of IInd World Aqua Congress* 26–28 November, 2008, New Delhi, India.

Sondhia S. 2008b. Determination of imazosulfuron persistence in rice crop and soil. *Environmental Monitoring and Assessment* **137**(1-3): 205–211.

Sondhia S. 2008c. Evaluation of leaching potential of butachlor in clay soil. *Geobios* **36(**4): 249.

Sondhia S. 2009a. Leaching behaviour of metsulfuron in two texturally different soils. *Environmental Monitoring and Assessment* **154**(1–4): 111–115.

Sondhia S. 2009b. Persistence of oxyfluorfen in soil and detection of its residues in rice crop. *Toxicological & Environmental Chemistry* **91**(3): 425–433.

Sondhia S. 2010. Persistence and bioaccumulation of oxyfluorfen residues in onion. *Environmental Monitoring and Assessment* **162**(1&4): 163–168.

Sondhia S. 2013a. Dissipation of pendimethalin in the soil of field pea (*Pisum sativum* L.) and detection of terminal residues in plants. *Journal of Environmental Science and Health part B* **48**(12): 104–1048.

Sondhia S. 2013b. Harvest time residues of pendimethalin in tomato, cauliflower and radish under field conditions. *Toxicological & Environmental Chemistry* **95**(2): 254–259.

Sondhia S. 2001. Determination and assessment of atrazine residues in potato (*Solanum tuberosum L.*) soil. *Geobios* **28**(2/3): 140–142.

Sondhia S. 2002c. *Studies of Herbicides Residues in Soybean–wheat cropping system*, NRCWS. Final report.

Sondhia S. 2002a. *Studies of Herbicides Residues in Soybean–wheat cropping system*, NRCWS. Final report.

Sondhia S. 2002b. Ultra–Violet Spectroscopic analysis of triazine herbicides in soil samples. p 25. In: *Proceedings of the Eastern Analytical Symposium*, held at, New Jersey, USA, 18–21 November, 2002. p 25.

Sondhia S. 2005b. Phytotoxicity and persistence of metribuzin residues in black soil. *Toxicological and Environmental Chemistry* **87**: 387–389.

Sondhia S. 2007a. Determination of imazosulfuron persistence in rice crop and soil. *Environmental Monitoring and Assessment* **137**(1–3): 205–211.

Sondhia S. 2007b. Fluazifop–p–butyl residues in soybean crop and soil. *Pesticide Research Journal* **19**(2): 248–250.

Sondhia S. 2007d. Annual Report, National Research Centre for Weed Science, Jabalpur.

Sondhia S. 2008d. Evaluation of potential risk of herbicides bioaccumulation in fishes. p 149–151. In: P*receding of TAAL The 12th World Lake Conference*, (eds: Sengupta L and Dalwani R).

Sondhia S. 2008e. Persistence of metsulfuron–methyl in wheat crop and soil. *Environmental Monitoring and Assessment* **147**(1–3): 463–469.

Sondhia S. 2008f. Terminal residues of imazethapyr in soybean grains, straw and soil. *Pesticide Research Journal* **20**(1): 128–129.

Sondhia S. 2008g. Terminal residues of imazethapyr in soybean grains, straw and soil. *Pesticide Research Journal* **20**(1): 128–129.

Sondhia S. 2009c. Persistence and leaching of sulfosulfuron under wheat cropping system. *Indian Journal of Agricultural Sciences* **79**(6): 484–487.

Sondhia S. 2009d. Persistence of metsulfuron–methyl in paddy field and detection of its residues in crop produce. *Bulletin of Environmental Contamination and Toxicology* **83**(6): 799–802.

Sondhia S. 2012a. Dissipation of pendimethalin in soil and its residues in chickpea (*Cicer arietinum* L.) under field conditions. *Bulletin of Environmental Contamination and Toxicology* **89**(5): 1032–1036.

Sondhia S. 2012b. Persistence of Herbicides Residues in Soil, water and food chain. *No.* 173: 96p.

Sondhia S. 2013. Evaluation of imazethapyr leaching in soil under natural rainfall conditions. *Indian Journal of Weed Science* **45**(1): 58–61.

Sondhia S. 2014a. Evaluation of cyhalofop–butyl leaching in sandy loam soil under field conditions. pp 287. In: *Proceedings of Biennial Conference of Indian Society of Weed Science Jabalpur,* India 15–17 February 2014.

Sondhia S. 2014b. Herbicides and human health implications in India. Retrieved from http: //www.eoearth.org/view/article/53118bf00cf262599060c9ec.

Sondhia S. 2014c. Herbicides residues: monitoring in soil, water, plants and non targeted organisms and human health implications: An Indian perspective. pp 15. In: *Proceedings of Biennial Conference of Indian Society of Weed Science Jabalpur*, India 15–17 February 2014 .

Sondhia S. 2014. Herbicides residues in soil, water, plants and non-targeted organisms and human health implications: an Indian perspective. *Indian Journal of Weed Science* **46**(1): 66–85.

Sondhia S. 2015. Residues of imazethapyr in field soil and plant samples following an application to soybean. *Indian Journal of Weed Science* **47**(2), 166–169.

Sondhia S. 2016. Liquid chromatographic determination of Imazosulfuron resin food commodity, water and soil using photo diode array detector. *Asian Journal of Chemistry* **28**(5): 1021–1023.

Sondhia S and Rajput S. 2012. Role of soil fungus in the enhanced biodegradation of penoxsulam, a rice herbicide in agricultural soil. pp 18. In: *Proceedings of 2nd International Science Congress*, Mathura 8–9 December 2012.

Sondhia S and Waseem U. 2012. Enhanced biodegradation of pyrazosulfuron–ethyl in soil of rice field. pp 19. In: *Proceedings of 2nd International Science Congress,* Mathura.

Sondhia S. 2002b. *Studies of Herbicides Residues in Maize–Potato Cropping system,* NRCWS. Final Report.

Sondhia S and Varshney JG. 2010. Herbicides. *Satish Serial Publication House, New Delhi*. p 567

Sondhia S**,** Khare RR and Baghel SS. 2012. Assessment of cyhalofop–p–butyl leaching in sandy clay soil and identification of secondary metabolites in soil and leachates by LC/MS/MS. pp 164. In: *Biennial Conference of Indian Society of Weed Science,* Trissur.

Sondhia S. 2006. Determination of terminal residues of haloxyfop in onion. *Indian Journal of Plant Protection* **34**: 258–259.

Sondhia S and Dubey RP. 2006. Terminal residues of butachlor and pendimethalin in onion. *Pesticide Research Journal* **18**: 185–186.

Sondhia S, Singh VP and Yaduraju NT. 2006. Persistence of butachlor in sandy clay loam soil and its residues in rice grains and straw. *Annals of Plant Protection Sciences* **14**(1): 206–209.

Sondhia S. 2007c. Evaluation of leaching potential of pendimethalin in clay loam soil. *Pesticide Research Journal* **19**(1): 119–121.

Sondhia S. 2007d. Persistence of imazosulfuron residues in rice crop and soil. *Pesticide Research Journal* **19**(2): 251–253.

Srivastava A, Gupta KC and Singh G. 1995. Dissipation of tralkoxydim herbicide from wheat crop and soil under sub–tropical conditions Issue. *Pesticide Science* **43**(1): 53–55.

Srivastava A, Trivedi P, Srivastava MK, Lohani M and Srivastava LP. 2011. Monitoring of pesticide residues in market basket samples of vegetable from Lucknow City, India. Quechers method. *Environment Monitoring and Assessment* **176**: 465–472.

Srivastava A, Gupta KC and Singh G. 1994. Residue analysis of tralkoxydim herbicide in soil, wheat grain and straw by reversed phase HPLC. *Pesticide Research Journal* **6**(2): 175–179.

Sundararajan R, Tamilselvan C. 1995. Raghunathan, R. 1993. Residues of herbicide oxyfluorfen in cabbage (*Brassica oleracea* convar. capitata var. capitata), potato (*Solanum tuberosum*) and groundnut (*Arachis hypogaea*). *Indian Journal of Agricultural Sciences* **63**(1): 56–58.

Suntres ZE. 2002. Role of antioxidants in paraquat toxicity. *Toxicology* **180**(1): 65–77.

Sushilkumar and Sondhia S. 2017. Chemical control of duck weed and its effect on water quality and residue. *Indian Journal of Weed Science* **49**(1): 105–107.

Sushilkumar, Sondhia S and Vishwakarma K. 2003. *Role of Insects in Suppression of Problematic Alligator Weed (Alternanthera philoxeroides) and testing of herbicides for its Integrated Management*. Final report ICAR, ADHOC Project 48 p.

Talbot AR, Shiaw MH, Huang JS, Yang SF, Goo TS, Wang SH, Chen CL, Sanford TR. 1991. Acute poisoning with a glyphosate–surfactant herbicide (‘Roundup’): A review of 93 cases. *Human Experimental and Toxicology* **10**(1): 1–8.

Tandon S, Pujari A and Sand NK. 2012. Degradation of fentrazamide herbicide in soil under aerobic condition. *Bulletin of Environmental Contamination and Toxicol*ogy **89**: 312–315.

Tilak KS, Veeraiah, P, Thathaji and M.S. Butchiram MS. 2007. Toxicity studies of butachlor to the freshwater fish Channa punctata (Bloch) *Journal of Environmental Biology* **28**(2): 485–487.

Vasmani LK and Vijyakumar 1978. Herbicidal activity of diuron for weed control in cotton and its residual toxicity to oats and wheat. Abstract, *Indian Society of Weed Science* 18 p.

Walia US, Bar LS, Dhaliwal BK. 1997. Resistance to isoproturon in *Phalaris minor* Retz. in Punjab. *Plant Prot Quarterly* **12**: 138–140.

Walia US, Singh K, Singh R and Kler DS 2000. Role of soil type on the efficiency and persistence of isoproturon. *Environment and Ecology* **18**(1): 39–42.

Waseem and Sondhia 2014. Study of effect of pyrazosulfuron–ethyl on soil fungi. p 114. In: *Procedings of Biennial Conference of Indian Society of Weed Science on “Emerging Challenges in Weed Management”* Februry 15-17, 2014. Directorate of Weed Science Research, Jabalpur.

Webster EP and Shaw ER. 1976. Carryover potential of pyrithiobac to rotational crops on a Mississippi black belt region clay soil. *Weed Technology* **10**: 140–144.

Yadav A, Bhatnagar A and Kaur M. 2013. Aberrations in the Chromosomes of *Cirrhinus mrigala* (Hamilton) upon exposure to Butachlor. *Iranian Journal of Toxicology* **7**(21): 858–865.

Yadav A, Faroda AS, Malik RK, Kumar V and Dharam Bir 1995. Persistence of pendimethalin applied in wheat under varying irrigation levels. *Crop Research Hisar* **9**(3): 399–402.

Yadav AS, Bhatnagar A and Kaur M. 2010. Assessment of gentoxic effects of butahcor in freah water fish, *Cirrhinus mrigala* (9 Hamilton). *Research Journal of Environmental Toxicology* **4**(4): 223–230.

Yaduraju NT, Kulshreshtha G, Sharma RP and Ahuja KN. 1993. Isoproturon for weed control in potato (*Solanum tuberosum*) and its residue in soil and tubers. *Indian Journal of Agricultural Sciences* **63**(11): 731–733.

Chapter 6

Weed problems and their management in cereal crops rice, wheat and maize in India

Tej Pratap, S.P. Singh, V.P. Singh*, Sirazuddin and Vishal V. Singh
Department of Agronomy, Govind Ballabh Pant University of Agriculture and Technology, Pantnagar, Uttarakhand 263 145
**Email: vpratapsingh@rediffmail.com*

Summary

Rice, wheat and maize are the three most imperative cereal crops of India in terms of area and production. Weeds are the major curb to the progress of sustainable and economically viable crop production. Weeds dictate most of the crop production practices and cause massive losses due to their presence. Farmers pursue numerous practices for managing weeds in these crops, of which at present the use of herbicides are on the top due to the scarcity of labours. This chapter explores the scope of chemical weed management, growing concerns over herbicide resistance, environmental and health hazards of pesticides including herbicides and declining profitability. A review on the research work regarding chemical management of weeds in these crops across India has been presented in this chapter. This chapter deals with the historic trend on the use of various herbicides, their effect on weed dynamics starting from the inception of chemical weed management to present date in major three cereals crops. In case of rice and wheat, there is a great shift in terms of herbicides starting from 2,4-D, butachlor, isoproturon to metsulfuron-methyl, pretilachlor, clodinafop, *etc.* while, in case of maize, still atrazine is the prominent herbicide. This chapter also highlights the loopholes of the past in terms of weed management.

Key words: Cereal crops Herbicide, Maize, Rice, Weeds, Wheat

Rice

India is one of the world's largest producers of rice and brown rice, accounting for 20% of all world rice production. Rice is India's pre-eminent crop, and is the staple food of the people of the eastern and southern parts of the country. In India during 2016-17, the area, production and productivity of rice was 43.20 m ha, 110.15 mt and 2.55 t/ha, respectively (DAC 2017). Though India ranks first in the world so far as area under rice cultivation is concerned, but in case of production it occupies second position (22%). Such unfortunate low production is due to low average productivity of 2.81 t/ha, which is far behind the world average of 3.747 t/ha. A careful study of the whole situation reveals that many factors are responsible for such low yield of rice. Out of these, severe infestation of weeds in rice fields offers the major obstacle to achieve the higher yield (Dikshit 1974). A broad spectrum of weed flora infests rice crop. The composition and competition by weeds for growth resources are dynamic and are dependent on soil, climate, cropping and management factors. Various studies were conducted regarding weed flora all over India and there is a serious need to investigate problems regarding weeds and to plan their proper management. Weed competition is one of the most important factors in limiting the yield of rice. Competition between crop and weed begins when the supply of any of the growth factor is limiting and falls below the demand of both crop and weeds, when they grow in close proximity. Weeds having faster growth rate, accumulate large amount of biomass in a short period, which interferes with the growth of rice plants and ultimately affects the yield of rice crop. Among the different weed species, grassy weeds pose greater competition. They have an extensive and fibrous root system. Similarly, sedges grow huge in number and cause serious competition for nutrients. The roots of the sedges also dominate the surface feeding zone and obstruct nutrient flow to crop roots. weeds interferes with rice growing by competing for one or more growth limiting resources *i.e.* nutrients, water, space, light and carbon dioxide, because of the limited supply of these valuable elements, their association therefore, leads to competition for these elements for the survival.

Generally, one-third duration of the crop period should be maintained weed free. The critical crop weed competition from 28-45 DAT in transplanted rice was reported by various workers (Raju and Reddy 1995, Nandal *et al.* 1999 and Singh *et al.* 2003). However it was reported that crop and weed competition up to 60 days stage of transplanted rice resulted in 72% reduction in grain yield (Singh *et al.* 2004). In addition to the concerns over water scarcity, labour scarcity is also a concern. In the traditional establishment method, both puddling and transplanting operations need a large amount of labour. Because of the increasing demand for labour in non-agricultural sectors and increasing labour costs resulting from the migration of rural labour to the cities, it is difficult to find labour at the critical time of transplanting (Chauhan 2012b). Government policies, for example, 100 days of work in people's home village, are also creating a labour scarcity in some regions, especially where farmers depend on migrant labourers from other states (Mahajan *et al.* 2013). Therefore, farmers in some areas are shifting from traditional transplanted rice to mechanized-sown dry-seeded rice (DSR) in response to the rising production costs and shortages of labour and water. A DSR crop can be sown under zero-till (ZT) conditions or after tillage using a seed drill. DSR has several advantages over puddled transplanted rice. However, weeds are the main biological constraint to the production of DSR (Chauhan 2012b, Chauhan and Johnson 2010, Chauhan and Opeña 2012, Chauhan *et al.* 2012b).

In a survey in Punjab, the dominant weed species reported by the farmers in DSR fields were *Cyperus iria* L., *Echinochloa colona* (L.) Link, *Eragrostis* spp., *Leptochloa chinensis* (L.) Nees, *Digitaria sanguinallis* (L.) Scop., *Dactyloctenium aegyptium* (L.) Wild. *Cyperus rotundus* L., and *Eleusine indica* (L.) Gaertn. (Mahajan *et al.* 2013). The main reasons for high weed pressure in DSR are the absence of a weed-suppressive effect of standing water at the time of crop emergence and the absence of a seedling size advantage to suppress newly emerged weed seedlings. Weeds in DSR systems are mainly managed by using herbicides and manual weeding. Manual weeding, however, is becoming less popular because of the labour scarcity and high wages. In the absence of manual weeding, farmers in irrigated areas mainly rely on herbicides to control weeds in DSR systems. The use of herbicides alone may not provide effective and season-long weed control. Because of the increased use of herbicides, the risk of herbicide resistance, and concerns about environmental contamination, there is an interest in integrating herbicide use with cultural weed management approaches (Kumar and Ladha 2011, Chauhan 2012b, 2013, Mahajan and Chauhan 2013). Important weeds of rice (**Table 1**) recorded during different time period in India have been mentioned (**Table 2**).

Chemical control of weeds in rice during 1950-2018

Table 1. Major weeds in rice fields

Grasses	Sedges	Broad-leaves
Echinochloa colonum	*Cyperus iria*	*Commelina diffusa*
Echinochloa crus-galli	*Cyperus difformis*	*Eclipta alba*
Panicum repens	*Cyperus rotundus*	*Eclipta prostrata*
Ischaemum rugosum	*Fimbristylis miliacea*	*Monochoria vaginalis*
Isachne globosa		*Murdannia nudiflora*
Digitaria sanguinalis		*Sphenoclea zeylanica*
Paspalum distichum		*Ludwigia perennis*
Cynodon dactylon		*Haeranthus africanus*
Agropyron repens		*Alternanthera sessillis*
Eleusine indica		*Caesulia axillaris*
Brachiaria ramosa		*Commelina benghalensis*
Eragrostis japonica		*Trianthema monogyna*
		Galinsoga parviflora

(Source: Annual Report, GBPUA&T, Pantnagar 2017)

Table 2. Periodically important weeds of rice

2008	2011	2017
Echinochloa crus-galli	*Echinochloa crus-galli*	*Echinochloa crus-galli*
Leptochloa chinensis	*Leptochloa chinensis*	*Leptochloa chinensis*
Cyperus rotundus	*Ischaemum rugosum*	*Echinochloa colona*
	Isachne globosa	*Ischaemum rugosum*
	Ludwigia spp.	*Paspalum distichum*
	Oryza sativa f. spontanea	*Isachne globosa*
		Fimbristylis miliacea
		Fimbristylis dichotoma
		Cyperus difformis
		Cyperus iria
		Cyperus rotundus
		Oryza sativa f. spontanea

(Source: Rao AN 2017)

There have been tremendous developments in herbicide technology rice past use, with a wide range of pre- and post-emergence herbicides now available to farmers. Improved selectivity and formulations allow safer, easier and more flexible application. Herbicide development and the results that can be achieved have been spectacular, but comparatively little research has been focused on cultural control and integrated weed management. While many rice production systems have come to rely on herbicides, the need to reduce costs, and the evolution of new weed problems and herbicide resistant ecotypes, suggests there should be greater emphasis on the judicious use of herbicides.

Very little attention was given during early past due to wan of skilful knowledge and proper techniques for various crop combinations. That time, ample labour forces were available for controlling weeds by mechanical method. The growth of industries was also limited and labourers were cheap. Therefore, manual and mechanical methods were used on large scale for control of weeds. For transplanted rice, in tropical Asia, weeds were usually controlled by hand rotary weeders or by hand pulling (Moomaw *et al.* 1966 and IRRI Reporter 1969). The earlier attempt in India to control weeds by herbicides was made in 1937 in Punjab for controlling *Carthamus oxycantha* by using sodium arsenite. 2,4-D was first tested in India in 1946. Since then, a number of herbicides have been imported and tested for their effectiveness in controlling many weed species. In 1952, ICAR initiated schemes for testing the field performance of herbicides in rice in different states of India.

Butachlor was found suitable both for direct-seeded and transplanted rice in controlling most of the annual grasses and 24 broadleaved weeds to some extent (Mukhopadhyay *et al.* 1971). De Datta (1974) reported that butachlor continued to look promising in controlling weeds in rice fields and was widely used in Asia. In the transplanted conditions, early suppression of initial weeds was achieved due to puddling operation and it resulted in lowering the weed population in transplanted rice (Ranjan and Mahapatra 1979). Bensulfuron-methyl, a member of sulfonylurea herbicides, is a broad-spectrum herbicide for the control of broad-leaf-weeds and sedges in the rice fields. As a selective herbicide for direct seeding and mechanical transplanting rice fields, bensulfuron is active at a rate as low as 30-70 g/ha and has a good herbicidal activity on most annual and perennial weeds in the rice fields. This is used as a mixture with pretilachlor, butachlor, mefenacet and other grass-killing herbicides for the effective control of grassy weeds. The mode of action by bensulfuron-methyl is similar to other sulfonylurea herbicides. The primary site of bensulfuron-methyl is the inhibition of ALS (acetolactate synthase), which is an important acid biosynthesis and secondary effects on the cell division and retardation of plant growth (Ray 1984 and Takeda *et al.* 1985).

Dimitrios *et al.* (2000) reported that yield of drained rice is higher under cyhalofop-butyl treated plot as early post-emergence. Pretilachlor belongs to acetamides group of herbicides. It is selective systemic herbicide absorbed primarily by the germinating root with translocation throughout the plant. It is applied either as pre-emergence or early post-emergence to control the annual grasses and broad-leaf weeds but mainly used as a grass killer in transplanted rice. It is selective broad spectrum pre-emergence herbicide for use in early season in transplanted rice with cell division inhibitor as its mode of action. It controls grassy and sedges weed species, *viz. Echinochloa crus-galli*, *Echinochloa colona*, *Leptochola chinensis*, *Cyperus rotundus*, *Cyperus iria*, *Cyperus difformis*, and *Fimbristylis millacea* in rice fields. Pretilachlor is supplied with surfactant under the trade name ‘Sofit’ but the trade name ‘Rifit’ does not contain extra surfactant. Bhowmick *et al.* (2000) found that pretilachlor at 0.8 kg/ha effectively controlled the weeds in transplanted rice and recorded the maximum grain and straw yields, which were at par with hand weeding. Ethoxysulfuron + anilofos (0.02 + 0.375 kg/ha) as post-emergence application and hand weeding twice were equally effective in recording the number of panicles per/m^2 and grains per panicle.

Choubey *et al.* (2001) obtained effective control of *Echinochloa colona* with post-emergence application of cyhalofop-butyl at 80 g/ha. Singh and Singh (2001) revealed that higher gross income recorded with butachlor 1.0 kg/ha + one hand weeding were at par with two hand weeding. The higher grain yield was recorded with the pre-emergence application of butachlor followed by one hand weeding treatment and it was at par with butachlor followed by two hand weeding treatments (Madhavi and Reddy 2002). Application of cyhalofop-butyl at 120 g/ha was reported to reduce the weed population and total weed dry weight (Saini 2003). Singh *et al.* (2004) observed that application of butachlor alone 1.25 kg/ha was effective against annual grasses. According to Rajkhowa and Gogoi (2004) application of butachlor 1.5 kg/ha as pre-emergence herbicide recorded significantly lower weed density and dry matter accumulation over weedy check. Application of butachlor 1.5 kg/ha as pre-emergence + 2, 4-D 0.5 kg/ha as post-emergence herbicide produced grain yield similar to hand weeding twice at 30 and 50 DAT (Singh *et al.* 2004). Singh *et al.* (2005) has observed a shift from grasses weeds to non grasses and annual sedges due to application of herbicides like butachlor, anilofos and pretilachlor in most of the rice growing areas of the country. Singh *et al.* (2006) found that pre-emergence application of butachlor along with 2,4–D (1.5 + 0.5 kg/ha) followed by one hand weeding were effective ways to minimize weed competition and enhance grain yield of rainfed lowland rice.

In India, Northern parts of the country have received much attention regarding the inventories of the weed flora of cultivated fields, compared with other parts. Much work has been done in Punjab and Rajasthan areas. Among the herbicidal treatments, the lowest dry weight of weeds was recorded with butachlor 1.5 kg/ha + one hand weeding, which was statistically similar to two hand weeding (Ramphoolpuniya *et al.* 2007). Application of butachlor at 1.25 kg/ha gave the efficient weed control and ultimately gave the maximum number of effective tillers/ha (Mirza Hasanuzzaman *et al.* 2008). Nasimulbari (2010) reported that butachlor provided better weed control efficiency and contributed to better crop growth and grain yield compared to other treatments. Ramana *et al.* (2008) noticed that pre-emergence application of oxadiargyl at 80 g/ha + mechanical weeding with star weeder resulted in improved weed control and higher grain and straw yield and proved economically remunerative over butachlor and pretilachlor. The highest number of filled grains/panicle, 1000 grain weight and grain yield of rice were recorded with pre-emergence application of oxadiargyl 75 g/ha, which was at par with hand weeding twice at 20 and 40 DAT (Yadav *et al.* 2009, Deepthi Kiran and Subramanyam 2010). Mirza Hasanuzzaman *et al.* (2009) recorded that the highest harvest index with pre-emergence application of oxadiargyl + one hand weeding. Metsulfuron-methyl + chlorimuron-ethyl was effective against control of broad-leaved weeds and sedges (Samar Singh *et al.* 2003). Pre-emergence application of mixture of almix + 2,4-D (15 + 500 g /ha) was most effective against grasses and sedges, when applied at 8 DAT and reduced total weed density and total dry matter with higher weed control efficiency (Mukherjee and Singh 2005). The performance of metsulfuron-methyl + chlorimuron-ethyl 4 g/ha was found superior in controlling *Eclipta prostrata* and provided excellent control of broad-leaved weeds and sedges (Singh and Tewari 2005). Almix 8 g/ha was found significantly superior in reducing the population of all type of weeds with higher weed control efficiency of 97.2% for broad-leaved weeds, 60.0% for sedges and 21.6% for grasses (Purshotam Singh *et al.* 2007). Ramana *et al.* (2008) reported that pre-emergence application of metsulfuron-methyl + chlorimuron-ethyl at 8 g/ha resulted in effective weed control as compared to other weed control treatments. Singh *et al.* (2008) reported that the density of sedges and broad-leaved weeds in Almix treated plots were less as compared to application of butachlor, anilofos and pretilachlor alone. Application of Almix 4 g/ha mixed with butachlor 938 g/ha at 3 DAT was at par with twice hand weeding at 20 and 40 DAT in controlling weeds and achieving higher grain yield (Patra *et al.* 2006). Singh *et al.* (2005a) observed that bensulfuron methyl (Londax power) at different doses (40 g/ha and 50 g/ha) applied alone or as tank mixture with butachlor 1000 g/ha reduced the density of all the sedges and broad-leaved weeds and increased the grain yield. (Rajkhowa and Barua 2007). Application of pretilachor followed by 2,4-D (0.75 - 0.5 kg/ha) was most effective in lowering the weed density of grassy, broad-leaved weeds and their dry weight and thus enhancing yield attributes and yield of rice and maximizing weed control efficiency (Mandhata Singh and Singh 2010).

Sunil *et al.* (2010) found that pre-emergence application of bensulfuron-methyl + pretilachlor at 0.06 + 0.60 kg/ha followed by one hand weeding at 40 DAS recorded significantly higher grain yield (4.42 t/ha) and straw yield (5.02 t/ha) with lower weed population and their dry weight resulted in higher profit in aerobic rice cultivation. Bensulfuron-methyl at 60 g/ ha tank mix with pretilachlor 450 g/ha applied at 20 DAS were found to be effective in controlling weeds with weed control efficiency of 92.2% and produced 5.53 t/ha of grain yield and this herbicide was found at par with twice hand weeding at 20 and 40 DAS (Sanjoy Saha and Rao 2010). Walia *et al.* (2008) observed that integration of pre-emergence application of pendimethalin 1 kg/ha followed by post-emergence application of 2,4-D 500 g/ha enhanced the weed control and recorded higher grain yield. Pre-emergence application of butachlor + sequential application of 2,4-D 0.5 kg/ha on 40 DAS recorded highest grain yield of 4.36 t/ha (Swapan Kumar Maity and Mukherjee 2009). Post-emergence application of 2,4-D with pre-emergence application of pretilachlor enhanced the yield attributes and yield of rice as reported by Mandhata Singh and Singh (2010).

Mukherjee and Singh (2005) found superiority in grain yield and net monetary returns with the appliances of chlorimuron-ethyl + metsulfuron-methyl + 2,4-D for transplanted rice over other weed control means. Cheema *et al.* (2005) reported that ethoxysulfuron (Sunrice 15WG) alone 25 and 30 g/ha reduced total weed density and dry weight in the range of 66.29 to 73.95% and 69.23 to 85.71%, respectively. Shahbaz *et al.* (2007) found there was lowest dry matter accumulation by

Alternanthara triandra under the application of ethoxysulfuron that might be due to better killing capacity of ethoxysulfuron against broad-leaf weeds over weedy check. Singh *et al.* (2005) from Pantnagar reported that bensulfuro-methyl at 30 to 60 g/ha applied alone or as tank mixture with butachlor at 1.0 kg /ha reduced the density of all the sedges as well as *Caesulia axillaris* and *Commellina benghalensis*. At higher doses of bensulfuion methyl (50 and 60 g/ha), there was almost complete control of sedges and non-grassy weeds. The differences in grain yields due to various doses of bensulfuron-methyl were non-significant and yields were at par with weed free treatment. Bispyribac-sodium belongs to the pyrimidinal thiobenzoates group of herbicides. It is recently introduced herbicide have the similar mode of action as the sulfonylureas. It is highly selective, post-emergence, low mammalian toxic and low dose (15-40 g/ha) required herbicide has become popular to control weed in rice growing area either transplanting or direct-seeded (Das 2008).

Yadav *et al.* (2010) from Karnal reported that penoxsulam at 25 g/ha as pre-emergence (3 DAT) and 22.5 g/ha as post-emergence (10-12 DAT) application provided satisfactory control of all types of weeds consequently resulting in grain yield of transplanted rice similar to weed free plot. Penoxsulam was particularly better against broad-leaf weeds and sedges than the application of butachlor and pretilachlor. Patra *et al.* (2011) observed that application of chlorimuron-ethyl + metsulfuron-methyl 0.004 kg/ha mixed with butachlor 0.938 kg/ha at 3 days after transplanting (DAT) was at par with hand weeding twice at 20 and 40 DAT in controlling weeds and higher grain yield. This application increased the grain yield by 45.1% over the un weeded check. Shekhra *et al.* (2011) found that application of bensulfuron-methyl + pretilachlor (6.6%) 0.06 + 0.60 kg/ha + one inter cultivation at 40 DAT recorded significantly lower weed population and weed dry weight and higher grain yield. This was at par with bensulfuron-methyl + pretilachlor (6.6%) 0.06%+0.60 kg/ha. Sah *et al.* (2012) observed that pre-emergence application of chlorimuron-ethyl + metsulfuron-methyl (0.025 kg/ha) at 3 DAT *fb* sequential application of 2,4-DEE (0.5 kg/ha) at 20 DAT was found most effective in minimizing weed population and their dry matter accumulation and increasing weed control efficiency and grain yield next to two hand-weeding, both were at par 80.1% and 77.7% increase in grain yield was recorded in two hand weeding and chlorimuron-ethyl + metsulfuron-methyl followed by 2,4-DEE (0.025+0.5 kg/ha), respectively.

Ethoxysulfuron belong to the sulfonylureas group of herbicide, which acts as acetolactate synthase inhibitor (ALS). It acts by reducing the levels of three branched–chain aliphatic amino acids. It is highly selective, post-emergence low mammalian toxic and low dose (10-40 g/ha) requires herbicide gaining popularity to control weed in transplanted rice. Nath and Pandey (2013) reported application of penoxsulam 25 g/ha significantly reduced the weed population and dry weight of weeds. Penoxsulam is a triazolopyrimidine sulfonamide herbicide used to control grasses, broad-leaf and sedges weeds in rice crop. It is early post-emergence herbicide absorbed mainly via leaves and secondarily via roots. Parthipan and Ravi (2016) found that post-emergence application of bispyribac sodium at 25 g/ha at 15

DAT followed by hand weeding at 45 DAT produced higher grain yield and was at par with two hand weeding due to lower crop weed competition. Ramesha *et al.* (2017) reported that application of penoxsulam 83.3 ml/ha controlled all types of weeds and increased the grain yield of rice. Herbicide recommended for controlling weeds in rice given (**Table 3**).

Table 3. Herbicides recommended for rice cultivation

Crop	Herbicides	Dose (kg/ha)	Stages of application
Rice nursery	Pretilachlor 50 EC	1.0	Pre-emergence
	Bispyribac-sodium 10% SC	0.02	post-emergence
Transplanted rice	Butachlor 50% EC	1.5	Pre-emergence
	Anilofos 30% EC	0.4	Pre-emergence
	Pretilachlor 50% EC	0.5-0.75	Pre-emergence
	Oxadiargyl 80% WP	0.1	Pre-emergence
	2,4-D ethyl ester 38% EC	0.85	Post-emergence
	Metsulfuron methyl 20% WG	0.004	Post-emergence
	Bispyribac-sodium 10% SC	0.020	Post-emergence
	Bensulfuron Methyl 60% DF	0.060	Pre-emergence
	Penoxsulam 24% SC	0.022-0.025	Pre-emergence
	Penoxsulam 24% SC	0.020-0.022	Early post-emergence
	Azimsulfuron 50% DF	0.035	Post-emergence
	Ethoxysulfuron 15% WDG	0.0125-0.015	Post-emergence
	Fenoxaprop-p-ethyl 9.3% EC	56.25	Post-emergence
	Pyrazosulfuron-ethyl 10% WP	0.010-0.015	Pre-emergence to early post
Direct-seeded rice	Pendimathalin 30% EC	1.0-1.5	Pre-emergence
	Metsulfuron-methyl 20% WP	0.004	Post-emergence
	Bispyribac-sodium 10% SC	0.020	Post-emergence
	Azimsulfuron 50% DF	0.035	Post-emergence
	Cyhalofop-butyl 10% EC	0.075-0.080	Post-emergence
	Oxyflourfen 23.5 EC	0.150-0.240	Post-emergence

(Annual Report, GBPUAT, Pantnagar 2017)

Future thrust

There have been tremendous developments in herbicide technology with a wide range of pre, post-emergence and ready mix combination of herbicides since the use of herbicides in the country. Improved selectivity and formulations allow safer, easier and more flexible application. Herbicide development and the results that can be achieved have been spectacular, but comparatively little research has been focused on cultural control and integrated weed management. While many rice production systems have come to rely on herbicides, the need to reduce costs, and the evolution of new weed problems and herbicide resistant ecotypes, suggests that there should be greater emphasis on the judicious use of herbicides. The research related to herbicides must go beyond herbicide screening to application techniques, enhancing herbicide efficiency and integrating with ecological methods of weed management.

Wheat

Wheat occupies the most imperative position among the food grain crops in the world, both in terms of area as well as production. It is the second most important food grain crop next to rice in India in terms of area and production. In India, during 2017-18 the area, production and productivity of wheat was 30.4 mha, 97.11 mt and 3216 kg/ha, respectively (DAC 2017). As a result of ever increasing population, India will need 109 m tonnes of wheat during the year 2020 AD, which can be achieved by increasing its productivity 4.29 t/ha and annual growth rate of 4.1% (Mishra 2007). Biotic stress of weeds to the crop is amenable for the major amount of yield loss. Acquaintance with high yielding dwarf wheat varieties coupled with elevated facilities of fertilizers and irrigation have undeniably augmented the grain yield of wheat crop in the past. But, it has also triggered the problem of insect-pests and diseases, in general, and weeds in particular. It has been found that weeds account for about one third of total losses caused by various biotic stresses. Weeds cause yield reduction to the tune of 15 to 50% or sometime more depending upon the weed density and dynamics. (Sirazuddin *et al.* 2016).

With the inception of cultivation of high yielding dwarf wheat varieties along with intensive cultivation of cereals, the population of grassy weeds like *Phalaris minor* and *Avena ludoviciana* was amplified at much faster rate replacing broad-leaf weeds in wheat fields (Malik and Singh 1993, Singh *et al.* 1995, Balyan and Malik 2000). The shift of weed flora in favour of wild oat and some other broad-leaf weeds was further been intensified due to alteration in input availability and crop sequence in wheat. The problem of *P. minor* was grim under rice-wheat cropping systems (Malik *et al.* 1995) while that of *A. ludoviciana* was more severe in irrigated, well drained and light-textured soils predominantly in the areas other than rice-wheat sequence (Panwar *et al.* 2000).

Weeds, not only cause significant losses in quantity, but the quality of the crop is also influenced. Grain yield losses in wheat caused by weeds vary between 10 to 52% (Gill and Brar 1975, Bhan and Singh 1979, Gupta 1984, Walia *et al.* 1990, Gogoi *et al.* 1993). Moderate infestation of *P. minor* alone can cause 15-20% reduction in grain yield of wheat (Walia and Gill 1985) and even total crop failure under heavy infestation of *P. minor* (2000-3000 plants/m^2 at all the places) has already been reported in Haryana (Malik *et al.* 1995). Whereas, infestation of broadleaf weeds in wheat may lead to the reduction of grain yield to the tune of 7-50 per cent depending upon their intensity (Kurchania *et al.* 2000). Important weeds of wheat recorded during surveys conducted in India have been mentioned year wise in (**Table 4**).

Estimates showed that weeds in India caused an annual loss of ` 1980 crores in 2005 (Yadav and Malik 2005). Yogita *et al.* 2018 published an alarming report which revealed that weeds lead to India losing an average of $11 billion each year in 10 major crops, based on 1,581 farm trials in 18 states. In wheat alone, weeds lead to loss of $ 3376 million. Hence, it is very much relevant to get the sight of the historic

Table 4. Four important weeds of wheat different time recorded during surveys conducted in India

1968	*Carthamus oxycantha, Asphodelus tenuifolius, Chenopodium album, Convolvulus arvensis* (Parker 1968)
1971	*Chenopodium album, Anagallis arvensis, Asphodelus tenuifolius, Fumaria parviflora* (Adlakha *et al.* 1971)
1984	*Phalaris minor, Avena ludoviciana, Asphodelus tenuifolius, Chenopodium album* (Malik *et al*. 1984)
1995	*Phalaris minor, Avena ludoviciana, Medicago denticulate, Chenopodium album* (Singh *et al.* 1995)
2017	*Phalaris minor, Avena ludoviciana Chenopodium album, Melilotus alba, M. indica, Medicago denticulate, Fumaria parviflora, Vicia sativa, Anagalis arvensis Lathyrus aphaca* (Annual report, GBPUAT, Pantnagar 2017)

trend of weed infestation, dynamics and chemical management in wheat in India to not only understand the loopholes of the past in terms of weed management, but also to tackle the intensifying problem of weeds in wheat in present as well as in future.

Chemical control of weeds in wheat during 1950-2000

Urbanization, industrialization, labour constraints at peak growth periods, small and marginal family size and under certain particular situations, where weeds are very intricate to remove manually, the herbicide use becomes inescapable. Chemical control of weeds, in general, has been realized to be more cost-effective and easy compared to manual weeding.

In India, till seventies, manual and mechanical removal was one of the best options available with the farmers to tackle weeds in their fields and this was supplemented by cultural methods as labour was in plenty and herbicides options were not available for use. But, with the advent of labor costs, herbicides started to take shape successful achievements occurred in eighties. Among these, cultural method was the most indispensable and effective method which included tillage, crop rotation, intercropping, mulching, solarisation *etc.* With the introduction of high yielding varieties and herbicide, new era of easy method attracts farmers in spite of manual, mechanical and cultural methods. The era of 2,4-D, since 1944 just after 2nd world war, a new paradigm of weed control was there with the farmers. The first farmer who used 2,4-D as per Nebraska Farmer magazine was Carl H. Leonard of Wayne country, Nebraska in 1947 in corn. In India, the first chemical (herbicide) weed control was started in 1952, when ICAR sanctioned 13 co-coordinated weed control schemes in various parts of country, 36 sophisticated herbicides were imported and some of them gave promising results.

With the advancement in time, the acceptance of 2,4-D was increased and different researchers published the effect of 2,4-D on wheat crop and its associated weeds. Khan *et al.* (1970) also reported that sodium salt of 2,4-D at 0.84 to 1.12 kg/ha gave maximum control of weeds followed by hand weeding at 45 DAS and both methods significantly increased grain yield over weedy check. Mani *et al.* (1972) reported that the use of 2,4-D at 0.5 kg/ha as post-emergence gave effective

Table 5. The predominant weeds associated with wheat crop in different wheat growing zones in India

Zone	Weed species generally infesting
NHZ [J&K (except Jammu and Kathua distt.); H.P. (except Una and Paonta Valley); Uttarahand (except Tarai area); Sikkim and hills of West Bengal and N.E. States]	*Anagallis arvensis* L., *Avena fatua* L., *Avena ludoviciana* Dur., *Capsella bursa-pastoris* (L.) Medik., *Chenopodium album* L., *Convolvulus arvensis* L., *Coronopus didymus* L., *Fumaria parviflora* Lamk., *Juncus bufonius* L., *Lathyrus aphaca* L., *Lolium temulentum* L., *Medicago denticulata* L., *Melilotus alba* Lamk., *Phalaris minor* Retz., *Poa annua* L., *Polygonum nepalense* Meissn., *Ranunculus spp., Sorghum halepense* (L.) Pers., *Stellaria media* (L.) Vallars, *Veronica persica* Poir., *Vicia sativa* L.
NWPZ [Punjab, Haryana, Delhi, Rajasthan (except Kota and Udaipur divisions) and Western UP (except Jhansi division), parts of J&K (Jammu and Kathua distt.) and parts of HP (Una distt. and Paonta valley) and Uttarakhand (Tarai region)]	*Alhagi pseudoalhagi* (Beib.) Desv., *Anagallis arvensis* L., *Argemone mexicana* L., *Avena fatua* L., *Avena ludoviciana* Dur., *Asphodelus tenuifolius* Cav., *Carthamus oxycantha* Beib, *Chenopodium album* L., *Chenopodium murale* L., *Convolvulus arvensis* L., *Coronopus didymus* L., *Circium arvense* L., *Daucus carota* L., *Euphorbia helioscopia* L., *Fumaria parviflora* Lamk., *Lathyrus aphaca* L., *Malva neglecta, Malva parviflora*, *Medicago denticulata* Willd, *Melilotus alba* Lamk., *Melilotus indica* All., *Phalaris minor* Retz., *Poa annua* L., *Polygonum plebejum* R. Br., *Polypogon monsplensis* (L.) Desf., *Rumex dentatus* L., *Solanum nigrum*, *Spergula arvensis* L., *Stellaria media* (L.) Vallars, *Trigonella incise* Benth., *Trigonella polycerata*, *Veronica agrestis* L., *Vicia sativa* L., *Vicia hirsute* Koch.,
NEPZ (Eastern UP, Bihar, Jharkhand, Orissa, West Bengal, Assam and plains of N.E. States)	*Ageratum conyzoides* L., *Alternanthera sessilis* (L.), *Anagallis arvensis* L., *Argemone mexicana* L., *Asphodelus tenuifolius* Cav., *Avena fatua* L., *Brachiaria mutica*, *Brachiaria ramose*, *Cannabis sativa* L., *Celosia argentea* L., *Chenopodium album* L., *Chenopodium ficifolium*, *Chenopodium murale* L., *Cirsium arvense* (L.), *Commelina benghalensis* L., *Convolvulus arvensis* L., *Coronopus didymus* (L.), *Cyanotis cuculata*, *Cynodon dactylon* Pers., *Cyperus iria* L., *Cyperus rotundus* L., *Desmodium triflorum* (L.) DC., *Digitaria ciliaris* (Retz) Koel., *Digitaria sanguinalis* (L.) Scop., *Drymaria vilosa*, *Echinochloa colona* (L.) Link, *Eclipta alba*, *Eclipta prostrate* L., *Eleusine indica* Gaerts., *Eragrostis ferroginia* Beauv., *Euphorbia dracunculoides*, *Fibristylis miliacea*, *Fumaria indica* Pugsley, *Fumaria parviflora*, *Galinsoga parviflora* Cav., *Gnaphalium pensylvanicunm* Willd., *Gnaphalium purpureum* , *Grangea maderaspatana* (L.) Poir., *Lathyrus aphaca* L., *Lathyrus sativa* L., *Leucas aspera*, *Ludwigia perennis*, *Medicago denticulata*, *Melilotus alba* Lamk., *Melilotus indica* All., *Mimosa pudica* L., *Murdannia nudiflora*(L.) Brenan, *Oxallis carniculata* L., *Panicum repens* L., *Parthenium hysterophorus* L., *Paspalum scorbiculatam* L., *Phalaris minor* Retz., *Physalis minima*, *Poa annua* L., *Polygonum barbatum* L., *Polygonum erectum*, *Polygonum plebejium* R. Br., *Polypogon monsplensis* (L.) Desf., *Rumex dentatus* L., *Scirpus articulates*, *Solanum nigrum*, *Spergula arvensis* L., *Sporoboles indicus* (L.) R.Br. Var.diader, *Stellaria media* (L.) Vallars, *Vicia hirsute* Koch., *Vicia sativa*, *Xanthium stumarium*,

Zone	Weed species generally infesting
CZ (Madhya Pradesh, Chhattisgarh, Gujarat, Kota and Udaipur divisions of Rajasthan and Jhansi division of Uttar Pradesh)	*Achyranthus aspera* L., *Alhagi pseudolhagi* (Beib.) Desv., *Amarantus viridis* L., *Anagallis arvensis* L., *Argemone maxicana* L., *Asphodelus tenuifolius* Cav., *Avena fatua* L., *Avena ludoviciana* Dur., *Boerhaavia* spp., *Brassica kaber* , *Brassica sinensis, Chenopodium album* L., *Chenopodium murale* L., *Chrozophera perviflora* L., *Cichorium intybus* L., *Cirsium arvense* L., *Convolvulus arvensis* L., *Cynodon dactylon* Pers., *Cyperus iria* L., *Cyperus rotundus* L., *Dactyloctenium aegyptium* L., *Digera arvensis, Digitaria adscendens, Dinebra retroflexa* (Vahl.) Panzer, *Echinochloa colona* (L.) Link, *Eclipta alba, Eleusine indica* Gaerts., *Eragrostis cilienensis* (All) Link., *Eragrostis major, Euphorbia geniculata* Ortega, *Euphorbia hirta* L., *Fumaria parviflora, Lathyrus aphaca* L., *Launaea asplenifolia* (willd.) Hook. f., *Medicago denticulata, Melilotus alba* lamk., *Melilotus indica* All., *Melilotus parviflora, Melilotus sativa, Melotropicum indicum, Parthenium hysterophorus* L., *Phalaris minor* Retz., *Phyllanthus fraternus* Webster., *Physalis minima, Ranunculus acutus, Rumex dentatus* L., *Solanum nigrum, Sonchus asper* (L.) Hill., *Spergula arvensis* L., *Sphaeranthus indicus* L., *Stellaria media* (L.) Scop., *Suaeda maritime* (L.) Dum., *Tephrosia pururea, Tribulus terrestris* L., *Tridax procumbens* L., *Vicia hirsute* Koch., *Vicia sativa, Xanthium strumarium,*
PZ (Maharashtra, Karnataka, Andhra Pradesh, Goa, plains of Tamil Nadu)	*Alternanthera sessilis* L., *Amarantus graceizans* L., *Anagallis arvensis* L., *Argemone mexicana* L., *Asphodelus tenuifolius* Cav., *Avena fatua* L., *Bidens pilosa, Brachiaria eruciformis* L., *Brassica arvensis* L., *Cassia spp., Celosia argentia, Chenopodium album* L., *Commelina benghalensis* L., *Convolvulus arvensis* L., *Chrozophera perviflora* L., *Cynodon dactylon* Pers., *Cyperus rotundus* L., *Digera arvensis, Digitaria adscendens, Dinebra retroflexa, Echinochloa colona* (L.) Link, *Euphorbia hirta* L., *Lactuca runcinata* DC., *Lagascea mollis, Leucas aspera, Melilotus alba* Lamk., *Parthenium hysterophorus* L., *Phyllanthus spp., Portulaca oleracea* L., *Physalis minima, Setaria verticillata, Sonchus wightianus* DC., *Spergula arvensis* L., *Sphaeranthus senegalensis* DC., *Trianthema portulacastrum, Zizipus jujube* Lamk.

NHZ-Northern Hill Zone; NWPZ - North Western Plains Zone; NEPZ - North Eastern Plains Zone; CZ - Central Zone; PZ - Peninsular Zone

control of *Chenopodiuvn album, Anagallis arvensis, Medicago hispida* with significant reduction in weed biomass and increase in yield attributes of wheat. Hooda *et al.* (1974) stated that post-emergence application of 2,4-D at 30 DAS gave excellent results by controlling the broad-leaf weeds and significantly reduced the dry matter accumulation of weeds over un-weeded. Verma *et al.* (1975) reported that 2,4-D 0.5 kg/ha urea solution applied at 4-6 leaf stage of crop gave effective weed control of weeds, which increased the grain yield by 26.2% over un-weeded control. 2,4-D controls only broad-leaved weeds. Problem of grassy weeds was still dependent on physical means of weed management. The advent of isoproturon, another herbicide seeks attention after seventies and the reports across the country regarding its impact were quiet good in wheat fields during initial days.

Post-emergence application of isoproturon at 0.75 to 1.5 kg/ha at 30 DAS was found to be quite safer and gave most promising results in reducing the dry matter accumulation of weeds in wheat crop (Kassasion 1977). Bhardwaj (1980) also reported that post-emergence use of isoproturon from 0.75 to 1.25 kg/ha at a month old crop effectively controlled the most common weed like *Phalaris minor* as well as many non-graminaceous weed, including *Chenopodium album*, *Anagallis arvensis*. Randhawa *et al.* (1981) found that post-emergence application of isoproturon 1.0 kg/ha proved versatile in controlling the *Phalaris minor, Avena fatua* and some broad leaf weeds in dwarf wheat.

2,4-D (2,4-dichlorophenoxy acetic acid), which revolutionized the concept of weed control in the previous decade was being used in combination with mineral fertilizers to boost up the yield of crops and to increase the mortality of weeds, It also provides single window application of herbicides and top dressing of fertilizers. With the same objective, Jain *et al.* 1974 conducted an experiment and reported that 2,4-D alone and in combination with 3% urea gave 5 to 20 and 20 to 30% increased grain yield, respectively over control. Reduction in grain and straw yield caused by weeds was 22.5 and 30.5%, respectively over control. Isoproturon was recommended in 1977 (Gill *et al.* 1978) for *P. minor* control and the majority of Indian farmers successfully relied on isoproturon or isoproturon + 2,4-D for weed control in wheat over a period of 10–15 years. Isoproturon’s wide acceptance was due to its broad spectrum weed control and wide application timing, along with its selectivity under wheat and mustard intercropping.

Later on in 1980s to 1990s, isoproturon remained very promising herbicide for the control of *Phalaris minor* on the basis of experimental results, this herbicide has been recommended at the rate of 0.75 to 1.0 kg/ha as post-emergence and being used on commercial scale by the farmers in the country (Tomar *et al.* 1983). Patel (1989) stated that both pre- and post-emergence application of isoproturon 1.0 kg/ha were quite cheaper and time saving than manual feeding. Irrespective of application time, isoproturon at 0.33-0.75 kg/ha reduced *P. minor* population; however, wheat yield was reduced at the 0.75 kg isoproturon rate applied before irrigation (Ahuja and Yaduraju 1989). Balyan *et al.* (1988) applied isoproturon 1.0 kg/ha from 20-50 days after sowing (DAS) and found that all weeds were most susceptible to applications at 20-30 DAS than to later ones.

Isoproturon recommended against *P. minor* in late 1980s minified huge losses in wheat but unremitting use of this herbicide for more than 10-15 years resulted in the evolution of herbicide resistance in rice - wheat (R-W) cropping system (Walia *et al.* 1997, Malik and Singh 1993, 1995). This was the most severe case of herbicide resistance in the world resulting in total crop failure under heavy infestation (2000-3000 plants/m^2) (Malik and Singh, 1995). Modern dwarf wheat varieties having high harvest index survived due to this herbicide but their high productivity endangered because of the development of herbicide resistance in this weed (Malik *et al.* 1998). The resistance affected area ranged between 0.8 and 1.0 million hectares in North-West India mostly contained in the states of Punjab and Haryana. These two states accounted for around 3 million hectares of rice-wheat cropping land out of India's 10 million hectares R-W cropping system and about 35% of India's wheat production. After reporting resistance in 1992-93, many biotypes of *P. minor* found resistant to isoproturon (Malik and Singh 1993, 1994, 1995; Malik and Malik 1994, Malik *et al.* 1995, 1996, 1997; Malik 1996, Yadav *et al.* 1995, 1996, 1997; Balyan *et al.* 1997). The resistant biotypes from Haryana required 2-8 times (Malik and Singh 1995), 5-6.5 times (Yadav *et al.* 1996) and 6.3 to 11.2 times (Malik and Yadav 1997) more dose of isoproturon compared to prestine populations to cause 50% growth reduction. Resistance was also quantified and confirmed against this herbicide in various biotypes of *P. minor* from Punjab and N-W India (Yadav *et al.* 1996, Malik *et al.* 1998). The resistance was found to be of metabolic in nature (Malik *et al.* 1995, Singh *et al.* 1996, Kirkwood *et al.* 1997). However, G.B.P.U.A.T, Pantnagar, reports isoproturon resistance first in 2011 (Annual Report, Pantnagar).

Based on intensive research in Haryana, Punjab and Uttar Pradesh in conjuction with chemical companies, four alternate herbicides (clodinafop, fenoxaprop, sulfosuefuron and tralkoxydim) all of which provide effective control of *P. minor* were recommended in 1997-98 wheat growing season and the recommendation of isoproturon was withdrawn with the following year. These alternate herbicides brought the *P. minor* infestation under control and restored wheat yields to their previous levels. The yield levels of wheat in Haryana which was reduced to 3.45 t/ha in 1994-95 in resistance affected areas was increased to 4.35 t/ha in 1999-2000 due to these new herbicides with a cost: benefit ratio of 1: 6.

Chemical control of wheat during 1990 to 2018

Singh *et al.* (1993) reported that pre-emergence application of isoproturon at 1.0 kg/ha effectively controlled the *Phalaris minor, Lathyrus aphaca, Melilotus indica* and *Vicia sativa* in wheat on non-saline and saline soils of Haryana. Thakur *et al.* (1995) tested different rates of isoproturon (1.0, 1.5 and 2.0 kg/ha) as post-emergence application for weed control in wheat. From the results they reported that the application of 2.0 kg/ha isoproturon resulted into the highest weed control efficiency, but it had an adverse effect on crop growth, which reduced the grain yield also. Balyan and Malik (1993) reported that post-emergence application of isoproturon 1.02 + 2,4-D 0.48 kg/ha recorded maximum control of broad spectrum weeds, which gave the highest grain yield at Hissar (Haryana). Pandey and Singh (1994) found that metsulfuron-methyl 4 g/ha killed all creeping thistles (*Crisium arvense)* and inhibited the growth of the grassy weeds *(Avena fatua* and *Phalaris minor)* for a month and thus it gave good control of broad-leaf weeds mainly *Chenopodiwn album, Melilotus indica* and *Anagallis arvensis* on sandy loam soils of New Delhi. Panwar *et al.* (1996) emphasized that in formulated mixture of isoproturon 0.5 kg + 2,4-D 0.15 kg/ha applied at 20 DAS gave the best control of *Chenopodium album* and *Phalaris minor* in wheat. They further elaborated that metsulfuron-methyl (MSM) 4 g/ha gave good overall weed control. MSM applied plots resulted lowest total weed dry weight by killing the majority of broad-leaf weeds, *viz. Chenopodium album and Melilotus indica.* The weed control efficiency, based on weed biomass was higher under metsulfuron-methyl 4 g/ha + 2, 4-D 0.25 kg/ha followed by metsulfuron 4 g/ha alone than control and other treatments (Annual Report, Jabalpur 1995-96). Findings of Ray *et al.* (1996) revealed that application of isoproturon 0.5 kg/ha + metsulfuron 4 g/ha at 25 DAS significantly increased yield attributes and grain yield of wheat over weedy check mainly due to reduction in dry matter production by weeds.

Hence, during 1990-2000, isoproturon alone application was found to be less effective/ineffective while combination of different herbicides, *viz.* isoproturon + 2,4-D and metsulfuron + 2,4-D got acceptance by farmers for the control of weeds. Isoproturon resistance multiplied with the increasing number of years due to increase dose of herbicides (Yadav *et al*. 2002). But red signals of resistance against alternate herbicides (clodinafop, fenoxaprop, sulfosuefuron and tralkoxydim) were speculated in 2002 and thereafter. It warranted for integration of different weed control methods. While managing herbicide resistance, the main focus of change that emerged in the rice-wheat cropping system was the evolution of zero tillage in wheat. After seeing this opportunity which emerged from the crisis of herbicide resistance, the Indian Council of Agricultural Research (ICAR) and National Agriculture Technology Project (NATP) project authorities sanctioned a special project on the acceleration of such technologies for the larger benefit of farmers. In areas, where, the farmers were using graminicides like clodinafop and fenoxaprop, the broad-leaved weed flora particularly *Rumex* spp. increased enormously. Under these conditions, broad-spectrum weed control and combinations of herbicides was the demand of the decade and later on some combinations came into use.

Singh *et al.* (2001) tested the effect of metribuzin on weed control and grain yield of wheat at Pantnagar. They found that all the treatments reduced the density and dry weight of weeds except for pre-emergence application of 210 g/ha metribuzin. Weed density was lowest with application 355 or 450 g/ha metribuzin which was at par with the metribuzin 350 g/ha. Post-emergence application of 140 g/ha metribuzin completely controlled *Chenopodium album* and *M. indica,* however, the symptoms of phytotoxicity were observed with post-emergence application of metribuzin. The highest reduction in weed density was recorded in metribuzin-followed by chlorsulfuron (30 g/ha) treated plots. The lowest nutrient depletion by weeds was recorded in metribuzin treated and hand weeded plots (Sharma et *al.* 2002).

Das and Yaduraju (2002) conducted a study to optimize metribuzin dose and timing to control isorpturon resistant *Phalaris minor.* They revealed that *P. minor* dry biomass was reduced in 150 g metribuzin + 250 lit. water/ha at 5 weeks after sowing and 150 g metribuzin + 500 L water/ha at 6 weeks after sowing. Metribuzin with lower water caused maximum reduction in dry matter production of the broad leaved weeds and of total (composite) weeds and significantly increased the number of ear bearing tillers and grain yield. The higher rates and higher spray volumes were more phytotoxic, effective in reducing the population and fresh biomass accumulation of *P. minor,* wild oats and total weeds than the lower rates.

Saini and Singh (2001) from Palampur, reported that the lowest dry weight was recorded for clodinofop-propargyl (0.10 and 0.15 kg/ha) and diclofop methyl (0.80 kg/ha) in the first year, and for clodinofop propargyl (0.15 kg/ha), metribuzin (0.25 kg/ha), tralkoxydim (0.40 kg/ha) and manual weeding in the second year. Metribuzin although effectively controlling weeds, was toxic to wheat in the first year. Clodinofbp-propargyl 0.15 kg/ha and diclofop-methyl (0.50 kg/ha) were most effective in enhancing the yield and yield component in both year.

In conventional tillage, the performance of sulfosulfuron at 25 g/ha, clodinafop at 60 g/ha and sulfosulfuron+metsulfuron at 25 + 1.6 g/ha was similar, where fields were dominated by *P. minor*. However, in zero tillage, overall tank mix application of sulfosulfuron+metsulfuron was the most effective treatment for control of the weed flora and improving wheat yield. Metsulfuron alone due to its effectiveness against broad-leaved weeds only, was inferior (Chhokar *et al.* 2007).

Post-emergence clodinafop (60 g/ha), fenoxaprop (120 g/ha), pinoxaden + S (30 g/ha plus 0.5% surfactant), mesosulfuron+S (12–15 g + 625 ml surfactant/ha) and sulfosulfuron+S (25 g/ha + 0.35% surfactant) and pre-emergence fluazolate (150 g/ha) and pendimethalin (1250 g/ha) were very effective in controlling isoproturon resistant *P. minor* and improving wheat yields. To prolong the effectiveness of these herbicides, their rotational use at optimum dose and time with proper application technology integrated with other weed control tactics was advocated (Chhokara *et al.* 2008).

Carfentrazone-ethyl, another broad-leaf weed killer was found promising against many broad-leaf weeds (Punia *et al.* 2005), and it may prove effective against *Malwa parviflora* (which is not effectively controlled by 2,4-D and metsulfuron) in wheat. Sulfosulfuron was found to cause residual toxicity to succeeding crops like sorghum and maize grown after wheat harvest. So, this herbicide was strictly restricted to those areas where rice-wheat cropping sequence is followed. Since, almost last two decades, new herbicides and ready mix herbicides are being used, which have solved the early day's problems of single group weed killers or herbicide resistance.

Three field experiments were conducted during 2008-09 to 2012-13 along with large plot adaptive trials during 2012-13 with the objective to evaluate the efficacy of sequential applications of pendimethalin applied pre-emergent followed by clodinafop, sulfosulfuron, or pinoxaden applied post-emergent and tank-mix applications of metribuzin with these post-emergence herbicides for the management of herbicide-resistant *P. minor* in wheat. Clodinafop 60 g/ha or sulfosulfuron 25 g/ha at 35 days after sowing (DAS) and pendimethalin 1000 g/ha as pre-emergence did not provide consistently effective control of *P. minor* in wheat. An increase in the dose of clodinafop from 60 to 75 g/ha and of sulfosulfuron from 25 to 30 g/ha also did not improve their efficacy to a satisfactory level. However, pinoxaden 50 g/ha provided effective control (97-100%) of *P. minor* but not of broad-leaf weeds.

The tank-mix application of metribuzin with clodinafop 60 g/ha or sulfosulfuron 25 g/ha at 35 DAS and the sequential application of pendimethalin 1000 g/ha or trifluralin 1000 g/ha just after sowing followed by clodinafop 60 g/ha or sulfosulfuron 25 g/ha at 35 DAS provided 90-100% control of *P. minor* along with broad-leaf weeds in wheat, thus resulting in improved grain yields (4.72-5.75 t/ha) when compared to clodinafop 60 g/ha (3.85-5.60 t/ha) or sulfosulfuron 25 g/ha alone (3.95-5.10 t/ha). The efficacy of mesosulfuron + iodosulfuron (a commercial mixture) 14.4 g/ha against *P. minor* was not consistent across the experiments and over the years. The ready-mix combination of fenoxaprop + metribuzin (100 +175 g /ha) at 35 DAS provided effective control of weeds but its varietal sensitivity needs to be determined before its use in field conditions. The tank-mix or sequential application of herbicides would be a better option than their applications alone to manage the serious problem of herbicide-resistant *P. minor* in wheat (Yadav *et al.* 2016).

The tank mix application of metsulfuron-methyl with clodinafop and sulfosulfuron being at par with the application of isoproturon alone produced significantly higher spike length, number of spikes/m row length and seeds/spike of wheat over farmer's practice. The maximum values of yield attributes, *viz.* spikes/m, spike length, seeds/spike and 1,000-seed weight (42.6 g) were observed with tank mix application of clodinafop + metsulfuron-methyl and found significant over farmer's practice. The maximum net return (` 45,098) and benefit: cost ratio was recorded with tank mix application of clodinafop and metsulfuron-methyl, *i.e.* ` 12,997 and 0.54, being higher over farmer's practice (2,4-D at 0.75 kg/ha). Energy output has direct relation with total biomass production. The maximum energy output and sustainability yield index (SYI) was recorded with tank-mix application of metsulfuron-methyl and clodinafop followed by sulfosulfuron + metsulfuron-methyl, while farmer's practice had lowest energy output and SYI. Similarly, energy-use efficiency and energy productivity were also higher with tank-mix application of metsulfuron-methyl with clodinafop and sulfosulfuron compared to farmer's practice (2,4-D at 0.75 kg/ha) in Malwa Plateau of Central India (Singh 2013).

An another field experiment with respect to different wheat establishment methods conducted at Pantnagar during *Rabi* season of 2013-2014 revealed that highest grain (4.69 t/ha) and biological yield (12.13 t/ha) was obtained in the plots treated with clodinafop-propargyl at 60 g/ha. Grain and biological yield loss under roto tilled wheat, conventional wheat and zero tilled wheat due to weeds was 75.9% and 30.8%, 22.3% and 11.5% and 18.3% and 14.3%, respectively. Ready mix of clodinafop-propargyl + MSM at 64 g/ha in conventional and zero tilled wheat recorded 100% weed control efficiency at 60, 90 DAS and at maturity as mixed weed dynamics was recorded under the same whereas, in case of roto tilled wheat, where *Phalaris minor* population was dominating achieved 100% weed control efficiency with the sole application of clodinafop-propargyl at 64 g/ha. Highest B: C ratio (2.5) was achieved under clodinafop-propargyl at 60 g/ha which was at par with ready mix of clodinafoppropargyl + MSM at 64 g/ha. Energy intensity (3.0) was lowest under RTW with clodinafop-propargyl at 60 g/ha. The lowest population of bacteria (6.87 log cfu) and actinomycetes (5.46 log cfu) was recorded under ready

Table 6. Herbicides recommendation for weed control in wheat

Herbicide	Dose kg a.i./ha	Time of application
Metribuzin 70%	0.170-0.210	30 days stage
Clodinafop-propargyl 15% WP	0.06	30 days stage
Clodinafop 15% + MSM 1% WP	0.060+0.004	30 days stage
Sulfosulfuron 75% WG	0.025	30-35 days stage
Fenoxaprop-p-ethyl10% EC	0.100 - 0.120	30 days stage
2,4-D Dimethyl Amine Salt 58% SL	0.5-0.75	35-40 days stage
2,4-D Ethyl Ester 38% EC	0.45-0.75	35-40 days stage
Metsulfuron-methyl 20% WG	0.004	35-40 days stage
Carfentrazone-ethyl 40% DF	0.02	35-40 days stage
Pinoxaden 5.1% EC	0.05	35-40 days stage
Pendimethalin	1.00	0-3 days stage
Tralkoxydim	0.350	30-35 days stage
Triasulfuron	0.02	30-35 days stage

(Source: Annual Report, Pantnagar 2017 and Mishra *et al.* 2016)

mix of clodinafop-propargyl + MSM at 64 g/ha (Sirazuddin *et al.* 2016). At present the herbicides which are currently in use for effective weed control in wheat have been presented in the (**Table 6**).

Way ahead

Development of cross resistance or multiple cross resistance in *Phalaris minor* in wheat will continue to amplify, as the weed develops mechanisms of resistance against new herbicides. This weed is a major threat to wheat productivity in North-Western India, and as such needs to be addressed with integrated weed management approaches, including crop and herbicide rotations, herbicide combinations along with cultural and mechanical methods. Despite several decades of modern weed control measures, weeds continue to be a constant threat to agricultural productivity. Herbicide-resistant weeds and weed population shifts continue to generate new challenges for agriculture. Weed community convolution, integrated approaches to weed management may help to reduce economic effects and improve weed control practices. Integrated weed management accentuates the combination of management techniques and scientific knowledge in a manner that considers the causes of weed problems rather than reacts to existing weed populations. The best approach may be to integrate cropping system design and weed control strategies into an ample system that is environmentally and economically feasible. This will help producers to manage herbicides and other inputs in a manner that preserves their effectiveness and move weed scientists toward the development of more diverse and integrated approaches to weed management. Relatively little attention has so far been paid to research on weed management in organic and conservation agriculture, hence, researchers must work in this direction either.

Maize

Maize is the third most imperative grain crop in India after rice and wheat with respect to area and productivity. Maize has been major cereal crop and known as

'Queen of Cereals', because of its great productivity potential and adaptability to wide range of environments and occupies an significant place in world's economy, grown over an area of 177 million hectares with a total production of 967 million tonnes. Maize is a miracle crop; it is grown in more than 130 countries across the world. Major maize growing countries are USA, China, Brazil, Mexico, France, Argentina, Italy and India. India contributes about 15% and 5% to total maize-area, while 8% and 2.4% to total production in Asia and the world, respectively (FAO STAT 2014). In India, the total area under maize is 9.9 million hectares, having a production of 18.73 million tonnes and average productivity of 779 kg per hectare (DAC 2017). It has the highest yield potential, which is fluctuated by multiple factors, *viz.* weeds, nutrients, pests and diseases. Amongst all, weeds account for 28 to 100% yield loss (Patel *et al*. 2006).

Though, maize is a vigorous and tall growing plant, it is susceptible to competition from weeds. High rainfall, high humidity and high temperature provide very conducive conditions for the lavish growth of the weeds. Weeds compete with crop plants for light, space, water and nutrients, especially during the early stages of growth as they are more adapted to agro-ecosystems than crop plants. Wide spacing in maize allows abundant growth of varied weed species, which trims down the photosynthetic efficiency, dry matter production and partitioning to economic parts and there by reduces sink capacity of crop resulting in poor grain yield (Vaid *et al.* 2010). Numerous means have been evolved to keep the weeds under check. Accordingly, a number of mechanical, cultural and chemical methods of weed control have been devised, tested and perfected. Each of these methods has their advantages and disadvantages. Poor weed management is one amongst the numerous factors that significantly influences the yield of the crop. Yogita *et al.* 2018 found that weeds lead to loss of $ 736 million in maize.

Trend of weed spectrum in maize

Major weeds of maize are given in (**Table 7**). Singh *et al.* (1980) observed that *Echinocloa colonum, Echinocloa crus-galli, Cynodon dactylon* and *Cyperus rotundus* were dominant weeds in maize at Doon valley. Gill *et al.* (1987) found *Eleusine aegypticum, Eragrostis tenella, Cyperus rotundus, Digera arvensis, Commelina benghalensis* and *Tribulus terrestris* as dominant weed spectrum at

Table. 7 Major weeds of maize

Maize	Grasses	*Echinochloa colona* *Dactyloctenium aegyptium* *Cynodon dactylon*
	BLWs	*Aegeratum conyzoides* *Commelina benghalensis* *Celosia argentia* *Galinsoga parviflora* *Oxalis latifolia* *Trianthema portulacastrum*
	Sedges	*Cyperus rotundus*

Source: Annual Report, GBPUAT, 2017

Ludhiana. While at Bapatla, Gupta *et al.* (1987) recorded dominant weed as *Cyperus rotundus, Cynodon dactylon, Chloris barbata, Trianthema portulacastrum, Amaranthus viridis, Tridox procumbense* and *Euphorbia hirta.* Thakur and Singh (1989) reported that *Cyperus rotundus, Eleusine indica, Echinocloa colonum, Digitaria sanguinalis* and *Dactyloctenium aegypticum* were predominant at silking stage of maize at Himachal Pradesh. Under the mid hill conditions of Himachal Pradesh, *Echinochloa colonum, E. crus-galli, Cyperus iria, C. esculentus, Commelina benghalensis* and *Ageratum conyzoides* were the dominant weeds associated with the maize crop (Saini and Angiras 1998). Sandhu *et al.* (1999) documented *Eleusine aegyptiacum, Eragrostis tenella, Leptochloa panacea, Trianthema portulacastrum, Digera arvensis* and *Cyperus rotundus* were the predominant weed species associated in maize in Punjab. *Commelina benghalensis, Chenopodium album, Cyperus rotundus, Cynodon dactylon, Portulaca oleracea, Phyllanthus niruri, Amaranthus viridis, Acalypha indica* and *Tridex procumbens* reported as the most problematic weeds in maize in Bangalore (Lamani *et al.* 2000). Malviya and Singh (2007) reported *Cyperus rotundus* L., *Cynodon dactylon* (L). Pers., *Eclipta alba, Solanum nigrum, Digera arvensis, Phyllanthus niruri, Echinochloa colonum,* and *Commelina benghalensis* as predominant weed species infesting maize at Faizabad in Uttar Pradesh.

Chemical weed management in maize during 1950 to 2018

In general, farmers used to take up the inter cultivation practices with conventional methods like hand weeding or bullock drawn implements mainly for the purpose of checking weed growth. These mechanical weedings in rainfed maize crop at early growth stage would not be possible in slushy field condition, as a result of frequent rains. Under such conditions, timely weed control might not be taken up leading to a rigorous crop weed competition that may result in a drastic diminution in crop yields, thus warranting the use of herbicides. Only 2,4-D herbicide was the option in 1960, S-triazines and other broad spectrum herbicides were came into fashion after seventies.

S-Triazines and some other broad spectrum herbicides established the concept of chemical weed control, but their continuous use at higher doses raised the question concentrating on the residual effect of triazines on crops succeeding to maize (Sinha and Sinha 1970). It was therefore imperative to study the possibility of reducing the dosage of some effective herbicides like atrazine and combining with some other post-emergence herbicides, thus minimising their residue problems in the soil. Atrazine belongs to the heterocyclic nitrogen compounds and comes under triazines. It is a soil and leaf applied herbicide. The triazines move in the transpiration stream mostly in the apoplast of treated plants and inhibit photosynthetic electron transport (Baker and Terry 1991). Reports across India on herbicides used in maize during seventies and eighties are as follows:

Favourable effects of atrazine and simazine on the grain yield of maize was noticed by Sahora and Singh (1970) and Gill and Brar (1974). Gupta (1972) observed an increased stover yield with pre-emergence application of atrazine at 1.0 to 1.75 kg/ha. Rai and Yadav (1973) achieved some success in controlling weeds in maize by use of pre- and post-emergence herbicides. Madhulety (1974) observed increased germination of maize with atrazine at 2.0 and 4.0 kg/ha. Atrazine proved to be an effective pre-emergence herbicide (Sidhu *et al.* 1975). Atrazine at 1.5 kg/ha proved equally effective as two hand weedings on a sandy loam soil, however, at higher dose (2.0 kg/ha) it resulted in more effective weed control and finally higher yields on a sandy loam soil (Sidhu *et al.* 1975). Dry matter accumulation of weeds was considerably reduced by atrazine and simazine (Sidhu *et al.* 1975). Bhan *et al.* (1976) found that pre-emergence application of atrazine at 1.0 kg/ha was considered to be the best for the most acceptable level of weed control and the highest yield of spring maize at Pantnagar. A consistency in checking the dry weight of weeds was observed under pre-emergence spray of pendimethalin at 1.5 kg/ha (Joshi and Dutta 1976). Gill *et al.* (1977) found simazine and atrazine to be effective and selective herbicides for weed control in *Kharif* maize. Pinto (1978) reported that *Cyperus rotundus* was resistant to pendimethalin application in maize. Hence, on the basis of reports, atrazine was the only option during 1970-80 for effective weed management in maize.

In this decade also, reports suggested that atrazine remained the dominating herbicide in maize. Singh *et al.* (1980) observed that pre-planting incorporated herbicides were more effective than pre- or post-emergence treatments. Pre-emergence application of either simazine at 2.0 kg/ha or atrazine at 1.5 kg/ha was found to control the weeds effectively in maize (Chakor and Awasthi 1983). Mehta *et al.* (1985) indicated that the application of 2.0 kg/ha atrazine was most effective and economical and was at par with 3 hand weeding. Pre-emergence application of atrazine at 0.5 kg/ha reduced the dry weight of dominant weeds significantly (Balyan and Bhan 1987). Singh *et al.* (1987) concluded that atrazine at 1.0 kg/ha gave better control of weeds in maize crop than pendimethalin. The density of *Cyperus rotundus* and *Cynodon dactylon* followed a trend of decrease with an increase in the dose of atrazine up to 4.0 kg/ha and the weed species *Cynodon dactylon* was found more susceptible to atrazine (Rao *et al.* 1988). At Palampur, Kumar and Singh (1989) based on the pot studies reported that atrazine provided effective control of *Ageratum conyzoides.* Rapparini (1989) suggested pre-emergence use of metolachlor to be a better alternative to atrazine. Thereby, it seemed that pendimethalin and metolachlor came into use but their acceptance by farmers remained very low as compared to atrazine.

A good amount of information was accessible on the use of triazine herbicides for weed control in maize, but the information was very meager on the efficiency of other probable effective herbicides like pendimethalin and oxyfluorfen in checking the weed problems in maize crop particularly under rainfed conditions, (Sreenivas 1992).

The reports across the country regarding herbicidal impact on maize during 1990-2000 are as follows:

Varshney (1990) concluded that pre-emergence application of atrazine to maize at 2.0 kg/ha was the efficient treatment for controlling weeds (67%) and enhancing seed yield by 143% over weedy control. Similarly, pre-emergence application of atrazine at 0.75 kg/ha resulted in an excellent control of weeds in maize crop at Hissar (Sangwan *et al.* 1991). Vaishya and Singh (1992) reported that pre-emergence application of atrazine recorded significantly higher grain yield of maize crop. Sreenivas and Satyanarayana (1994) found that atrazine *fb* 2,4-D resulted in highest grain yield in maize while significantly reducing the dry matter of the weeds.

Sharma and Thakur (1998) reported that metolachlor at 1.5 kg/ha + atrazine 0.75 kg/ha gave the highest grain yield due to the significant reduction in weed density and dry matter accumulation by weeds. Pandey *et al.* (1999) reported that, in maize, atrazine was more effective against *A. conyzoides* and *Commelina benghalensis* than pendimethalin. During the above said decade, apart from atrazine, metalochlor, pendimethalin, 2,4-D and their integration got attention for managing weeds in maize.

Atrazine kept on using as a dominant herbicide in the decade 2000-2010 either alone or with some other herbicides like alachlor, pendimethalin, metalochlor. Comparative findings across India are as follows:

Pandey *et al.* (2000) reported atrazine (0.625 kg/ha) + alachlor (1.00 kg/ha) to be the most effective chemical control for *Ageratum conyzoides* at Almora. Atrazine at 2.0 and 1.5 kg/ha provided the lowest weed dry weights, whereas, atrazine at 1.0 kg/ha did not provide acceptable weed control in maize (Saini 2000). The significantly higher number of cobs, cob length, grains per cob and grain yield were obtained with atrazine at 2.0 and 1.5 kg/ha. The weed control efficiency decreased and thus dry weight of weeds increased with delay in the time of application of atrazine from pre-emergence (PE) until 18 DAS. The yield attributes and grain yield were statistically similar with atrazine applied as pre- and post-emergence at 6 or 12 DAS. According to Sinha *et al.* (2001) at Pusa, Bihar reported that integration of atrazine 1.5 kg/ha and 2,4-D 0.8 kg/ha proved to be the best among chemical treatments in controlling the weeds in maize crop. Pandey *et al.* (2001) at Almora, reported atrazine to be more effective than pendimethalin or alachlor against *Ageratum conyzoides*. Sharma and Gautam (2003) reported that the blanket application of atrazine in maize resulted in tallest plants and highest dry matter accumulation by the crop at Pantnagar. Kolage *et al.* (2004) at Rahuri, Maharashtra concluded that atrazine at 1.0 kg/ha was the most effective in influencing weed intensity and weed index. It was next only to weed free control in terms of weed control efficiency. At Udaipur, Chalka and Nepalia (2005) obtained comparable maize equivalent yield with metolachlor, alachlor and hand weeding. Chalka and Nepalia (2005) obtained comparable net returns with metolachlor 1.0 kg/ha, alachlor 2.0 kg/ha and hand weeding 30 DAS. Kolage *et al.* (2004) reported that application of atrazine at 1.0 kg/ha recorded the highest net returns (` 12 766/ha) and benefit: cost ratio (2.50) at Rahuri, Maharashtra. Walia *et al.* (2007) reported that application of atrazine 0.75 kg/ha, atrazine 0.5 kg + pendimethalin 0.50 kg/ha, atrazine 0.50 kg + alachlor 0.75 kg/ha and atrazine 0.5 kg + trifluralin 0.60 kg/ha reduced dry matter accumulation by weeds significantly than pre-emergence application of atrazine 1.0 kg/ha alone. At Palampur, Chopra and Angiras (2008) found that atrazine 1.5 kg/ha resulted in significantly lower count and dry matter of weeds.

Recently, tembotrione a pigment synthesis inhibitor (42% SC), which is a broad spectrum systemic herbicide of triketene group has been tested in India and proved to be successful in managing all categories of weeds infesting the maize field during latter stages. Singh *et al.* (2012) from Pantnagar reported that post-emergence application of tembotrione 120 g/ha along with surfactant (1000 ml/ha) was found most effective to control the grassy as well as non-grassy weeds as compared to other herbicidal treatments applied as pre or post-emergence with maximum weed control efficiency (90%). Recent findings across India are as follows:

Inalli *et al.* (2014) recorded lowest weed dry weight in alachlor 0.75 kg/ha + pendimethalin 0.5 kg/ha as PE followed by 2,4-D 0.5 kg/ha as PoE at 30-35 DAS as compared to all other treatments. Owla *et al.* (2015) reported that lowest density and dry weight of monocot and dicot weeds at 30 and 60 DAS was observed in filed treated with alachlor at 2.0 kg/ha and atrazine at 0.4 kg/ha followed by HW at 30 DAS, which was significantly superior to metribuzin followed by HW at 30 DAS. Significantly lower density and dry weight/m^2 was recorded with atrazine (50 %) at 1.25 kg/ha as compared to all other chemical treatments (Shanker *et al.* 2015). Swetha *et al.* (2015) recorded lowest weed density and dry weight of weeds in tembotrione + atrazine at 105 + 250 g/ha + stefes mero as PoE. Patil *et al.* (2016) recorded higher weed control efficiency (82.54 %) and lower weed index (7.65%) in atrazine 50 WP at 0.5 kg/ha PE + pendimethalin 38.7 CS at 0.5 kg/ha PE and significantly lower weed density and dry weight of weed were also recorded under the same treatment combination. The most recent recommendation of herbicides for weed management is given in the **Table 8**.

Table 8. Recommended herbicides in maize

Crops	Herbicide	Dose (kg/ha)	Stages of application
Maize			
	Atrazine 50% WP	1.0	Pre-emergence
	Alachlor 50% EC	2.5	Pre-emergence
	2,4-D Dimethyl Amine Salt 58% SL	0.5	Post-emergence
	2,4-D Ethyl Ester 38% EC	0.9	Post-emergence
	Tembotrione 34.4% SC	0.12	Post-emergence

Source: Annual report, Pantnagar 2017

Conclusion

Few herbicides like atrazine, pendimethaline, metribuzin, 2,4-D, tembotrione are accessible for weed control in maize. In the current scenario, farmers are applying only atrazine as pre-emergence and 2,4-D as post-emergence in maize, but these herbicides manage only broad-leaf weeds. Control of grasses and sedges remain a significant predicament for the farmers, especially when too high or too low soil moisture obstructs the inter-cultural operations. Scarcity of labour during critical stages of weeding is also a gigantic problem for the farmers. Timely weeding is most imperative to minimize the yield losses and therefore, under such state of affairs, the only effective tool is left to control the weeds through the use of chemicals. Use of PRE and POE herbicides would make the herbicidal weed control more acceptable to farmers, which will not change the existing agronomic practices but will allow for complete control of weeds.

References

Adlakha PA, Srivastva AK, Sirohi SS and Sharma VK. 1971. Weed flora of Ludhiana. *Indian Journal of Weed Science* **54**: 37–44.

Ahuja KN and Yaduraju NT. 1989. Integrated control of weeds in wheat with special reference to *Phalaris minor. Indian Journal of Agronomy* **34**(3): 318–321.

Annual Report. 1995–96. All India Coordinated Project on Weed Control. JNKVV, Jabalpur.

Annual Report. 2016–17. All India Coordinated Research Project on Weed management. GBPUA&T, Pantnagar.

Annual report 2017–18. Department of Agriculture, Cooperation & Farmers Welfare Ministry of Agriculture & Farmers Welfare Government of India.

Baker FWG and Terry PJ. 1991. Tropical grassy weeds. pp. 73–84. In: *Chemical Control of Grassy Weeds*, (Ed. Collins SC) CAB International.

Balyan RS and Malik RK. 1993. Chemical control of complex weed flora in wheat *Haryana Journal of Agronomy* **9**(1): 74–76.

Balyan RS and Bhan VM. 1987. Studies on cultural and chemical weed control in maize. *Indian Journal of Agronomy* **32**(1): 41–43.

Balyan RS, Yadav A, Garg VK and Malik RK. 1997. Response of isoproturon resistant and susceptible biotypes of littleseed canary grass to the tank mixture of atrazine and isoproturon. *Pestology* **21**: 13–15.

Balyan RS, Malik RK and Bhan VK. 1988. Effect of time of application of isoproturon on the control of weeds in wheat *(Triticum aestivum). Indian Journal of Weed Science* **20**(1): 10–18.

Bhan VM and Singh SP. 1979. Latest method of controlling weeds in wheat. *Haryana Farming.* **8**: 1.

Bhan VM. 1983. Effect of hydrology, soil moisture regime and fertility management on weed population and their control in rice. pp. 47–56. In: *Proceedings of the Conference on Weed Control in Rice at International Rice Research Institute*, Aug 31–Sep 4. Los Banos, Philippines.

Bhan VM, Singh M and Maurya RA. 1976. Time and level of atrazine application variables in spring maize. *Indian Journal of Agronomy* **21**(4): 401–404.

Bhardwaj RBL. 1980. Relative effectiveness of some broad spectrum herbicides in controlling grassy weeds in wheat, *Abstract Papers Weed Science Conference* ISWS/ OUAT, Bhubaneshwar.

Bhowmik MK, Ghosh RK and Pal D. 2000. Bio–efficacy of new promising herbicides for weed management in summer rice. *Indian Journal of Weed Science* **32**(1&2): 32–58.

Bouman BAM, Hengsdijk H, Hardy B, Bindraban PS, Tuong TP and Ladha JK. Los Banos, Philippines. International Rice Research Institute.

Chakor IS and Awasthi OP. 1983. Cultural–cum–chemical weed control in maize under rainfed conditions of Himachal Pradesh. *Indian Journal of Weed Science* **15**(1): 65–68.

Chalka MK and Nepalia V. 2005. Production pojential and economics of maize *(Zea mays)* intercripped with legumes as influenced by weed control. *Indian Journal of Agronomy* **50** (2): 119–122.

Chauhan BS and Johnson DE. 2010. The role of seed ecology in improving weed management strategies in the tropics. *Advances in Agronomy* **105**: 221–262.

Chauhan BS and Opeña J. 2012. Effect of tillage systems and herbicides on weed emergence, weed growth, and grain yield in dry–seeded rice systems. *Field Crops Research* **137**: 56–69.

Chauhan BS, Mahajan G, Sardana V, Timsina J and Jat ML. 2012b. Productivity and sustainability of the rice–wheat cropping system in the Indo–Gangetic Plains of the Indian subcontinent: problems, opportunities, and strategies. *Advances in Agronomy* **117**: 315–369

Chauhan BS. 2012b. Weed ecology and weed management strategies for dry–seeded rice in Asia. *Weed Technology* **26**: 1–13.

Cheema *et al.* 2005. Sorgaab for weed control in transplanted fine rice (*Oryza sativa* L.) *International Journal of Agricultural Biology* **7**: 6.

Chhokar RS, Sharma RK, Jat GR, Pundir, AK and Gathala MK. 2007. Effect of tillage and herbicides on weeds and productivity of wheat under rice–wheat growing system. *Crop Protection* **26**: 1689–1696.

Chhokar RS, Singh S and Sharma RK. 2008. Herbicides for control of isoproturon–resistant littleseed Canarygrass (*Phalaris minor*) in wheat. *Crop Protection* **27**: 719–726.

Chopra P and Angiras NN. 2008. Effect of tillage and weed management on productivity and nutrient uptake of maize *(Zea mays). Indian Journal of Agronomy* **53**(1): 66–69.

Choubey NK, Kolhe SS and Tripathi RS. 2001. Relative performance of cyhalofop–butyl for weed control in direct seeded rice. *Indian Journal Weed Science* **33**(3&4): 132–135.

Das TK. 2008. *Weed Science: Basics and Application*. Jain Brothers Pub, New Delhi, First edition, 901 p.

Das TK and Yaduraju NT. 2002. Optimization of metribuzin use for controlling isoproturon resistant *Phalaris minor* Retz. in wheat. *Pesticide Research Journal* **14**(1): 47–56.

De Datta SK. (1974). Weed control in rice: Present status and future challenge. *Philippines Weed Science Bulletin* **1**: 1–16.

Deepthi Kiran Y and Subramanyam D. 2010. Performance of pre– and post–emergence herbicides on weed flora and yield of transplanted rice (*Oryza sativa*). *Indian Journal of Weed Science* **42**(3&4): 229–331.

Dikshit NN. 1974. Prospect for increasing rice production in rainfed areas of Eastern U.P. *Rice Research Workshop. AICRIP* Hydrabad, India, File, 25–27.

Dimitrios A, Ntanos Spyridon D, Koutroubas and Mavrotas C. 2000. Barnyard grass (*Echinochloa crus–galli)* control in water–seeded rice (*Oryza sativa*) with Cyhalofop butyl. *Weed Technology* **14**: 383–388.

Directorate of Economics and Statistics, 2017. *Annual Report*, Department of Agriculture and Cooperation (DAC).

FAO STAT. 2014. *Food & Agriculture Organization Corporate Statistical Database*. Available online at http://faostat3.fao.org/faostat–gateway/go/to/browse/Q/QC/E.

Gill HS and Brar LS. 1974. Atrazine, simazine, nitrofen and alachlor for weed control in maize (*Zea may* L.) and their residual effect on wheat. *Journal of Research Punjab Agricultural University* **11**: 269–73.

Gill HS and Brar LS. 1975. Importance of herbicides in the agriculture of Punjab and Haryana. *Pesticides* **9**: 20–24.

Gill HS, Brar LS and Walia US. 1977. Effect of some herbicidal and cultural treatments on weed intensity and grain yield of maize. *Indian Journal of Agricultural Sciences* **47**(2): 89–95.

Gill HS, Brar LS and Walla US. 1987. Comparative bioefficacy of new brand formulations of atrazine and simazine for weed control in maize. *Journal of Research Punjab Agricultural University* **24**(2): 209–214.

Gill HS, Walia US and Brar LS. 1978. Control of *P. minor* and wild oat in wheat with herbicides. *Pesticides* **12**: 53–56.

Gill KS. 1994. Sustainability issues related to rice – wheat production in Asia. pp. 36–60. In: RAPA publication.

Gogoi AK, Kalita H, Pathak AK and Deka J. 1993. Crop–weed competition in rainfed wheat (*Triticum aestivum*). *Indian Journal of Agronomy* **38**: 815–816.

Gopal R, Jat RK, Malik RK, Kumar V, Alam MM, Jat ML, Mazid MA, Saharawat YS, McDonald A and Gupta R. 2010. *Direct Dry–Seeded Rice Production Technology and Weed Management in Rice Based Systems*. International Maize and Wheat Improvement Center, New Delhi, India. *Technical Bulletin* 28 p.

Gupta RK, Naresh RK, Hobbs PR and Ladha JK. 2002. *Adopting Conservation Agriculture in Rice–Wheat Systems of the Indo Gangetic Plains: New Opportunities for Saving on Water*. pp. 207–222. In: *Proceedings of the International Workshop on Water–wise Rice Production*.

Gupta KM, Rao YG and Rao AY. 1987. Chemical weed control in maize crop. *The Andhra Agricultural Journal* **34**(2): 213–214.

Gupta OP. 1972. The effects of atrazine in maize and wheat rotations. *Pest articles and news summaries* **18**(3): 290–291.

Gupta OP. 1984. *Scientific Weed Management*. Todays and Tomorrow Printers and Publishers, New Delhi.

Hooda IS. 1974. Chemical control of grassy weeds in dwarf wheat. *Indian Journal of Weed Science* **6**(2): 83–87.

Inalli Kamaiah, Arvinda Kumar BN and Babu Ramesh (2014). Efficacy of tank mixture herbicides for weed control in maize. *Biosciences* **7**(14): 1835–1838.

IRRI Reporter. 1969. March–April **5**(2).

Jabusch TW and Tjeerderma RS. 2005. Partitioning of penoxsulam–a new sulfonamide herbicide. *Journal of Agricultural and Food Chemistry* **53**: 7179–7183.

Joshi OP and Dutta NP. 1976. The effect of simazine on yield and nutrient uptake by maize and wheat. *Indian Journal of Weed Science* **8**(2): 108–114.

Kamble S, Yogeesh ALN, Prashanth SM, Channabasavanna AS and Channagoudar RF. 2015. Effect of weed management practices on weed growth and yield of maize. *International Journal of Science, Environment and Technology* **4**(6): 1540–1545.

Kassasion L. 1977. Chemical weed control I winter cereals of Hofcil Agril. Res. Centre. Ministry of Agriculture and water. *Saudi Arabia Pub. No. 111. Weed Abstracts* **27**(1): 3210.

Khan RA, Malik DS and Dubey SK. 1970. Control of weeds in wheat field effect of 2,4-D and interculture operation on the weed and grain yield of wheat. *Indian Journal of Weed Science* **2**(1): 26–30.

Kirkwood RC, Singh S and Marshall G. 1997. *Mechanism of isoproturon resistance in Phalaris minor, implications and control measures*. pp. 204–207. In: *Proceedings 16th Asian-Pacific Weed Science Society International.* Weed Management Towards Sust. Agric., Sept. 8-12, Kuala Lumpur, Malaysia.

Kolage AK, Shinde SH and Bhilare RL. 2004. Weed management in *Kharif* maize. *Journal of Maharashtra Agricultural Universities* **29**(1): 110–111.

Kumar V and Ladha JK. 2011. Direct seeding of rice: recent developments and future research needs. *Advances in Agronomy* **111**: 299–413.

Lamani CS, Palled YB and Shenoy H. 2000. Weed dynamics as influenced by integrated nutrient management in hybrid maize. *Current Research. University of Agriculture Sciences Bangalore* **29**(1–2): 21–22.

Madhavi M and Reddy MD. 2002. Relative efficacy of herbicides on performance of wet seeded rice. *Indian Journal of Weed Science* **34**(1&2): 128–130.

Madhulety TY. 1974. *Studies on Biochemical and Physiological Effects of Lasso and Atrazine on Maize (Zea mays L.).* M.Sc.(Ag) thesis, Andhra Pradesh Agricultural University, Hyderabad.

Mahajan G and Chauhan BS. 2013. The role of cultivars in managing weeds in dry–seeded rice production systems. *Crop Protection* **49**: 52–57.

Mahajan G, Chauhan BS and Gill MS. 2013. Dry–seeded rice culture in Punjab state of India: lessons learned from farmers. *Field Crops Research* **144**: 89–99

Malik RK. 1996. Herbicide resistant weed problems in developing world and methods to overcome them. pp. 665–667. In: *Proceedings Second International Weed Control congress,* Copenhagen.

Malik RK and Malik YS. 1994. Development of herbicide resistance in India. Appropriate Weed Control in South–East Asia, (Eds. Sastromoto SS and Bruce A). CAB Int. pp. 64–82.

Malik RK and Singh S. 1993. Evolving strategies for herbicide use in wheat: Resistance and integrated weed management. pp. 225–238. In: *Indian Society of Weed Science International Symposium,* Integrated Weed Management for Sust. Agri., 18–20 Nov. 1993, Hisar, India.

Malik RK and Singh S. 1994. Effect of biotype and environment on the efficacy of isoproturon against wild canary grass. *Test of Agrochemicals and Cultivars* No. 15 (*Annals of Applied Biology 124, Supplement*). pp. 52–53.

Malik RK and Singh S. 1995. Littleseed canary grass (*Phalaris minor* Retz.) resistant to isoproturon in India. *Weed Technology* **9**: 419–425.

Malik RK and Yadav A. 1997. Potency of alternate herbicides against isoproturon resistant littleseed canary grass. pp. 208–213. In: *Proceedings of 16th Asian - Pacific Weed Science Society Conference*, Weed Management Towards sustainable agriculture. Sep. 8–12, Kaulalampur, Malaysia. *Session* 4A. Herbicide Resistant *Phalaris minor* in Wheat–A Sustainability Issue

Malik RK, Bhan VM, Katyal SK, Balyan RS and Singh BV. 1984. Weed management problems in rice–wheat cropping system in adoption of weed control technology in Haryana. *Haryana Agricultural University Journal of Research* **14**: 45–50.

Malik RK, Gill G and Hobbs PR. 1998. Herbicide resistance in *Phalaris minor* – a major issue for sustaining wheat productivity in rice–wheat cropping system in Indo–Gangetic Plains. Rice–Wheat Consortium Paper Series 3, 36p. New Delhi, India: Rice–Wheat Consortium for Indo–Gangetic Plains.

Malik RK, Yadav A, Balyan RS and Singh S. 2000. Zero–till wheat sowing and alternate herbicides against resistant *Phalaris minor* in rice–wheat cropping system. *Indian Journal of Weed Science* **32**: 220–222.

Malik RK, Yadav A, Malik YS and Singh S. 1997. Development of resistance to herbicides in *Phalaris minor* and mapping the variation in weed flora. Int. Group Meeting on Wheat–Research Need Beyond 2000 AD, Aug. 12–14, 1997. 26p.

Malik RK, Yadav A, Malik YS, Balyan RS and Singh S. 1996. Management of resistance in *Phalaris minor* against isoproturon. *Indian Farming* **2**: 9–10.

Malik RK, Yadav A, Siddqui S, Garg VK, Balyan RS and Malik RS. 1995. Effect of isoproturon on growth and photosynthesis of herbicide resistant and susceptible biotypes of littleseed canary grass. *Indian Journal of Weed Science* **27**: 49–51.

Malik RK, Yadav A, Singh S, Malik RS, Balyan RS, Banga RS, Sardana PK, Jaipal S, Hobbs, PR, Gill G, Singh S, Gupta RK and Bellinder R. 2002. Herbicide resistance management and evolution of zero tillage – a success story. *Research Bulletin* – 2002 of CCS Haryana Agricultural University, Hisar, India. 43p.

Mani VS, Gupta RS, Gautain KC and Mishra BN. 1972. Chemical control of grassy weeds in wheat. *Indian Farming* **22**(12): 21–22.

Mawiya A and Singh B. 2007. Weed dynamics, productivity and economics of maize *(Zea mays)* as affected by integrated weed management under rainfed condition. *Indian Journal of Agronomy* **52**(4): 321–324.

Mehta HM, Trivedi GC and Patel HR. 1985. *Effect of farm yard manure, fertilizer and herbicide at different level of their application on weed control and yield of maize.* In *Proceedings of Annual Conference of Indian Society of Weed Science,* Department of Agronomy, Gujarat Agricultural University, Anand, India.

Mirza H, Ali MH, Alam MM, Akher M and Kazi Fakhrul Alam. 2009. Evaluation of pre–emergence herbicides and hand weeding on the weed control efficiency and performance of transplanted Aus rice. *American– Eusasian Journal of Agronomy* **2**(3): 138–143.

Mirza H, Md. Obaidulislam and Md. Shafiuddinbapari. 2008. Efficacy of different herbicides over manual weeding in controlling weeds in transplanted rice. *Australian Journal of Crop Science* **2**(1): 18–24.

Mishra B. (2007). *The Evolving Indian Wheat Sector*. In: Joint Indo–Australian Workshop on Marker assisted Breeding in Wheat. Delhi on 11–13 October 2007

Mishra JS, Rao AN, Singh VP and Kumar R. 2016. Weed management in major field crops.https://www.researchgate.net/publication/309771518.

Moomaw JC, Novero UP and Tauro AC. (1966). Rice weeds control in tropical monsoon climate–Prospects and Problems. *International Rice Commission* **16**(4): 1–16.

Mukherjee D and Singh RP. 2005. Effect of micro–herbicides on weed dynamics, yield and economics of transplanted rice. *Indian Journal of Agronomy* **50**: 292–295.

Mukhopadhyay SK, Ghosh BC and Maity H. 1971. Weed problems in upland rice and approaches to solve the problem by use of new herbicides. *Oryza* **8**(2): 267–274.

Naik KR 1994. *Effect of Weed Control Methods under Different Moisture Regime and Nitrogen Levels on Growth and Yield of Dwarf Wheat,* Ph.D) Theses submitted to JNKVV, Jabalpur.

Nandal DP, Hariom and Dhiman SD. 1999. Management of weeds with herbicides in transplanted rice. *Indian Journal of Weed Science* **31**(1&2): 75–77.

Nasimulbari Md. 2010. Effects of herbicides on weed suppression and rice yield in transplanted wetland rice. *Pakistan Journal of Weed Science* **16**(4): 349– 361.

Nath CP and Pandey PC. 2013. Evaluation of herbicides on grain yield and nutrient uptake in Rice (*Oryza sativa* L.). *Bioinfolet* **10**(1B): 282–287.

Owla ML, Nepalia V, Chouhan GS, Singh Dilip. 2015. Effect of fertility levels, nutrient sources and weed control on weed dynamics and yield of quality protein maize (*Zea mays*) and relative nitrogen and phosphorus uptake. *Indian Journal of Agronomy* **60**(2): 267–272.

Pandey AK, Prakash V, Singh RD and Mani VP. 2000. Effect of herbicide mixtures and cultural practices on maize and associated weeds under midhills of N–W Himalayas. *Annals of Agricultural Research* **21**(1): 58–64.

Pandey AK, Prakash V, Singh RD and Mani VP. 2001. Integrated weed management in maize. *Indian Journal of Agronomy* **46**: 260–265.

Pandey AK, Singh Prem Prakash Ved , Singh, RD and Chauhan VS. 1999. Direct and residual effect of weed control measures in maize (*Zea mays*) and wheat (*Triticum aestivum*) cropping system under mid–hill conditions of N–W Himalayas. *Indian Journal of Weed Science* **31**(3&4): 204–209.

Pandey J and Singh RP. (1994). Effect of sulphonyl urea herbicides on weed control in wheat. *Indian Journal of Agronomy* **39**(4): 565–568.

Panwar RS, Katyal G, Malik RK and Pahuja SS. 2000. Effect of diclofopmethyl alone and in combination with other herbicides on weed control in wheat. *Indian Journal of Weed Science* **32**: 83–85.

Panwar RS, Malik RK and Rathi SS. 1996. Effect of tralkoxydix and its combination with other new herbicides on the control of weeds in wheat *Indian Journal of Agronomy.* **41**(3): 401–405.

Parker C. 1968. Weed problems in India, West Pakistan and Ceylon. *PANS* 14: 217–228.

Parthipan T and Ravi P. 2016. Productivity of transplanted rice as influenced by weed control methods. *African Journal of Agricultural Research* **11**(16): 1445–1449.

Patel MC. 1989. *Effect of chemical weed control under different dfferentp1antrrg geometry and sowing dates on growth and sink potential of dwarf wheat WH 147.* Ph. D. Thesis submitted to JNK *V,* Jabalpur.

Patel VJ, Upadhyay PN, Zala SV and Patel BD. 2006 Residual effect of herbicide applied as alone and mixture to *kharif* maize on succeeding *rabi* oat and mustard. *Indian Journal of Weed Science* **38**(3–4): 258–262.

Patil S, Halepyati AS, Chittapur BM, Swamy M. 2016. Influence of weed management practices on growth, yield, nutrient uptake and economics of baby corn *(Zea may* L.). *Journal of Farm Sciences.* **29**(1): 23–27.

Patra AK, Halder J and Mishra MM. 2011. Chemical weed control in transplanted rice in Hirakud command area of Orissa. *Indian Journal of Weed Science* **43**(3&4): 175–177.

Patra AK, Haldar J and Tripathy SK. 2006. Chemical weed control in transplanted rice in Hirakud Command Area. *Annals of Agricultural Research New Series* **27**: 385–388.

Pinto ET. 1978. Evaluation trials with the herbicide stomp 330 E in maize. In *Proceedings II Simposio National de Heerbologia Oeiras Vol.II* 311–320 *Weed Abstract* **27**(50): 1472.

Punia SS, Sharma SD, Malik RS and Singh S. 2005. Evaluation of carfentrazone alone and in combination with metsulfuron against broadleaf weeds in wheat. pp. 50–51. In: *Extended Summaries of National Biennial Conference,* Indian Society of Weed Science, April 6–9, 2005 held at PAU, Ludhiana, India.

Rai RN and Yadav YS. 1973. Control of weeds in maize crop. pp. 36–37. In: *Annual Report* Consolidated of soil conservation research demonstration and training centres, S&A, Dehra Dun.

Raju RA and Reddy MN. 1995. Performance of herbicide mixture for weed control in transplanted rice. *Indian Journal of Weed Science* **27**: 106–107.

Ramana AV, Naidu GS and Lakshmi MB 2008. Effect of some new herbicides in rainfed upland rice (*Oryza sativa*). *The Andhra Agriculture Journal* **55**(2): 141–143.

Ramesha YM, Bhanuvally M, Gaddi AK, Krishamurthy D and Umesh MR 2017. Efficacy of herbicides against weeds in transplanted Rice (*Oryza sativa* L.). *International Journal of Plant and Soil Science* **18**(1): 1–8

Ramphoolpuniya PC, Bishot and DK Singh 2007. Nutrient update by crop and weeds as influenced by Trisulfuran, Trisulfuran + pretilachlor and bensulfuran-methyl in transplanted rice (*Oryza sativa* L.). *Indian Journal of Weed Science* **39**(3&4): 239– 240.

Randhawa PS, Singh D and Dhillan SS. 1981. Relative performance of different herbicides in controlling weeds in wheat *Journal of Research - Punjab Agricultural University.* **18**(1): 1–3.

Ranjan MS and Mahapatra 1C (1979). Relative efficiency of nitrogen management and weed control under two systems of rice cultivation. *Oryza* **16**(2): 137–139.

Rao DVS, Kona GRSS and Garg OK 1988. Effect of pre–emergence application of atrazine on weed control in maize (*Zea mays* L. var. Ganga Safed–2). *The Andhra Agricultural Journal*. **35** (l&2): 152–53.

Rapparini G 1989. Chemical weed control in maize without using atrazine. *Informatore Agrario* **45**: 143–190.

Ray TB 1984. Site of action of Chlorsulfuron. *Plant Physiology* **75**: 827–831.

Ray BC, Bhattacharya, SP and Mukhezjee A K. 1996. Efficiency of sulfonyl urea herbicides in controlling weeds of wheat. *Environment and Ecology* **14**(3): 646–650.

Sah A, Ansari AM and Ahmad E. 2012. Effect of herbicides on weeds, yield attributes, yield and economics of transplanted rice (*Oryza sativa* L.). *Progressive Agriculture* **12**(2):337 –343.

Sahora MS and Singh HG 1970. Effect of increasing levels of triazine herbicides on weed control in maize and residual effect on wheat. *Indian Journal of Weed Science* **2**(2): 97–104.

Saini JP 2000. Efficacy of atrazine as post–emergence herbicide for weed control in maize *(Zea mays)* under rainfefconditions. *Indian Journal of Agricultural Sciences* **70**(11): 801–803.

Saini JP 2003. Efficacy of cyhalofop–butyl against weeds in direct seeded puddled rice under mid hill conditions of Himachal Pradesh. *Indian Journal Weed Science.* **35**(3&4): 205–207.

Saini JP and Singh KP 2001. Efficacy of new herbicides against grass weeds in wheat *(Triticum aestivum)* under mid hill conditions of Himanchal Pradesh. *Indian Journal of Agronomy* **46**(2): 233–238.

Sandhu KS, Singh T and Singh S 1999. Weed composition of maize *(Zea mays)* fields in Punjab. *Indian Journal of Weed Science* **31**(1&2): 18–24.

Sangwan N, Panwar RS and Malik RK 1991. Effect of various herbicides on the nutrient uptake by weeds in winter maize. *Pestology* **15**(6): 12–14.

Saha S and Rao KS 2010. Evaluation of bensulfuron methyl for weed control in wet direct–sown summer rice. *Oryza,* **47**(1): 38–41.

Shahbaz *et al.,* 2007. Weed management in direct-seeded rice crop. *Pakistan Journal of Weed Science and Research* **13**(3–4): 219–226.

Sharma SK and Gautam RC 2003. Effect of dose and method of atrazine application on no–till maize (*Zea mays* L.). *Indian Journal of Weed Science* **35**(1/2): 131–133.

Sharma SN, Bohra JS, Singh PK and Srivastav RK (2002). Effect of tillage and mechanization of production potential of rice–wheat cropping system. *Indian Journal of Agronomy* **47**(3): 305–310.

Sharma V and Thakur DR. 1998. Integrated weed management in maize (*Zea mays*) under mid–hill condition of north–western Himalayas. *Indian Journal of Weed Science* **30**(3&4): 158–162.

Shekhra *et al.* 2011. Growth and yield of Aerobic rice as influenced by integrated weed management practices. *Indian Journal of Weed Science* **42**(3&4): 180–183.

Sidhu MS, Kumar V and Gill GS 1975. Comparison of different herbicides and their effect on growth, yield and control of weeds in maize. *Indian Journal of Weed Science*. **7**(1): 21–27.

Singh V Partap, Guru SK, Kumar A, Banga Akshita, Tripathi Neeta. 2012. Bioefficacy of tembotrione against mixed weed complex in maize. *Indian Journal of Weed Science* **44**(1): 1–5.

Singh CM, Indrabi A and Kumar S 1989. Integrated weed management in maize. *Indian Journal of Weed Science* **20**(3): 101–103.

Singh G, Singh VP, Singh M and Singh SP. 2004. Effect of fenoxaprop–p–ethyl on transplanted rice and associated weeds. *Indian Journal of Weed Science* **35**: 119–120.

Singh S, Singh H, Narwal S and Malik RK 2003. Performance of herbicides in transplanted rice. *Indian Journal of Weed Science* **35**: 114–116.

Singh DP, Singh JNNK and Singh G. 1987. Efficacy of certain herbicides on weed control in maize and their residual toxicity estimated by bioassay. *Indian Journal of Weed Science*. **17**(3): 14–21.

Singh DK and Tewari AN. 2005. Effect of herbicides in relation to varying water regimes in controlling weeds in direct seeded puddled rice *Indian Journal. Weed Science* **37**: 193–196.

Singh P, Singh P, Singh R and Singh KN. 2007. Efficacy of new herbicides in transplanted rice under temperate conditions of Kashmir. *Indian Journal of Weed Science* **39**: 167–171.

Singh G, Bhushan LS, Koranne KD and Friesen, 1980. Time of applying selected herbicides for control of weeds in maize in Doon valley. *Indian Journal of Agronomy* **25**(1): 88–91.

Singh G, Singh VP and Singh M. 2004. Bio–efficacy of metribuzin and prometryn in wheat. *Indian Journal Weed Science* **36**: 178–180.

Singh G, Singh VP, Singh M and Singh SP 2003. Effect of anilofos and triclopyr on grassy and non–grassy weeds in transplanted rice. *Indian Journal. Weed Science* **35**(1&2): 30–32.

Singh G, Singh Y, Singh VP, Singh RK and Saxena A. 2002. Bioefficacy of herbicides in zero–till wheat in rice–wheat cropping system. *Indian Journal. Weed Science* **34**(1&2): 5–8.

Singh RG, Singh VP,Singh G and Yadav SK. 2001. Weed management studies in zero till wheat–rice cropping system. *Indian Journal. Weed Science* **33**(3): 95–99

Singh S, Kirkwood RC and Marshall G. 1996. Uptake, translocation and metabolism of 14C isoproturon in wheat, susceptible and resistant biotypes of *Phalaris minor* Retz. pp. 529–534. In: *Proceedings Second International Weed Control Congress*, Copenhagen, Denmark, 25–28 June.

Singh S, Malik RK, Balyan RS and Singh S. 1995. Distribution of weed flora of wheat in Haryana. *Indian Journal Weed Science* **27**: 114–121.

Singh Samar, Malik RK, Bishnoi LK and Singh Samunder. 1993. Effect of tank mixture of Isoproturon and Tralkoxydim on the control of *Phalaris minor* in wheat. *Indian Journal. Weed Science* **25**(3&4): 11–13.

Singh T. 2013. Weed management in irrigated wheat (*Triticum aestivum*) through tank mix herbicides in Malwa Plateau of Central India. *Indian Journal of Agronomy* **58**(4): 525–528.

Singh VP and Singh Govindra. 2001. Weed control studies in spring rice under rainfed low valley situation of Utranjal. *Indian Journal Weed Science* **33**(1&2): 52– 55.

Singh VP, Singh Govindra and Singh Mahendra. 2005a. Effect of bensulfuron–methyl (Londax 60 DF) on sedges and non–grassy weeds in transplanted rice. *Indian Journal Weed Science* **37**(1&2): 40–44.

Singh VP, Singh RP and Singh V. 2006. Integrated weed management in direct seeded rainfed low land rice. *Indian Journal Weed Science* **38**(1&2): 49–53.

Sinha MP and Sinha TD. 1970. Efficacy and economics of weedicides at different fertility levels in maize and their residual effect on suceeding wheat crop. *Indian Journal of Weed Science* **2**(2): 112–116.

Sinha SP, Prasad SM, Singh SJ and Sinha KK. 2001. Integrated weed management in winter maize (*Zea mays*) in North Bihar. *Indian Journal of Weed Science* **35**(3&4): 273–274.

Sirazuddin, Singh SP, Singh VP, Mahapatra BS and Verma, H. 2016. Effect of weed control measures on yield, weed control, economics, energetics and soil microflora under different establishment methods of Wheat (*Triticum aestivum L.*). *International Journal of Bio-resource and Stress Management* **6**(6): 736–743.

Sreenivas G and Satyanarayana V. 1994. Integrated weed management in rainy–season maize (*Zea mays*). *Indian Journal of Agronomy* **39**(1): 166–167.

Sunil CM, Sekara BG, Murthy KNK and Shankaralingappa BC. 2010. Growth and yield of aerobic rice as influenced by integrated weed management practices. *Indian Journal of Weed Science* **42**(3&4): 180–183.

Swapan Kumar Maity and Mukherjee PK. 2009. Integrated weed management practices in dry direct seeded summer rice. *Indian Journal of Agriculture Science* **79**: 976–979.

Swetha K, Madhavi M, Pratibha G and Ramprakash T. 2015. Weed management with new generation herbicides in maize. *Indian Journal of Weed Science* **47**(4): 432–433.

Takeda S, Sweetser TB, Erbes DL, and Yuyama T. 1985. Mode of selectivity of Londex herbicide (DPX–F5384) in paddy rice. pp. 156–161. In: *Proceedings of 10th Asian-Pacific Weed Science Society Conference*.

Thakur DR, Singh KK and Thakur RC. 1989. Effect of weed control and fertilizer levels on weed growth and grain yield of rainfed maize. *Indian Journal of Agronomy* **34**(1): 50–52.

Thakur S, Malik RK, Sangwan N and Tamak J. 1995. Performance of traloxydix and isoproturon against *Phalaris minor* in wheat *Agriculture Science Digest* **15**(3): 153–155.

Tomar SS, Bajpai RP, Bisen CR, Tiwari JP and Namdeo KN. (1983). ReactionReactiion of wheat varieties to herbicides. *Indian Journal of Weed Science* **15**(1): 45–50.

Vaid S, Daizy RB, Singh HP and Kohli RK. 2010. Phytotoxic effect of Eugenol towards two weedy species. *The Bioscan* **5**(3): 339– 341.

Vaishya RD and Singh SS. 1992. Evaluation of herbicides for weed control in winter maize. P. 8. In: *Proceedings of Annual Weed Science Conference*, Hissar March 3–4, 1992.

Varshney JG. 1990. Efficacy of atrazine with adjuvants on weed suppression in maize in mid hills of Meghalaya. *Indian Journal of Weed Science* **22**(1&2): 27–31.

Verma VS, Rathi JS, and Chouhan MS. (1975). Efficacy of herbicides in controlling weeds in wheat. *Indian Journal of Agronomy* **20**(2): 184–185.

Walia US, Singh Surjit and Singh Buta. Integrated control of hardy weeds in maize. 2007 (*Zea mays* L.). *Indian Journal of Weed Science* **39**(1&2): 17–20.

Walia US and Gill HS 1985. Interaction between herbicide and nitrogen in the control of *P. minor* in wheat. *Tropical Pest Management* **31**: 266–271.

Walia US, Brar LS and Mehra SP 1990. Interaction effect of nitrogen levels and weed control measures in wheat. *Indian Journal of Weed Science* **22**: 28–33.

Walia US, MS Bhular, Sholly Nayyar and SS Walia. 2008. Control of complex weed flora of post–emergence herbicides. *Indian Journal of Weed Science* **40**(3&4): 161–164.

Walia US, Brar LS and Dhaliwal BK 1997. Resistance to isoproturon in *P. minor* in Punjab. *Plant Protection Quarterly* **12**: 138–140.

Yadav A, Balyan RS, Garg VK and Malik RK 1996. Resistance against isoproturon in different biotypes of littleseed canary grass. Test of agrochemicals and cultivars No. 17 annals applied biology **128** (Supplement): 34–35.

Yadav A, Garg VK, Balyan RS and Malik RK 1995. Response of isoproturon resistant biotypes of littleseed canary grass to alternate herbicides. *Pestology* **19**: 12–14.

Yadav A, Malik RK and Balyan RS 1997. Studies on alternate herbicides to control isoproturon–resistant littleseed canary grass. *Pestology* **21**: 26–28.

Yadav A, Malik RK, Chauhan BS and Gill G. 2002. Present status of herbicide resistance in Haryana. pp. 15–22. In *proceedings of. International Workshop on "Herbicide Resistance Management and Zero Tillage in Rice–Wheat Cropping Systems"*. (Eds. Malik RK, Balyan RS, Yadav A and Pahwa SK), held on 4–6 March 2002 at CCSHAU, Hisar.

Yadav A, Malik RK, Dharamvir Banga, Malik RS and Kumar V. 2004. Effect of herbicides alone and in tank mixture against complex flora of weeds in wheat *Indian Journal of Weed Science* **36**: 31–33.

Yadav A, Malik RK, Pahwa SK and Bellinder RR 2004a. Evolution of triasulfuron alone and as tank mixture with clodinafop, fenoxaprop, sulfosulfuron or tralkoxydim against complex weed flora in wheat. *Indian Journal of Weed Science* **36**: 41–46.

Yadav DB, Yadav A, Punia SS and Chauhan BS 2016. Management of herbicide–resistant *Phalaris minor* in wheat by sequential or tank–mix applications of pre– and post–emergence herbicides in north–western Indo–Gangetic Plains. *Crop Protection* **89**: 239–247.

Yadav DB, Yadav A and Punia SS. 2009. Evaluation of bispyribac–sodium for weed control transplanted rice. *Indian Journal of Weed Science* **41**: 23–27.

Yadav DB, Punia SS and Yadav A. 2010. Efficacy of bispyribac–sodium, azimsulfuron and penoxsulam for post emergence weed control in transplanted rice. p. 65. In: *Biennial conference on "Recent Advances in Weed Science Research–2010"*, Feb. 25–26, 2010, Indira Gandhi Krishi Vishwavidyalaya, Raipur.

Chapter 7

Interception of weed species in quarantine and weed risk analysis

Mool Chand Singh*, S.C. Dubey and Sushil Kumar[1]
ICAR-National Bureau of Plant Genetic Resources, New Delhi 110 012
[1]ICAR- Directorate of Weed Research, Jabalpur, Madhya Pradesh 482 004
Email: mchsingh@gmail.com

Summary

The plant quarantine units of our National Plant Protection Organization conducts seed quarantine tests of incoming seed and grain materials to detect the weed seeds. While examining the seed samples for quarantine objects, a number weed species have been detected and out of them several weed species are not reported from India. The Weed Risk Analysis (WRA) scores reveal that all the intercepted exotic weed species have the potential to become serious weed in agriculture. It is evident that seeds of most of exotic weeds were viable even after long storage at normal temperature indicating their ability to grow and spread under field conditions. The observations indicated that import of grain and seeds for propagation as well as for consumption could be source of introduction of exotic weeds into India. In order to prevent the introduction of weeds, particularly the one that are problematic in related countries need to be subjected to weed risk analysis. Weed seeds in imported samples could be serious threat to the country if not detected. Relatively unknown potential of these weeds spreading to larger areas may turn to noxious and warrant study of their effect on the ecosystems besides effect on human and animal health. Critical quarantine examination of all the imported seeds is necessary to check the introduction of new weeds into the country. There is also an urgent need to design safeguards and strengthening of quarantine regulations to lower the risk of their entry.

Key words: Exotic weeds, Interception, Plant quarantine, weed risk analysis, Weed

Introduction

Seeds and vegetative materials are being imported to develop new varieties or to increase agricultural production. Import of plant material in bulk like food grains is always of high plant quarantine risk. Increasing trade and globalization coupled with liberalized policies further increase the risk of introduction of exotic weeds through bulk imports. This could lead to decrease in native biodiversity, reduced productivity of different ecosystems, reduced input-use efficiency and increased production cost. The main source of weed introduction is through imported grain, seeds and planting materials. The risk of introducing weeds to new areas through grain intended for processing or consumption is typically considered less than that from seed or plants for planting. However, within the range of end uses for grain, weed risk varies significantly and should not be ignored. In the field, weed seed contamination of grain crops is affected by factors such as country of origin, climate, biogeography and production and harvesting practices. As it moves toward export, grain is typically cleaned and the effectiveness and degree of cleaning are influenced by grain size, shape and density as well as by grade requirements. Weed seeds have been intercepted on many occasions from these bulk shipment (Muthaiyan *et al.* 1984). At the point of import to India, 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 central Government had imported nearly 63 lakh metric tons of wheat during 2006-07 from different countries in which 25 weed species were intercepted. The National Invasive Weed Surveillance (NIWS) team has traced five invasive weeds, which came to India through this wheat import (John 2009) The implementation of new policy on 'Seed Development' by the Government of India has provided stimulus for the import of seeds of various crops from all over the world. This has increased the risk for the introduction of exotic weeds into India. 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.

India is an overwhelming agrarian country hence, there is a paramount need to save the agricultural and horticultural economy of the country from the ravages caused by weeds. It is estimated that one third of oilseeds, half of the food grains and an equal amount of pulses produced currently are lost due to weeds. The potential yield losses due to weeds could be as high as 65% depending upon the crop, type of weed species, degree of weed infestation, and management practices (Yaduraju *et al.* 2006). Gharde *et al.* (2018) have estimated a whooping $ 11 billion loss per year in 10 major crops based. Our farmers are already struggling to control weeds in their cultivated fields. The problem will further aggravated, if exotic weeds are introduced into our country along with imports of food grains. How an exotic weed after entry can cause loss to a nation in terms of loss to yield production, health, environment and biodiversity or in terms of resources required for its management may be understood with the invasiveness of some of the weeds like *Parthenium hysterophorus, Eichhornia crassipes, Mikenia micrantha, Lantana camare, Chormolaena odorata etc.* in India? A study was done by Sushilkumar and Varshney (2010) on cost estimate of *Parthenium* management after its introduction into India in 1955 along with imported cereals. They estimated that *Parthenium* had invaded about 35 million hectare land in India after its introduction and for the management of *Parthenium,* two hand weeding or two chemical sprays are essentially required to get relief. They estimated that Rs 18200 and 11900 crores will be required per year to mitigate the problem by manual labour and chemical spray, respectively. The losses caused by this weed may be much higher if we take into consideration the cost involved in restoration of biodiversity and aesthetic value already lost due to *Parthenium.* An estimated 8000 species of plants are believed to behave as weeds in agriculture, out of which about 250 species are considered potentially dangerous (Westbrooks 1998). According to Holm *et al.* (1979), there are 975 serious and principal weeds in different parts of the world that have not been recorded or reported from India. Australia and New Zealand top the list with 195 weed species **(Table 1)**.

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

Country	No. of weed species	Country	No. of weed species
Australia, New Zealand	195	South America	102
African countries	181	Europe	80
South East Asia and Japan	150	Central America	33
Middle East	118	Russia	20

(Source: (Holm *et al.* 1979)

Table 2 Major weeds introduced into India

Weed species	Year of Introduction	Place of origin
Achanthospermum hispidim	1946	Central America/Brazil
Argemone maxicana	17th or 18th Century	Mexico/Central America
Eichhornia crassipes	1914 – 1916	Brazil
Euphorbia odoratum	1845	Jamaica
Lantana camera	1809	Central America
Parthenium hysterophorus	1951-1955	Central and S. America
Phalaris minor	1955-1960	Mexico
Salvinia molesta	1955 – 1958	South America

(Source: Yaduraju *et al.* 2003)

An utmost vigilance is required to prevent the introduction of exotic weeds, because after introduction, they may becomes a problem for years together. The weed seeds if introduced as admixture with useful seed material after adaptation may become noxious weeds of the cultivated as well as wastelands and affect the agricultural production and biodiversity. Some of the weed species which were introduced along with the imported agricultural commodities have spread menacingly in the country **(Table 2).**

How weeds are detected and identified in quarantine?

Seed material of different agri-horticultural crops imported from different countries are screened for the presence of weed seeds. All samples of different crops are examined for weed seeds by passing through sieves of different pore sizes. Then each sample is spread in a thin uniform layer on a clean white drawing sheet and examined under high magnification with the help of illuminated magnifier. Intercepted weed seeds are segregated into different types on the basis of their shape, size, colour, texture and presence of any attachment and are observed under stereoscopic binocular. Identification of weed seeds is done up to species level based on their morphological characters using Weed Identification Guide (Anonymous 1998) and with the help of Weed Seed Identification Kit developed by Academy of Grain Technology, Australia (Anonymous 1997). Other available information about weed identification are also used which have been developed elsewhere like Naidu (2012) developed information on identification of weeds based on seedlings. Weed species which cannot be identified on the basis of their morphological characters are subjected to grow out test in glass house in isolation and identified on the basis of their vegetative/floral characters (Nayar and Pandey 2009). All weed seeds are tested for their viability by wet blotter method in Petri dishes under strict plant quarantine conditions in germination room maintained at 25±2^0 C and 95±2% relative humidity (ISTA, 1985); and germination is counted on the seventh day.

Weed seeds intercepted in imported grain from time to time in India

To supplement the public distribution system and to control food grain price level in the country, the Indian Government imported food grains from different countries like Argentina, Australia, Canada and USA *etc*.

Weed seeds in wheat imported from USA

Wheat was imported from USA and part of the import was made through the port of Madras from October 1982 to March 1983. While inspecting the wheat for quarantine objects, it was observed that they were contaminated with a number of weed seeds (Muthaiyan *et al*. 1984). The account of weed seeds intercepted, their frequency, number, viability and fungi on some of these weeds is given in **Table 3**.

Table 3. Weed seeds intercepted, their frequency, number, viability and seed borne fungi on the weed seeds in wheat imported from USA

Weed species	Family	Frequency in 130 samples	No. of seeds in 130 samples	Viability (%)	Fungus
Agropyron repens	Poaceae	130	9793	11	*Drechslera cynodontis*
Amsinckia intermedia	Boraginaceae	30	40	00	-
Anthemis cotula	Compositae	17	397	06	-
Avena barbata	Poaceae	05	22	00	-
Avena fatua	Poaceae	60	225	08	*Drechslera sorokiniana*
Bromus diandrus	Poaceae	16	21	00	*Fusarium sp*
Bromus secalinus	Poaceae	112	1850	00	*Drechslera. sorokiniana*
Bromus tectorum	Poaceae	85	892	02	*Botrytis cinerea*
Camelina microcarpa	Cruciferae	50	70	00	*Botrytis cinerea*
Centaurea americana	Compositae	18	18	00	-
Cicuta maculata	Umbeliferae	50	70	00	-
Convolvulus arvensis	Convolvulaceae	98	192	00	-
Conringia orientalis	Cruciferae	33	82	01	*Phoma* sp.
Cynosurus echinatus	Poaceae	84	744	02	-
Dactylis glomerata	Poaceae	91	837	00	-
Digitaria sanguinalis	Poaceae	126	1685	00	-
Galium aparine	Rubiaceae	32	45	00	*Trichurus spiralis, Fusarium moniliforme, F. solani, F. dimerum*
Glaucium corniculatum	Papavaraceae	18	20	00	-
Kochia scoparia	Chenopodiaceae	79	474	17	-
Lathyrus hirsutus	Leguminaceae	46	74	04	*Phoma* sp.
Lepidium perfoliatum	Cruciferae	03	05	04	*Fusarium oxysporum*
Lithospermum arvense	Boraginaceae	28	40	00	-
Lolium temulentum	Poaceae	39	90	01	-
Medicago lupulina	Leguminaceae	04	10	04	-
Medicago denticulata	Leguminaceae	11	321	45	-
Melilotus officinalis	Leguminaceae	02	03	40	-

Weed species	Family	Frequency in 130 samples	No. of seeds in 130 samples	Viability (%)	Fungus
Melochia corcoriflora	Sterculiaceae	24	26	00	-
Oenothera laciniata	Onagraceae	130	2348	00	-
Panicum fasiculatum	Poaceae	89	443	10	*Fusarium moniliforme*
Plantago aristata	Plantigonaceae	78	251	00	*Trichoconiella podwickii,Botrydiplodia thiobromae*
Plantago rhodosperma	Plantigonaceae	101	294	02	*Botrydiplodia thiobromae*
Polygonum aviculare	Polygonaceae	128	2163	22	*Fusarium moniliforme*
Polygonum convolvulus	Polygonaceae	130	2376	10	-
Polygonum lapathifolium	Polygonaceae	29	59	00	*Fusarium senitectum*
Polygonum persicaria	Polygonaceae	28	109	00	-
Poa bulbosa	Poaceae	11	12	00	-
Rumex acetosella	Polygonaceae	65	477	36	*Drechslera.rostrata*
Salsola kali	Chenopodiaceae	07	11	00	-
Saponaria vaccaria	Caryophyllaceae	57	88	00	-
Silene conoidea	Caryophyllaceae	09	10	00	-
Sorghum almum	Poaceae	16	16	00	-
Sorghum halepense	Poaceae	111	662	00	*Curvularia ergrostidis,* *Phoma* sp., *Drechslera.rostrata*
Thlaspi arvense	Cruciferae	102	4857	00	*Conatobotrys simplex*
Trifolium pratense	Leguminaceae	28	109	00	*Phoma* sp.
Torilis anthriscus	Unbelliferae	27	41	00	-
Vaccaria pyramidata	Caryophyllaceae	08	11	08	*Embellisia abundans*
Vicia hirsuta	Leguminaceae	07	06	00	-
Vicia sativa	Leguminaceae	23	23	00	-
Vicia villosa	Leguminaceae	34	77	10	-

Weed seeds in wheat imported from Australia

Wheat was imported through different south Indian ports from Australia during February 1997 to October 1998. While examining the wheat samples from quarantine point of view, forty-two species of weed seeds were intercepted, out of which 41 were identified up to species level and one up to generic level. Among 41 species identified, 32 were exotic to India (Holm *et al*. 1979). Several weed seeds were found viable even after long storage of seeds. The imported wheat was sent to non-wheat growing areas only for milling purpose and the millers were advised for collecting and destroying the debris including weed seeds by burning to reduce plant quarantine risk (Moolchand *et al*. 2000). Particulars of weed seeds identified, their percentage incidence and viability is given in **Table 4**.

Exotic weed seeds in wheat imported from Turkey and Ukraine

During the year 1999, wheat was imported from Turkey and Ukraine through Chennai port under Open General License (OGL). While examining the wheat for

Table 4. Weed seeds intercepted in Australia wheat, their percentage incidence and viability

Weed species	English name	Family	Percent incidence		Viability (%)
			Wt. basis	No. basis	
Not reported from India					
Avena sterilis	Sterile oat	Poaceae	0.0072	0.012	25
Bifora testiculata	Bifora	Apiaceae	0.001	0.004	80
Brassica kaber	Charlock	Brassicaceae	0.003	0.015	30
Brassica tournefortii	Wild turnip	Brassicaceae	0.0054	0.031	20
Bromus diandrus	Great brome	Poaceae	0.0242	0.077	35
Carrichtera annua	Ward’s weed	Brassicaceae	0.005	0.023	40
Carthamus lanatus	Saffron thistle	Asteraceae	0.0762	0.008	58
Cenchrus pauciflorus	Sandbur	Poaceae	0.012	0.004	46
Centaurea melitensis	Maltese cockspur	Asteraceae	0.017	0.005	60
Echium plantagineum	Paterson’s curse	Boraginaceae	0.023	0.012	-
Emex australis	Spiny emex	Polygonaceae	0.004	0.004	-
Galium tricornutum	Bed straw	Rubiaceae	0.016	0.004	-
Heliotropium europeum	Heliotrope	Boraginaceae	0.0036	0.015	-
Lithospermum arvense	Corn gromwell	Boraginaceae	0.013	0.008	10
Lupinus angustifolius	Lupin	Fabaceae	0.124	0.015	80
Malva parviflora	Dwarf mallow	Malvaceae	0.005	0.038	30
Medicago scutellata	Snail medic	Papilionaceae	0.001	0.008	60
Neslia paniculata	Ball mustard	Brassicaceae	0.0014	0.004	-
Papaver hybridum	Rough poppy	Papaveraceae	0.015	0.019	-
Phalaris paradoxa	Paradoxa grass	Poaceae	0.002	0.015	60
Polygonum convolvulus	Bind weed	Polygonaceae	0.016	0.019	58
Polygonum lapathifolium	Knot weed	Polygonaceae	0.0007	0.008	20
Raphanus raphanistrum	Wild radish	Brassicaceae	0.051	0.031	60
Rapistrum rugosum	Turnip weed	Brassicaceae	0.009	0.038	30
Reseda lutea	Mignonette	Resedaceae	0.0007	0.015	-
Rumex crispus	Curled dock	Polygonaceae	0.0005	0.012	-
Salva verbenaca	Wild sage	Lamiaceae	0.0004	0.004	11
Sylibum marianum	Variegated thistle	Asteraceae	0.002	0.004	09
Sisymbrium officinale	Hedge mustard	Brassicaceae	0.002	0.019	10
Vicia villosa	Russian vetch	Papilionaceae	0.001	0.004	-
Vulpia bromoides	Fescue	Poaceae	0.009	0.004	32
Reported from India					
Asphodelus fistulosus	Onion weed	Liliaceae	0.001	0.015	20
Avena fatua	Wild oat	Poaceae	0.024	0.038	60
Eucalyptus sp	Eucalyptus	Myrtaceae	0.028	0.004	-
Lolium perenne	Rye grass	Poaceae	0.077	0.058	40
Medicago denticulate	Burr medic	Papilionaceae	0.005	0.015	80
Phalaris minor	Canary grass	Poaceae	0.001	0.003	72
Polygonum aviculare	Knot weed	Polygonaceae	0.0005	0.002	13
Sonchus oleraceus	Sawthistle	Asteraceae	0.002	0.036	15
Sorghum halepense	Johnson grass	Poaceae	0.0012	0.007	50
Tribulus terrestris	Puncture vine	Zygophyllaceae	0.0024	0.029	-
Vicia sativa	Vetch	Papilionaceae	0.008	0.024	55

(Source: Moolchand *et al.* 2000**)**

quarantine objects, a total of 22 types of weed seeds were intercepted. Out of these 21 were exotic to India and one was indigenous. Out of 21 exotic weed seeds, 8 were considered serious in nature. The frequency was found between 02 to 20 in 20

Table 5. Exotic weed seeds in wheat imported from Turkey and Ukraine

Weed species	Family	Frequency in 20 samples	Viability (%)	WRA score
Turkish wheat				
Agrostemma githago	Caryophyllaceae	07	20	07
Avena sterilis	Poaceae	20	80	11
Bifora testiculata	Apiaceae	02	00	03
Brassica kaber	Brassicaceae	20	80	03
Brassica tournefortii	Brassicaceae	20	90	07
Bromus diandrus	Poaceae	19	20	10
Carrichtera annua	Brassicaceae	03	35	04
Lolium temulentum	Poaceae	20	30	09
Neslia paniculata	Brassicaceae	05	00	06
Rumex crispus	Polygonaceae	06	02	07
Ukraine wheat				
Agrostemma githago	Caryophyllaceae	10	25	07
Amsinckia intermedia	Boraginaceae	17	30	07
Centaurea melitensis	Asteraceae	18	40	08
Galium tricorne	Rubiaceae	09	20	04
Lithospermum arvense	Boraginaceae	11	05	07
Polygonum lapathifolium	Polygonaceae	12	00	07
Raphanus raphanistrum	Brassicaceae	06	22	08
Reseda lutea	Resedaceae	05	60	09
Synapsis arvenses	Brassicaceae	03	00	06
Vicia villosa	Papilionaceae	20	80	03
Vulpia bromoides	Poaceae	02	10	07

(Source: Moolchand *et al.* 2003)

samples. The weed risk analysis scores reveal that 14 species have potential to become weed in India. Seventeen weed species were found viable even after long storage (Moolchand *et al*. 2003).

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.

Table 6. Weeds intercepted in imported seeds during 2012 to 2017 at ICAR-NBPGR, New Delhi

Weed intercepted	Crop	Country
*Anthemis cotula**	Barley	ICARDA (Syria)
*Avena sterilis**	Wheat	USA
*Avena barbata**	Wheat	USA
*Bifora testiculata**	Wheat	Australia, Mexico, USA
*Carrichtera annua**	Barley	ICARDA (Syria)
Cenchrus pauciflorus	Barley & Maize	Chile, ICARDA (Syria)
Centaurea calitrapa	Carrot	Chile
*C. maculosa***	Coriander	Russia
*C. solstitialis***	Coriander	Russia
*Convolvulus erubescens**	Barley	Morocco
*Cichorium pumilum***	Berseem	Uzbekistan
Echinochloa crusgalli	Paddy	China
*E. crus-pavonis***	Paddy	China
*Fallopia convolvulus**	Barley	Morocco
Galium aparine	Barley	Lebanon
*G. boreale**	Barley	ICARDA (Syria)
*G. tricornutum**	Barley	Lebanon
*G. trifidum**	Barley	ICARDA (Syria)
*Ipomoea hederacea**	Barley	ICARDA (Syria) ,USA
Melilotus alba	Methi	ICARDA (Syria)
*Ostrya virginiana**	Barley	ICARDA (Syria)
*Phalaris arundinacea**	Barley	ICARDA (Syria)
*P. paradoxa**	Wheat	ICARDA (Syria) ,USA
Polygonum aviculare	Wheat	France
*P. cilinode**	Linseed	Switzerland
*P. cuspidatum***	Barley & Wheat	Morocco, Poland
*P. lapathifolium**	Paddy	China
P. convolvulus	Barley, Wheat	ICARDA (Syria), USA
P. hydropiper	Lentil	ICARDA (Syria)
*P. hydropiperoides**	Linseed	Switzerland
*P. persicaria**	Barley	ICARDA (Syria)
P. lapathifolium	Linseed	Switzerland
*Ranunculus bulbosus**	Barley	ICARDA (Syria)
*Raphanus raphanistrum**	Wheat	Australia
*Rumex crispus**	Wheat	ICARDA (Syria) ,USA
*Salsola vermiculata***	Lentil	Canada
*Silene noctiflora**	Lucerne & Mustard	Netherlands, Switzerland
*Taraxacum otticinale**	Barley	ICARDA (Syria)
*Trifolium pretense**	Methi	ICARDA (Syria)
Vicia angustifolia, V. tetrasperma,*V. villosa*	Lucerne	Switzerland

*Weed species not reported from India ** Weed species listed in Plant Quarantine (regulation of Import into India) Order 2003

Weed risk analysis (WRA)

Weed risk analysis is a question based scoring system, containing several questions about the weed species. The questions include details of the plant's climatic preferences, biological attributes, reproduction and dispersal methods. A minimum number of questions must be answered before an assessment is made. The WRA uses responses to the questions to generate a numerical score that is positively correlated with the weediness (Groves *et al*. 2001).

Methodology of weed risk analysis (WRA)

The WRA system is designed to run on Microsoft Excel 2007 in MS Windows operating system. The basis of the WRA is to answers 49 questions based on the main attributes and impacts of weeds. These are combined into scoring system, which in the absence of any evidence to the contrary, gives an equal weight to nearly all questions. These cover a range of weedy attributes in order to screen for plants that are likely to become weeds of an environment and/or agriculture. The questions are divided into three sections producing identifiable scores that contribute to the total score. Most questions are answered, as yes, no or don't know. Biogeography consists the documented distribution, climate preferences, history of cultivation, and weediness of a plant elsewhere in the world, i.e. apart from the proposed recipient country. Weediness elsewhere is a good predictor of a plant becoming a weed in new areas with similar environmental conditions (Forcella and Wood 1984). The questions concerning the history of cultivation recognizes the important human component of propagule pressure (Williamson and Fitter 1996), but such data are obviously never available for the proposed new country. The global distribution and climate preferences, where these are available, are used to predict a potential distribution in the recipient country.

Undesirable attributes are characteristics such as toxic fruits and unpalatibility, or invasive behavior, such as a climbing or smothering growth habit, or the ability to survive in dense shade. Biology and ecology are the attributes that enable a plant to reproduce, spread and persist (Noble 1989) such as whether the plant is wind dispersed or animal dispersed, and whether the seeds would survive through passage of an animal's gut. Availability of information is often very limited for new species which can restrain the utility of screening systems. To ensure that at least some questions were answered for each section, the WRA system requires the answer to two questions in Section-A, two in Section- B and six in Section-C before it will give an evaluation and recommendation. The recommendation can be compared with the number of questions, answered as an indication of its reliability which obviously improves as more questions are answered. Answers to the questions provide a potential total score ranging from 0 to 29 for each plant. The total score is partitioned between answers to questions considered to relate primarily to agriculture, to the environment, or common to both. The plants which have score between 0-6 are non-weeds, 7-11 are common weeds and those having > 12score, are serious weeds (Singh *et al*. 2010).

Quarantine weeds for India

Government of India has strengthened the existing system and brought into force, the new Plant Quarantine (Regulation of Import into India) Order 2003. Enforcement of this order is mainly intended to prevent the introduction and spread of exotic pests that are destructive to the country. According to the special provisions for Quarantine weeds (clause 3(12) and (Schedule VIII) of Plant Quarantine (Regulation of Import into India) Order 2003, no consignment of seed or grain contaminated with Quarantine weeds shall be permitted unless devitalized.

Thirty-one weed species, which are listed in Schedule VIII are *Allium vineale, Ambrosia maritima, Ambrosia psilostachya, Ambrosia trifida, Apera-spica-venti, Bromus secalinus, Cenchrus tribuloides,Centaurea diffusa, Centaurea maculosa, Centaurea solstitialis, Cichorium pumilum, Cichorium spinosum, Cordia curassavica, Cuscuta australis, Cynoglossum officinale, Echinochloa crus-pavonis, Froelichia floridana, Helianthus californicus, Helianthus ciliaris, Heliotropium amplexicaule, Leersia japonica, Matricaria perforatum, Polygonum cuspidatum, Proboscidea lovisianica, Salsola vermiculata, Senecio jacobaea, Solanum carolinense, Striga hermonthica,Thesium australe, Thesium humiale* and *Viola arvensis.*

Conclusion

Import interception data presented here shows that all imported grain and seed commodities sampled were a source of associated weed contaminants. The observations indicated that import of grain and seeds for propagation as well as for consumption could be source of introduction of exotic weeds into India. In order to prevent the introduction of weeds, particularly the one that are problematic in related countries need to be subjected to weed risk analysis. Weed seeds in imported samples could be serious threat to the country if not detected. Relatively unknown potential of these weeds spreading to larger areas may turn to noxious and warrant study of their effect on the ecosystems besides effect on human and animal health. Critical quarantine examination of all the imported seeds is necessary to check the introduction of new weeds into the country. There is also an urgent need to design safeguards and strengthening of quarantine regulations to lower the risk of their entry.

References

Andow DA. 2003. Pathways-based risk assessment of exotic species invasions. pp. 439–455. In: *Invasive species: vectors and management strategies*, (Eds. Ruiz GM and Carlton JT), Island Press, Washington.

Anonymous. 1997. *Weed Seed Identification Kit*. Academy of Grain Technology, Australian Wheat Board, Victoria, Australia.

Anonymous. 1998. *Weed Identification Guide*. Southern Weed Science Society, USA.

Forcella, F and Wood TJ. 1984. Colonization potentials of alien weeds are related to their native distribution- implications for plant quarantine. *Journal of Australian Institute of Agricultural Science* **50**: 35–41.

Groves RH, Penetta FD and Virtue JG. 2001. *Weed Risk Assessment*. CSIRO Publishing, 150, Oxford Street, P O Box 1139, Collingwood, VIC 3066, Australia.

Holm L, Pancho JV, Herberger JP and Plucknett DL. 1979. *A Geographical Atlas of World World Weeds*. John Wiley & Sons, New York.

Joseph John, 2009. Wheat import mixed blessing, hunt on for invasive weeds. *Indian Express,* September 25, 2009.

Moolchand, Rajak RK, Radhey Shyam, Reddy OR, Vijaykuma CSK and Indira M. 2000. Interception of weed seeds in wheat imported from Australia. *Indian Journal of Weed Science* **32**(3&4): 210–212.

Moolchand, Upadhyay RK and Reddy OR. 2003. Exotic weed seeds in wheat imported from Turkey and Ukraine. *Annals of Agriculture Science Research* **24**(3): 689–692.

Moolchand, Lal B, Agarwal PC, Pandey A, Joshi KD, Chand D and Khetarpal RK. 2010. Weed seeds intercepted in *Trifolium* spp. germplasm imported from USA and Egypt. *Indian Journal of Plant Genetic Resources* **23**(1): 136–140.

Moolchand and Priyadarshi MB. 2014. Predicting invasive plants using weed risk assessment. *Indian Journal of Weed Science* **46**(1): 91–95

Muthaiyan MC, Sridevi and Kumarasamy M. 1984. Weed seeds in wheat imported as food grain. *Plant Protection Bulletin* **36**: 87-90.

Nayer ER and Pandey A. 2009. Detection and identification of weeds in quarantine. In: *Training Manual on Biosecurity*

Noble IR. 1989. Attributes of invaders and the invading process: terrestrial and vascular plants. pp. 301–310. In*: Biological Invasions: A Global Perspective* (Eds. JA Drake, HA Mooney, FD Castri, RH Groves, FJ Kruger, M Rejmanek and M Williamson). Chichester: John Wiley

PQ Order 2003. *Plant Quarantine* (regulation of Import into India) Order 2003. Department of Agriculture, Cooperation & Farmers Welfare, Ministry of Agriculture & Farmers Welfare, Govt. of India.

Sushilkumr and Varshney Jay G. 2010. Parthenium infestation and its estimated cost management in India. *Indian Journal of Weed Science* **42**(1&2): 73–77.

Weber E. 2003. Invasive plant species of the world: a reference guide to environmental weeds. *CABI Publishing, Wallingford* (2003). 548p.

Westbrooks R. 1998. Invasive plants, Changing the Landscape of America: Fact Book: *Federal Interagency committee for the Management of Noxious and Exotic Weeds,* Washington, D.C. 109 p.

Williamson M and FitterX FD. 1996. The characteristics of successful invaders. *Biological Conservation* **78**: 163-170.

Yaduraju NT and Moolchand. 2001. Weeds of plant quarantine significance for India. pp 57–61. In: Proceedings of First Biennial Conference in the New Millennium on Weed Science. UAS, Bangalore, May 23-24, 2001.

Yaduraju NT, Prasadbabu MBB and Gogoi AK. 2003. Green Invaders-A growing threat to agriculture and environment. pp. 1–9. In: Proceedings of National Seminar on Alien Invasive Weed in India. Assam Agricultural University, Jorhat, April 27-29, 2003.

Yaduraju NT, Prasadbabu MBB and Chandla P. 2006. Herbicide Use. pp. 192–210. In: *Agriculture and Environment*. (Eds. Swaminathan MS and Chadha KL). Malhotra Publishing House, New Delhi, India.

Chapter 8

Weed management research in pulses and oilseeds in India

J.S. Mishra
ICAR Research Complex for Eastern Region, Patna, Bihar 800 014
Email: jsmishra31@gmail.com

Summary

Weeds are one of the major deterrents in sustaining the productivity of pulses and oilseeds in India. They compete with crop for nutrients, soil moisture, sunlight and space and reduce the yield by 15 to 60%. The initial duration of 15-60 days is very critical for weeds competition. Different methods of weed management in pulses and oilseeds including preventive, cultural, mechanical, and chemical are being used with varying degree of success. Considering the diversity of weed problem, no single method, whether manual, mechanical or chemical could reach the desired level of efficiency under all situations. Hence, the most promising single approach to manage weeds combines manual, cultural and mechanical methods with herbicides. Research on weed management in pulses and oilseeds in India is more than five decades old. In this chapter, an attempt has been made to compile the research work done in India on various aspects of weed management in major pulses and oilseed crops in the last 50 years.

Key words: Crop-weed competition, Herbicides, Losses, Oilseeds, Pulses, Weeds

Introduction

Weeds continue to have major impact on crop production in spite of efforts to eliminate them. Weed problems vary according to crop, region and soil type. Most of the area under pulses and oilseeds is rainfed/dryland. Weeds compete with the crop plants for soil moisture and nutrients, which are the most limiting factors for growth under such situation. When improved agricultural technologies are adopted, efficient weed management becomes even more important, otherwise the weeds rather than the crop benefit from the costly inputs. Among pulses, pigeonpea, greengram, blackgram and cow pea are rainy season crops; however, these are also grown during summer under assured irrigation facilities in quick succession of potato and *rai* crops. Chickpea, field pea, lentil, lathyrus and rajmash are grown during winter both under rainfed and irrigated eco-systems. In some parts of Madhya Pradesh, Chhatishgarh, Andhra Pradesh, lentil, lathyrus and blackgram are also grown as *utera* in late paddy–fallow system. In oilseeds, soybean, groundnut, sesame, niger and castor are grown mainly during rainy season, and rape-seed mustard, linseed, sunflower and safflower are grown during winter. Pulses and oilseeds are mostly grown as inter/ mix cropping system to avoid risk of weather vagaries and utilizing land resources effectively.

Research on weed management in pulses and oilseeds in India is more than five decades old. Earliar mostly cultural and mechanical methods of weed control were compared for their weed control efficiency at the regional research stations, started by State Government. During this period relative feasibility, efficiency and economics of various herbicides were evaluated. However, the overall impact of the research remained marginal. The systematic research in weed control was started since 1978 through the All India Coordinated Research Project on Weed Management (AICRP-WM) Scheme by ICAR in collaboration with USDA.

Weed survey

Survey of weed flora in different crops including pulses and oilseeds was one of the major activities of AICRP-WC programme. With the establishment of AICRP WC centres in State Agricultural Universities in different agro-ecological regions in a phased manner, weed survey in almost all the oilseeds and pulses was conducted across different agro-ecological regions. Based on the weed survey reports, the existing weeds in pulses and oilseeds of different seasons have been grouped as below (**Table 1**).

Trianthema portulacastrum is the most serious problem during monsoon and spring/summer seasons through out the country. In some parts of the country under unirrigated conditions, *Pluchea lanceolata* and *Carthamus oxyacantha* are very serious weeds in pulses. The seeds of *Lathyrus aphaca, Vicia sativa* and *V. hirsuta are* such in shape and size that their separation from produce of lentil, chickpea and field pea is difficult and are serious problem in seed production and processing of these crops. *Saccharam spontaneum* and *Asphodelus tenuifolius* are also posing serious threat in chickpea and mustard cultivation in Bundelkhand region of Uttar Pradesh, south Haryana, northern and central Madhya Pradesh. *Cichorium intybus, Medicago denticulata* and *Convolvulus arvensis* are also the

Table 1. Major weeds in pulses and oilseeds

Nature of weeds	Scientific name	Common name	Family
Rainy season			
Annual grasses and sedges	*Echinochloa colona* (L.) Link	Jungle rice	Poaceae
	Echinochloa crus-galli (L.) Beauv.	Barnyard grass	Poaceae
	Eleusine indica (L.) Gaertn.	Goose grass	Poaceae
	Dactyloctenium aegyptium (L.) Willd.	Crowfoot grass	Poaceae
	Digitaria sanguinalis (L.) Scop.	Large crabgrass	Poaceae
	Setaria glauca (L.) Beauv.	Yellow foxtail	Poaceae
	Panicum maximum Jacq.	Guinea grass	Poaceae
	Cyperus spp.	Nut grass	Cyperaceae
	Fimbristylis spp.	Globe fingerush	Cyperaceae
	Scirpus grosus L.	*Murak*	Cyperaceae
Broad-leaf weeds	*Trianthema portulacastrum* L.	Carpet weed	Aizoaceae
	Physalis minima L.	Ground cherry	Solanaceae
	Amaranthus viridis L.	Slender amaranth	Amaranthaceae
	Cleome viscosa L.	Cleome	Capparidaceae
	Celosia argentia L.	Cock's Comb	Amaranthaceae
	Commelina benghalensis L.	Day flower	Commelinaceae
Perennials	*Cyperus rotundus* L.	Nut grass	Cyperaceae
	Cynodon dactylon (L.) Pers.	Bermuda grass	Poaceae
	Sorghum halepense (L.) Pers.	Johnson grass	Poaceae
	Saccharum spontaneum L.	Tiger grass	Poaceae

Nature of weeds	Scientific name	Common name	Family
Winter season			
Annual grasses	*Phalaris minor* (L.) Retz.	Littleseed canary grass	Poaceae
	Avena sterilis spp. *ludoviciana* (L). Dur.	Wild oat	Poaceae
	Poa annua L.	Annual blue grass	Poaceae
	Polypogon monspeliensis (L.) Desf.	-	Poaceae
	Lolium temulentum L.	Rye grass	Poaceae
Broad-leaf weeds	*Chenopodium album* L.	Common lambsquarters	Chenopodiaceae
	Melilotus alba Medicus	White sweet clover	Fabaceae
	Spergula arvensis L.	Corn spurry	Caryophyllaceae
	Carthamus oxyacantha Bieb.	Wild safflower	Asteraceae
	Gnaphalium indicum L.	Cud weed	Asteraceae
	Pluchea lanceolata Oliv.	Arrowwod	Asteraceae
	Launia nudicaulis H.K.	-	Asteraceae
	Melilotus indica (L.) All.	Yellow sweet clover	Fabaceae
	Lathyrus aphaca L.	Wild pea	Fabaceae
	Convolvulus arvensis L.	Field bindweed	Convolvulaceae
	Anagallis arvensis L.	Scarlet pimpernel	Primulaceae
	Asphodelus tenuifolius Cav.	Wild onion	Liliaceae
	Medicago denticulata Willd.	Bur clover	Fabaceae
	Rumex dentatus L.	Wood sorrel	Polygonaceae
	Fumaria parviflora Lamk.	Fumitory	Fumariaceae
	Vicia sativa L.	Common vetch	Fabaceae
	Vicia hirsuta L.	Common vetch	Fabaceae
	Coronopus didimus (L.) Sm.	Swinecress	Cruciferae
	Solanum nigrum L.	Black nightshade	Solanaceae
Perennials	*Cirsium arvense* (L.) Scop.	Canada thistle	Asteraceae
	Cyperus rotundus L.	Nut grass	Cyperaceae
	Cynodon dactylon (L.) Pers.	Bermuda grass	Poaceae
	Saccharum spontaneum L.	Tiger grass	Poaceae
Parasitic weeds	*Cuscuta* spp.	Dodder	Convolvulaceae
	Orobanche spp.	Broomrape	Orobancheaceae
Spring/summer season			
Annual grasses and sedges	*Cynodon dactylon* (L.) Pers.	Bermuda grass	Poaceae
	Digitaria sanguinalis (L.) Scop.	Large crabgrass	Poaceae
	Eleusine indica (L.) Gaertn.	Goose grass	Poaceae
	Setaria glauca (L.) Beauv.	Yellow foxtail	Poaceae
	Panicum maximum Jacq.	Guinea grass	Poaceae
	Cyperus rotundus L.	Nut grass	Cyperaceae
Broad-leaf weeds	*Trianthema portulacastrum* L.	Carpet weed	Aizoaceae
	Amaranthus viridis L.	Slender amaranth	Amaranthaceae
	Portulaca quadrifida L.	Purselane	Portulacaceae
	Physalis minima L.	Ground cherry	Solanaceae
	Solanum nigrum L.	Black nightshade	Solanaceae

emerging problematic weeds in winter pulses and oilseeds. *Cuscuta* is another important parasitic weed causing a lot of damage in mungbean and urdbean in coastal Andhra Pradesh, Tamil Nadu and parts of Madhya Pradesh. The reports of its infestation are also available in other pulses like chickpea and lentil and oilseeds like niger and linseed. Similarly, *Orobanche* is severely damaging the mustard crop in rainfed areas of Rajasthan and Haryana.

Crop-weed competition and losses

Weeds compete with the crops for nutrients, moisture, sunlight and space and cause serious damage to crop in terms of yield and quality. Weed competition depends greatly on nature and intensity of weed flora, soil type, agroclimatic conditions and management practices. Pulses, being poor competitor to weeds especially during initial growth stages, suffer considerable yield loss. Ali and Lal (1989) reported that among various production inputs, weed management was found to be the most important, contributing 30.9 per cent in pigeonpea, 109.7 per cent in urdbean and 60 per cent in mungbean towards total productivity. In chickpea, weed management contributed maximum followed by fertiliser use and insect pest and disease control. Sekhon *et al.* (1993) reported that un-weeded check caused 29, 48, 34, 41 and 61% losses in the grain yield of pigeonpea, mungbean, urdbean, field pea, chickpea and lentil, respectively. The potential yield loss varies from 18 to 90% depending upon the growing conditions, crop species and management practices and the total loss in pulses under conventional practices have been worked out to be 739.8 thousand tonnes valued at ` 3251.10 millions (Sahoo and Saraswat 1988). Weeds indirectly reduce the yield potential by serving as alternate host to a number of crop pests, *e.g., Vicia sativa* in chickpea provides shelter to *Helicoverpa armigera*, a major pest of chickpea (Chauhan *et al.* 1991). Paradker *et al.* (1993 and 1997) reported *Cichorium intybus* as the most competitive weed in chickpea followed by *Phalaris minor*. A density of 50 weeds/m^2 of *C.intybus* caused 56.8% reduction in seed yield of chickpea. Mishra *et al.* (1997) observed that density of *Vicia sativa* even at 30/m^2 caused significant reduction in lentil yield. Competitive impact of *Phalaris minor* on *Rabi* pulses and oilseeds reveled greater competetional stress was in chickpea followed by linseed, safflower and peas. During *Kharif* season *Echinochloa* spp. caused greater competitive stress in soybean (57.4%), pigeonpea (46.9%) and blackgram (45.7%) (AICRP- WC 1997-98). Weeds in soybean depleted the soil fertility by taking 53.24 kg N and 9.30 kg P/ha under unweeded check (Chhokar *et al.* 1997). Yield loss due to weeds ranges from 20 to 85% depending on crop cultivars, nature and intensity of weeds, spacing, duration of weeds infestation and environmental conditions (Tiwari and Kurchania 1990, Tiwari *et al.* 1996, Singh and Singh 1992). In India, Mishra and Singh (2001) found that Ivyleaf mornigglory (*Ipomoea hederacea*) even at 1/m^2 reduced the soybean yield by 44%. Presence of 5 to 80 *Commelina communis*/m^2 caused 10.6 to 58.4% reduction in seed yield (Mishra *et al.*, 2002). *Euphorbia geniculata*, another major weed of soybean reduced its seed yield by 12-30% with increasing densities from 10-120 plants/m^2 (Mishra and Singh 2003).

The initial duration of 15-60 days is very critical for weeds competition and therefore, any kind of weed-control measure that could be effective for controlling weeds during this period should be adopted (Bhan *et al.* 1974, Dahiya 1979, Varshney 1989, Chhokar *et al.* 1995). The critical period varies from 15-30 days after sowing (DAS) in greengram, blackgram and cowpea; 15-45 DAS in sunflower, sesame and rapeseed-mustard; 30-45 DAS in peas; 20-45 DAS in soybean; 30-60 DAS in castor, lentil, chickpea, frenchbean, and groundnut and 15-60 DAS in pigeonpea depending upon nature and intensity of weed flora, agro-climatic situations and management practices (Mishra 1997). The critical period of crop-weed competition and yield losses in different pulses and oilseeds are given in **Table 2**.

Table 2. Critical period of crop-weed competition and yield losses and nutrient depletion due to weeds

Crops	Critical period (Days after sowing)	Average yield reduction (%)
Pulses		
Pigeonpea	15-60	20-40
Greengram	15-30	30-60
Blackgram	15-30	30-50
Cowpea	15-30	30-50
Chickpea	30-60	15-25
Peas	30-45	20-30
Lentil	30-60	20-30
Oilseeds		
Soybean	20-45	40-60
Groundnut	40-60	40-50
Sunflower	30-45	30-50
Castor	30-60	30-35
Safflower	15-45	35-60
Sesamum	15-45	15-40
Rapeseed-mustard	15-40	15-30
Linseed	20-45	30-40

Source: Mishra (1997), Gautam and Mishra (1995)

Weed management practices

Cultural

Stale seedbed technique: A stale seedbed technique is one where successive flushes of weeds are destroyed before planting of any crop and therefore, less number of weeds is expected to interfere with the crop. Where light rains occur for an extended period before the onset of monsoon or irrigation is available, it may be possible to kill several flushes of weed growth before planting. Stale seedbed was found more effective in reducing weed population in soybean (Jain *et al.* 1990 and Jain *et al.* 1995).

Use of weed competitive crops and cultivars: Crops differ in relative growth rate, spreading habit, height, canopy structure and inherent competitive characters and accordingly differ in their weed suppressing ability. A quick growing and early canopy producing crop would be expected to be better competitors against weeds than crops and cultivars lacking these characters. In peas, cultivar *JP-885* showed significant reduction in weed growth and higher yield of pea as compared to *JM-1* (Mishra and Bhan 1997). In common bean, cultivars varying in growth habit differed in their ability to compete with weeds (Malik 1990). Tiwari *et al.* (1997) observed that different soybean varieties did not influence the population of barnyard grass and total weed population as well as their biomass. However, greater weed control efficiency was noted in variety '*Durga*' followed by, *JS 80-21*, *JS 72-44* and *JS 76-205* compared with *JS 75-46*. Increased competitive ability of cultivars has been attributed to early emergence, seedling vigour, and increased rate of leaf expansion, rapid creation of dense canopy, increased plant height, early root growth and increased root size. Future breeding and variety testing programmes should take factors of crop competitive ability into consideration.

Crop rotation: The composition and density of weed seed bank are frequently a reflection of longterm crop rotations and management system. In mono-cropping system, numerous weed species persist and expand rapidly but crop rotation helps in interrupting life cycle of weeds and prevents any weed species to become dominant. Incidence of parasitic weeds like *Cuscuta* and *Orobanche* can be managed through crop rotation by rotating host crop with trap crop. Problem weed *Euphorbia geniculata* was found to infest soybean-chickpea rotation more severely than soybean-wheat rotation (Mishra and Singh 2000). Rotation among crops having drastically dissimilar life cycles or requiring different management practices is useful in disrupting weed cycle. Sankaran and Chinnamuthu (1993) found that *Paspalum dilatum* was nearly eliminated after three crops of rice-maize-mungbean, whereas *Digitaria ciliaris* became dominant. The parasitic weeds *Cuscuta* and *Orobanche* can be effectively managed through crop rotation by rotating host crop with trap crops, as they induce germination of parasitic weed seeds but they themselves are not parasitised. Due to lack of suitable host, *Cuscuta* seedlings will emerge and die.

Intercropping: Intercropping suppresses weeds better than sole cropping and thus, provides an opportunity to utilize crop themselves as tool of weed management. In wide spaced pulses, such as pigeonpea, intercropping is a common practice, which besides covering risk reduces weed infestation. Intercropping of mungbean and urdbean in pigeonpea suppressed weeds and increased the total productivity (Patel *et al.* 1983). Sekhon *et al.* (1993) showed that intercropping of mungbean in pigeonpea (1:1) decreased the quantum of weeds and produced numerically higher grain yield than the sole pigeonpea. Pigeonpea + mungbean with one hoeing at 30 DAS produced grain yield equivalent to two hoeings (30 + 45 DAS) done in sole pigeonpea. Mishra and Gautam (1995) reported that intercropping of maize with soybean, groundnut, pigeonpea and blackgram suppressed the weed growth by 15.4 to 33.7% as compared to sole crop of maize.

Planting geometry, plant density and sowing time: Planting density and pattern modify crop canopy structure and inturn, influence weed smothering ability. Effective weed control in in soybean (Raghuvanshi *et al.* 1990) and mustard (Mishra *et al.* 1990) by close sowing with low seed rate. A seed rate of 125 kg/ha in 20 cm row apart in soybean found effective to minimize weed intensity than other sowing management (Jain and Tiwari 1993). Malik *et al.* (1988) reported that in chickpea, the maximum emergence of most competitive weed *Chenopodium album* L., occurred when crop was sown on November 5 and declined gradually with delay in sowing. However, in most winter pulses this can not be a viable approach as delayed sowing invariably results in reduced yield. Sinha *et al.* (1988) reported that early sowing (10 August) and closer row spacing (30 cm) reduced the weed growth and increased the dry matter accumulation, leaf area index (LAI), net assimilation rate (NAR), crop growth rate (CGR) and grain yield of irrigated pigeonpea at Kalyani (West Bengal). In a study on the date of sowing and weed control treatments at Ludhiana, pigeonpea sown on 15 May had less weed problem as compared with 5 June sowing as the dry matter of weeds was 1580 and 2280 kg/ha under two respective dates in the un-weeded plots (Sekhon *et al.* 1993). Less weed problem in case of May sowing could be due to less soil moisture as hot and dry climate is prevailing at that time. A seed rate of 125 kg/ha in 20 cm row apart in soybean found effective to minimize weed intensity than other sowing management (Jain and Tiwari 1992). Yadav *et al.* (1999) also observed that higher seed rate (150 kg/ha) significantly reduced the weed incidence and enhanced the soybean yield as compared with the lower seed rates (125 and 100 kg/ha). Singh and Bajpai (1994) reported that change in crop geometry under different methods of sowing did not give significant weed control, however, crop sown at 30 cm-row spacing smothered weed growth by 15.0 and 14.2% compared with 40 cm-row spacing and broadcast method of sowing, respectively. Reduction in row spacing from 45 to 25 cm increased the weed control efficiency by 21.7% and grain yield by 15.6% (Nimje 1996).

Nutrient management: Crops and weed compete for the same nutrient pool. Increasing soil fertility can alter the competitive interaction between crops and weeds. Increased N level upto 120 kg/ha reduced the weed biomass in mustard (Mishra and Kurchania 1999).

Soil solarization: Solarization is a method of heating soil surface by using plastic sheets placed on moist soils to trap the solar radiation. The process would raise the surface soil temperature by 8-12°C as compared to non-solarized soils. Many annuals, some perennials and parasitic weeds are sensitive to this treatment. Singh *et al.* (2000) observed that soil solarization for 3-4 weeks during summer significantly reduced the population and drymatter production of major weeds in soybean. This also increased the soybean yield. Weeds like *E. colona*, *Commelina communis*, *Ageratum conyzoides*, *Euphorbia geniculata* and *Corchoru*s sp. were completely controlled, whereas *P.niruri* and *C.iria* were found tolerant to soil solarization. It has potential to raise the maximum soil temperature by 8-12 ^{0}C over unfilmed control (Yaduraju 1993). In a long term trial conducted at IARI, New Delhi; it was found that solarization gave 33 and 52% more yield of soybean over hand weeding and herbicide treatment, respectively. The corresponding increase in the succeeding wheat crop was 10 and 25% (Yaduraju and Ahuja 1996). Soil solarization for a period of 32 days improved the growth of soybean and increased the seed yield by 78% (Kumar *et al.* 1993). Singh *et al.* (2004) observed that soil solarization for 5 weeks during summer significantly reduced the population and dry matter production of major weeds and increased the seed yield of soybean. Although very efficient, the solarization has not found wider adaptability, as the treatment cost is relatively high. However, with repeated use of the same films the cost can be reduced substantially.

Mulching: Rajput (1980) and Rajput and Sastry (1986) reported that soybean yield increased by 29 and 13% under white plastic and straw mulching, respectively over control. Mulching at 5 tonnes/ha though effectively suppressed the weed growth and increased the seed yield but not economically effective (Singh *et al.* 1992, Nimje 1996). Black polyethylene coupled with neem leaves mulching result in low weed population and dry matter in rainfed chickpea Varshney (1997).

Mechanical

Mechanical weed control involves removal of weeds with various tools and implements including hand weeding and hand pulling. Inter-culture operations are performed primarily to destroy the weeds present in the field and create favorable soil conditions for plant growth. One hand weeding in winter season and two hand weeding in rainy season during critical stage of crop-weed competition provide satisfactory control of weeds in almost all the crops. Two hand weeding 15 and 30 (DAS) days after sowing in soybean (Dubey *et al.* 1984 and Lokras *et al.* 1985) reduced the weed growth. In soybean, Upadhyay *et al.* (1992) reported that weeding with 'kolpa' at 10 and 25 DAS was effective for controlling weeds. In groundnut, mechanical weeding twice at 25 and 40 DAS proved effective against weeds (Rathi *et al.* 1987 and Nimje 1992). In sesame two handweeding at 20 and 35 DAS recorded highest benefit-cost ratio (Jain *et al.* 1994). Hand weeding once at 30 DAS (Singh and Bajpai 1994) and twice at 15 and 30 DAS (Dubey *et al.* 1984 and Lokras *et al.* 1985). showed significant reduction in weed density with marked increase in grain yield. Upadhyay *et al.* (1992) reported that weeding with 'kolpa' at 10 and 25 DAS was effective for controlling weeds.

Herbicidal

Several herbicides have been tested under AICRP on Weed Control and elsewhere in varying agro-ecological regions. The most of them are recommended for weed control in different pulses and oilseed crops (**Table 3 and Table 4**).

Results of multi-location studies under the All India Coordinated Pulse Improvement Programme showed that fluchloralin, pendimethalin at 1.0 and 0.75 and oxadiazon at 0.75 kg/ha, respectively, were quite effective in controlling weeds in pulses (Ali and Mishra 2000). Pre-emergence application of pendimethalin at 1.0

Table 3. Promising herbicides for different pulses and oilseed crops

Herbicide	Dose (kg/ha)	Crops	Weeds controlled
Pre-plant incorporation			
Fluchloralin	0.75-1.0	All pulses and oilseeds	BLW and Grasses
Trifluralin	0.75-1.0	All pulses and oilseeds	BLW and Grasses
Pre-emergence			
Alachlor	1.5-2.0	Rainy season pulses and oilseeds	Grasses
Butachlor	1.5-2.0	Soybean, sesamun, niger	Grasses
Isoproturon	0.75-1.0	Mustard, linseed	BLW and Grasses
Linuron	1.0-1.5	Chickpea, peas, lentil	BLW and Grasses
Metolachlor	1.0	Soybean, pigeonpea, greengram, blackgram	Grasses
Metribuzin	0.50-0.75	Soybean, peas	BLW and Grasses
Oxadiazon	0.75-1.0	Soybean, groundnut, mustard, sunflower	BLW and Grasses
Oxyfluorfen	0.10-0.20	Soybean, linseed, blackgram, greengram	BLW and Grasses
Pendimethalin	1.0	All pulses and oilseeds	BLW and Grasses
Post-emergence			
Bentazon	1.0	Soybean, linseed	BLW and Sedges
Chlorimuron ethyl	0.008-0.012	Soybean	BLW
Fluazifop-butyl	0.25-0.50	Soybean	Grasses
Clodinafop-propargyl	0.060	Chickpea, peas, lentil, mustard	Grasses
Haloxyfop	0.050	Soybean	Grasses
Imazethapyr	0.10-0.15	Soybean	BLW and Grasses
Lactofen	0.15-0.20	Soybean	BLW
Metsulfuron-methyl	0.004-0.006	Soybean	BLW
Quizalofop-ethyl	0.050	All pulses and oilseeds	Grasses
Sethoxydim	0.25-0.50	Soybean	Grasses

BLW-Broad-leaved weeds

kg/ha or pre-plant incorporation of fluchloralin at 0.5 kg/ha gave good weed control in chickpea, rajmash (Ali 1988), field pea and lentil. Pre-plant incorporation of fluchloralin has been found effective against most of the annual grassy and non-grassy weeds. At higher dose, it stunted plant growth, reduced root growth at early stages. However, crop recovers at later stage without any adverse effect on productivity. In chickpea and lentil higher rates may delay germination (Singh 1993). Pre-emergence application of linuron at 0.75 kg/ha and methabenzthiazuron at 1.31 kg/ha reduced the number and dry weight of root nodules in field pea significantly (Singh *et al.* 1994). By and large, herbicides applied at their recommended doses have only temporary effect on nodulation by pulse crops.

Alachlor controls most of the annual grasses, annual sedges and few broad-leaved weeds. It is less effective during winter season in field pea, chickpea and lentil due to predominance of broad-leaved weeds. Oxadiazon provides effective control of most of the annual grasses and broad-leaved weeds associated with pulse crops. At higher doses, it causes phytotoxicity to most of the pulses. Pendimethalin is another effective herbicide for the control of annual broad-leaved and grassy weeds in winter pulses. *Avena* spp. and most of the leguminous weeds are not effectively controlled by pendimethalin. Metribuzin, under higher soil

Table 4. List of promising herbicides in different oilseed/pulse based inter-cropping systems

Inter cropping system	Herbicides	Dose (kg/ha)	Time of application
Maize + soybean	Oxadiazon	0.75-1.0	Pre-emergence
	Pendimethalin +	1.5	Pre-emergence
	Hand weeding	1	30 DAS
	Metolachlor	1.0-1.5	Pre-emergence
Maize + groundnut	Pendimethalin	1.0	Pre-emergence
	Oxadiazon	0.50	Pre-emergence
	Metolachlor	1.0-1.5	Pre-emergence
Sunflower + groundnut	Pendimethalin +	1.0	Pre-emergence
	Hand weeding	1	35 DAS
Sunflower + greengram/sesame	Fluchloralin	1.0	PPI
Sorghum + soybean	Fluchloralin	1.5	PPI
Pigeonpea + sesamum	Fluchloralin	1.0	PPI
Sorghum + pigeonpea	Metolachlor +	0.75	Pre-emergence
	Hand weeding	1	30-35 DAS
	Pendimethalin	1.0	Pre-emergence
Pigeonpea + soybean	Fluchloralin +	1.5	PPI
	Hand weeding	1	40 DAS
	Pendimethalin	1.25	Pre-emergence
	fb fluazifop-butyl	0.50	25 DAS
Pigeonpea + groundnut	Pendimethalin +	1.0	Pre-emergence
	Hand weeding	2	30 and 45 DAS
Sugarcane + soybean/groundnut	Thiobencarb	1.25	Pre-emergence
Sugarcane + mustrad	Oxyfluorfen	0.20	Pre-emergence
	Isoproturon	0.75-1.0	Post-emergence
Wheat + mustard	Pendimethalin	1.50	Pre-emergence
	Oxyfluorfen	0.20	Pre-emergence
	Isoproturon	1.0	Pre-emergence
Wheat + mustard/linseed	Isoproturon	1.0	Pre-emergence
Lentil + linseed	Pendimethalin	1.0	Pre-emergence
	Fluchloralin	1.0	PPI
Rice + soybean/groundnut	Butachlor +	1.5	Pre-emergence
	Hand weeding	1	40 DAS
Groundnut + pearlmillet	Prometryn	0.80	Pre-emergence
Groundnut + pigeonpea	Pendimethalin+	1.0	Pre-emergence
	Hand weeding	1	30 DAS
	Alachlor	1.5	Pre-emergence
Potato + mustard	Pendimethalin	1.0	Pre-emergence
	Isoproturon	0.75	Pre-emergence
Pea + mustard	Pendimethalin	1.0-1.25	Pre-emergence
Chickpea + linseed/mustard	Pendimethalin	1.0	Pre-emergence

moisture condition, causes phytotoxicity to winter season pulses. Post-emergence application of fomesafen at 125-375 g/ha provided effective control of *Trianthema portulacastrum* in mungbean (Singh 1993) and fluazifop-butyl and haloxyfop-methyl gave good control of *Echinochloa colona* (Balyan *et al*. 1987).

Integrated weed management

In most of the studies, it is reported that use of pre-plant or pre-emergence herbicide followed by one manual/mechanical weeding has been found effective and economical in pulses and oilseed crops. In pigeonpea + soybeen intercropping system, pre plant incorporaton of fluchlorlin (1.5 kg/ha) followed by inter-cultivation at 40 days after sowing at Bhopal (Nimje 1993), Metolachlor (1 kg/ha) coupled with one inter cultivation and hand weeding at Dharwad (Hiramath and Agasimani 1999) and two hoeings + one hand weedings and pendimethlain at 0.75 kg/ha and 1.0 kg/ha both supplemented with one hand weeding at Sehore (Vyas *et al.* 2003*)* registered satisfactory weed control and greater productivity.

At Kanpur, in groundnut + pigeonpea intercropping, pendimetalin (1.0 kg/ha) manifested excellent control of associated weeds including *Trianthema monogyna* but was ineffective against *Commpelian benghalensis*. Integration of single hand weeding with pendimethalin (1.0 kg/ha) realized 544 kg/ha (28.30%), more ground nut equivalent yield than its sole application and was at par with to manual weedings (Tewari and Rathi 1995). In field pea, cross sowing of a dwarf pea cultivar 'Aparana' caused weed growth suppression to the magnitude of 39.62% resulting in increased grain yield (17.6%) over unidirectional sowing. Sowing of dwarf pea (*Aparana*) 20 cm apart followed hand hoeing and removal of weeds from interspaces manually gave at par seed yield (1.35 t/ha) to that obtained under

Table 5. Integrated methods of weed control in different crops

Crop	IWM System	Reference
Soybean	Narrow row spacing (20 cm) + higher seed rate (125 kg/ha) + oxadiazon 1.0 kg PE	Jain and Tiwari (1990)
	Cv. JS 72–44 + 30 cm row spacing + butachlor 2.0 kg PE	Thakur and Dubey (1990) Jain *et al.* (1988)
	Higher fertility (30 kg N + 80 kg P_2O_5/ha) + oxadiazon 1.0 kg/ha or fluchloralin 1.0 kg/ha or metribuzin 0.5 kg/ha	
Groundnut	Alachlor or pendimethalin 1 kg PE + Hand hoeing or hand weeding at 30 DAS	Rathi *et al*. (1986)
Greengram	Oxadiazon 0.55 kg/ha + HW at 30 DAS	Bajpai *et al.* (1988)
Blackgram	Fluchloralin 0.5 kg PPI + 1 HW 42 DAS	AICRP- WC (1978-84)
Mustard	120 kg N + isoproturan 1.0 kg or Oxadiazon 0.75 kg/ha PE Higher seed rate (6.25 kg/ha) + herbicides	Mishra and Kurchania (1999)
Peas	Variety '*JP 885*' + fluchloralin or pendimethalin 1.0 kg + 1 HW at 30 DAS	Mishra and Bhan (1997)
Lentil	Fluchloralin 0.5 kg + 1 HW at 30 DAS	Mishra *et al.* (1996)

sowing 20 cm apart followed one hand weeding (1.45 t/ha) and the cost involved was comparatively less in former (` 940 /ha) than later ` 1175/ha (Tewari *et al.* 2003).

In pigeonpea, weeds could be effectively controlled with pre-emergence application of oxadiazon at 0.5 kg/ ha HW at 45 DAS (Brar *et al.*1990) or with pre-emergence application of pendimethalin at 1 kg/ ha + HW at 60 DAS (Patel *et al.*1993). In rainfed mungbean, Bajpai *et al.* (1988) found that the highest net income with oxadiazon at 0.5 kg/ha as pre-emergence + HW at 30 DAS.

In chickpea, pre-plant incorporation of fluchloralin at 0.90 kg/ha followed by one manual weeding at 30 DAS effectively controlled weeds and provided higher yields (Gedia *et al.* 1989). In field pea, the highest seed yields were obtained with 0.5 kg pendimethalin + HW at 30 DAS (Sharma and Vats 1988). Mishra and Bhan (1997) obtained higher grain yield due to better weed control with application of fluchloralin or pendimethalin 1.0 kg/ha + weeding at 30 DAS in field pea. The lower dose of pendimethalin (0.75 kg/ha) + weeding 45 DAS was effective in controlling weeds in lentil crop at Faizabad, Kanke and Kanpur (Ali and Nath 1998). In rice-lentil sequence under dryland conditions of Varanasi, weeds were effectively controlled in lentil crop with the application of paraquat + no preparatory tillage + prometryne as pre-emergence (Ali and Mishra 2000). In lentil, Mishra *et al.* (1996) obtained higher grain yield by integrating 0.50 kg fluchloralin as PPI with HW at 30 DAS. Integration of pendimethalin 0.75 kg/ha with one hand weeding at 30 DAS proved more effective than herbicide application alone (Nehra and Malik 1999). Integration of lower doses of herbicides with manual or mechanical weeding would not only be effective and economical but it also reduces the pesticide load in the environment.

Integration of lower rates of pre-emergence of linuron (750-1000 g/ha), acetachlor and alachlor each at (1000 g/ha) with one hand weeding at 40 DAS provided excellent control of all weeds (Balyan *et al.* 1999a, Balyan *et al.* 1999b). Sowing at 30 cm-row spacing and manual weeding at 30 DAS or application of fluchloralin 1.0 kg/ha was found to control weeds effectively and increased the grain yield of soybean (Singh and Bajpai 1994). Nimje (1996) observed that pre-plant incorporation of fluchloralin 1.0 kg/ha + interculturing at 40 DAS provided effective control of weeds in soybean. Integration of alachlor 1.25 kg/ha as pre-emergence and one hand weeding at 40 DAS under the crop density of 4,44,000 plants/ha (30 x 7.5 cm spacing) was found the most effective method under the irrigation regime of 0.60 IW: CPE ratio for getting higher yield and economic return (Veeramani *et al.* 2000).

Herbicide mixtures and their sequential application

Most of the herbicides control a group of specific weeds (grasses or broadleaved). However, the soybean crop suffers with mixed weed flora (grasses, broadleaved and sedges). Therefore, for a broad-spectrum weed control it is necessary either to use herbicide mixtures or their sequential application. Post-emergence herbicides can be used as sequential application with all pre-planting or pre-emergence herbicides depending upon nature of weed flora. Balyan *et al.* (1999) reported that sequential application of pre-emergence linuron (750 to 1000 g/ha) and post-emergence fluazifop (500 g/ha) provided better control of all weeds than their single application. Mixture of fluazifop-p-butyl (0.50 kg/ha) + sethoxydim (0.25 kg/ha) provided broad-spectrum weed control and higher yield of soybean (Singh *et al.* 1999). Tank mixture of fomesafen and haloxyfop at 200+150g/ha and chlorimuron + haloxifop at 6 +150 g/ha provided season long weed control and produced grain yield of soybean similar to weed free condition (Balyan and Malik 2003).

Weed management in pulse-based intercropping systems

Weeds constitute one of the major constraints to increase agricultural production in many areas practicing intercropping. Finding an intercrop, which will suppress the growth of weeds but not crop, has been difficult. Cowpea and mungbean planted as "Smother crops" between the rows of sorghum and sorghum / pigeonpea intercrop showed promise as a means of minimising weed infestation and reducing the number of hand weedings without significantly affecting the main crop yields. Weed suppressing ability of intercrop is dependent upon such factors as the component crops and cultivars selected, crop density, relative proportion of the component crops, their spatial arrangement and the fertility and moisture status of the soil (Moody and Shetty 1981). The critical period of crop-weed competition in intercropping is longer than in sole crops, therefore, the weeding operations are to be continued for a longer period to obtain desirable yield. Sole crop of sorghum needed 4-5 weeks of weed free period, whereas sorghum + pigeonpea intercropping needed a weed-free period extended to 7 weeks (ICRISAT 1977).

Weed control may be more difficult in intercropping than in sole crops. The main method of weed control in intercropping is manual or mechanical (Moody and Shetty 1981). Very few herbicides are recommended and used to control weeds in intecropping system since it has been difficult to find compounds that will control a broad spectrum of weeds without causing damage to the component crops. In pigeonpea-based intercropping system, Mahapatra (1991) reported that pre-emergence application of thiobencarb at 1.0 kg/ha for pigeonpea + rice intercropping, oxadiazon at 0.5 kg/ha for pigeonpea + urdbean intercropping system and manual weeding for pigeonpea + groundnut intercropping gave the highest net returns.

Future research thrusts

1. Resource conservation technologies i.e. zero tillage and bed planting are coming up. There is a need to intensify the research work related to interaction studies with the tillage operations and weed management practices in pulses/oilseeds-based cropping systems.
2. Weed seed bank studies have been initiated under rice-wheat cropping system in All India Coordinated Research Programme on Weed Control.

However, research work to manage the weed seed bank in pulses/oilseeds-based cropping systems is also needed.

3. Pulses/oilseeds are usually taken as inter/mix cropping system. Intercropping could be used as tool of weed management. Low cost technology may be developed for the intercropping systems prevailing under different agro-ecological regions.
4. Pulses and oilseeds are grown in sizeable area under rainfed situation in the country and identification of herbicides in pulse/oilseed- based cropping system for different eco-system is needed. Soil moisture is one of the most important factors affecting efficiency of herbicides. Since these crops are mostly grown under moisture stress conditions, the information on moisture herbicide relationship must be collected. This information could attribute to optimizing herbicide use efficiency through factor adjusted dose recommendations.
5. The availability of post-emergence herbicides, particularly those against broad-leaved weeds is limited. There is need to identify more effective herbicides with broader spectrum weed control and wider adaptability. Effective weed control system for hard to control weeds like *Asphodelus tenuifolius, Vicia sativa, Lathyrus aphaca, Convolvulus arvensis, Medicago denticulata, Cirsium arvense, Saccharum spontaneum* and parasitic weeds like *Cuscuta* spp. in pulses and oilseeds and *Orobanche* spp. in mustard need to be developed.
6. Pulses are grown during all the three seasons, *viz*. rainy, winter and summer, therefore, residual effect of herbicides applied in rainy season pulses must be studied in succeeding winter and summer seasons.
7. Pulses, especially lentil and lathyrus, are sown under *utera* condition in late rice-fallow system. Weed management schedule needs to be developed in this system.
8. Testing of low cost implements/tools for managing the weed problem in pulses could be proved farmers friendly especially for small and marginal farmers. The work needs to be intensified.

References

AICRP–WC. 1978–84. *All India Coordinated Research Project on Weed Control, Consolidated Report (1978–1984)*, NRC for Weed Science, Jabalpur, India

AICRP– WC. 1997–98. *All India Coordinated Research Project on Weed Control, Annual Report (1978–1984)*, NRC for Weed Science, Jabalpur, India

Ali M. 1988. Response of chickpea genotypes to population densities and atonite spray under late sown conditions. *Indian Journal of Pulses Research* **1**: 128–133

Ali M and Lal S. 1989. Priority inputs in pulse production. *Fertiliser News* **34**(11): 17–21

Ali M and Mishra JP. 2000. *Technology for production of winter pulses*. Indian Institute of Pulses Research Kanpur, pp.43–45

Ali M and Nath O. 1998. Integrated management of weeds in lentil. pp. 105. In *Abstracts of National Symposium on Management of Biotic and Abiotic Stresses in Pulse Crops* IIPR, Kanpur, June 26–28, 1998.

Balyan RS and Malik RK. 2003. Effect of post–emergence herbicides for weed management in soybean (*Glycine max* L.). *Indian Journal of Weed Science* **35**: 62–66.

Balyan RS, Malik RK, Vedwan RPS and Bhan VM. 1987. Chemical weed control in chickpea (*Cicer arietinum*). *Tropical Pest Management* **33**(1): 16–18.

Balyan RS, Malik RS, Panwar RS and Pahwa S K. 1999b. Chemical weed control studies in soybean. (*Glycine max* L.). *Indian Journal of Weed Science* **31**: 234–238.

Balyan RS, Pahwa SK, Dhankar RS and Malik RK. 1999a. Efficacy of linuron and fluazifop–p–butyl against weeds in soybean. (*Glycine max* L.). *Indian Journal of Weed Science* 31:229–233.

Bhan VM, Singh M and Maurya RA. 1974. Studies on requirement of weed free maintenance in soybean. *Indian Journal of Weed Science* **6**: 12–16.

Chauhan R, Dahiya B and Khokhar KS. 1991. Weeding *Vicia sativa* L. to help check pod borer (*Helicoverpa armigera*) damage in chickpea (*Cicer arietinum* L.). *ACIAR Food Legume Newsletter* **15**(3).

Chhokar RS, Balyan RS and Pahuja SS. 1995. The critical period of weed competition in soybean (*Glycine max* L.). *Indian Journal of Weed Science* **27**: 197–200.

Chhokar RS, Balyan RS and Pahuja SS. 1997. Nutrient removal by weeds in soybean (*Glycine max*) under integrated weed management. *Indian Journal of Agronomy* **42**: 138–141.

Dahiya SS. 1979. *Crop–Weed Competition in Soybean crop in Relation to Chemical and Mechanical Method of Weed Control.* M.Sc. thesis, HAU, Hisar.

Dubey SK, Jain HC, Koshta LD and Raghu JS. 1984. Integrated weed control in soybean. *Indian Journal of Weed Science* **16**: 238 – 243.

Gautam, K.C. and Mishra, J.S. 1995. Problems, prospects and new approaches in weed management. *Pesticides Informations* **21**(1): 7–19.

Gedia KM, Malviya DD and Patel JC. 1989. Studies on cultural and chemical weed control in chickpea. *Indian Journal of Agronomy* **34**: 511–513

ICRISAT. 1977. *Weed Research Annual Report,* 1976–77. International Crop Research Institute for Semi–Arid Tropics, Hyderabad.

Jain HC and Tiwari JP. 1992. Influence of herbicides on the growth and yield of soybean (*Glycine max*) under different spacing and seeding rates. *Indian Journal of Agronomy* **37**: 86–89

Jain HC and Tiwari JP. 1993. Influence of herbicides on weed control in soybean under different spacing and seed rate. *JNKVV Research Journal* **27**(2): 7–12.

Jain HC, Dubey SK and Bisen JS. 1988. Influence of weed control and fertility levels on soybean. *Indian Journal of Weed Science* **20**(2): 68–74.

Jain HC, Tiwari JP and Jain NK. 1990. Influence of herbicides on nodulation under different row spacing and seedrate in soybean. *Indian Journal of Weed Science* **22**(3&4): 11–16.

Kumar B, Yaduraju NT, Ahuja KN and Prasad D. 1993. Effect of soil solarization on weeds and nematodes under tropical Indian conditions. *Weed Research* **33**: 423–429.

Mahapatra PK. 1991. Weed control in intercropping system based on pigeonpea (*Cajanus cajan*). *Indian Journal of Agricultural Sciences* **61**: 885–888.

Malik RK, Balyan RS and Bhan VM. 1988. Effect of herbicides and planting dates of weeds in chickpea. *Indian Journal of Weed Science* **20**: 75–81

Malik VS. 1990. *Impact of White Bean (Phaselous vulgaris L.) Cultivars, Row Spacing and Seeding Density on Annual Weed Interference*. M.Sc. thesis, Univ. Guelph, ON. 93p.

Mishra JS, Singh VP and Bhan VM. 1996. Response of lentil (*Lens culinaris*) to dates of sowing and weed control in Jabalpur. India. *LENS* **23**(1&2): 18–23

Mishra JS, Singh VP and Bhan VM. 1997. Effect of interference by common vetch (*Vicia sativa*) on yield and yield components of lentil (*Lens culinaris*). *Indian Journal of Agricultural Sciences* **67**: 320–321.

Mishra JS and Gautam KC. 1995. Ways to control weed in Inter cropping systems. *Indian farming*. **45**(3): 23–25.

Mishra JS and Kurchania SP. 1999. Effect of nitrogen levels, planting geometry and herbicides on weed growth and yield of Indian mustard. *Indian Journal of Weed Science* **31**(3&4): 187–190.

Mishra JS and Singh VP. 2000. *Euphorbia geniculata*: An emerging problem weed of soybean. *Weed News* **4**: 2–4.

Mishra JS and Singh VP. 2003. Interference of *Euphorbia geniculata* in soybean–chickpea cropping system. *Indian Journal of Weed Science* **35**: 225–227.

Mishra JS, Singh VP and Yaduraju NT. 2002. Interference of common dayflower (*Commelina communis* L.) in soybean (*Glycine max* L.). *Indian Journal of Weed Science* **34**: 295–296.

Mishra JS. 1997. Critical period of weed competition and losses due to weeds in major field crops. *Farmer and Parliament* **23**: 19–20.

Mishra JS and Singh VP. 2001. Interference of Ivy leaf morning-glory (*Ipomoea hederacea* L.) in soybean (*Glycine max* L.). *Indian Journal of Weed Science* **33**:87–88.

Mishra JS and Bhan VM. 1997. Effect of pea cultivars and weed control on weed growth and yield of pea. *Indian Journal of Agronomy* **42**(2): 316–319.

Mishra JS, Singh VP and Bhan VM. 1997. Effect of Interference for common vetch (*Vicia sativa*) on yield and yield components of lentil. *Indian Journal of Agricultural Science* **67**(7): 320–21.

Moody K and Shetty SVR. 1981. Weed management in intercropping system. pp. 229–237. In: *Proceedings of International Workshop on Intercropping*, ICRISAT, Patancheru.

Mutushankaranarayana A, Chellamuthu V, Rajamannar A and Rajpandian JSR. 1990. Effect of herbicides on weed control in rainfed cotton + urdbean intercropping. *Indian Journal of Weed Science* **20**: 91–93.

Nehra OP and Malik RK. 1999. Weed management studies in Faba bean (*Vicia faba* L.). *Indian Journal of Weed Science* **31**: 130–132.

Nimje PM. 1992. Weed and nitrogen management in groundnut crop in vertisols. pp. 58. In: *Abstracts of Annual Conference of Indian Society of Weed Science*, HAU, Hisar.

Nimje PM. 1993. Weed management in pigeonpea/ soybeen intercropping system. In: *Proceedings International Symposium Indian Society of Weed Science, Hisar, November 18–20, Vollume III*.

Nimje PM. 1996. Effect of row spacing, mulching and weed control on weed growth and yield of soybean (*Glycine max*). *Indian Journal of Agronomy* **41**: 427–432

Patel CL, Patel ZG and Patel HC. 1983. Non–cash technology for minimizing weed growth in pigeonpea. *Indian Journal of Weed Science* **15**:143–146.

Raghuwanshi MS, Jain HC, Kurchania SP, Gogulwar NM and Raikwar KK. 1990. Crop–weed association in soybean under different seed rates, row spacings and weed control methods. p. 62. In: *Abstracts of Biennial Conference of Indian Society of Weed Science* April 4–5, 1990 JNKVV, Jabalpur.

Rajput RP and Sastry PSN. 1986. Effect of different mulches on yield, its attributes and quality of soybean crop under rainfed conditions. *Indian Journal of Plant Science* **4**: 22–27.

Rajput RP. 1980. Response of soybean to climate and soil environment. Ph.D. Thesis IARI, New Delhi.

Rathi GS, Sharma RS and Dubey MP. 1986. Studies on integrated weed control in rainfed groundnut. *Indian Journal of Weed Science* **18**(4): 223–246.

Sahoo KM and Saraswat VN. 1988. Magnitude of losses in the yields of major crops due to weed competition in India. *Pesticides Information* **14**: 2–9

Sankaran S and Chinnamuthu CR. 1993. Integrated weed management in rice based cropping systems. pp. 69–74. In Proceedings *of International Symposium, Indian Society of Weed Science*, Hisar, November 18–20, 1993.

Sekhon HS, Singh G and Brar JS. 1993. Effect of chemical, mechanical and cultural manipulations on weed growth and grain yield of various pulse crops. pp. 141–146. In *Proceedings of International Symposium, Indian Society of Weed Science* Hisar, November 18–20, 1993.

Sharma AR and Vats OP. 1988. Growth, yield and nutrient uptake of field pea as affected by different herbicides. *Indian Journal of Weed Science* **18**: 250–253.

Shetty SVR and Rao MR. 1979. Weed management studies in pigeonpea based intercropping. pp. 665–672. In: *Proceedings of VI Asian–Pacific Weed Science Society Conference*, July 11–17, 1977.

Singh BD and Singh BP 1998. Effect of weed control measures on weed infestation, nodulation and yield in chickpea/mustard intercropping system. p.101. In *Abstracts of National Symposium on Management of Biotic and Abiotic Stresses in Pulse Crops*, June 26–28 1998, Kanpur.

Singh G. 1993. Integrated weed management in pulses. pp. 335–342. In *Proceedings of International Symposium, Indian Society of Weed Science* Hisar, November 18–20, 1993.

Singh S, Gautam KC and Prasad R. 1989. Studies on weed control in lentil sown after rice under zero tillage. *LENS Newsletter* 16(1): 22–27

Singh Sahadev, Singh AN and Bhan VM 1995. Studies on the chemical control of weeds in summer *mung* bean. *Indian Journal of Weed Science* **27**(3&4): 158–159.

Singh VK and Bajpai RP. 1994. Influence of crop geometry and weed control method on yield and economics of rainfed soybean (*Glycine max*). *Indian Journal of Agronomy* **39**: 671–673

Singh VP and Bhan VM. 1997. Influence of dates of sowing weed control measures and row spacing in soybean. *Indian Journal of Weed Science* **29**(3&4): 115–119.

Singh VP, Dixit A, Prasadbabu MBB and Mishra JS 2000. Effect of period of soil solarization and weed control measures on weed growth and yield of soybean (*Glycine max* L.). 1457–1459. In: *Extended Summaries, International Conference on Managing Natural Resources for Sustainable Agricultural Production* in the 21st Century Feb. 14–18, 2000; New Delhi, India.

Singh VP, Dixit Anil, Mishra JS and Yaduraju NT. 2004. Effect of period of soil solarization and weed control measures on weed growth and productivity of soybean (*Glycine max*). *Indian Journal of Agricultural Sciences* **74**: 324–328.

Singh VP, Mishra JS and Bhan VM. 1999. Integrated weed management in soybean. (*Glycine max* L.). *Indian Journal of Weed Science* **31**: 267–268.

Singh, Gurcharan, Kundra HC, Brar LS, Gupta RP and Singh G. 1994. Effects of herbicides on soil microorganism dynamics, Rhizobium–legume symbiosis and grain yield of pea (*Pisum sativum* L.). *Annals of Agricultural Research* **15**: 22–26

Singh S, Bhan VM and Singh AN. 1998. Response of wheat and associated weeds to irrigation regime, nitrogen and 2,4-D. *Indian Journal of Agronomy* **43**(4): 662–667.

Sinha AC, Mandal BB and Jana PK. 1988. Physiological analysis of yield variation in irrigated pigeonpea in relation to time of sowing, row spacing and weed control measures. *Indian Agriculturists* **32**: 177–185

Sinhg G and Singh D 1992. Weed control efficacy of oxyfluorfen, acifluorfen, metribuzin and linuron in soybean (*Glycine max* L.). *Indian Journal of Weed Science* **24**: 97–99.

Tewari AN, Rathi KS and Singh B. 1997. Control of *Sorghum halfpence* in pigeon pea intercropped with soybean. *Indian Journal of Weed Science* **29**: 31–33.

Tewari AN, Tewari SN, Rarhi JPS, Singh B and Tripathi AK. 2003. Effect of cultural and chemical methods on weed growth and grain yield of dwarf pea. *Indian Journal of Weed Science,* **35**(1&2). 49–52.

Thakur GS, Dubey RK and Tripathi AK. 1990. Evaluation of herbicides for weed management in berseem. pp. 55. In: *Abstracts of Biennial conference of Indian Society of Weed Science*. April 4 –5, JNKVV, Jabalpur.

Tiwari JP and Kurchania SP. 1990. Survey and management of weeds in soybean–ecosystem in Madhya Pradesh. *Indian Journal of Agricultural Sciences* **60**(10): 672–676.

Tiwari JP, Kurchania SP, Paradkar NR and Bhalla CS. 1996. Bioefficacy of chlorimuron-ethyl for weed control in soybean (*Glycine max*). *Indian Journal of Agricultural Sciences* **66**: 583–588.

Upadhyay VB, Sharma Manorama, Acharya VN and Nakely NR. 1992. Cultural and chemical weed control in soybean in regions of MP. 77 p. *Abstracts Annual Conference ISWS* 1992 HAU, Hisar.

Urkurkar JS and Chnadrakar BL. 1992. Herbicidal manipulation to improve efficiency of fertilizer nitrogen in direct sown rice. pp. 33. In: *Abstracts of Annual Conference of Indian Society of Weed Science Hissar,* March 3–4, 1992.

Varshney JG. 1989. Studies on critical stages of weed removal in soybean. *Indian Journal of Weed Science* **21**: 49–54.

Varshney JG. 1997. Effect of mulches and solarisation on weed infestation in rainfed chickpea, *Annual Report* 1996–97. pp. 56–57. Indian Institute of Pulses Research, Kanpur.

Veeramani A, Palchamy A, Ramasamy S and Rangaraj G. 2000. Integrated weed management in soybean (*Glycine max*) under different moisture regimes and population densities. *Indian Journal of Agronomy* **45**: 740–745.

Vyas MD, Jain RC and Dubey Swapnil. 2003. Productivity and weed control efficiency of integrated weed management practices in pigeon pea + soybeen intercropping system under rainfed condition. *Indian Journal of Weed Science* **35**(1&2): 87–89.

Yadav RP, Srivastava UK and Dwivedi SC. 1999. Effect of seed rate and weed control methods on yield of soybean (*Glycine max*) under rainfed condition. *Indian Journal of Agronomy* **44**: 795–799.

Chapter 9

Herbicide tolerant crops in India

C. Chinnusamy* and M.S. Bhullar[1]
Department of Agronomy, Directorate of Crop Management, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu 641 003
[1]Department of Agronomy, Punjab Agricultural University, Ludhiana, Punjab 141 004
**Email: chinnusamy.c@tnau.ac.in*

Summary

Herbicide tolerant crops in general provide broad spectrum of weed control, with reduced crop toxicity and less herbicide carry-over on succeeding crops. In many crops, their use will decrease the cost of effective weed management in the short to medium term. However, they offer the farmer a powerful new tool that, if used wisely, can be incorporated into an integrated pest-management strategy that can be used for many years to more economically and effectively manage weeds. In maize and cotton transgenic crops, post emergence weed management with glyphosate proved to be the better management option for the control of weeds.

Key words: Carry over effect, Glyphosate, Productivity, Profitability, Transgenics, Weed management

Weed management is an important component of crop production. Earlier, hand weeding and crop rotations dominated as common weed management practices, hand weeding was gradually replaced with mechanical weeding in the developed world. Mechanical weed control practices are now viewed to be unsatisfactory due to the high-energy requirements and other associated costs including environmental pollution, and now been largely replaced by herbicides, which provide selective weed control with minimal soil disturbance and cost. Most preferred herbicides combine weed killing potency with low- or non-environmental persistence. However, very effective broad spectrum herbicides lack selectivity thus limiting their use in some cropping operations. The continuous use of few available selective herbicides is also speeding up development of herbicide resistance in weeds hence making it difficult to achieve effective control in some crops.

The discovery of a potential herbicide requires screening of nearly 5,00,000 compounds which makes it costly affair. Another more popular approach to crop herbicide selectivity is development of crop cultivars with tolerance to already existing effective broad spectrum herbicides so as to expand crop options in which they can be used. Two methods can be used to develop crops with resistance to herbicides; 1) conventional plant breeding utilizing lines that are known to be tolerant to specific herbicides that could confer resistance to susceptible crops from closely related species. However, this approach has limitations in that naturally herbicide resistant plants are found more among weed species because crops. Also, conventional plant breeding takes a long time to produce a single useful line 2) A faster approach is the use of biotechnology techniques such as *in vitro* cell culture, mutagenesis and selection in physiologically inhibitory concentrations of herbicides (also referred as brute force selection) or genetic transformation of already existing crop cultivars with genes than confer resistance to herbicides.

Herbicides in Indian agriculture

In India, about 6000 tons of herbicides are currently used for weed control, mainly in irrigated crops (wheat and rice), soybean and plantations crops. Herbcides, however, form only 12% of total pesticides use in India. A wide variety of weeds (perennial and annual) are generally encountered in crop fields specific weeds pre-dominate different cropping systems and zones. Both broad spectrum/ non-selective and selective herbicides are in use. Continuous use of same herbicides has led to development of resistant weeds and has exacerbated weed problems. For example, in rice-wheat cropping system of Punjab and Haryana, *Phalaris minor* developed resistance against isoproturon in late 1990 has now developed cross resistance to clodinafop, pinoxaden, sulfosulfuron and mesosulfuron + iodosulfuron (Bhullar *et al.* 2017) herbicides. Non-selective herbicides which kill all type of vegetation in the field are generally applied before sowing/emergence of crop plants or as directed-post application in between crop rows only. However, some crop plants enjoy naturally endowed tolerance to specific herbicides. For example, 2,4-dichlorophenoxyacetic acid (2,4-D) kills only broad-leaved weeds and can be used as a selective herbicide in monocot crops like rice, wheat and maize. Similarly, maize is naturally tolerant to atrazine and simazine. It is important to recall that although a large number of chemicals have been approved for weed control, their widespread and continuous use is not desirable owing to their toxicity and long-term effects on the environment.

Biotechnological approach

Biotechnological interventions for development of herbicides resistant crops are being widely adopted in various parts of the world. From genesis of commercialization during 1996 to 2017, herbicide tolerance has consistently been the dominant group. Crops containing transgenes that impart resistance to post-emergence, non-selective herbicides such as glyphosate and glufosinate have major impact. These products allow farmer to more effectively use reduced or no-tillage, eliminate use of some of more environmentally suspect herbicides and use fewer herbicides to manage nearly entire spectrum of weed species in crop production. In some cases, non-selective herbicides used with herbicide resistant crops reduce plant pathogen problems because of the chemicals' toxicity to certain microbes. Herbicide tolerant crops can be produced by either insertion of a "foreign" gene (transgene) from another organism into a crop, or by regenerating herbicide tolerant mutants from existing crop germplasm.

Herbicide tolerant crops

Introduction of transgenic crops resistant to broad-spectrum, non-selective herbicides was rightfully perceived as a better strategy in terms of weed management. Two herbicides that fitted this approach best were glyphosate and glufosinate; both compounds are amino acid analogues that have molecular targets in amino acid biosynthesis pathways. In each case, there appears to be only one compound that is a viable herbicide targeting molecular site. Herbicide tolerant crops are produced by the stable insertion of a gene that expresses a modified plant synthase protein in the receptor plant that is tolerant to particular herbicides (Lebrun *et al.* 1997). Herbicide-resistant crops were the first major wave of transgenic crops. From 1988, 20 to 30% of annual applications to Animal and Plant Health Inspection Service of the US Department of Agriculture for permits to field test transgenic crops have been for herbicide-resistant crops, with a total of 26% of all permits from 1987 to 2004 (Duke and Cerdeira 2009). To date, companies have sought regulatory approval for nine HT crops: soybean [*Glycine max* (L.) Merr], cotton (*Gossypium hirsutum* L.), corn (*Zea mays* L.), argentine canola (*Brassica napus* L.), polish canola (*Brassica rapa* L.), alfalfa (*Medicago sativa* L.), sugarbeet (*Beta vulgaris* L.), creeping bentgrass (*Agrostis stolonifera* L.) and wheat (*Triticum aestivum* L.) (AGBIOS 2018).

History of herbicide resistant crops development

History of herbicide tolerant genetically modified (HRGM) crops goes back to initial efforts made by scientists who developed and released bromoxynil-resistant cotton in 1995, and glufosinate-resistant canola in the same year. Since then, successful efforts have been made to develop number of commercial crops (alfalfa, canola, cotton, maize, sugarbeet and soybean) by genetic manipulation (Reddy and Boykin 2010). HRGM crops were developed to simplify weed management and reduce associated costs. Till date, HRGM crops modified for resistance against mainly to three herbicides (bromoxynil, glufosinolate and glyphosate) have been released. Out of these, bromoxynil-resistant crops have been retracted from their commercial use. Since bromoxynil is a selective herbicide and cannot be effective for broad spectrum weed control it does not qualify for the basic requirement for which concept of HRGM was developed.

Glyphosate acts by blocking the shikimate pathway though specific inhibition of the enzyme 5-enolpyruvylshikimate- 3-phosphate synthase (EPSPS). Attempts to alter structure of the EPSP synthase enzyme in such a way that it is functional in the production of EPSP and phosphate as well as insensitive to glyphosate have been quite intensive in last two decades. Padgette *et al.* (1995), concentrated on the G101A (glycine to alanine substitution at position 101) of petunia EPSP synthase, but no resulting plants were highly glyphosate tolerant and bound PEP substrate comparably to wild-type EPSP synthase. A naturally occurring EPSP synthase gene was identified from *Agrobacterium sp*. strain CP4, whose protein product had favorable glyphosate tolerance kinetic parameters such as high glyphosate tolerance and tight binding of PEP. Development of glyphosate resistant crops (GRCs) utilized CP4 gene from *Agrobacterium* sp., which encodes a glyphosate-resistant form of EPSPS, initially introduced in soybean. The vast majority of commercial GRCs in the market today contain CP4 EPSPS gene that confers glyphosate resistance. Glufosinate (or phosphinothricin) is a competitive inhibitor of glutamine synthetase, an enzyme required for assimilation of nitrogen into the amino acid glutamine. Since 1997, only glufosinate-resistant canola, cotton, and corn have been introduced in USA with moderate success; glufosinate resistant canola has been particularly successful in Canada. Other crops that have been transformed successfully for glufosinate resistance include wheat, rice, maize, sugarbeet, oilseed rape, alfalfa, potato and tomato. Glufosinate tolerant maize and canola are already in the market in North America, and soybeans are currently under development.

The breakthrough in HRGM technology came during last decade of 20th century. Glyphosate-resistant crops like canola, soybean, and cotton had been released for commercial use in USA during 1996-97. Since their release, adoption of glyphosate tolerant crops gained momentum and popularity among farmers due to obvious benefits like flexibility in application time, broad-spectrum weed control and reduced crop injury. Due to its non-selectivity, glyphosate can be used easily in non-cropped areas, orchard as well as for cropped areas for broad-spectrum weed control (Reddy and Nandula, 2012). For its several benefits in weed management, Duke and Powles (2008) regarded glyphosate as “once-in-a-century herbicide”. Later, many more HRGM crops like alfalfa, corn and sugarbeet were also released for commercial use by incorporating resistance against either glufosinate or glyphosate. Among these, glyphosate-resistant crops got preference over glufosinate-resistant crops due to superior yield performance (Reddy and Nandula 2012). As a step forward, stacked events were introduced by combining two traits (herbicide tolerance and insect resistance) into a single crop like cotton or corn. Further, this technology has been refined by incorporating resistance against two herbicides (glyphosate and glufosinate) or even more to facilitate rotational use of herbicides which has been advocated by many to avoid or ‘at least’ to delay the development of resistance against herbicides by the weed species. The current transgenic herbicide-resistant crops and gene transferred for herbicide resistance are given in **Table 1**.

Status of herbicide tolerant crops

Biotech crops reached 190 million hectares (Mha) during 2017 from 1.7 Mha in 1996, in 24 countries, an increase of 4.7 Mha compared to 2016, makes biotech crops the fastest adopted crop technology in the history of modern agriculture. The recent emphasis is on inclusion of several transgenes in a single hybrid or variety commonly referred as ‘stacked genes’ or ‘stacked traits’. For example, some maize and cotton hybrids have been genetically engineered to contain two transgenes, one for insect tolerance and another for herbicide tolerance (*e.g.* Bt/glyphosate, or Bt/glufosinate). Furthermore, some maize hybrids have three traits, two for herbicide tolerance and one for insect tolerance (*e.g.* Liberty, Clearfield, and Bt). Stacked traits occupied ~25% of the global 190 Mha as per James (2018). From the genesis of commercialization in 1996 to 2017, herbicide tolerance has consistently been the dominant trait. In 2017, herbicide tolerance deployed in soybean, maize, canola, cotton, sugar beet and alfalfa, occupied 59%, stacked double and triple traits 26% and insect resistant varieties 15% of total global biotech area of 190 Mha. Over the past few years, several herbicide resistant crops (HTCs), both transgenic and non-transgenic, have become available in many countries for commercial cultivation (**Table 2**). But in India, the technology of herbicide tolerant crops is in initial stage of field evaluation. Efforts have been made to evaluate and consolidate the agronomic management and advantages of herbicide tolerant transgenic crops.

Table 1. Current transgenic herbicide-resistant crops and genes responsible for resistance

Crop	Herbicide	Trait gene (s)	Year of release
Alfalfa	Glyphosate*	*EPSP synthase*	2005
Canola	Glyphosate	*EPSP synthase* and goxv 247	1996
	Glufosinate	*Phosphinothricin-N-acetyltransferase*(*pat*)	1995
	Bromoxynil	*bxn(*bromoxynil specific nitrilase)	2000
Cotton	Bromoxynil**	*bxn (*bromoxynil specific nitrilase)	1995
	Glyphosate	*EPSP synthase*	1996
		Two modified *EPSP synthase*	2006
		EPSP synthase	2009
	Glufosinate	*Phosphinothricin-N-acetyltransferase*(*pat*)	2004
Maize	Glyphosate	Three modified *EPSP synthase*	1998
		Two modified *EPSP synthase*	2001
	Glufosinate	*Phosphinothricin-N-acetyltransferase*(*pat*)	1997
	Glyphosate + glufosinate	*EPSP synthase + Phosphinothricin-N-acetyltransferase*(*pat*)	-
Soybean	Glyphosate	*EPSP synthase*	1996
		EPSP synthase	2009
	Glufosinate	*Phosphinothricin-N-acetyltransferase*(*pat*)	2009
Rice	Glufosinate***	*Phosphinothricin-N-acetyltransferase*(*pat*)	2006
Sugarbeet	Glyphosate****	*EPSP synthase*	1999

*Returned to regulated status in 2007 by legal intervention; **Removed from marke; ***Deregulated, but not commercialized; ***Removed from market, but reintroduced in 2008

Sources: Duke and Cerdeira 2010, Green and Castle 2010, Reddy and Nandula 2012

Problems of herbicide tolerant crops

Herbicide tolerant crop cultivation may lead to the development and occurrence of "super weeds". Glyphosate-resistant weeds have now been found in 18 countries worldwide and many glyphosate-resistant weed species have been identified since Roundup-tolerant crops were introduced in 1996. But herbicide resistance is a problem for farmers regardless of whether they plant GM crops. Some 64 weed species are resistant to the herbicide atrazine for example, and no crops have been genetically modified to withstand it. Farmers had historically used multiple herbicides, which slowed the development of resistance. They also controlled weeds through ploughing and tilling practices that deplete topsoil and release carbon dioxide, but do not encourage resistance. The GM crops allowed growers to rely almost entirely on glyphosate, which is less toxic than many other chemicals and kills a broad range of weeds without ploughing. Farmers planted them year after year without rotating crop types or varying chemicals to deter resistance. However, using chemicals to control weeds is still more efficient than ploughing and tilling the soil, and is less environmentally damaging. When farmers start to use more sustainable farming practices together with mixtures of herbicides they will have fewer problems. The adoption of alternative weed management strategies solves the problem of herbicide resistant weeds and is sustainable in the long run (Owen 2001; **Table 3**).

Table 2. Major HT (with single and stacked genes) approved in different counties

Crop	Countries
Alfalfa	*Australia, Canada, Japan, Mexico, New Zealand, Philippines, Singapore, South Korea, USA*
Argentine Canola	*Australia, Canada, Chile, China, EU, Japan, , Malaysia, Mexico, New Zealand, Philippines, Singapore, South Africa, South Korea, Taiwan, USA*
Carnation	*Australia, Colombia, EU, Malaysia*
Chicory	*USA*
Cotton	*Argentina, Australia, Brazil, Canada, China, Colombia, Costa Rica, EU, Japan, Malaysia, Mexico, New Zealand, Paraguay, Philippines, Singapore, South Africa, South Korea, Taiwan, USA*
Creeping bentgrass	*USA*
Flax, Linseed	*Canada, Colombia, USA*
Maize	*Argentina, Australia, Brazil, Canada, China, Colombia, Cuba, EU, Honduras, Indonesia, Japan, Malaysia, Mexico, New Zealand, Panama, Paraguay, Philippines, Russian Federation, Singapore, South Africa, South Korea, Switzerland, Taiwan, Thailand, Turkey, USA, Uruguay, Vietnam*
Polish Canola	*Canada*
Potato	*Australia, Canada, Japan, Mexico, New Zealand, Philippines, South Korea, USA*
Rice	*Australia, Canada, Colombia, Honduras, Mexico, New Zealand, Philippines, Russian Federation, South Africa, USA*
Soybean	*Argentina, Australia, Bolivia, Brazil, Canada, Chile, China, Colombia, Costa Rica, EU, India, Indonesia, Japan, Malaysia, Mexico, New Zealand, Paraguay, Philippines, Russian Federation, Singapore, South Africa, South Korea, Switzerland, Taiwan, Thailand, Turkey, USA, Uruguay, Vietnam*
Sugar beet	*Australia, Canada, China, Colombia, EU, Japan, Mexico, New Zealand, Philippines, Russian Federation, Singapore, South Korea, Taiwan, USA*
Wheat	*Australia, Colombia, New Zealand, USA*

Source: ISAAA GM Approval Database. http://www.isaaa.org/gmapprovaldatabase/.

A major environmental concern associated with herbicide tolerant crops is their potential to create new weeds through outcrossing with wild relatives or simply by persisting in the wild themselves. This potential, however, is assessed prior to introduction and is also monitored after the crop is planted. The current scientific evidence indicates that, in the absence of herbicide applications, GM herbicide-tolerant crops are no more likely to be invasive in agricultural fields or in natural habitats than their non-GM counterparts (Dale *et al.* 2002). The herbicide tolerant crops currently in the market show little evidence of enhanced persistence or invasiveness. Another major issue related to HT crops is the transgene spread to wild crops however the results are not conclusive in this area.

Prospects of herbicide tolerant crops

Broad spectrum weed control

Non-selective herbicides such as glyphosate and glufosinate aid in broadening the spectrum of weeds controlled, which is particularly important in no-till systems, and those “weedy” fields. Genetically modified herbicide tolerant maize and spring oil seed rape cultivars used were tolerant to glufosinate ammonium (Liberty, 200 g/ha), which gave post-emergence broad spectrum control of annual grasses and broad leaved weeds. In general, glyphosate is the most

Table 3. Assessment of commonly used tactics for herbicide-resistant weed management

Tactic	Benefits	Risks	Potential impact
Herbicide rotation	Reduced selection pressure, control HR weeds	Lack of different MOAs, phytotoxicity, cost, limited weed spectrum of alternatives	Excellent
Herbicide mixtures	Reduced selection pressure, improved control, broader weed spectrum	Poor activity on HR weed species, increased cost; potential phytotoxicity	Excellent
Variable application rate and timing	Better control of HR species, more efficient herbicide use	Lack of herbicide residual activity, timing may be too late to protect yield potential, more applications	Good to excellent
Adjusted herbicide rates	Better control of target species	Increased target-site selection pressure with higher rates, increased nontarget site with lower rates (polygenic resistance)	Poor to fair
Precision herbicide application	Decreased herbicide use, reduced selection pressure	Increased cost of application, unavailability of weed population maps; poor understanding of weed seedbank dynamics; increased variability of control	Poor
Primary tillage	Decreased selection pressure, consistent efficacy; depletion of seedbank	Increased time required, increased soil erosions, increased costs, additional tactics needed	Good to excellent
Mechanical weed control strategies	Decreases selection pressure; consistent efficacy, relatively inexpensive	Increased time required, high level of management skill needed, additional tactics needed, potential for crop injury	Poor to fair
Crop selection/ rotation	Changes agro-ecosystem, allows different herbicide tactics, reduced selection pressure	Economic risk of alternative rotation crop, lack of adapted rotation crop, rotation crops similar and thus minimal impact on the weed community, herbicides, requird, lack of research base, inconsistent impact on HR weed populations	Fair to good
Adjusted time of planting	Potential improved efficacy on target weeds, reduced selection pressure	Requires alternative strategies (tillage or herbicide), potential for yield loss, need for increased rotation diversity	Poor to fair
Adjusted seeding rate	Reduced selection pressure, improved competitive ability for the crop	Increased seed cost, potentially increased pest problems, increased intraspecific competition, reduced potential yields	Fair
Planting configuration	Improved competitive ability, reduced selection pressure	Unavailability of mechanical startegies, emphasis on herbicides, equipment limitations	Good
Cover crops, mulches, intercrop systems	Improved competitive ability, reduced selection pressure, improved systems biodiversity, allelopathy	Inconsistent effect on HR weeds, lack of understanding about systems, limited research base, potential crop yield loss, need for herbicide to manage the cover crop, lack of good cover crops	Poor
Seedbank management	Reduced HR weed pressure, reduced selection pressure	Lack of understanding about seedbank dynamics, requires aggressive tillage, emphasis on late herbicide applications, high level of management skill needed	Fair to good
Adjustment of nutrient use	Improved competitive ability for the crop, efficient use of nutrient	Lack of research base, inconsistent results, potential crop yield loss	Poor

Source: Owen 2001

widely used herbicide in the world and literature about its use and characteristics is extensive (Woodburn 2000). The systemic activity of glyphosate also helps with the control of perennial weeds and their perennial vegetative structures such as stolons and rhizomes (France *et al.* 1997). It is especially true for control of perennial grassy species such as quack grass (*Elytrigia repens* (L.) Beauv.), foxtail barley (*Hordeum jubatum*) and Johnson grass (*Sorghum halepense* (L.) Pers.).

Results of field trials conducted at Tamil Nadu Agricultural University (TNAU), Coimbatore, has clearly revealed that application of glyphosate at 2700 g/ ha recorded lower weed density, dry weight and higher weed control efficiency (>90%) when compared to other doses of glyphosate and hand weeding in cotton. Similarly at Punjab Agricultural University (PAU), Ludhiana, potassium salt of glyphosate at 900 and 1800 g/ha applied twice as post emergence gave effective control of weeds and produced significantly higher seed cotton yield of Roundup Ready Bt cotton hybrid than hand weeding (Kaur *et al.* 2013; **Table 4**). Systemic activity of glyphosate also helped with the control of perennial weeds and their perennial vegetative structures such as stolons and rhizomes (Chinnusamy and Bhullar 2015).

Post-emergence application of glyphosate at 900 and 1800 g/ha registered lower weed density, dry weight and higher weed control efficiency in transgenic Hishell and 900 M Gold maize hybrids at PAU Ludhiana (**Table 5**) and in transgenic 30V92 and 30B11 maize hybrids compared to their state and national checks at TNAU, Coimbatore (**Table 6**) and at Hissar, Haryana (Punia 2017).

Similarly, the field trials carried out at PAU, Ludhiana also clearly revealed that glyphosate at 900 and 1800 g/ha applied at 25 days after sowing recorded effective control of sedges, grasses and broadleaf weeds and significantly reduced weed population and dry matter as compared to University recommended practice and was safe to both the transgenic hybrids (**Table 5**). Single application of glyphosate as early or late post-emergence effectively controlled the broad spectrum of weeds in maize. In another study at Directorate of Weed Research, Jabalpur by Sushilkumar *et al.* (2017), transgenic stack hybrid maize (MON 89034X NK 603) having both insect protection and herbicide tolerant traits were effective against lepidopteron insect pests with “dual mode of action” but were not found resistant

Table 4. Glyphosate on weed control and yield in transgenic cotton (Coimbatore and Ludhiana)

Weed management techniques	TNAU, Coimbatore		PAU, Ludhiana	
	Weed control (%)	Seed cotton yield (t/ha)	Weed control (%)	Seed cotton yield (t/ha)
Glyphosate 900 g/ha	92.3	2.54	95.9	1.13
Glyphosate 1350 g/ha	93.7	2.71	96.5	1.43
Glyphosate 1800 g/ha	96.6	2.91	97.2	1.35
Glyphosate 2700 g/ha	97.3	3.14	-	-
Hand Weeding 15 & 30 DAS	85.2	2.50	84.3	1.03

Chinnusamy and Bhullar (2015)

Table 5. Weed control and grain yield in transgenic maize hybrids (Coimbatore & Ludhiana)

Weed management techniques	TNAU, Coimbatore		PAU, Ludhiana	
	Weed control (%)	Grain yield (t/ha)	Weed control (%)	Grain yield (t/ha)
Hishell PoE glyphosate at 1800 g/ha	96.69	10.34	95.2	8.50
900 M Gold PoE glyphosate at 1800 g/ha	95.41	10.46	90.8	8.14
Hishell PE atrazine at 0.5 kg/ha + HW+ IC	91.54	9.23	68.6	7.71
900 M Gold PE atrazine at 0.5 kg/ha+ HW+ IC	88.38	8.77	74.4	7.16
Proagro PE atrazine at 0.5 kg/ha + HW+ IC	84.84	7.43	69.9	5.98
CoHM 5 PE atrazine at 0.5 kg/ha + HW+ IC	82.92	7.08	71.7	7.73

Chinnusamy and Bhullar (2015)

Table 6. WCE and grain yield in transgenic corn hybrids (Coimbatore)

Weed management techniques	Weed control efficiency (%)	Grain yield (t/ha)
30V92HR glyphosate at 1800 g/ha	99.53	12.21
30B11HR glyphosate at 1800 g/ha	98.97	11.98
30V92 pre-emergence atrazine 0.5 kg/ha + HW+ IC	72.57	10.23
30B11 PE atrazine 0.5 kg/ha + HW+ IC	70.33	9.76
BIO9681 PE atrazine 0.5 kg/ha +HW+ IC	68.73	8.00
CoHM5 PE atrazine 0.5 kg/ha +HW+ IC	68.56	7.33

Chinnusamy and Bhullar (2015)

to aphids and grass hoppers. Beneficial insects were observed to visit transgenic Bt maize and conventional maize entries with no significant difference.

Sushilkumar *et al.* (2017) studied the effect of insects injury on transgenic maize and conventional maize by artificial inoculation of stem borer *Chilo partellus*. Injury by insect was found nil up to 55 DAS and leaf injury score (LIS) was less than one in all the transgenic entries of '*Hishell*' and '*900M Gold*'. In all other conventional entries, stem borer infestation was observed and the LIS was more than one. There was about 31 to 43% infestation in conventional '*900 Gold*' while in local check conventional, it was 100% ('*HQPM-1*') followed by national check (*Proagro 4640*). Tunnel length taken at the harvest time after tearing the stems also revealed highest tunnel length in national check and local check, which correlated highest infestation per cent of stem borer after artificial inoculation (**Table 7**). The Central Compliance Committee (CCC) also visited the site of trial on 18.10.2010 and monitored the insect attack and was convinced with the results.

A field study was carried out by Dixit *et al.* (2016) at Directorate of Weed Research, Jabalpur for the consecutive two years during *Kharif* 2009 and 2010 to evaluate the weed control efficiency and crop productivity with K salt of glyphosate formulation in field conditions. Treatments consisted of two transgenic stacked hybrids named *Hishell* and *900M Gold* applied with glyphosate as early post-emergence at 900, 1 800 and 3 600 g/ha during *Kharif* season of 2010 with two conventional hybrids namely *Proagro-4640* and *HQPM-1*. Early post-emergence

Table 7. Effect of artificial infestation of stem borer (*Chilo partelus*) and mean leaf injury score (LIS 1-9 scale) at 15 DAI (days after inoculation) in transgenic and conventional maize hybrids

Treatment	Infestation at 55 DAS (%)	Mean leaf injury (LIS) score at 55 DAS	Tunnel length (cm) at harvest
Hishell (MON 89034xNK 603) + round up 900 g/ha	4.05 (0)	1.00	0
Hishell (MON 89034xNK 603) + round up 800 g/ha	4.05 (0)	1.00	0
Hishell (MON 89034xNK 603) + round up 3600 g/ha	4.05 (0)	1.00	0
900 M Gold (MON 89034xNK 603) + round up 900 g/ha	4.05 (0)	1.00	0
900 M Gold (MON 89034xNK 603) + round up 1800 g/ha	4.05 (0)	1.00	0
900 M Gold (MON 89034xNK 603) + round up 3600 g/ha	4.05 (0)	1.00	0
Hishell conventional (P) + atrazine 1000 g/ha and endosulfan 35 EC 250 g/ha	39.23 (40.0)	3.20	1.63
Hishell conventional (control)	26.56 (20.0)	2.13	2.47
Hishell conventional (control) + endosulfan 35 EC 1250 g/ha	30.79 (26.7)	2.60	1.63
900 M Gold conventional (P) + atrazine 1000 g/ha and endosulfan 35 EC 1250 g/ha	23.28 (20.0)	2.67	1.97
900 M Gold conventional (control)	30.79 (26.7)	2.73	1.80
900 M conventional (control) + endosulfan 35 EC 1250 g/ha	43.08 (46.7)	3.33	2.23
National check conventional (P) + atrazine 1000 g/ha and endosulfan 35 EC 1250 g/ha	35.00 (33.3)	3.27	1.77
National check conventional control	39.23 (40.0)	3.27	3.13
Local check conventional (P) + atrazine 1000 g/ha and endosulfan 35 EC 1250 g/ha	85.94 (100.0)	7.00	3.40
Local check conventional (control)	78.44 (93.3)	5.93	3.63
LSD (p=0.05)	10.58	0.94	0.99

Source: Sushilkumar *et al.* 2017

application of glyphosate at all doses registered lower weed density and 100% weed control efficiency in all transgenic corn hybrids at 21 DAS and at harvest. Significantly higher numbers of cobs/plot were observed in transgenic hybrids as compared to conventional entries. While more cob length was observed with *Hishell* Transgenic hybrids at all doses as compared to *900 M Gold* transgenic hybrids. *Hishell* and *900 M Gold* transgenic hybrids performed better with regard to grain yield ranging between 6-10 t/ha, which was approximately 3 to 4 times higher than the average yield of maize crop/ha, *i.e.* 2.30 tonnes/ha during both the years. *Hishell* at all rates of glyphosate application performed equally well in terms of yield but the yield of *900 M Gold* decreased as the dose was enhanced from 1 800 to 3 600 g/ha during second year of experimentation.

Less carry-over effect of herbicides

Glyphosate and glufosinate have almost no soil residual activity because they are tightly bound to soil organic particles. Hence, there are few restrictions for planting or replanting intervals or injuries to subsequent crops. Herbicide tolerant crops facilitate crop rotation by providing flexibility in selection of potential rotational crops and will not cause any residual effect on succeeding crops, which were proved through field trials. For example, glyphosate application in transgenic maize/cotton hybrids did not affect germination , vigour and yield of succeeding green gram, sunflower, soybean, pearlmillet and cucumber crops can be planted or seeded directly into treated areas of glyphosate because it has no pre-emergent activity even when applied at high rates.

Reduced crop injury

Various post-emergence type herbicides used for weed control in soybean, canola or corn can cause crop injury and ultimately yield loss. Crop injury is more severe when the crop is under stress or unfavourable environmental conditions occur. In contrast, crop injury is reduced with the use of herbicide tolerant crops. Phytotoxicity symptoms were not noticed in cotton with glyphosate at lower doses, *viz.* 900, 1350, 1800 and 2700 g/ha. Glyphosate causes almost no crop injury, compared to some traditional herbicides like lactofen and chlorimuron, especially when applied to cotton. The greatest beneût to growers is the broad-spectrum weed control with post-emergence application of glyphosate to cotton without crop injury. Regarding transgenic maize hybrids, there was no phytotoxic symptom observed in transgenic maize hybrids due to application of various doses of glyphosate throughout the crop growth in both the trials. No injury was recorded in maize crop due to application of PoE glyphosate product at various levels of concentrations.

Environmentally safe herbicides

In general, glyphosate and glufosinate have lower toxicity to humans and animals compared to some other herbicides. Since they are absorbed the organic particles in soil and decompose rapidly, they pose little danger for leaching and contamination of ground water or toxicity to wildlife. Glyphosate applied at lower doses like 900, 1350, 1800 and 2700 g/ha recorded with more number of bacteria, fungi and actinomycetes. In transgenic maize hybrids, PoE application of glyphosate at lower doses like 900 and 1800 g/ha recorded with more number of bacteria, fungi and actinomycetes population compared to atrazine applied treatments (**Table 8**). This is due to glyphosate applied directly on the weeds that added organic materials to the soil, during decomposition of organic material microbial population might have been increased. Reports showed that glyphosate was available to soil and rhizosphere microbial communities as a substrate for direct metabolism leading to increased microbial biomass and activity. Results of earlier trials revealed that glyphosate had only small and transient effects on the soil microbial community, even when applied at greater than field rates. Many studies, however, indicates towards carcinogenicity of glyphosate which is a cause for concern; studies are however, not conclusive to date. And, the emphasis in HT crops is likely to be shifted to other herbicide like glufosinate ammonium, 2,4-D, dicamba, imidazolinone herbicides.

Management of herbicide resistant weeds

Since the discovery and report of triazine resistance almost 40 years ago, weeds resistance to herbicides have been well documented. For example, there are

Table 8. Glyphosate on soil microbes(x 10-4 CFU/g) in transgenic maize (Coimbatore)

Weed management techniques	Bacteria	Fungi	Actinomycetes
30V92HR Glyphosate at 1800 g/ha	39.77	28.54	13.26
30B11HR Glyphosate at 1800 g/ha	39.11	28.61	12.90
30V92 PE atrazine 0.5 kg/ ha+ HW+IC	30.47	26.34	11.23
30B11 PE atrazine 0.5 kg/ha + HW+IC	31.07	26.81	11.67
BIO9681 PE atrazine 0.5kg/ha+HW+IC	28.28	26.00	11.56
CoHM5 PE atrazine 0.5 kg/ha +HW+IC	27.08	25.61	11.82

Chinnusamy and Bhullar (2015)

40 dicot and 15 monocot weed species known to have biotypes resistant to triazine herbicides. Also, at least 44 weed species have been reported to have biotypes resistant to one or more of 15 other herbicides or herbicide families. List of herbicide-resistant weeds will continue to grow, especially with repeated use of herbicides with the same mode of action. Many of the selective herbicides in maize and soybean have similar or identical mechanisms of action such as the inhibition of enzymes. Therefore, herbicide (*e.g.* glyphosate and glufosinate) tolerant crops particularly cotton can provide a new mode of action when used in an integrated weed management programme as an aid in resistance management.

Weed management flexibility

Herbicide tolerant technology is simple to use. It requires neither special skills nor training. The technology does not have major restrictions and is flexible, which is probably one of the reasons for such wide adoption by producers. In particular, crops that are tolerant to broad-spectrum herbicides such as glyphosate extend the period of herbicide application for effective weed control, which is helpful in dealing with rainy and windy days during the optimal periods for weed control measures. In contrast, poor weather during the critical period for weed control can greatly limit the effectiveness of more selective herbicides. Total weed density was significantly lowered with non-selective post-emergence application of glyphosate in transgenic cotton and maize hybrids when compared to hand weeding plots in transgenic cotton national and state checks in transgenic maize without any injury to crops.

Increased productivity and profitability

Cotton crop being slow in its initial growth and is grown with wider spacing, is always encountered with severe weed competition during early stages, which results in lower yield. A broad spectrum of weeds with wider adaptability to extremities of climatic, edaphic and biotic stresses is infesting the cotton fields. High persistence nature of weeds is attributed to their ability of high seed production and seed viability. Hand weeding or hoeing twice is the most commonly adopted method of weed control in cotton. However, complete weed control could not be achieved by using any single method alone. Herbicidal weed control seems to be a competitive and promising way to control weeds at initial stages of crop growth. Higher yield of herbicide tolerant transgenic cotton recorded with glyphosate at 2700 g/ha over hand weeding twice during winter season (**Table 4**) due to efficient control of weeds during the cropping period as observed at TNAU, Coimbatore and PAU, Ludhiana field trials. Roundup Ready Flex cotton could provide producers with acceptable weed control without compromising cotton yield. Glyphosate at 2700 g/ha recorded with higher gross and net returns and B:C ratio in herbicide tolerant transgenic cotton.

Higher grain yield was recorded with PoE application of glyphosate at 900, 1800 and 3600 g/ha in *Hishell* and *900 M Gold* transgenic hybrids (**Table 5**), even though higher and comparable weed control and yield were obtained with glyphosate at 900 and 3600 g/ha, higher net return and benefit cost ratio was recorded in glyphosate at 1800 g/ha in transgenic *900 M Gold* in all the four seasons in trial I. Post-emergence application of glyphosate at 900 and 1800 g/ha registered higher grain yield in transgenic *30V92* and *30B11* corn hybrids in the maize trial II compared to their state and national checks (**Table 6**). Average yield obtained in transgenic hybrids was 10 t/ha and conventional transgenic maize hybrids was 8 t/ha at TNAU, Coimbatore. Research reports of PAU, Ludhiana revealed that morphological and phenotypic characters of both the transgenic hybrids were similar to their non-transgenic counterparts. Transgenic hybrids with glyphosate applications recorded higher maize grain yield, net return and B:C ratio as compared to university recommendation practices in transgenic or non-transgenic maize hybrids. Earlier research findings brought out that yields of herbicide resistant maize hybrids were maximum with glyphosate at 0.84 kg/ha when applied at fifth leaf stage.

Indian experiences with herbicide resistant crops

As such, in India no HRGM crop is being grown, but Bt-cotton has been there in the fields for quite some time and as on date stands successful with high and widespread adoption. In 2014, adoption of Bt cotton in India increased by 600,000 hectares to a record 11.6 Mha, equivalent to a high adoption rate of 95% of 12.2 Mha total cotton area (Choudhary and Gaur 2015). According to Professor Deepak Pental in India and many parts of the world with very large populations dependent on agriculture for livelihoods, transgenic technology can make significant contribution to achieve higher productivity. For example, GM crops have helped to develop herbicide resistant crops that have allowed soil conservation though no-till in addition to effective weed management. Further, talking on the risks and concerns about the GM technology, he emphasized that most of the perceived risks are imaginary and unscientific. However, at the same time, he also expressed his concern over the introduction of herbicide resistance trait in crops that are grown in their regions of biodiversity (Watts *et al.* 2015).

Field level trials on stacked events in corn with glyphosate and insecticide resistance have been conducted in recent past, commercial approval for such any event is still not granted. An evaluation of herbicide and insect resistant stacked corn (TC 1507 x NK603) was done at Tamil Nadu Agricultural University, Coimbatore (Sivagamy and Chinnusamy 2015). Results indicated that potassium salt of glyphosate at 1.8 kg/ha provided broad spectrum weed control and increased productivity with higher grain yield. Currently, Supreme Court of India put a 10-year moratorium on field trials of GM crops in the country. At laboratory level, efforts are being made for development of HRGM crops. Scientists, at International Centre for Genetic Engineering and Biotechnology (ICGEB), New Delhi, have developed glyphosate resistant rice plants by successfully re-transforming rice EPSP synthase encoding gene after introducing *in vitro* mutagenesis for herbicide tolerance (Reddy 2015) Further, testing and evaluation of HRGM rice plants is underway. If this technology could be commercialized, would prove a milestone for rice farming in India. At the same time, several other efforts are also being made at laboratory level.

Environmentalists and several social organizations have raised question over utility/practicality of GM and more so of HRGM technology. The concerns are the herbicide tolerance trait is essentially a labour saving and hence a labour displacing trait. In a labour surplus country like India, it will have negative socio-economic implications. Weeds are largely nutritious leafy greens which are a valued and free source of nutrition in the family's diet and serve as fodder for the livestock that rural families maintain as additional income sources. In addition, HRGM deprive rural communities of the weeds as medicinal plants which form the basis of indigenous healing traditions for themselves and veterinary purpose. Indian farmers traditionally grow inter/mixed cropping, where HRGM crops become more challenging one. However, giving an option for a new technologies do not put ban on any other practices. Adoption of any technology is solely depending on the choice of users, and no technology can be imposed forcefully until technology proved beneficial to the stakeholders. The best option would "let us make the technology available and leave it to users to adopt or not to adopt the HRGM crops technology".

Resolutions on GM crops status in India

A round table meeting was held at the National Academy of Agricultural Sciences, New Delhi on12 February, 2014 under the Chairmanship of Prof. M.S. Swaminathan, former Member Rajya Sabha, Govt. of India and Founder Chairman, M.S. Swaminathan Research Foundation, Chennai. The potential of GM crop technology including HRGM in solving the issues like low farm productivity, malnutrition and hidden hunger problems in the underprivileged sections of our society were very well discussed. Important resolutions emerged from the meeting are

- Genetically modified crop technology is a promising, relevant and efficient technology for low-input high-output agriculture for crop improvement where conventional breeding tools have not been effective. GM technology will be a tool to improve agricultural crops for their nutritional value, nutrient & water use efficiency, productivity, tolerance/resistance to biotic and abiotic stresses.

- Present de facto moratorium on the field trials of GM crops should be lifted at the earliest. It is putting the clock back in relation to progress in harnessing the benefits of GMO technology in agriculture. Confined field trials are essential for the evaluation of productivity performance as well as food and environmental safety assessment. The non-conductance of regular field trials is a handicap as well as disincentive in harnessing the benefits of a wide array of transgenic material available with different research organizations.
- Indian biosafety regulatory system is in compliance with the international regulatory consensus based guidelines. The system, put in place under the Environment Protection Act (1986) should dynamically evolve, update, adopt and implement the biosafety protocols and procedures. The bill on Biotechnology Regulatory Authority of India introduced by the Government needs to be pursued further taking into account the observations by all stakeholders. Meanwhile the existing three tier system of IBSC, RCGM and GEAC has done a good job and should be strengthened with adequate infrastructure and technical support to continue with the confined field trials so that the research progress is not halted.
- After biosafety clearance by the GEAC, ICAR should play a key role in the commercial release of the GM crops to prevent undue proliferation of large number of hybrids/varieties. The national regulatory system should integrate capacity building as a necessary operational requirement to keep pace with scientific advancement through international collaborations to evolve as the most effective system including collaborations with countries such as USA, Australia, Canada, Norway and Brazil.
- Scientists should communicate with public and policy makers about the safety and benefits of GM crop products and remove the undue fears and apprehensions about GM crop adoption. A media resource centre may be set up for providing up-to-date scientific information to media representatives and dispel any misinformation. The Academy may set up two committees on the pattern set up by the Royal Society of London, a. Committee on Public Understanding of Science, b. Committee on Political Understanding of Science.
- Until the time a Parliament approved autonomous National Biotechnology Regulatory Authority comes into existence, RCGM&GEAC should have full time chairpersons as recommended by SAC to PM and GEAC should issue ‘Decision Documents’ at the time of allowing field trials of a GM event and at the time of final release of a GM event for commercialization.
- The GEAC should function like a statutory body and make final decision on approval of the GM event for environmental release. The “No- Objection” certification from state governments for conduct of confined field trials is not required as their products will not get to farmers or consumers.
- Agriculture is a state subject and it is important that the State Agricultural Universities and State Departments of Agriculture are involved in the implementation of the field trials but without losing time. Some states are

declaring themselves an organic state which precludes the use of GM crops. However, organic farming would require effective methods to face the challenge of pests and diseases.

- Return from investments in biotechnology research is very high. Public and private sectors should develop a joint strategy which will help to ensure the inclusiveness of access to improved technologies among all farmers, small or large. To achieve a zero hunger challenge of the United Nations by 2025, we must double the small farm productivity. Such an increase will be possible only through the intelligent and intensive applications of new technologies such as biotechnology in agriculture.

In the light of experience available and views of experts on the subject in India, it is inferred that HRGM technology is viable option in Indian context too. However, we have to be careful in selection of crops as well as strategy so that risks of gene flow can be minimized up to the extent possible. A location-specific and stringent evaluation of biosafety aspects has to be worked out before commercialization of HRGM crops in India.

Conclusion

Herbicide tolerant crops in general provide broad spectrum of weed control, reduced crop injury and phyto-toxicity, less herbicide carry-over on the succeeding crops. Herbicides like glyphosate and glufosinate are environmentally safe with less persistence and residues, new means for weed resistance management, crop and weed management are flexible and simple, better performance in terms of yield and higher profitability in terms of income of HT crops**.** In many crops, their use will decrease the cost of weed management in short to medium term. However, they offer farmer a powerful new tool that, if used wisely, can be incorporated into an integrated pest management strategy that can be used for many years to more economically and effectively manage weeds. In maize and cotton transgenic crops, post emergence weed management with glyphosate proved to be the better management option for weed control.

References

AGBIOS. 2018. Agbios GM Database. Available at http://www.agbios.com/ dbase.php. Accessed: January 9, 2018.

Bhullar MS, Kaur N, Kaur P and Gill G. 2017. Herbicide resistance in weeds and its management. *Agricultural Research Journal* **54**(4): 436–444.

Chinnusamy C and Bhullar MS. 2015. Prospects of herbicide tolerant crops and their relevance to Iindian agriculture. *Indian Farming* **65**(7): 20–23.

Choudhary B and Gaur K. 2015. *Biotech Cotton in India*, 2002 to 2014. *ISAAA Series of Biotech Crop Profiles*. ISAAA: Ithaca, NY.

Dale PJ, Clarke B and Fontes EMG. 2002. Potential for the environmental impact of transgenic crops. *Nature Biotechnology* **20**(6): 567–574.

Dixit A, Raghuvanshi MS, Singh VP and Sushilkumar. 2016. Efficacy of potassium salt of glyphosate on weed control and yield in transgenic maize. *Indian Journal of Agricultural Sciences* **86**(10): 1324–32.

Duke SO and Cerdeira AL. 2009. Transgenic crops for herbicide resistance. Transgenic Crop Plants 2: *Utilization and Biosafety* **2**: 133.

Duke SO and Cerdeira AL. 2010. Transgenic crops for herbicide resistance. pp. 133–165. In: *Transgenic Crop Plants Utilization and Biosafety*. (Eds. Kole C, Michler CH, Abbot AG and Hall TC), Springer: Heidelberg, Germany.

Duke SO and Powles SB. 2008. Glyphosate: a once-in-a-century herbicide. *Pest Management Science* **64**(4): 319–25.

Franz JE, Mayo MK Mayo and Sikorski JA. 1997. Toxicology and environmental properties of glyphosate. pp. 103–137. In: *Glyphosate: A Unique Global Herbicide*. Monograph 189. American Chemical Society, Washington D.C.

Green JM and Castle LA. 2010. Transitioning from single to multiple herbicide-resistant crops. pp. 67–92. In: *Glyphosate Resistance in Crops and Weeds: History, Development, and Management* (Ed. Nandula VK). John Wiley & Sons, Inc., Hoboken, New Jersey, USA.

James C. 2018. Global status of commercialized biotech/GM crops. *International Service for the Acquisition of Agri- Biotech Applications (ISAAA) Brief 42-2018*: Executive Summary. http://www.isaaa.org/resources/publications/briefs/42/executive summary/default.asp.

Kaur T, Walia US, Bhullar, MS, Kaur, R and Shergill LS. 2013. Sustaining cotton productivity in semi-arid sub-tropical India. pp. 166–175. In: *Climate Change and Crop Production* (Eds. JS Gagar, Arunachalan A and Singh AK) Aavishkar Publishers, Jaipur.

Lebrun M, Sailland A and Freyssinet G. 1997. Mutant 5-enol pyruvylshikimate-3-phosphate Synthase Gene Encoding for Said Protein and Transformed Plants Containing Said Gene. *International Patent Publication*. WO97/04103-A2. 25p.

Owen MDK. 2001. World maize/soybean and herbicide resistance. pp. 101–63. In: *Herbicide Resistance and World Grains*, (Eds. Powles SB, Shaner D L), CRC Press: Boca Raton, FL.

Padgette S, Kolacz, KH, Delannay X and Re, DB. 1995. Development, identification and characterization of a glyphosate-tolerant soybean line. *Crop Science* **35**(5): 1451–1461.

Punia SS. 2017. Evaluation of herbicide tolerant transgenic corn hybrids in India. *Proceedings 26th APWWS Conference at Kyoto*, Japan 19-22 September 2017.

Reddy KN and Boykin Boykin JC. 2010. Weed control and yield comparisons of twin and single-row glyphosate resistant cotton production systems. *Weed Technology* **24**: 95–101.

Reddy KN and Nandula VK. 2012. Herbicide resistant crops: History, development and current technologies. *Indian Journal of Agronomy* **57**(1): 1–7.

Reddy MK. 2015. http://www.icgeb.org/reddy-lab.html (accessed on January, 2015)

Sivagamy K and Chinnusamy C. 2015. Evaluation of herbicide and insect resistant transgenic hybrids (TC1507 x NK 603) for higher productivity. p.420. In: *Proceedings Volume II (Oral). 25th Asian-Pacific Weed Science Society Conference*, Hyderabad.

Sushilkumar, Raghuvanshim MS, Anil Dixit and Singh VP. 2017. Glyphosate tolerant and insect resistant transgenic Bt maize efficacy against shoot borer, cob borer and non-target insect pests. *Indian Journal of Weed Science* **49**(3): 241–247.

Watts A, Kumari A, Muthusamy SK and Meena RP. 2015. Genetically modified crops: Need for rational evaluation. *Science Reporter* **52**(11): 14-17

Woodburn, A.T. 2000. Glyphosate: Production, pricing and use worldwide. *Pest Management Science* **56**: 309–319.

WSSA (Weed Science Society of America). 2007. *Herbicide Handbook*. 9th ed. Lawrence, KS: WSSA.

Chapter 10

Resource conservation and weed management through mulches

V.K. Choudhary* and Santosh Kumar
ICAR-Directorate of Weed Research, Jabalpur,
Madhya Pradesh 482 004
**Email: ind_vc@rediffmail.com*

Summary

Mulching is a non-chemical weed management crop production technique that involves placement of organic or inorganic materials on the soil surface to provide a more favourable environment for plant growth and development. Non-synthetic "natural" mulches contain fibres or residues from plants or animals and use of synthetic materials as mulch (plastic mulch) are used as an alternative method. These can provide several benefits including weed suppression, soil moisture conservation, improved water filtration, enhanced soil stabilization and porosity, microbial population activity, more efficient use of soil nutrients, reduction of certain insect pests and decreased plant disease. Organic materials get decomposed over the period, whereas, disposing of used plastic films, which cause pollution, has led to development of photodegradable and biodegradable mulches. Mulches especially contribute to weed management in non-herbicidal used crops by reducing weed seed germination, blocking weed growth, and favouring the crop by conserving various resources at site.

Key words: Mulch, Soil moisture conservation, Weed management, Yield improvement

Introduction

The highly diverse agriculture and farming systems are beset with different types of weed problems. Weeds cause 10-80% crop yield losses besides impairing product quality and causing health and environmental hazards (Choudhary *et al.* 2012a). Invasive alien weeds are a major constraint to agriculture, forestry and aquatic environment. Crop-specific problematic weeds are emerging as a threat to cultivation, affecting crop production, quality of product and income of farmers. Weeds affect everyone in the world by reducing crop yield and crop quality, delaying or interfering with harvesting, interfering with animal feeding (including poisoning), reducing animal health, preventing water flow, as plant parasites, *etc*. Weeds are common everywhere and cause loss of many billion Dollars annually.

Weeds were considered the most important biotic stress in a survey of organic vegetable growers. Worldwide, every year the herbicide consumption represents 47.5% out of the 2 million tons of pesticide consumed. However, the heavy use of herbicides has given rise to serious environmental and public health problems. Researchers have been reported new challenges, particularly in the light of the emergence of weeds resistant to herbicides and concerns and questions about herbicide residues in food, soil, groundwater-atmosphere because of the potential problems associated with herbicides use are injurious to non-target vegetation, crop injury, residues in soil and water, *i.e.*, reduction of soil and water quality, toxicity to other non-target organisms, concerns for human health and safety and herbicide-resistant weed populations. Therefore, effective and safe weed management practices such as soil solarization, mulching, hot water, biological control, natural herbicides, some cultural treatments etc. Out of these, mulching is a very important method and widely used for controlling weeds mainly due to use of locally available material with considerably lower cost.

The practice of mulching has been widely used as a management tool in many parts of the world. It dampens the influence of environmental factors on soil by increasing soil temperature controlling diurnal/seasonal fluctuations in soil temperature (Lalitha *et al.* 2001). However, the effect varies with soils, climate, kind of mulch material used and the rate of application. The surface mulch favourably influences the soil moisture regime by controlling evaporation from the soil surface (Ji *et al.* 2001, Pawar *et al.* 2004), improves infiltration, soil water retention, decreases bulk density (Kladivko and Unger 1994, Choudhary and Kumar 2013, Choudhary *et al.* 2013) and facilitates condensation of soil water at night due to temperature reversals (Tisdall *et al.* 1991, Choudhary and Kumar 2013). Modification of the soil microclimate by mulching favours seedling emergence (Han *et al.* 1989) and root proliferations (Choudhary *et al.* 2012a) and suppress weed population (Lalitha *et al.* 2001, Choudhary *et al.* 2012a, Choudhary and Kumar 2013, Choudhary 2016).

Mulch may be organic (crop residue, stubble mulch) or inorganic (plastic sheet, gravels, *etc.*) in composition. Organic mulch adds nutrients to soil when decomposed by microbes and help in carbon sequestration (Choudhary *et al.* 2012b, Choudhary and Kumar 2013). Plastic mulch is the most widely used inorganic mulch materials in many countries. Mulching with the help of plastic film has played a major role in crop production by creating mechanical protection at the soil surface and is microclimate favourable in terms of temperature distribution, retention of humidity and the supply of CO_2 to the stomata of lower leaves of small plants (Otsuki *et al.* 2000, Choudhary *et al.* 2012b, Choudhary and Kumar 2013). In India, limited works with plastic mulch on plantation crops (Varadan *et al.* 1990) and vegetable crops (Pawar 1990, Sudha and Nanjappa 1999) have been reported. However, use of plastic mulch for field crops is still at a developmental stage in India.

Mulching provides a physical barrier and reduces the weed germination and emergence, and clean crop. It favours into the reduction of weed seed germination, weeds growth and keeps the weed as minimum as possible (Vander Zaag *et al.* 1986). Mulching at soil surface can prevent weed seed germination or physically suppress seedling emergence. Loose materials such as crop residues (straw), bark and composted municipal green waste can provide effective weed control (Merwin *et al.* 1995). Saw dust is a soil improver and weed suppressor as it conserves soil moisture, decreases run-off, increases infiltration and percolation, decreases evaporation and weed growth can be substantial under clear mulch (Waterer 2000). Type of mulch plays crucial role in emergence and growth of weeds, as white or transparent mulch and green covering has little effect on weeds, whereas brown, black, blue or white on black (double colour) films prevent emerging weeds (Bond and Grundy 2001). Ossom *et al.* (2001) also observed significant differences in weed control between mulched and un-mulched plots of eggplant. Mulches on soil surface act as insulator for solar radiation and decreases evaporation, maintains the soil temperature congenial for crop growth, reduces runoff and increases infiltration rate (Arshad *et al.* 1999). Adding crop residue can improve several soil biological, chemical, and physical characteristics (Ferrero *et al.* 2005), affect the quantity of rainwater entering the soil and evaporation, promote soil stability, and reduce soil erosion and runoff (Pabin *et al.* 2003). Applications of crop residue mulches increase soil organic carbon contents (Saroa and Lal 2003). Eastern Himalaya follows almost monocropping of paddy with special harvesting technique of only removing panicles. This resulted into abundant paddy straw being left in the field (Choudhary *et al.* 2012b).

Types of mulching materials

Organic mulches

Compost / manure / peat: These are the materials, which can be used for mulching (50-75 mm thick) and can be of quite an attractive appearance. These materials should be well rotted before laying else can cause damage to plants. These materials will have positive effect on the soil fertility (Choudhary *et al.* 2012b) especially for the home garden and orchards and is inexpensive. It must be free from the weed seeds. These types of mulch provide better performance for plant, and is successful in the area where these are commercially available. It can be easily prepared.

a. **Peat moss:** Though expensive, this mulch is attractive and easy to handle. Dry peat moss requires considerable time and water to become moist, so it should be applied only to lesser depth (< 75 mm) and avoided in drought-prone areas. Its lower pH makes it especially desirable for acid-loving plants.

b. **Pine bark and Pine needles:** Pine bark is usually a dark-coloured mulch with size ranging from shredded to large-sized particles, called nuggets. Large pine bark nuggets float in water and may not stay in place during a heavy rain. They may also attract termites and other insects. A 50-75 mm layer of pine needles makes excellent mulch for acid-loving trees and shrubs. This mulch allows water to penetrate easily and also supplies nutrients as they decompose. The collection of these barks and needles is only limitation.

c. **Sawdust:** Partially rotted, aged sawdust makes satisfactory mulch (50 mm thick) that lasts for a long time as it is prone to caking and has a high carbon to nitrogen ratio. It contains only half the nutrients of straw, is slow to break down and causes nitrogen robbery so should not be incorporated into the soil until it has broken down to a brown ‘soil’ and worms are found in it. Softwood sawdust takes longer than hardwoods to decompose. To overcome nutrient deficiencies, nitrogen can be added to sawdust and composted before spreading it on the soil.

d. Grass-clippings: Grass clippings are an effective and easily available mulch (100-150 mm thick) that can be applied straight from the mower box to most areas of the garden. It should have adequate thickness that allows air to penetrate in it and should be used only before flowering. Add additional layers as clipping decompose. Do not use clipping from lawn treated with herbicides. They provide their own nitrogen if incorporated fresh, but may cause nitrogen robbery after long drying.

d. Straw: Straw of crops possess similar qualities to grass clippings if it is put in a thick layer (50-100 mm) or 4 t/ha (Choudhary 2016). This provides substantial weed suppression and get decomposed after some time and provides additional nutrients to the crops.

e. Newspaper: Apply sheets of newspaper and anchor it with other material. They are prone to blow away and once wet are soon broken up or penetrated by weeds. If other mulch materials are not available, cover edges of paper with soil on non-windy days. This is readily available, economical but somewhat difficult to apply. Two to three newspaper sheets can be placed to get effective result. They can be useful underneath loose mulches, as they stop the soil from mixing. Newspaper should be wax-free, non-coloured as they may be chemical contaminated. Paper alone begins to tear and blow away within 2-3 weeks after field application due to rapid biodegradation and loss of strength when wet.

Benefits of organic mulching

Mulch reflects a lot of the sun and keeps the soil cooler and prevents evaporation. This is especially useful in hot, dry climates. When the soil is covered with mulch, weeds do not grow under it in absence of light. Mulches prevent soil erosion, as it prevents wind or running water to come in contact of soil and prevents them from being blown or washed away. Mulches spread over soil, slow down rainwater run-off, and increase the amount of water that soaks into the soil and increases water availability for crops. Organic mulches also improve the condition of the soil. As these mulches slowly decompose, they provide organic matter which not only helps to keep the soil loose but also becomes food for the beneficial earthworms and other soil micro-organisms. This creates a very good porous soil, improves root growth, increases the infiltration of water and improves the water-holding capacity of the soil. Decaying organic matter also becomes a source of plant nutrients. It maintains a more even soil temperature and keeps feet clean allowing access to field even when damp.

Limitation of organic mulching

Mulches can keep the soil too moist, restricting oxygen in the root zone on poorly drained soils. If mulch is applied close to or in contact with the stem, trapped moisture creates an environment conducive to development of diseases and pests. Many organic types of mulches also encourage and provide breeding locations for pests such as snails, slugs, mice, *etc*. Certain types of mulches such as hay and straw contain seeds that may become weeds.

In-organic mulches

a. **Gravel, pebbles and crushed stones:** These materials are usually used for perennial crops. Small rock layer of 30-40 mm provides good weed control. But they reflect solar radiation and can create a very hot soil environment during summer.

b. **Polyethylene mulches:** Non-organic mulches generally lack the soil improving properties particularly to improvement in soil particle aggregation, structure formation and regulation of soil reactions. Among the different inorganic mulches, the use of plastic mulches is most common owing to its properties of moderating the hydrothermal regimes of microclimate of crops, show positive effects on weed control, prevention of soil dryness and crusting, water saving by preventing evaporation from surface, prevention of soil erosion and reduction of nutrient loss by leaching.

c. **Aluminium-coated plastic and foil:** Use is limited to vegetable which have reduction in insect pests, such as aphids, and viruses carried by insects. One layer of either one of these materials provides excellent weed control. These materials decompose very slowly, but they are very expensive mulches.

d. **Colour of film:** Soil environment can be managed precisely by a proper selection of plastic mulch composition, colour and thickness. Films are available in variety of colours including black, transparent, white, silver, blue red, etc. But the selection of the colour of plastic mulch film depends on specific targets. Generally, the following types of plastic mulch films are used in horticultural crops.

   i. **Photo-degradable plastic mulch:** These mulch film gets destroyed by sun light in a shorter period.

   ii. **Bio-degradable plastic mulch:** These mulch film is easily degraded in the soil over a period.

   iii. **Black plastic film:** It helps in conserving moisture, controlling weed and reducing outgoing radiation.

   iv. **Reflective silver film:** It generally maintains the root-zone temperature cooler.

   v. **Transparent film:** It increases the soil temperature and preferably used for solarization.

Advantages of inorganic mulching: Moisture conservation, Soil conservation, Soil temperature moderation, Soil solarization (with transparent plastic mulch controls disease pest), Weed control *etc*.

Methods in mulching

a. **Surface mulching:** Mulches are spread on surface to reduce evaporation and increase soil moisture.

b. **Vertical mulching:** It involves opening of trenches of 300 mm depth and 150 mm width across the slope at vertical interval of 300 mm.

c. **Polythene mulching:** Sheets of plastic are spread on the soil surface between the crop rows or around tree trunks.

d. **Pebble mulching:** Soil is covered with pebbles to prevent transfer of heat from atmosphere.

e. **Dust mulching:** Inter-culture operation that creates dust that breaks continuous capillaries, and deep and wide cracks thus reducing evaporation from the exposed soil areas.

f. **Live vegetative barriers:** Subabul and *Glyricidia* when used as live vegetative barriers on contour key lines not only serve as effective mulch when cut and spread on ground surface but also supply nitrogen to the extent of 25 to 30 kg/ha, besides improving soil moisture status.

Limitations of mulching

Mulches do have a few drawbacks, which are as follows:

(i) Some materials are costly for large-scale adoption.

(ii) Some mulch is not readily available.

(iii) In case of sawdust or straw mulch, nitrogen starvation occurs sometimes.

(iv) Heavy mulching over a period of years may result in build-up of soil over the crown area of the plants.

(v) Continuously using the same type of mulch (pine bark) lowers the soil pH and soil becomes acidic which may cause plant death by changing the soil's reaction. Conversely, hardwood bark mulch, although initially acidic, may cause the soil to become too basic or alkaline, causing acid-loving plants to quickly decline. Soil pH's above 6.5 usually create micronutrient deficiencies of iron and manganese. One can avoid this by periodically rotating the type of mulch used.

(vi) Difficulty in application of top-dressed fertilizers.

(vii) Some of the mulch materials (plastic mulches) are not degradable.

(viii) In areas where the incidence of termites is very high, application of organic mulch needs frequent irrigation and spray of termiticides.

(ix) Some of the organic mulches have allelopathic effects on crops.

Effect of mulches on weeds and management

Choudhary *et al.* (2013) revealed that use of mulch considerably reduced the weed emergence and growth which significantly lowered the weed parameters under mulching. Density, dry weight, index and persistency index of weeds were lower under mulched plot (7.5 no./m^2, 4.4 g/m^2, 20.6 and 11.6%, respectively), whereas mulched plots had 65% higher weed-smothering efficiency than the bare soil. Reduced weed germination and infestation by restricting the penetration of solar radiation under mulch resulted in higher weed-smothering efficiency.

However, bare soil induced the germination of weeds resulted lower weed-smothering efficiency (Hiltbrunner *et al.* 2007, Patel *et al.* 2009). Placement of mulch reduced the weed species and provided the congenial condition for crops to grow and develop (Moonen and Barberi 2004).

Application of crop residues as mulch significantly reduced the weed density and dry biomass resulted better weed suppression ability. Choudhary and Kumar (2014) also reported that in maize-based cropping system application of straw mulch prevented rapid germination and establishment of weeds during early stage of crop in mustard and frenchbean which lowered the weed density by 35.4% and weed dry biomass by 31.3% over without mulch (Choudhary 2016). Lowered weed germination and infestation by restricting the penetration of solar radiation under mulch led to better weed suppression. However, germination of weeds was induced under without mulch resulting in lower weed suppression (Hiltbrunner *et al.* 2007, Patel *et al.* 2009). Choudhary *et al.* (2012a) found that black polythene mulch recorded the minimum weed dry weight throughout the crop growth period with 74.1% weed control efficiency. However, the maximum weed dry weight throughout the crop growth period was observed with no mulch. It was also noticed that transparent polythene mulch induced grasses (*Echinochloa colona* and *Cynodon dactylon*) to emerge quickly over others and accumulate more dry weight because of having the higher photosynthetic efficiency, therefore, weed control efficiency was comparatively lower (Patel *et al.* 2009). But sedges and broad-leaves were more with no mulch having profuse canopy coverage and high competing ability. Choudhary (2016) reported that application of mulches, significantly reduced weed dry biomass and maximum weed smothering efficiency (69.5%) was noticed over without mulch in maize. Similarly, mulched plots had significant reduction in weed dry biomass with the highest weed smothering efficiency was obtained with mulched plots over without mulch in frenchbean. The weed smothering efficiency followed the reverse trend of weed dry biomass and had 61% weed smothering efficiency.

Yordanova and Nikolov (2017) reported that, the tested mulching materials had a depressing effect on weed species, except for the gallant-soldiers (*Galinsoga parviflora* Cav.). Mulching with barley straw and with grass windrow has a significant depressing effect on weeds, especially on *Echinochloa crus-galli* L., *Amaranthus retroflexus* L. and *Veronica hederefolia* L. Barley straw mulch is good against weed infestation, but keeps the soil cool and reduces yield. Rajablariani *et al.* (2012) evaluated tomato (*Lycopersicon esculentum* L.) under different type of plastic mulch along with bare soil. Mulching increased marketable yield relative to bare soil as the plants grown on silver/black plastic mulch indicated a 65% increase in marketable yield compared to control treatment. The plastic mulches resulted to the tune of 84-98% reduction in weed biomass. Bobby *et al.* (2017) revealed that at 30, 60 and 80 DAS, weed density (5.0, 7.3 and 6.0 no./m^2, respectively) and weed dry weight (2.2, 2.4 and 2.5 g/m^2, respectively) were the lowest with the use of black polythene mulch whereas control recorded the highest weed density (37.0, 40.0 and 39.0 no./m^2 respectively) and weed dry weight (27.9, 28.2 and 27.8 g/m^2, respectively). Highest weed control efficiency (92.1, 91.4 and 91.0%, respectively) was registered with black polythene mulch followed by paddy straw mulch (55.9, 56.0 and 56.9% respectively). In okra, field comprised *Commelina benghalensis, Echinochloa colona, Cyperus iria, Dinebra sp, Phyllanthus niruri* and *Physalis minima* weed species. Application of 10 t/ha FYM along with black polythene mulch significantly suppress the weed density and dry biomass and recorded 100% weed control efficiency (DWR 2012-13). In tomato crop weed comprised with *Medicago denticulata, Avena ludoviciana, Cichorium intybus, Anagallis arvensis* and *Phalaris minor*application of 10 t/ha of farm yard manure along with black polythene mulch completely controlled the weed density and dry biomass (100%) and harvested yield 37.65 t/ha (DWR 2013-14).

Effect of mulch on soil moisture

During rainy season the effect of mulch is not that promising as far as moisture conservation is concern. However, the effect has more pertinent in rainfed situation and pre- and post-rainy season. Choudhary (2016) revealed that the water use efficiency has not much improved in maize, but was considerably improved by 5.2 to 10.5% in frenchbean and 20.6 to 21.7% in toria on placement of paddy straw mulch at 4 t/ha over without mulch. As application of crop residues on soil surface altered the water distribution and influenced the evaporation and transpiration (Huang *et al.* 2005). Placement of mulch modified soil profile moisture distribution resulted better utilization of conserved soil profile moisture and better water use efficiency. Huang and Shao (2003) also revealed that excessive rain might lower the water use efficiency. However, it was noticed that under mulched plot, water use was considerably better and converted into economic yield of crops. Similar findings were also reported earlier in groundnut (*Arachis hypogaea* L.) (Ramakrishna *et al.* 2006), yellow sarson (*Brassica rapa* L.) (Sarkar *et al.* 2007), wheat (*Triticum aestivum* L.)–corn system (Dong *et al.* 2009), and pea (Choudhary 2015).

Application of paddy straw mulch had 4.8 and 1.8% higher porosity and water filled pore space over no mulch. As mulching helped in better aggregation of the soil and improved soil structure (Khurshid *et al.* 2006). Choudhary (2016) reported that application of paddy straw mulch reduced runoff and evapo-transpiration, better infiltration, this encouraged the soil to store more water to the tune of 5.1, 6.6 and 9.4% higher over bare soil at maximum water holding capacity, water content at -0.3 and -15.0 bars. Choudhary *et al.* (2013) reported that between mulches, paddy straw mulch had registered 18.5, 17.4 and 14.5% higher soil moisture over bare soil at 25, 50 and 75 DAS, respectively. The amount of moisture conserved was higher on paddy straw mulch at various days after sowing and different soil profile depths. Better storage of moisture was recorded in sub-surface over surface due to more infiltration of excess rainwater impounded in furrows. Similar findings were also noticed by other researchers (Pabin *et al.* 2003, Ferrero *et al.* 2005). Choudhary (2015) found that placement of mulch in maize has considerably higher soil moisture content on top soil than no mulch. Higher moisture contents were observed with

Imperata cylendrica (15.1, 16.5 and 17.6%) at 0–10, 10–20 and 20–30 cm soil depths, respectively and minimum with without mulch (11.7, 13.1 and 14.3% respectively). *Imperata cylendrica* recorded more soil moisture content followed by paddy straw mulch over bare soil. This might be due to presence of high lignin and poly-phenol in *Imperata cylendrica* exhibited resistant against quicker decomposition (Hartemink and O'Sullivan 2001) and helped to retain the soil moisture for longer time.

Rathore *et al.* (1998) revealed that the mulch materials reduced evaporation loss and conserved more moisture in the soil profile. Mulch acts as an insulator for solar radiation and does not permit solar radiation to contact the soil, which avoids evaporation loss from the soil profile. Choudhary *et al.* (2016) found that mulched plot took little more time to harvest due to available soil moisture and favourable growth condition which prolonged the life-cycle of crop. Choudhary *et al.* (2013) revealed that among different mulches used in pea, *Imperata cylendrica* had higher soil moisture content 28.6, 26.1 and 22.7% respectively followed by paddy straw mulch (24.8, 24.5 and 21.0% respectively) in different depths. However, lower soil moisture content was recorded with no mulch. This might be due to no protection of top soil from direct exposure to environment as indicated by Sarkar *et al.* (2007).

Choudhary and Kumar (2014) found that mulched applied plots recorded comparatively higher soil moisture 30, 60 and 90 DAS (15.9, 13.7 and 12.4% respectively) over without mulch. Mulch primarily affected the field microclimate by modifying the radiation budget of the surface and suppressing soil water evaporation. These microclimate factors strongly affect the soil temperature and moisture in the root zone, which in turn influenced the plant growth and productivity (Korir *et al.* 2006). Use of mulch also helped in better utilization of water and recorded 31% higher water-use efficiency over without Mulch.

Choudhary *et al.* (2012a) revealed that in Capsicum black polythene mulch and paddy straw mulch used water more efficiently than other mulches (736.0 and 692.0 kg/ha/cm, respectively) mainly due to better availability of applied water, reduced loss of water due to lesser evaporation, percolation and lower weed density throughout the crop growth period (Tiwari *et al.* 2003). However, WUE was low with no mulch followed by transparent polythene mulch (532.0 and 587.0 kg/ha/cm, respectively). Choudhary (2016) reported that placement of mulch improved the water use by 10.5% higher over without mulch. Placement of mulch noticed with 21.5% improvement of water use and 7.5% better WUE over without mulch. During summer season in toria, water use was improved by 35.8%, whereas, WUE was improved by 21% over without mulch plots.

Effect of mulch on soil temperature

Kumar *et al.* (2012) compared between paddy straw mulch and no mulch, the relative change of soil temperature was least on paddy straw mulch. Soil temperature at 8.00 h was comparatively higher, whereas, at 12.00 and 16.00 h, it was comparatively lower with paddy straw mulch than no mulch. This might be because soil received lesser radiation to increase the soil temperature. Besides water content was also higher on paddy straw mulch which required little higher energy to increase the soil temperature. The diurnal temperature fluctuation at this stage involved slow warming of mulched soil during the day and slower cooling at night. The paddy straw mulch and the water below the mulch would reduce the effects of long wave radiation and thus reduce the rate of decrease in soil temperature at night (Zhang *et al.* 2009). The range of soil temperature largely influenced the growth and establishment rate of maize, as increment of soil temperature enhances the growth of maize and root penetration. However, lower soil temperature has retarded effects on shoot elongation and dry matter accumulation (Ramakrishna *et al.* 2006). Wei Qin *et al.* (2015) reported that, soil mulching (with plastic or straw) reduces evaporation, modifies soil temperature and thereby affects crop yields. The soil temperature of the 10-cm mulching treatment was significantly higher than that of the no-mulching treatment, and the average soil temperature of the mulching treatment increased by 2.3 ^{0}C before July and nearly 1.2 ^{0}C after July (Wang *et al.* 2015). Maiti and Kumar (2016) found that dry mulches generated from *Stylosanthes hamata*, *Crotalaria juncea*, *Sesbania sesban*, and *H. sabdariffa* not only enhance SOC but also their dry parts ameliorate surface temperature during summer and helps in moisture conservation.

Effect of mulch on soil improvement

The soil organic carbon was considerably improved by 1.9% than no mulch (Choudhary and Kumar 2014). Choudhary *et al.* (2012b) revealed that best crop management with mulches recorded 7.6, 6.7 and 2.4% respectively higher porosity followed by traditional crop planting with mulch over traditional 'jhum' cultivation. Bulk density was improved when residues were incorporated and mulched with various crop residues in sequential crop. Similarly, the chemical parameters like N (25.4, 19.6 and 6.7%, respectively), P (45.2, 39.8 and 12.9% respectively) and K (31.3, 25.9, and 5.0% respectively) were recorded higher on best crop management with mulch, best crop management and traditional crop planting with mulch over traditional 'jhum' cultivation. The exposure of soil organic carbon was minimum to environment with improved practice. This reduced the oxidative soil environment resulting in least decomposition of crop residues and soil organic carbon. Recycling of crop residues has been suggested to improve overall soil fertility by increasing the available N, P and K to support sustainable crop production. The benefits of incorporating un-decomposed straw have also been recognized in tropical environments. Kumar and Goh (2000) reported that incorporation of crop residues is essential for sustaining soil productivity through replenishing soil organic matter. Soil organic matter is not only a key indicator of soil quality, but it also supplied essential nutrients upon mineralization (N, P, and S) and improves soil physical, chemical, and biological properties (Kumar *et al.* 2001, Goh *et al.* 2001).

Choudhary *et al.* (2013) revealed that among various mulches, paddy straw mulch, maize stubbles and *Imperata cylendrica* had 36.1, 31.7 and 21.3% respectively higher green pod yield of pea and 24.8, 20.4 and 14.6%, respectively higher stover yield over no mulch. Similarly, paddy straw mulch had higher harvest index followed by maize stubbles and lowest with no mulch. Higher yield of pea with paddy straw mulch and maize stubble was due to increased dry matter accumulation in the early stage and optimized dry matter distribution at the later stages. It created the favourable soil moisture and temperature which stimulate the tillage and mulch for yield of green pod, seed and stover and harvest index also had shown positive effect.

Choudhary *et al.* (2013) revealed that maximum root length of pea was recorded with paddy straw, maize stubble and *Imperata cylendrica* (29.5, 22.3 and 50.7% respectively) and root numbers/plant (27.8, 17.2 and 34.2%, respectively) higher over bare soil. However, they also reported that root density had not shown any specific trend. Use of mulches improved the bulk density and reduced the soil compaction which in turn enhanced the aeration and microbial activities in the soil. It resulted in increased root penetration and accumulation feeding and thus increased plant growth and yield. The results obtained were in line with the findings of Mbah *et al.* (2010). The interaction of variables also exhibited significant difference on root length, root dry weight and root volume.

Choudhary *et al.* (2013) found that in maize, the higher soil organic carbon was obtained with paddy straw mulch, mainly due to incorporation and decomposition of paddy straw which increased the total soil organic carbon on top soil. The cumulative carbon stocks, rate of change in carbon stock and comparison from initial carbon stocks were followed the similar trend to soil organic carbon. The highest change of carbon stock was noticed with ridges and furrow with no mulch (1.42 Mg C/ha) followed by raised bed with no mulch (1.15 Mg C/ha). However, higher accumulation was noticed with zero tillage with paddy straw mulch (1.09 Mg C/ha) and conventional tillage with paddy straw mulch (0.76 Mg C/ha). Reduction in tillage intensity and use of crop residues leads to accumulate more soil organic matter (Saroa and Lal 2003).

Effect of mulch on root parameters

Choudhary and Kumar (2014a) revealed that between the placed mulch and without mulch, all the root parameters were recorded higher with mulch treatment except root numbers and specific root length in maize-based cropping system in mid hills of Eastern Himalaya. The higher values of root parameters in mulch might be due to least compact soil and sufficient moisture, whereas root number and specific root length were higher when no mulch was applied. This was due to lower availability of moisture and compactness of soil which forced the plant to produce more roots, rather go in deep. Interestingly, interaction of sequence crop and mulch had no significant effect on the root growth parameters.

Choudhary and Bhambri (2013) found that no mulch had maximum root dry weight (11.06 g/plant) followed by transparent polythene mulch. However, lower root dry weight was observed with black polythene mulch followed by paddy straw mulch. In black polythene and transparent polythene mulch, the loss of water was very meagre due to less exposed area and low weed density. These led to uptake water by plant for longer time with sufficient quantity therefore the development of root was near the surface of ground. Yield was inversely linearly related with root dry weight (R^2= 0.98). Choudhary *et al.* (2013) reported that in the mulch plots, paddy straw mulch registered 19.1% higher root length, 15.7% more fibrous roots, 16.3% better root dry weight, 32.8% improved root volume and 14.1% superior root density over no mulch. The use of mulches not only improved the bulk density but also reduced the compaction of soil which might have enhanced the aeration and microbial activities in the soil thus resulting to increased root penetration and cumulative feeding. The findings on root parameters are in line with the observations of Mbah *et al.* (2010).

Effect of mulch on yield

Placement of previous crop residues on surface as mulch, season after season, improved the total dry matter accumulation and sink source (LAI) and further improved the sink size which contributed more toward yield and was the most important factor for improving the yield of mulched plots (Liu *et al.* 2002, Xie *et al.* 2006). Improvement of growth parameters under mulched plot was mainly due to better availability of water, appropriate aeration near root zone, which encouraged plant for developing strong root system (Khurshid *et al.* 2006). Choudhary *et al.* (2014b) found that application of straw mulch has considerably increased the crop yield. Pod yield of pea was highest with paddy straw mulch (2.75 t/ha) followed by maize stubble mulch (2.66 t/ha) and *Imperata cylendrica* (2.45 t/ha) over no mulch (2.02 t/ha). Choudhary and Kumar (2014) found that the placement of mulch materials reduced evaporation loss and conserved more moisture in the soil profile. Choudhary *et al.* (2013) reported that mulching with paddy straw mulch witnessed the higher yield attributes and grain and stover yield (11.1 and 6.5%, respectively) over no mulch. This was due to prevalence of better environmental condition under mulch which resulted in good yield. Similar finding was also corroborated by Sarkar *et al.* (2007).

Choudhary and Kumar (2014) reported that mulched treatment of sequential crop registered higher yield with 35% in groundnut, 26% in Indian mustard, 24% in pea and 18% in Frenchbean over no-mulched Plot. The maize-equivalent yield was recorded 154.6% higher with maize-frenchbean with mulch, followed by 131.2% without mulch. Kumar *et al.* (2012) reported that mulching under field conditions provides a measure of temporal fluctuations in soil biochemical properties under several different temperature regimes. The use of mulch has become an important cultural practice in the commercial production of vegetables in many regions of the world to maximize water use and prevent diseases for strawberry (Gupta and Acharya 1993). Placement of crop residues as mulch in pea significantly reduced the weed biomass and improved the crop yield (Choudhary *et al.* 2015). Mulching also improves plant growth, berry weight, fruit yield and quality in strawberry (Sharma and Sharma 2003, Singh and Asrey 2005).

Choudhary and Bhambri (2013) reported that black polythene mulch recorded the highest water use efficiency, followed by paddy straw mulch. This may be due to the higher yield recorded from the black polythene mulch by better availability of applied water, reduced loss of water by evaporation, percolation and lower weed population throughout the crop growth period (Singh *et al.* 2007). However, the lowest water use efficiency was recorded on paddy straw mulch, followed by transparent polythene mulch due to lower yield. It may be attributed to favourable climatic conditions and creation of weed free environment by black mulch polyethylene in fields, which led to higher TSS and ascorbic acid content and lower acidity in fruit (Gupta and Acharya 1993, Hassan *et al.* 2000, Sharma *et al.* 2004). Kumar *et al.* (2012) reported that placement of black polythene mulch in strawberry have significantly better growth, flowered and fruited early, produced larger fruit and higher yield, with slightly higher incidence of albinism (19.8%), but with lower incidence of botrytis rot (14.9 %) than those mulched with transparent polythene, paddy straw and pine needle mulch. Mulches show positive effects on moisture, heat, air regime of the soil and restrict the idle evaporation and weed growth (Bu *et al.* 2002, Kumar *et al.* 2012). The more favourable water regime manifested in higher yields makes mulching not only soil protective, but economically favourable as well (Yang *et al.* 2006). The extent of reduction in fruit yield of chilli has been reported to be in the range of 60-70% depending on the intensity and weed density in standing crop (Patel *et al.* 2004, Choudhary *et al.* 2012a). It is well established that 30 to 60 day after transplanting is the most critical for crop-weed competition in chilli. Hence, managing weeds during this period is most critical for higher yields. But, the competing weeds pose problem greatly and need effective management to obtain higher yields.

Choudhary and Bhambri (2013) explained that placement of black polythene mulch recorded the highest yield of capsicum, which was 6.3, 26.1 and 28.5% higher than paddy straw mulch, transparent polythene mulch and no mulch, respectively. Black polythene mulch along with paddy straw mulch had better dry matter accumulation, dry mater partitioning at different plant parts, and crop growth parameters which led to higher capsicum yield than other mulches. The results in the present investigation also corroborate the observations of other for different crops (Tiwari *et al.* 2003, Patel *et al.* 2009). Choudhary and Kumar (2014) exhibited that weed biomass was recorded low in mulched plot than the no mulch. This might be due to the mulching of various crop residues on sequential crops reduced the germination and emergence of weed seeds from the seed bank by preventing the solar radiation interception. Soybean and pea are also having smothering effect, soil binding, increasing infiltration rate, N fixing and improving the microbial activity in soil (Singh and Yadav 2006). Improved practices recycled the crop residues in better manner, even mulched material also get incorporated on surface which led to build up of soil organic matter. Similarly, hedge row materials incorporation improves the overall soil health than control which resulted to poor microbial population due to burning of biomass after harvesting the economic part of the crops. Team *et al.* (2017) evaluated rice straw, sorghum straw, sesame straw, and Sudan grass were compared with control in sesame. The organic mulching (10 t/ha) were uniformly applied in soil surface. The analyzed results indicated that organic mulching had significant effect on soil moisture content at 0–0.2 m, 0.21–0.4 m, and 0.41–0.6 m in every two-week interval after sowing and grain yield of sesame. They recorded the highest sesame yield (664 kg/ha) with Sudan grass while the lowest grain yield (190 kg/ha) with no mulch. Hasan *et al.* (2005), Kayum *et al.* (2008), Moreno and Moreno (2008) resulted polythene mulches significantly increased the marketable yield of tomato, Moniruzzaman *et al.* (2007) in cauliflower, Jenni *et al.* (2003) in lettuce. Application of 10 t/ha FYM along with black polythene mulch gave 13.84 t/ha of okra pod yield (DWR 2012-13). Yield improvement in plastic mulched crops (vegetable and fruit crops) over no mulch has been given in **Table 1**.

Table 1. Increase in yield of vegetable and fruit yield through plastic mulching

Crops	Increase in yield (%)	Crops	Increase in yield (%)
Broccoli	15.6	Guava	25.9
Cauliflower	18.6	Mango	45.2
Brinjal	36.7	Papaya	64.2
Tomato	69.1	Ber	27.1
Okra	6.9	Pineapple	14.6
Bitter gourd	20.1	Banana	34.0
Chilli	16.8	Litchi	12.6
Cabbage	14.3		

Source: NCPAH, New Delhi (National Committee on Plasticulture Applications in Horticulture)

Effect of mulch on economic parameters

Besides beneficial effects on earliness, polyethylene film as a mulch can enhance plant growth and development, increase yield, decrease soil evaporation and nutrient leaching, reduce incidence of pests and weeds, and improve fruit cleanliness and quality yield (Lamont 1993, Farias-Larios and Orozco-Santos 1997, Walters 2003, Decoteau 2007, Diaz-Perez *et al.* 2007, Hutton and Handley 2007) and finally increase gross return, net return and benefit: cost ratio of fruit and vegetable crops. Sutagundi (2000) reported that treatment receiving straw mulch recorded significantly higher net returns (` 30,894/ha) and benefit: cost ratio (1.80:1) compared to control as result of soil water conservation in chilli.

Conclusion

Water is precious resource available especially in rainfed area. Judicious use of these for crop production has paramount importance in Indian Agriculture. Thus, water conservation measures need to be adopted. Mulching has been advocated as an effective means for conserving soil moisture. Weeds are major yield reducers, suppression of weeds since beginning of crop growth is desired to achieve optimum growth and development of plants, which will lead to better crop harvest. Mulch covers soil surface around the plants to create congenial condition for the growth. This may include temperature moderation, salinity and weed control. It exerts decisive effects on earliness, yield and quality of the crop.

Mulching is applicable to most field crops. Mulch provides better weed free environment to the crop plant, thus as per the availability and affordability suitable mulch may be selected and used to grow crop and to achieve quality and quantity produce.

References

Arshad MA, Franzluebbers AJ and Azooz RH. 1999. Components of surface soil structure under conventional and no-tillage in north-western Canada. *Soil Tillage Research* **53**: 41–47.

Bobby P, Seenivasan PN and Mishra P. 2017. Effect of different mulch materials on weed control in cucumber (*Cucumis sativus* L.) hybrid “Multistar” under shade net conditions. *International Journal of Pure and Applied BioScience* **5**(5): 1246–1251.

Bond W and Grundy AC. 2001. Non-chemical weed management in organic farming systems. *Weed Research* **41**: 383–405.

Bu YS, Shao HL and Wang JC. 2002. Effects of different mulch materials on corn seeding growth and soil nutrients’ contents and distributions. *Journal of Soil and Water Conservation* **16**(3): 40–42.

Choudhary VK and Bhambri MC. 2013. Crop productivity, water use and weed control efficiency of capsicum (*Capsicum annum* L.) under drip irrigation and mulching. *Journal of Agricultural Physics* **13**(2): 133–138.

Choudhary VK and Kumar PS. 2013. Crop and water productivity, profitability and energy consumption pattern of a maize-based crop sequence in the North Eastern Himalayan Region, India. *Archives of Agronomy and Soil Science* **59**(5): 653–669.

Choudhary VK and Kumar PS. 2014. Influence of mulching on productivity, root growth and weed dynamics of maize (*Zea mays*)-based cropping systems. *Indian Journal of Agronomy* **59**(3): 364–370.

Choudhary VK, Bhambri MC, Pandey N and Sharma HG. 2012a. Effect of drip irrigation and mulches on physiological parameters, soil temperature, picking patterns and yield in capsicum (*Capsicum annum* L.). *Achieves of Agronomy and Soil Science* **58**(3): 277–292.

Choudhary VK, Dixit A and Bhagawati R. 2016. Scaling-up of toria (*Brassica campestris*) productivity using diverse agro-techniques in eastern Himalayan region. *Indian Journal of Agricultural Sciences* **86**(1): 37–41.

Choudhary VK, Dixit A, Bhagawati R, Vishwakarma AK and Brajendra. 2015. Influence of locally available mulches on soil moisture content, root behaviour, weed dynamics and productivity of pea (*Pisum sativum* L.). *Progressive Research- An International Journal* **10** (Special Issue): 1372–1375.

Choudhary VK, Kumar PS and Bhagawati R. 2012b. Production potential, soil moisture and temperature as influenced by maize-legume intercropping. *International Journal of Science and Nature* **3**(1): 41–46.

Choudhary VK, Kumar PS and Kanwat M. 2013. Influence of tillage and mulch on growth, yield, root characters and soil moisture dynamics of pea (*Pisum sativum*) in Arunachal Pradesh. *Madras Agriculture Journal* **100**(10-12): 812–815.

Choudhary VK, Kumar PS, Kanwat M and Bhagawati R. 2012b. Improvement of *jhum* with crop model and carbon sequestration techniques to mitigate climate change in Eastern Himalayan Region, India. *Journal of Agricultural Science* **4**(4): 181–189.

Choudhary VK. 2015. Tillage and mulch effects on productivity and water use of pea and soil carbon stocks. *Archives of Agronomy and Soil Science* **61**(7):1013–1027.

Choudhary VK. 2016. Response of land configuration and mulches on maize-frenchbean-toria cropping system. *Agronomy Journal* **108**(5): 2147–2157.

Decoteau DR. 2007. Leaf area distribution of tomato plants as influenced by polyethylene mulch surface color. *HortTechnoloy* **17**: 341–345.

Díaz-Pérez JC, Gitaitis R and Mandal B. 2007. Effect of plastic mulches on root zone temperature and on the manifestation of tomato spotted wilt symptoms and yield of tomato. *Science Horticulture* **114**: 90–95.

Dong W, Hu C, Chen S and Zhang Y. 2009. Tillage and residue management effects on soil carbon and CO_2 emission in a wheat–corn double cropping system. *Nutrient Cycling Agroecosystems* **83**: 27–37.

DWR. 2012-13. *Annual Report*. ICAR-Directorate of Weed Research, Jabalpur (MP). Pp. 1-118.

DWR. 2013-14. *Annual Report*. ICAR-Directorate of Weed Research, Jabalpur (MP). Pp. 1-125.

Ferrero A, Usowicz B and Lipiec J. 2005. Effects of tractor traffic on spatial variability of soil strength and water content in grass covered and cultivated sloping vineyard. *Soil Tillage Research* **84**: 127–138.

Goh KM, Pearson DR and Daly MJ. 2001. Soil physical, chemical and biological indicators of soil quality in conventional, biological and integrated apple orchard management systems. *Biological Agricultural & Horticulture* **18**: 269–292.

Gupta R and Acharya C L. 1993. Effect of mulch induced hydrothermal regime on root growth, water-use efficiency, yield and quality of strawberry. *Journal of Indian Society of Soil Science* **41**: 17–25.

Han KY, Lee KS, Suh JK and Lee YS. 1989. The effects of polyethylene film mulch on the growth and yield of a spring crop of kidney beans. *Research Republic Rural Development* Admin. (Horticult.), Korea **31**(3): 18–22.

Hartemink AE and O'Sullivan JN. 2001. Leaf litter decomposition of *Piper aduncum, Gliricidia sepium* and *Imperata cylindrica* in the humid lowlands of Papua New Guinea. *Plant Soil* 230: 115–124.

Hasan MF, Ahmed B, Rahman MA and Khan MMH. 2005. Environmental effect on growth and yield of tomato. *Journal of Biological Sciences* **5**(6): 759–767.

Hassan GI, Godara AK, Kumar J and Huchehe AD. 2000. Effect of different mulches on yield and quality of 'Oso Grande' strawberry. *Indian Journal of Agricultural Sciences* **70**: 184–5.

Hiltbrunner J, Jeanneret P, Liedgens M, Stamp P and Streit B. 2007. Response of weed communities to legume living mulches in winter wheat. *Journal of Agronomy and Crop Sciences* **193**: 93–102.

Huang M and Shao M. 2003. Water use efficiency and sustainability of different long term crop rotation system in the Loess Plateau of China. *Field Crops Research* **72**: 95–114.

Huang YL, Chen LD, Fu BJ, Huang ZL and Gong J. 2005. The wheat yields and water-use efficiency in the Loess Plateau: Straw mulch and irrigation effects. *Agriculture Water Management* **72**(3): 209–222.

Hutton MG and Handley DT. 2007. Effects of silver reflective mulch, white inter-row mulch, and plant density on yields of pepper in Maine. *HortTechnology* **17**: 214–219.

Jenni S, Dubuc JF and Stewart KA. 2003. Plastic mulches and row covers for early and midseason crisp head lettuce produced on organic soils. *Canadian Journal of Plant Science* **83**: 921–929.

Ji SN, Unger PW and Ji SN. 2001. Soil water accumulation under different precipitation, potential evaporation, and straw mulch conditions. *Soil Science Society of American Journal* **65**(2): 442–448.

Kayum MA, Asaduzzaman M and Haque MZ. 2008. Effects of indigenous mulches on growth and yield of tomato. *Journal of Agriculture and Rural Development* **6**(1-2): 1–6.

Khurshid K, Iqbal M, Arif MS and Nawaz A. 2006. Effect of tillage and mulch on soil physical properties and growth of maize. *International Journal of Agriculture and Biology* **8**:593–596.

Kladivko EJ and Unger PW. 1994. Residue effects on soil physical properties. pp. 123–141. In: *Managing Agricultural Residues*. Lewis Publishers Inc., Boca Raton, USA,

Korir NK, Aguyoh JN and Gaoqiong L. 2006. Enhanced growth and yield of greenhouse produced cucumber under high altitude areas of Kenya. *Agricultura Tropica et Subtropica* **39**(4): 249–54.

Kumar K and Goh KM. 2000. Crop residues and management practices: effects on soil quality, soil nitrogen dynamics, crop yield and nitrogen recovery. *Advances in Agronomy* **68**: 197–219.

Kumar K, Goh KM, Scott WR and Frampton CM. 2001. Effects of ^{15}N-labeled crop residues and management practices on subsequent winter wheat yields, nitrogen benefits and recovery under field conditions. *Journal of Agricultural Science* **136**: 35-53.

Kumar PS, Choudhary VK and Bhagawati R. 2012. Influence of mulching and irrigation level on water use efficiency, plant growth and quality of strawberry (*Fragaria* × *ananassa*). *Indian Journal of Agricultural Sciences* **82**(2): 127–133.

Lalitha BS, Nagaraj KH and Anard TN. 2001. Effect of soil solarisation on weed dynamics and yield of groundnut–tomato sequence. *Mysore Journal of Agricultural Sciences* **35**(3): 226–231.

Lamont Jr WJ. 1993. Plastic mulches for the production of vegetable crops. *HortTehnology* **3**: 35–39.

Liu J, Xu SA, Zhou GY and Lu HH. 2002. Effects of transplanting multicropping spring maize with plastic film mulching on the ecological effect, plant growth and grain yield. *Journal of Hubei Agriculture College* **2**: 100–102.

Maiti SK and Kumar A. 2016. Energy plantations, medicinal and aromatic plants on contaminated soil. *Bioremediation and Bioeconomy*: 29–47.

Mbah CN, Nwite JN, Njoku C, Ibeh LM and Igwe TS. 2010. Physical properties of an ultisols under plastic film and no mulch and their effect on the yield of maize. *World Journal of Agricultural Science* **6**: 160–165.

Merwin IA, Rosenberger DA, Engle CA, Rist DL and Fargione M. 1995. Comparing mulches, herbicides and cultivation as orchard groundcover management systems. *HortTecgnology* **5**: 151–158.

Moniruzzaman M, Faisal SM, Sarkar MAR, Hossain IM. Ali AM and Talukder MAH. 2007. Effects of irrigation and different mulches on yield of profitability of cauliflower. *Asian Journal of Plant Science* **6**: 338–343.

Moonen AC and Barberi P. 2004. Size and composition of the weed seed bank after 7 years of different cover-crop–maize management systems. *Weed Research* **44**: 163–77.

Moreno MM and Moreno A. 2008. Effect of different biodegradable and polythene mulches on soil properties and production in a tomato crop. *Scientia Horticulturae* **116**: 256–563.

NCPAH, New Delhi (National Committee on Plasticulture Applications in Horticulture). pp. 1–200.

Ossom EM. 2001. Effect of mulch on weed infestation, soil temperature, nutrient concentration, and tuber yield in *Ipomoea batatus* (L.) Lam. in Papua New Guinea. Tropicul Agriculture (Trinidad) **78**(1): 144–151.

Otsuki K, Kamichika M, Urimoto M and Inoue M. 2000. Modification of microclimate and soil moisture by recycled paper mulch in microirrigated fields. pp. 1–7. In: *Proceedings of the Sixth International Micro Irrigation Congress,* Cape Town, South Africa, 22–27 October 2000,.

Pabin J, Lipiec J, Wlodek S and Biskupski A. 2003. Effect of different tillage systems and straw management on some physical properties of soil and on the yield of winter rye in monoculture. *International Agrophysics* 1**7**: 175–181.

Patel AB, Barevadia TN, Patel BD and Meisuriya M. 2004. Effect of cultural and chemical methods on weed and fruit yield of green chilli. *Indian Journal of Weed Science* **36**(3&4): 300-301.

Patel DB, Patel RH and Patel RB. 2009. Effect of drip irrigation, mulches and nitrogen fertigation on yield and yield attributes of okra (*Abelmoschus esculentus*). *Indian Journal Agriculture Science* **79**: 12–15.

Pawar HK. 1990. Use of plastic as mulch in scheduling of irrigation to ginger in semi-arid climate. pp. 99–109.In: *Proceedings of the 11th International Congress on the Use of Plastics in Agriculture*. New Delhi, India, 26th February–2nd March 1990,

Pawar SN, Divekar SP, Ghule SB and Kadale AS. 2004. Effect of mulching on moisture conservation and yield of summer groundnut. *Journal of Soil and Crops* **14**(2): 410–413.

Rajablariani HR, Hassankhan F and Rafezi R. 2012. Effect of coloured plastic mulches on yield of tomato and weed biomass. *International Journal of Environmental Science and Development* **3**(6): 23–28.

Ramakrishna A, Tam HM, Wani SP and Long TD. 2006. Effect of mulch on soil temperature, moisture, weed infestation and yield of groundnut in northern Vietnam. *Field Crops Research* **95**:115–125.

Rathore AL, Pal AR and Sahu KK. 1998. Tillage and mulching effects on water use, root growth and yield of rainfed mustard and chickpea grown after lowland rice. *Journal of Science and Food Agriculture* **78**: 149–161.

Sarkar S, Paramanick M and Goswami SB. 2007. Soil temperature, water use and yield of yellow sarson (Brassica napus L. var, glauca) in relation to tillage intensity and mulch management under rainfed lowland ecosystem in eastern India. *Soil Tillage Research* **93**: 94–101.

Saroa GS and Lal R. 2003. Soil restorative effects of mulching on aggregation and carbon sequestration in a Miamian soil in Central Ohio. *Land Degradation and Development* **14**: 481–493.

Sharma RR and Sharma VP. 2003. Mulch influences fruit growth, albinism and fruit quality in strawberry (*Fragaria x ananassa* Duch). *Fruits* **58**: 221–27.

Sharma RR, Sharma VP and Pandey SN. 2004. Mulching influences plant growth and albinism disorder in strawberry under subtropical climate. *Acta Horticulturae* **662**: 187–191.

Singh R and Asrey R. 2005. Growth, earliness and fruit yield of micro-irrigated strawberry as affected by time of planting and mulching. *Indian Journal of Horticulture* **62**(2): 148–151.

Singh R and Yadav DS. 2006. Effect of rice residues and nitrogen on performance of wheat under rice-wheat copping system. *Indian Journal of Agronomy* **51**(4): 247–250.

Singh R, Sharma RR and Goyal RK. 2007. Interactive effects of planting time and mulching on 'Chandler' strawberry (*Fragaria* × *ananassa* Duch.). *Scientia Horticulturae* **111**(4): 344–351.

Sudha T and Nanjappa HV. 1999. Effect of soil solarization on weed control in tomato nursery. *South Indian Horticulturea* **47**: 229–230.

Sutagundi RH. 2000. Effect of mulches and manures on growth and yield of chilli (*Capsicum annuum* L.). MSc (Agri.) Thesis University Agricultural Sciences, Dharwad (2000). pp. 20–35.

Team G, Tsegay A and Abrha B. 2017. Effect of organic mulching on soil moisture, yield, and yield contributing components of sesame (*Sesamum indicum* L.). *International Journal of Agronomy*, Article ID 4767509, 6 pages.

Tisdall JA, Baverly RD and Radcliffe DE. 1991. Mulch effect on soil properties and tomato growth using micro-irrigation. *Agronomy Journal* **83**: 1028–1034.

Tiwari KN, Singh A and Mal, PK. 2003. Effect of drip irrigation on yield of cabbage (*Brassica oleracea* L. var. *Capitata*) under mulch and no mulch conditions. *Agricultural Water Management* **58**: 19–28.

Vander Zaag, Demagante A, Acasia R, Domingo A, Hagerman H. 1986. Response of solanum potatoes to mulching during different seasons in an isohyperthemic environment in the Philippines. *Tropical Agriculture* (Trinidad) **63**: 229–239.

Varadan KM, Madhavachandran K, Joseph EJ and Jayakumar M. 1990. Effect of irrigation and mulching on soil moisture and soil temperature under coconut. *Journal of Plantation Crops* **18**(1): 55–58.

Walters SA. 2003. Suppression of watermelon mosaic virus in summer squash with plastic mulches and row covers. *HortTechnology* **13**: 352–357.

Wang X, Li Z and Xing Y. 2015. Effects of mulching and nitrogen on soil temperature, water content, nitrate-N content and maize yield in the Loess Plateau of China. *Agricultural Water Management* **161**: 53–64.

Waterer DR. 2000. Effect of soil mulches and herbicides on production economics of warm-season vegetable crops in a cool climate. *HortTechnology* **10**: 154–159.

Wei Qin, Chunsheng Hu and Oenema. 2015. Soil mulching significantly enhances yields and water and nitrogen use efficiencies of maize and wheat: a meta-analysis, *Scientific Reports, Article number: 16210.*

Xie Z, Wang Y, Jiang W and Wei X. 2006. Evaporation and evapotranspiration in a watermelon field mulched with gravel of different sizes in northwest China. *Agricultural Water Management* **81**:173–184.

Yang Y, Liu X, Li W and Li C. 2006. Effect of different mulch materials on winter wheat production in desalinized soil in *Heilonggang* region of North China. *Journal of Zhejiang University Sciences B*. 7(11): 858–67.

Yordanova M and Nikolov A. 2017. Influence of plant density and mulching on weed infestation in lettuce (*Lactuca sativa* var. romana Hort.). *Journal of Agriculture and Veterinary Science* **10**(10): 71–76.

Zhang SL, Lovdahl L, Grip H, Tong YA, Yang XY and Wang QJ. 2009. Effects of mulching and catch cropping on soil temperature, soil moisture and wheat yield on the Loess Plateau of China. *Soil Tillage Research* **102**: 78–86.

Chapter 11

Mechanization in weed management: Global review

V.K. Tewari* and C.R. Chethan[1]
Agricultural and Food Engineering, Department, Indian Institute of Technology Kharagpur, West Bengal 721 302
[1]ICAR-Directorate of Weed Research, Maharajpur, Jabalpur, Madhya Pradesh 482 004
**Email: vktfeb@agfe.iitkgp.ernet.in*

Summary

One of the major contributors for crop yield reduction is weeds, which are perennial problem to the farmers and pose a serious biotic constraint in agricultural production systems. The weeds alone cause a loss of total agricultural production up to 37%, if not managed properly. In India farmers are losing close to 15-20% crop yield even after practicing a traditional weed control methods. It is because of the inefficiency and non-accuracy of the traditional methods. Thus, there is a tremendous scope for enhancing crop yield by adopting a recommended weed control practices; it can be achieved by practicing mechanized weed management. Timeliness of weeding operation, improved weeding efficiency, reduced human drudgery and one-third saving of operational cost can be achieved at farmer's field by practicing the mechanized weed management. Mechanized weed management includes both mechanical (physical), cultural as well as chemical method of weed control, where implements, machine system or mechanical power systems are used as a source. The system includes, hand weeding tools, wheel hoes, brush cutters, power weeders, tractor operated weeders, thermal weeders, robotic weeders, micro irrigation systems, soil solarization tools or sheets, knapsack sprayers, solar powered sprayers, engine operated sprayers, tractor P.T.O operated sprayers, aerial sprayers, weed wipers, wick applicators *etc.*

Key words: Mechanical weeders, Mechanization, Robotic weeders, Sensors, Sprayers, Thermal weeders

Introduction

India is the second most populous country in the world with an estimated population of 1.25 billion in 2014 and an annual growth rate of 1.3%. About two-third of the population live in rural areas with about 50% still dependent on agriculture for their livelihood (Singh 2015). The biggest challenge in agriculture is to meet the growing food demand of the country as well as the labour shortage in agricultural sector. During the year 2011, more than 263 millions of workers were engaged in agricultural sector; but it has been estimated that, by the year 2020, the agricultural worker population will reduce to 230 million, which is 40.6% of total workers of the nation (Mehta 2013). Further, the Indian farmers have the lowest earnings per capita because of the low yield per hectare, which may be due to so many factors. However, one of the major factors for crop yield reduction is due to the weeds.

Weeds are a perennial problem with the farmers and pose a serious biotic constraint in agricultural production systems globally. They are omnipresent and reduce yield and quality of crops substantially. Weeds compete with crop plants for moisture, nutrients and sunlight and can have a detrimental impact on crop yields and quality, if uncontrolled. Therefore, weeding is the most important farm operation in agriculture to improve quality and quantity of crop production, but it is laborious. Further, the labour requirement for weeding depends on weed flora, weed intensity, time of weeding and soil moisture at the time of weeding and efficiency of the worker. Often several weedings are necessary to keep the crop weed free. The weeds alone cause a loss of total agricultural production up to 37% and actual total economic loss of about US$ 11 billion from 10 major crops of India (Annual Report 2017, Gharde *at al.* 2018), if not managed properly. It has been estimated that on an average, the weed control costs around ` 6000/ha in *Kharif* crops and around ` 4000/ha for *Rabi* crops, which comes to the tune of 33% and 22%, respectively of the total cost of cultivation of *Kharif* and *Rabi* crops (Yaduraju and Mishra 2017).

The data available at the ICAR-Directorate of Weed Research (DWR), Jabalpur, India shows that, with the traditional weed control methods, farmers are losing close to 15-20% crop yield and there is a tremendous scope for enhancing crop yield by adopting recommended weed control practices. Existing weed control methods for row crops include a combination of pre-emergence herbicide application and/or pre-emergence tillage, mechanical cultivation, post-emergence herbicide application and hand hoeing. The herbicide based weed control system may be both biologically efficacious and economically effective with less environmental impact.

However, weed management through herbicides are limited to certain period. Due to continuous and repeated use of a given herbicide weeds may develop resistant against that herbicide and pose a serious threat to crops. An integration of different weed management practices and/or application of different herbicides with diverse target group of weeds as pre- or tank mix under farmers' field are the need of the hour. Mechanized weed control systems of sensor based or non-sensor based systems are found to be the most effective and better solution for both dry land and wet land conditions (Gite and Yadav 1990, Tewari *et al.* 2014, Chandel *et al.* 2017, Chethan and Krishnan 2017).

Mechanized weed management

Mechanized weed management is the process of using agricultural machinery to perform the weeding operation or weed control methods, which greatly increase farm worker's productivity. Mechanization in weed management includes both mechanical (physical), cultural as well as chemical method of weed control, where implements, machine system or mechanical power systems are used.

Mechanical method of weed control

A large variety of implements are used for mechanical control of weeds, from basic hand tools to sophisticated tractor pulled or self-propelled implements. However, in general these implements are classified into two groups: cultivating tools – soil disturbing tools and cutting tools – non soil disturbance tools specially used in conservation agriculture.

Mechanical weed control is mainly associated with cultivating tillage, often referred to as tertiary tillage, but also primary and secondary tillage as well as mowing and cutting have strong impacts on weeds (Rueda-Ayala *et al.* 2010). The cultivation tillage is inter-cultural operation involve the shallow tillage operations after the crop sowing or planting. Usually, it includes whole crop cultivation (full surface), inter-row cultivation (between crop rows) and intra-row cultivation (between crops), which are performed primarily to destroy the weeds present in the field and create favorable soil conditions for crop growth (Vanhala *et al.* 2004). Climate and soil type play an important role in the possibilities for mechanical weed control. Monitoring the early development of weeds is necessary for timing of weed harrowing at the optimum stage. Repeated intercultural operations under those conditions will not only discourage germination of weed seeds (which normally occurs in the soil layer) but also aids in conserving precious soil moisture.

Cultivation tillage is performed in growing crops with harrows, hoes, brushes and a number of special tools for intra-row weed control, which mainly involves burring of weeds in soil, uprooting and tearing of weed plants (Dierauer and Stöppler-Zimmer 1994, Van der Weide *et al.* 2008, Rueda-Ayala *et al.* 2010). In arable crops, currently, six different mechanical weeding mechanisms are available *viz.* harrow, sweep, ducksfoot, rotary powered hoe, ground driven rotary hoe and rotary brush devices specially for high speed inter row weeding (Pullen and Cowell 1997). However, at present hand hoeing and manual weeding are the most common practices performed for weed control in India.

The data obtained from the Directory of Agriculture Machinery and Manufacturers, Government of India (2018) has shown that work rate for various weeding implements vary due to variation in crop growth, row and plant spacing, weed intensity, soil conditions and other factors. Typical work rates of hand hoe (Khurpi) might be varying from 300-500 man-h/ha. For hand hoeing between rows, by chopping hoe, labour requirement varies from 200-300 man-h/ha. Operation of the push-pull type weeder along the row in typical conditions requires 100-125 man-h/ha. For animal drawn weeding tools (blade hoe and blade harrow) labour requirement varies from 6-20 man-h/ha.

Types of mechanical weeding tools

The classification of the mechanical weeders is done on the basis of suitability to the crops and cropping condition, power source, sensing and guidance system *etc*. The classification of the mechanical weeders is given in **Table 1**.

Manual weeding tools

Weeding by manually operated weeders is having a higher weeding efficiency. The efficiency can be obtained in the range of 80 to 95%. Production cost of this type of weeders is very low compared to other weeders, so that small and marginal farmers can afford, however the area coverage will be low (Shekar *et al.* 2010, Deshmuk, 2012, Sarkar *et al.* 2016). Some of the manual weeding tools like

Table 1. Classification of mechanical weeders

Criteria	Classification	Tools
Power source	Manual weeding tools	Hand hoe (Khurpi), grubber, straight blade hoe, wheel hoe, cono weeders *etc*.
	Animal drawn weeders	Sweeps, duck foot cultivator, harrows *etc*.
	Power operated weeders	Self propelled rotary weeders, tractor operated rotary weeders and cultivators, brush cutters *etc*.
Weeding in cropping system	Whole crop weeders	Spring tyne/ rolling/ chain harrows and rotary hoes
	Inter-row weeders	All types of sweeps, hoes, shovels, rotary weeders, brush weeders
	Intra-row weeders	All types of sweeps, hoes, shovels, rotary weeders, brush weeders, torsion weeders, finger weeders
Soil engagement	Soil engaging type	All cultivating tools
	Non-soil engaging type	All weed cutting tools like, mowers, strimmers brush cutters *etc*.
Sensing system	Sensor based system	Robotic weeders, optical/ ultrasonic/ infrared red/ laser/ thermal etc. sensors based weeders
	Non-sensor based system	All conventional weeding tools
Weeding system	Thermal weeders	Microwave/ laser/ infra red/ steam, hot air blown/ electric/ flame weeder
	Non-thermal weeders	All conventional weeding tools

khurpi, spade, grubber, wheel hoe, peg tooth weeder, star weeder, cono weeder *etc*. are described below and given in **Figure 1 (a to g).**

Hand hoe (khurpi): It is a sharp straight tool, operated in sitting and squatting position. Inter and intra row weeding for all type of crops can be done **[Figure 1(a)]**.

Straight blade hoe: It is a long handled hand tool operated in standing position by pulling action. Inter and intra row weeding for all type of crops can be done **[Figure 1(b)]**.

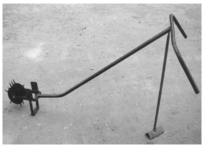
Grubber weeder: It is a long handled hand tool consists of three tynes, operated in standing position by pulling action. Inter and intra row weeding can be done **[Figure 1(c)]**.

Twin wheel hoe weeder: It consists of V or straight blade mounted on a frame attached with long handle. It is best suitable to operate in between crop rows such as wheat, maize, dryland rice etc. [**Figure 1(d)**].

Cono weeder: It consists of a conical drums mounted on a frame attached with long handle. It is used to weed-out the plants in puddled conditions like in transplanted lowland rice **[Figure 1(e)]**.

Cycle wheel hoe: It consists of a small V blades mounted on a frame attached with long handle. It is best suitable to operate in between crop rows such as wheat, maize, dryland rice *etc*. **[Figure 1(f)].**

Peg type hoe: It consists of small diamonds shaped pegs welded on rods in a staggered manner. It is best suitable to operate in between crop rows such as wheat, maize, dryland rice etc. **[Figure 1(g)].**



Mechanics of manual weeding

A manually push-pull weeder is operated in a standing position. At the start of the weeding operation an operator executes a short “push” on the handle of the weeder in the forward direction. This is followed by a very small rearward pull which completes one “cycle”. During the process of pushing a force, F, is applied through the inclined handle of the weeder at an angle, á, **(Figure 2).** This causes the blade, B, to penetrate the soil and shear off a thin sheet of soil along with weed roots, R, on the forward direction, F_d. The weeder is then pulled back to the original surface level. During this stroke the blade simply slides back over the weeded portion. The operator then moves forward to start the second “cycle”. This “cycle” of push-pull continues until weeding is completed along a crop row.

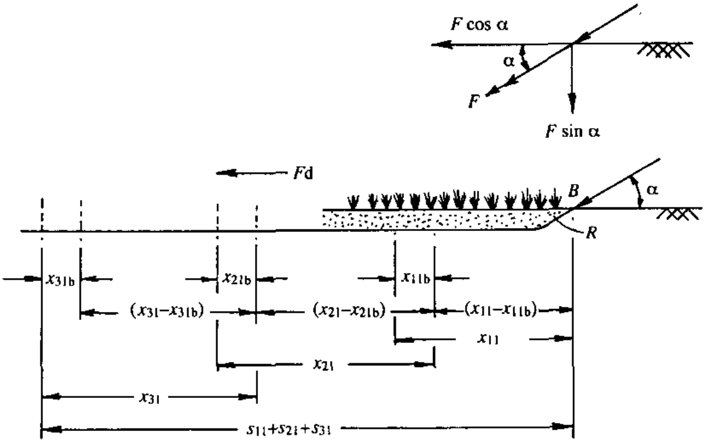


Figure 2. Schematic representation of the operation of a push-pull weeder

Forces acting during operation

The forces acting during cutting through the pushing stroke are also illustrated in **Figure 2**. The force, F, applied at the handle at an operating angle, á, may be resolved into two components, namely, the horizontal component, F cos á, and the vertical component, F sin á. For simplicity it may be assumed that the component F sin á causes the penetration of the cutting blade and F cos á, the shearing of a thin sheet of soil along with roots of weeds present in the row.

Relative grading of performance of different blades

In order to evaluate the relative performance of different blades of a push-pull weeder, a performance index, P_i, was developed. The parameters considered were quality, Q_1, and quantity, Q_2, of weeding work done and the power required, $\bar{P}_u$.

Performance index

$$P_i = K\frac{Q_1 Q_2}{\bar{P}_u} \qquad (1)$$

Where, P_i	performance index of the weeder,
Q_1	quality of weeding work done,
Q_2	quantity of weeding work done per unit time,
$\bar{P}_u$	average power used in the weeding operation,
K	a constant of proportionality. It may be assigned any value, preferably a positive integer. In the present case the value is 1.

The parameters Q_1, Q_2 and $\bar{P}_u$ can be evaluated as follows.

Quality of work done (Q_1)

This term refers to the qualitative assessment of the performance of the weeder in terms of complete removal of weeds without causing damage to the crop. This may be expressed as follows:

$$Q_1 = \left(1 - \frac{P_d}{P_t}\right) \times \eta_w \qquad (2)$$

Where, P_t	total number of plants along a crop row length before the weeding operation,
P_d	total number of plants completely damaged in the same row length after the weeding operation,
η_w	weeding efficiency

and

$$\eta_w = \frac{W_1 - W_2}{W_1}$$

Where, W_1 total number of weeds present in between two crop rows in unit area before the weeding operation,

W_2 total number of weeds remaining after the weeding operation in the same area.

Quantity of work done (Q_2)

This parameter refers to the actual area weeded per unit time by the weeder and is expressed as

$$Q_2 = \frac{W_b \times S}{T} \times \eta_f \tag{4}$$

Where W_b width of cut of the weeding blade,

S total forward displacement covered during any trial,

T total time taken to cover the above displacement, S,

η_f field efficiency of the weeder (expressed as a percentage, the ratio of actual time spent on weeding a given crop area to the total time including lost time in turning *etc*. recorded for that area).

The total forward displacement of the weeder, S, in the total time, T, during a weeding trial may be given with reference to **Figure 2** as follows:

$$S = \sum_{1}^{n} (x_{if} - x_{ib}) \tag{5}$$

and

Where x_{if} forward displacement in the *i*th cycle,

x_{ib} backward displacement in the *i*th cycle,

Θ_i time taken for the *i*th push-pull cycle.

Hence, the area weeded per unit time can be expressed as:

$$Q_2 = W_b \times \frac{\sum_1^n (x_{if} - x_{ib})}{\sum_1^n \Theta_i} \times \eta_f \tag{6}$$

Average power used in the weeding operation ($\bar{P}_u$)

The average power was obtained by calculating the average energy used per unit time. The energy used per push-pull cycle in a given trial run can be expressed as the summation of the product of the force components with the corresponding displacements in the horizontal and vertical directions.

Therefore, the energy used in the *i*th cycle of a given trial can be expressed as follows.

$$E_i = (F_{if} x_{if} + F_{ib} x_{ib}) \cos \alpha + (F_{if} + F_{ib}) d \sin \alpha \tag{7}$$

Where, F_{if} forward (push) force,

F_{ib} backward (pull) force,

d depth of penetration of the blade into the soil (constant),

α mean operating angle (constant).

Hence, the power employed during the *i*th cycle may be given as,

$$P_{ui} = E_i/\Theta_i \tag{8}$$

And the average power employed during weeding trails with n cycles may be given as,

$$\bar{P}_u = \frac{1}{n}\sum_{1}^{n} E_i/\Theta_i \tag{9}$$

Animal drawn weeders

Since 2000 onwards, the increased mechanization level in India has reduced the draft animals drastically. However, draft animals play a pivotal role in some parts of the country especially for small and marginal farmers. Commonly used animal drawn weeders **[Figure 3 (a&b)]** are provided with rigid tines with shovel, sweeps and duck foot sweeps. Hoes with triangular blades are also effective and used in certain parts of the country. The shovels are especially suitable for light soils for intercultural operations when weed intensity is less. The sweeps and duck foot sweeps are quite effective when weed intensity is high and conservation of soil moisture is important. The soil manipulation is quite less for the sweeps and duck foot sweeps. The blades of the triangular blade hoe manipulate the soil to a greater extent during the operation. They are quite suitable when weed intensity is high but soil moisture conservation is not that much important. During the operation of the triangular blades, the small weeds are either mixed with the soil or buried hence less chances of survival.

Figure 3(a). Sweep and duck foot sweeps

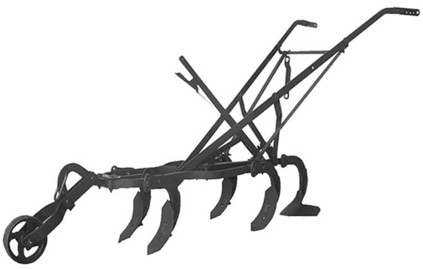


Figure 3(b). Shovel type tyne

Power operated weeders

Power operated weeders can save about 75% of time of operation and 20% of cost of weeding. Drudgery, health related issues involved in weeding operation can be avoided up to 100%. In general, power operated weeders are distinguished by the type of blades used for weeding operation, *i.e.* fixed or rotary blades. Examples of power operated weeders are tractor drawn cultivators with shovels, sweeps and duck foot sweeps and hoes with rotary tines. This will allow for easy movement of the wheels of the power units without damaging the crop plants. Power tillers with proper grouped tines can also be effectively used for weeding operation. The self propelled weeding (power weeder) makes use of small gasoline engine to rotate a set of weeding rolls through a worm reduction unit. The weeding rolls are mounted over a shaft and are spaced as per the crop row spacing. These are walking type of machine and are used mainly in low land conditions.

Self propelled/power tiller operated weeders: These are of self propelling type, powered by the engine. These type of weeders are mainly used for inter weeding operation in both dry and wet land conditions (**Figure 4**) and their width of operation can be adjusted according to the crop conditions (Sarkar *et al.* 2016, Deshmuk 2012).

(Source: AICRP on FIM, ICAR, New Delhi; V.S.T Tillers Tractors Ltd.)

Figure 4. Self propelled weeders

Brush cutters: These are the engine operated high speed rotating blade or wire based weeds cutting tools. Weeding is done by rotating a blade or wire at higher speeds parallel to ground, where the rotating portion comes in contact with the weeds (**Figure 5**).

Figure 5. Rotating blade type brush cutter

(Source: www.turnertools.in)

Tractor operated weeders: these are of rotary type as well of dragging type weeding implements powered by tractor PTO or drawbar. Inter row weeding and simultaneous operation of inter and intra weeding can be done in single operation. **Figure 6-8** shown a few of them being used in different parts of the world.

Inter-row cultivation: Inter-row cultivation may also be carried out with rolling cultivators and PTO-driven cultivators (Melander 2006). In some cases, instead of cutting blades, horizontal rotating brushes are used for special soil conditions. The weeds are brushed by rotation of hard polypropylene fibres and the control mechanisms are mainly by burial with soil and uprooting of weeds so they stay exposed to desiccation, stripping leafs and breaking stems (Melander 1997). Some of the tractor operated inter row weeders are given in **Figures 9 to 11**.

Figure 6. Chain harrow
(Source: May-Bridge Harrows, Canada)

Figure 7. Tyne harrow
(source: https://cy.wiktionary.org/wiki/oged)

Figure 8. Rotary harrow (source: Avant techno; www. ua.all.biz)

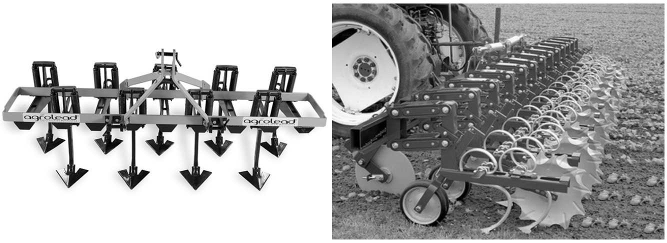


Figure 9. Tractor drawn sweeps
(source: www.agrolead.com.tr; http://yscsfarm.weebly.com/cultivator.html)

Figure 10. Rotary weeders
(source: www.Mygreen.Farm; CoEFM, Ludhiana, India)

Figure 11. Earthing up cum ridging type weeders
(source: Ramakumar Industries, Tamil Nadu, India)

Intra-row cultivation: Intra-row cultivation is the removal of weeds between the crops. Number of implements for intra-row weeding is available in the market, but most of them are technically poor, which means that they are simply pulled along the rows and the success of their performance is highly dependent on crop-weed selectivity factor (Rueda-Ayala *et al.* 2010). Among the most common low-tech implements are finger weeders and torsion weeders, which originate from North America but have been simplified by several companies. The disadvantage of the finger and torsion weeders compared with the harrow is that they need very accurate steering to be able to work close to the crop plants without causing too much crop damage. Accurate steering requires a relatively low working speed and hence the working capacity is also low (Van der Weide *et al.* 2008) (**Figures 12 and 13**).

Figure 12. Finger weeder (source: Thomas Hatzenbichler Agro-Technik GmbH, Andrä, Austria)

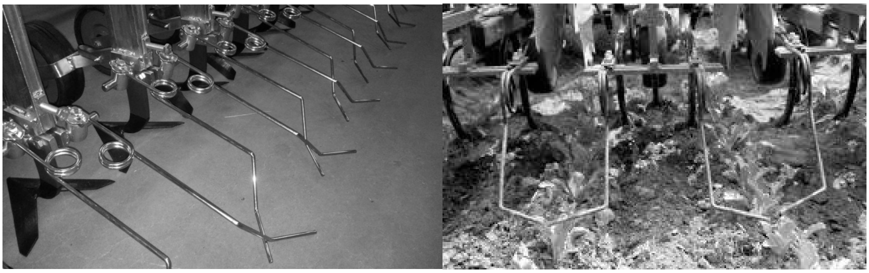


Figure 13. Torsion weeders (source: www.haknl.com; www.frato.nl; Ascard 2014)

Figure 14. Brush weeder (source: NaturaGriff, France)

Intra-row brush weeding is another method with similar constraints to those of finger and torsion weeding. A brush is placed on either side of the row and each brush is rotated by a hydraulic motor (**Figure 14)** to create either uprooting or soil coverage of the intra-row weeds, depending on the direction of rotation (Melander 1997).

Finger and brush weeders are more effective than the torsion weeder against weeds with true leaves, but the use of all three weeders is recommended against small weed plants to ensure effectiveness. The amount of hand weeding can be reduced by 40–70% using finger or torsion weeders (Van der Weide *et al.* 2008). Wind blower is another option for intra-row weeding like finger and torsion weeders.

Figure 15. The Pneumat blowing away small weeds in sown onion
(source: Van der Weide *et al.* 2008)

Weed blower or Pneumat weeder: The weed blower or Pneumat weeder (trade name Pneumat weeder, Lu tkemeyer 2000, Van der Weide *et al.* 2008) uses compressed air to control weeds by blowing them out of the crop row. This type of weeders is not selective type, but they are effective in crops with wider rows such as tulip (*Tulipa sylvestris L.)* and may cause severe crop damage, if they are not used properly (**Figure 15**).

Thermal weeding

Thermal weeding is the method of weed control by burning out weed plants, seeds and seedlings within the soil by using different forms of thermal energy. This type of weed control method is sub-divided into two groups according to their mode of action (a) the direct heating methods (flaming, infrared weeders, hot water, steaming, hot air) and (b) indirect heating methods (electrocution, microwaves, laser radiation, UV-light), with freezing as a third and opposite plant stress factor (Rask and Kristoffersen 2007).

Flame weeder: Flaming equipment to burn of weeds has been developed in several countries including Germany, Holland, Sweden and Denmark. The main fuel used in the burners is liquefied petroleum gas (LPG), usually propane, but renewable alternatives such as hydrogen have also been evaluated (Bond and Grundy 2001). Flame weeding kills by an intense wave of heat that ruptures the plant cells. (**Figure 16**).

Figure 16. Flame weeder
(source: www.nerdist.com)

Infrared radiation based weeders: Infrared (IR) radiation, produced by heating ceramic or metal surfaces, is used to induce thermal injury to weed tissues. IR radiators, driven by LPG, operate at red brightness temperatures of about 900°C with essentially no visible flame on the combustion surface (Upadhyaya and Blackshaw 2007). The burners heat ceramic and metal surfaces that radiate the heat towards the target plants. Infrared weeders have the disadvantages of needing time to heat up, the IR panels are sensitive to mechanical damage, and they are more expensive than flame weeders (**Figure17**).

Figure 17. Infrared weeder
(source: www.angenendt.nl)

Steaming: It is used in glasshouses to sterilize the soil and control both weeds and diseases prior to crop establishment. Steam is applied under pressure beneath metal pans forced down onto freshly formed beds for periods of 3-8 minutes. The steam raises the soil temperature to 70-100 °C killing most weed seeds to a depth of at least 10 cm (White *et al.* 2000a & 2000b, Bond *et al.* 2003).

Electrocutioning: This method uses the electrical energy to kill the weeds. The control equipment consists of a generator, a transformer, one or more electrodes, and rolling coulters. Because of the plant's resistance to electrical current, electrical energy is converted to heat, volatilizes cellular water and other volatiles, and ruptures cells, causing plant death. Electric current travels through the root system and is dissipated into the soil. Plants with large below-ground parts are damaged to a lesser extent, and the root damage is greater in drier soils (Upadhyaya and Blackshaw 2007). Electrocutioning system uses an electrical shocks containing of very high voltage in the range of 5-50 kV (Vigneault *et al.* 1990).

Microwave radiation based weeders: Microwaves are electromagnetic radiation in the 300 MHz to 300 GHz frequency range. Absorption of microwaves causes water molecules within tissues to oscillate, thereby converting electromagnetic energy into heat. This dielectric heating has been exploited to kill weeds, seeds and insects (Upadhyaya and Blackshaw 2007). Microwave radiation utilizes ultra high frequency (UHF) electromagnetic energy with wavelengths. Most of the weed control through microwave radiation uses the frequency of 2450 Mhz. The energy use of microwave-based weed control in a field test ranged from 10,000 to 34,000 MJ/ha. Considering the low conversion efficiency from diesel fuel to microwave energy, these Figures correspond to diesel fuel consumptions of between 1000 and 3400 kg/ha (Sartorato *et al.* 2006). Microwave radiations contains high amount of energy, which are hazardous to health. Hence, these types of weeders have to manage carefully.

Ultraviolet Radiation: UV radiation is subdivided into three spectral bands: UV-A (320–400 nm). UV-B (280–320 nm) and UV-C (100–280 nm); where 100 nm corresponds to 3 x 10^{17} Hz. While UV-B radiation levels slightly above those found in solar radiation have been reported to influence weed and crop seedling growth and morphology, with species differing in their response. UV-C radiation is the most

Figure 18. Soil steaming
(source: Peruzi *et al.* 2018)

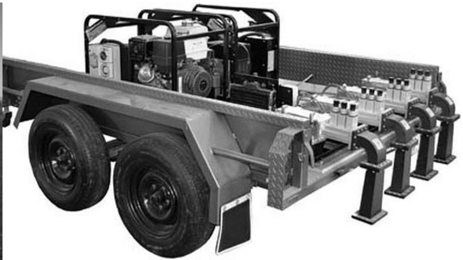


Figure 19. Microwave based weeder
(source: http://thehappydane.com.au)

damaging to plants. High levels of UV radiation (1–100 GJ/ha range) have been shown to control weeds. Weeds are damaged due to heating of the foliage following the absorption of UV radiation by plant tissues. The extent of UV-induced damage was influenced by weed species, stage of plant growth, and the height of the UV lamp above the canopy. Annual bluegrass buds protected by other tissue coverings escaped UV damage and the exposed plants produced new tillers (Upadhyaya and Blackshaw 2007).

Laser radiation based weeding: Lasers can be used to cut weed stems. Light absorption from CO_2 lasers by water molecules heats tissue contents and causes their explosive boiling (Langerholc 1979). Laser devices concentrate a large amount of energy into a narrow laser beam and quickly and accurately focus the laser beam on the targets. The energy in per unit area is high because the laser beam can be focalized on a tiny area (point). This method can also reach the purpose of weed control without cutting down the weed stems.

Weed control by micro irrigation

Water is the most limiting factor in Indian agricultural scenario. Irrigation systems are usually designed and managed with a crop of interest in mind. Within each method, there are several subcategories, each of which varies in water use efficiency, cost, yield, and weed management potential (Coolong 2013). Micro irrigation systems are the part of the mechanized agriculture, which revolutionized the irrigation systems in India and increased the crop productivity and production area. Herbigation is the process of applying herbicides to the soil with irrigation water and it has been introduced to improve the application of agricultural chemicals through irrigation systems. Precise application of water and chemicals is necessary to insure considerable increase on the crop productivity as well as minimizing the environment pollution (Hariharasudhan *et al.* 2017).

Chemical method of weed control

Herbicides are chemicals, which are designed to kill or control the unwanted plants (weeds) in cropping or non-cropping situations. In order to successful use herbicides, their application must be accurate and uniform. In cropping situations, herbicides are applied by low pressure agricultural sprayers.

Some of the agricultural sprayers used for herbicide application purpose are:

Manually operated Knapsack sprayer: Loaded on the back of worker during operations and liquid pressure is created by manually **[Figure 21(a)].**

Battery/ solar powered knapsack sprayers: Loaded on the back of worker during operations and liquid pressure is created by charged battery through solar power **[Figure 21(b)].**

Knapsack power sprayers: Loaded on the back of worker during operations and liquid pressure is created by the engine power [**Figure 21(c**)].

Trolley power sprayer: Loaded on the pulling trolley and pulled by the operator during operation. The liquid pressure is created by the engine power **[Figure 21(d)].**

Tractor mounted boom sprayers: Spray tank and nozzle boom are mounted on the tractor three point-linkage system and liquid pressure is created by the tractor P.T.O. It is best suitable in wider row spaced crops and crops at lower stages **[Figure 21(e)**].

Tractor power sprayers: Spray tank is mounted on the tractor three point-linkage system and it will be in stationary position. The liquid pressure is created by tractor P.T.O, but the boom will be carried by operators. It is suitable for all types of crops such as rice, wheat, maize, sugarcane, potato etc. **[Figure 21(f)].**

Garnett (1980) developed a wheel-barrow sprayer specifically to overcome problems associated with the use of herbicides by small holder farmer in advancing countries. The sprayer is constructed in the form of a wheel-barrow and uses a friction drive from the ground wheel to spin a rotary cut atomizer (the Micromax from Micron Sprayers). Pulling the wheel-barrow over the ground drives the peristaltic pumps (two Glen Creston pumps set 90^0 out of phase), which supply the nozzles feeding the spinning cup. The faster the operator walks. The greater the flow of herbicide and speed of rotation of the cup so that over a normal range of walking speeds a constant dose is applied per unit area. Swathe width can be varied by means of a shutter on the shroud surrounding the atomizer.

This sprayer is suited for both inter-row and overall spraying and provides a swathe width of 1.5 m and a volume rate of include constant dose rate of 20 1/ha at an average walking speed of 1 m/sec. the advantages include constant does rate, constant nozzle height, controllable swathe width, limited moving parts, ease of use, no need for batteries, reduced operator contamination.

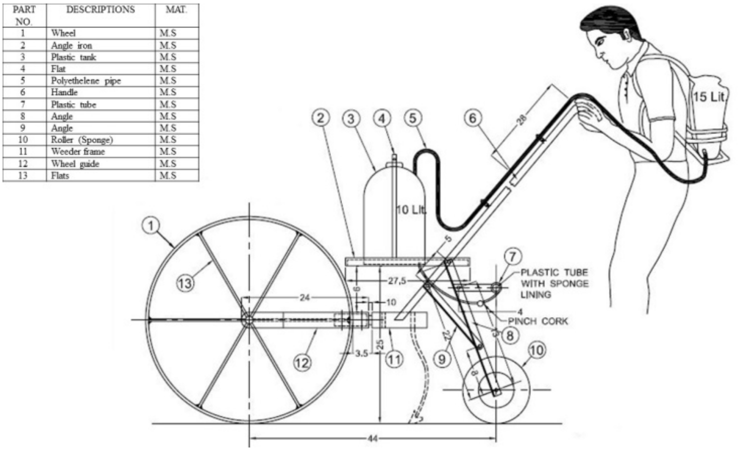
Coffee (1980) developed an electro-dynamic sprayer which is a new hand-held sprayer introduced by ICI and in which a high voltage is used to produce even-sized charged droplets. It avoids the application of mechanical force for either droplet production or droplet deposition. Instead of applying electrical force (coulombic field force) directly to the surface of the liquid, uniform jets of charged liquid are produced which in turn break up into electrically charged droplets. The droplets are manually repellant and of even size and deposit to form a uniform and tenacious coasting over the crop including stems and the undersides of the leaves.

The electro-dynamic sprayer consists of spray stick and a combination of nozzle and bottle – the Bozzle container. The contains are batteries and a solid state high voltage generator. The specially formulated ready-to-use spray liquid is contained in the Bozzle. Once the Bozzle is screwed on to the holder the sprayer is ready for chemical application. The advantages of electro-dynamic spraying system are accurate deposition of droplets of optimum size, even cover of all target with ability to cover hidden open surface, reduced drift to non-target areas, the use of ultra low volumes per hectare treated, improved operator and environmental safety, no moving parts, and ultra low energy consumption.

Weed wipers

Weed wipers are a development which has been given impetus by the increasing use of the non-selective freely-translocated herbicide glyphosate. Applicators of many different designs and types of construction are available. The hand-held wiper consists of a tublar handle or frame (which also acts as reservoir for the concentrated herbicide solution) and an applicator component of different designs and type of absorbent materials. Synthetic fibre-rope-wick is used, and also a cylindrical roller cover with spongy material. Both give the applicator a hockey stick shape. The herbicide solution permit the absorbent material and is applied by wipping the wick against the weed. By treating foliage with freely-translocated herbicides it is possible to ontrol both annual and perennial weeds (Dale 1979). The advantages of this equipment include no waste of chemical as it is applied directly to weeds, cheap to purchase and simple to operate, no maintenance, and complete elimination of drift. In arable crops it is more suited to control of weeds in inter-row areas and those that grow taller than the crop. At least with glyphosate, best results are obtained when nature weeds are treated, and it is limited to post-emergence use only.

Tewari (1985) patented in 1982 a low cost herbicide applicating machine with provision for attaching weeding blades. In this equipment (**Figure 22**) a ‘feed tank’ holds the herbicide, which is supported on a platform and may be connected, for more capacity, to a higher capacity tank mounted on the back of the operator. The chemical from ‘feed tank’ flows by gravity into a plastic tube from where a regulated amount of the chemical is allowed to drip and wet a sponge roller. The machine is pushed forward in between the crop rows that the wet roller wipes against the weeds which are, in turn, smeared with the chemical and subsequently killed. The platform with wheel has provision for attaching different weeder blades for mechanical control of weeds for which the herbicide application system has to be detached from the platform. The special features of this equipment include – no loss of herbicide solution during application, no damage to the crop plants, no additional discharge pressure is required, can be used as mechanical weeder also. The main disadvantage of this equipment is that there is no precise control on flow rate.



PART NO.	DESCRIPTIONS	MAT.
1	Wheel	M.S
2	Angle iron	M.S
3	Plastic tank	M.S
4	Flat	M.S
5	Polyethelene pipe	M.S
6	Handle	M.S
7	Plastic tube	M.S
8	Angle	M.S
9	Angle	M.S
10	Roller (Sponge)	M.S
11	Weeder frame	M.S
12	Wheel guide	M.S
13	Flats	M.S

Figure 22. Details of IITWAM:82

However, it is cheap and easy to handle and can be also be used in undulated land conditions, and best suited for small and marginal land holdings.

Bisen and Chethan 2017, developed a manually operated wick applicator to apply the non selective herbicides at ICAR – Directorate of Weed Research, Jabalpur, India. The concentrated herbicide solution is stored in a solution tank, which flows over to a cylindrical rolling pad through cut-off valve at pre-set rate. The cylindrical roller cover pad consists of fibrous cloth material, very efficient in keeping chemical solution and release only when it gets compressed. Different wetness rate of the roller cloth pad is ensured by the flow rate adjustments at cut-off valve (**Figure 23**).

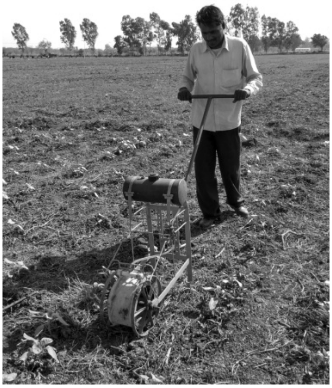


Figure 23. DWR wick applicator

Herbicide coated seeds

This is highly speculative approach to weed control but one which could become an interesting possibility due to the availability of such highly selective herbicides as fluazifop-butyl. An objective of future research could be to coat crop seeds with appropriate amount of herbicide to control weeds that grow within the crop row. The weeds growing in the inter-row area could then be either removed manually or treated with a suitable herbicide. This system offers a possibility of either completely removing or minimizing the need for any additional herbicide treatment. It would also readily integrate with the current practice of manual weed control which would specially be much more acceptable particularly in areas with surplus farm labor.

Innovative and emerging approaches for weed control

Researchers are working continuously to develop novel and emerging approaches for weed management. One such approach is the site specific management of the weeds. 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 (Rueda-Ayala *et al.* 2010). The objectives of site-specific weed management are to identify the variability, and to analyze and manage weeds according to their spatial and temporal variability (Blackshaw *et al.* 2007). If we manage weeds through site specific weed control methodologies we can save 50-80% of herbicide and 30-90% of operating costs (Nordmeyer *et al.* 1997).

New technologies for sensing crops and weeds in real-time with image analysis, global positioning systems (GPS), mapping tools in a geographical information system (GIS) and robotics using autonomous vehicles allow a precise operation of the machines. This may increase the efficacy of weed control and reduce operation costs (Gerhards et al. 2002). The block diagram for the sensing and measurement system is shown below (**Figure 24**).

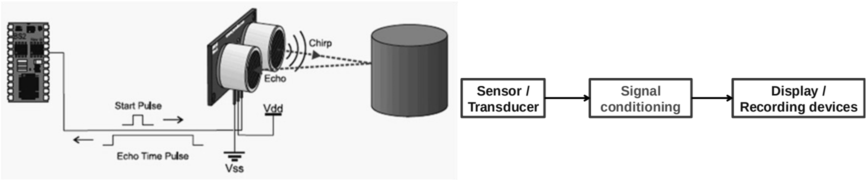


Figure 24. Block diagram of sensing and measurement system

Machine vision based approach: Machine vision is an optical sensor based system, which navigates the machine and simultaneously discriminates the weeds from crop. Main components of the system are: Image capturing device (by camera or optical sensors); Micro processors (image processing and system control); Weed control actuators. Slaughter *et al.* 1999 and Tian 2002, provided a conceptual diagram of the machine system for mechanical weeding tool management.

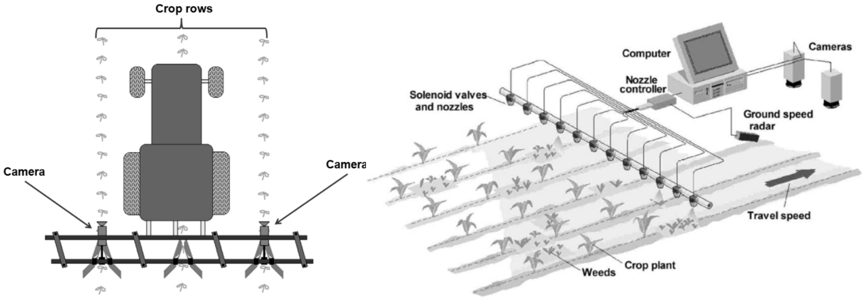
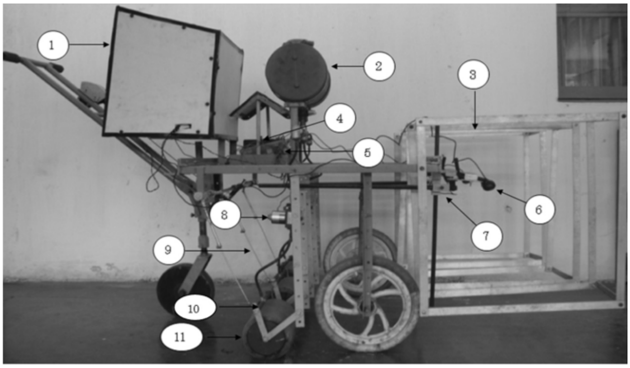


Figure 25. Schematic view of machine vision system for mechanical tool and herbicide application



1. Laptop, 2. Herbicide solution tank, 3. Deflector, 4. Battery, 5. Control Unit, 6. Web camera, 7. Camera height adjusting arrangement, 8. Solenoid valve, 9. Mechanical linkage for lifting rollers, 10. Dispensing manifold, 11. Herbicide applicating roller

Figure 26. Microcontroller based roller contact type herbicide applicator

Tewari *et al.* 2014, developed a microcontroller based roller contact type herbicide applicator for weed control under row crops at IIT Kharagpur (**Figure 26**). This system was based on manually operated three row roller contact type herbicide applicator specially developed for field crops. A control system was developed to apply the quantity of the herbicide based on quantified weed information. The unit consists of a camera for capturing the images of weeds, MATLAB software for image acquisition and processing in a laptop, a serial port communication for communicating between laptop and controller, a microcontroller for controlling the application of herbicide through a relay, and a dc solenoid valve for variable rate application of herbicide on the applicating roller.

Chandel *et al.* 2017, developed an on-the-go position sensing and controller predicated contact-type weed eradicator at IIT Kharagpur (**Figure 27**). Likewise, Abraham and Jose (2015) reported about the KAU developed weed wiper for effective application of glyphosate to control the weedy rice.

Figure 27. On-the-go position sensing and controller predicated contact-type weed eradicator

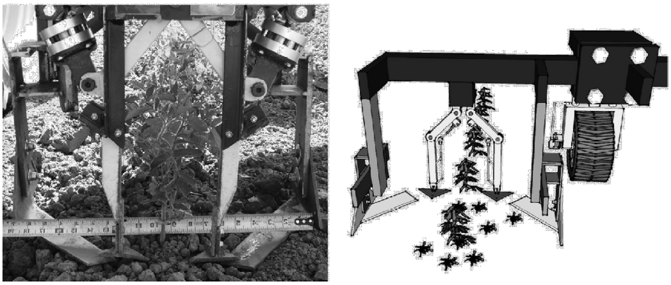


Figure 28. Automatic intra-row mechanical weeding co-robot

Perez-Ruy'z *et al.* (2014), developed a co-robotic intra-row weed control system (**Figure 28**). This system is an automatic intra-row, hoe-based weeding co-robot system with real-time pneumatic hoe actuation based on an accurate odometry sensing technique. In this system, mechanical weed control was achieved by a co-robot actuator that automatically positioned a pair of miniature hoes into the intra-row zone between crop plants.

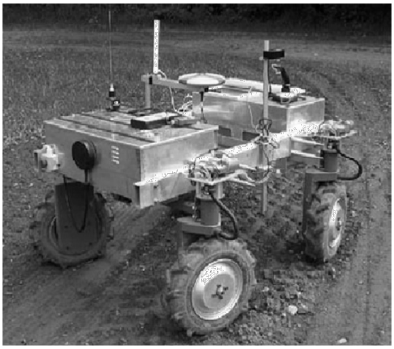


Figure 29. Autonomous RTK GPS guided weed-mapping robot

Slaughter *et al.* (2008) reported that, an autonomous robot, called the Autonomous Platform and Information system (**Figure 29**) was developed at Danish Institute of Agricultural Science, which automatically acquire images, map, and possibly process images of weeds and crops in agricultural fields; while suited for a wide range of plant growth stages, a particular focus was at the seedling (cotyledon to second true leaf stage) in order to provide optimum reduction in herbicide requirements for weed control.

Conclusions

Weed control is one of the costliest practices in crop production. The efficient and effective methods of weed control are the need of the hour as they invariably ensure higher crop productivity. Mechanized weed management can be achieved by using improved weeding tools, implements, machines, techniques which include, hand weeding tools, wheel hoes, brush cutters, power weeders, tractor operated weeders, robotic etc. The selection and operation of any technolosy should achieve ease of operation, safety and operator comfort, improved weed control efficacy, economized operation and environmental friendly.

Acknowledgement

The authors wish to acknowledge the authorities of ICAR for funding and Project Coordinator of AICRP on FIM under whose guidance and supervision the project have been conducted over the years at IIT Kharagpur. The authors also wish to acknowledge the contributions of several students who were involved in AICRP on FIM project at various stages of the design and development of the machines including weeding machine and other equipment.

References

Abraham CT and Jose N. 2015. Weedy rice invasion and its management. *Indian Journal of Weed Science* **47**(3): 216–223.

AICRP on FIM, ICAR, New Delhi, 2017. https://aicrp.icar.gov.in/fim/

Annual report 2016-17. ICAR - Directorate of Weed Research, Jabalpur, India.

Ascard J. 2014. Physical and cultural weed control in Scandinavia. 10th EWRS Workshop, Alnarp, Sweden.

Bisen HS and Chethan CR. 2017. Application of non-selective herbicide by DWR wick applicator. Pp.36-37, In: *DWR Technologies and Techniques.*ICAR-DWR, Jabalpur

Blackshaw RE, Anderson RL and Lemerle D. 2007. Cultural weed management. Pp.35–47, In: *Non-chemical Weed Management: Principles, Concepts and Technology.* (Eds.Upadhyaya MK, Blackshaw RE). CABI, Oxford.

Bond W and Grundy AC. 2001. Non-chemical weed management in organic farming systems. *Weed Research* **41**: 383-405.

Bond W, Turner RJ and Grundy AC. 2003. A review of non-chemical weed management. The Organic Association. http://www.organicweeds.org.uk.

Centre of Excellence for Farming Machinery (CoEFM), Ludhiana, India. http://www.cmeri.res.in/CMERI-Ludhiana.

Chandel AK, Tewari VK, Kumar SP, Nare B and Agarwal A. 2017. On-the-go position sensing and controller predicated contact-type weed eradicator. *Current Science* **114(7):** 1485-1494.

Chethan CR and Krishnan D. 2017. Dynamic push–pull strength data generation for agricultural workers to develop manual dryland weeders. *Current Science* **113(8):** 1601-1605.

Coffee RA. 1980. Spraying Systems for 1980s. In: *Proceedings of British. Crop Protection Conference* - Egham, UK.

Coolong T. 2013. Using irrigation to manage weeds: A focus on drip irrigation. Pp.161-179.In: *Weed and Pest Control-Conventional and New Challenges*. http://dx.doi.org/10.5772/54153.

Dale JE. 1979. A non –mechanical system of herbicide with a roper wick, *Proceedings of the National Academy of Sciences of the United States of America* . **25:**431-436.

Deshmuk, G. 2012. Rotary weeder for drudgery reduction of women during weeding in rice field. *Indian Journal of Weed* Science **44(2):** 132–134.

Dierauer HU, Stöppler-Zimmer H. 1994. *Unkrautregulierung ohne Chemie*. Ulmer, Stuttgart.

Elmore CL, Stapleton JJ, Bell CE and Devay JE. 1997. *Soil Solarization - A Non-pesticidal Method for Controlling Diseases, Nematodes, and Weeds*. Division of Agriculture and Natural Resources, University of California. Publication 21377.

Garnett RP. 1980. A low – volume herbicide applicator for tropical small-holder farmers. Pp.629-636. In: *Proceedings of 1980 British Crop Protectic Conference – Weeds*.

Gerhards R, Sökefeld M and Nabout A. 2002. Online weed control using digital image analysis. **Journal of Plant Disease and Protection 90:** 421–427.

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

Gite LP and Yadav BG. 1990. Optimum handle height for a push-pull type manually-operated dryland weeder. *Ergonomics* **33(12):** 1487-1494.

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

Hariharasudhan V, Chinnusamy C and Murali AP. 2017. Recent weed management techniques in micro irrigation system: Review. *Journal of Pharmacognosy and Phytochemistry* **6(6):** 324-326.

Horowitz M, Regev Y and Herzlinger G. 1983. Solarization for Weed Control. *Weed Science* **31:** 170-179.

Langerholc J. 1979. Moving phase transitions in laser-irradiated biological tissue. *Applied Optics* **18:** 2286–2293.

Latia Agribusiness Solutions Ltd.

LU¨ Tkemeyer L. 2000. Hydropneumatische Unkrautbekampfung in Reihenkulturen. Pp.661–666, *zeitschrift fu´r Pflanzenkrankheiten und Pflanzenschutz, Sonderheft XVII.*

May-Bridge Harrows, Canada. https://maybridgeharrows.com/

Mehta CR. 2013. Sustainable agricultural mechanization. In: *9th Technical Committee of Centre for Sustainable Agricultural Mechanisation,* Bhopal.

Melander B. 1997. Optimization of the adjustment of a vertical axis rotary brush weeder for intrarow weed control in row crops. *Journal of Agricultural Engineering Research* **68:** 39–50.

NaturaGriff, France. https://www.naturagriff.com/en/naturagriff.php

Nordmeyer H, Ha¨ usler A and Niemann P. 1997. Patchy weed control as an approach in precision farming. Pp.307–314. In: *Proceedings of the First European Conference on Precision Agriculture.* Warwick, UK.

Perez-Ruý´z MP, Slaughter DC, Fathallah FA, Gliever CJ and Miller BJ. 2014. Co-robotic intra-row weed control system. *Biosystems engineering* **126:** 45-55.

Peruzzi A and Frasconi C, Martelloni L and Fontanelli M. 2018. Use of steam and exothermic compounds for weed seed-bank control in bands (band-steaming). www.researchgate.net

Pullen DWM and Cowell PA. 1997. An evaluation of the performance of mechanical weeding mechanisms for use in high speed inter-row weeding of arable crops. *Journal of Agricultural Engineering Research* **67:** 27 – 34.

Ramakumar Industries, Tamilnadu, India. https://www.indiamart.com/ramakumarindustries/

Rask AM and Kristoffersen P. 2007. A review of non-chemical weed control on hard surfaces. *Weed Research* **47:** 370–380.

Rueda-Ayala VP, Rasmussen J and Gerhards R. 2010. Mechanical weed control. Pp.279-294, In: *Precision Crop Protection – the Challenge and Use of Heterogeneity.* (Eds. Oerke EC, Gerhards R, Menz G, Sikora RA.). Springer Netherlands.

Sarkar B, Kumar R, Mishra JS and Bhatt BP. 2016. Comparative performance of different weeding tools in winter maize (*Zea mays* L.). *Indian Jurnal of Weed Science* **48(3):** 330 – 332.

Sartorato I, Zanin G, Baldoin C and De Zanche C. 2006. Observations on the potential of microwaves for weed control. *Weed Research* **46:** 1–9.

Shekhar S, Chandra S and Roy DK. 2010. Performance evaluation of different weeding tools in maize. *Indian Journal of Weed Science* **42(1&2):** 95-97.

Singh G. 2015. Agricultural Mechanisation Development in India. *Indian Journal of Agricultural Economy* **70(1):** 64-82.

Slaughter DC, Chen P and Curley RG. 1999. Vision guided precision cultivation. *Precision Agriculture* **1(2):** 199–216.

Slaughter DC, Giles DK and Downey D. 2008. Autonomous robotic weed control systems: A review. *Computers and electronics in agriculture* **61:** 63-78.

Tewari VK, Kumar AA, Nare B, Prakash S and Tyagi A. 2014. Microcontroller based roller contact type herbicide applicator for weed control under row crops. *Computers and electronics in agriculture* **104**: 40–45.

Tewari VK, Kumar AA, Nare B, Prakash S and Tyagi A. 2014. Microcontroller based roller contact type herbicide applicator for weed control under row crops. *Computers and Electronics in Agriculture* **104:** 40–45.

Tewari VK. 1985. *Development Of A Weeder From Engineering And Ergonomic Consideration*. Ph.D. thesis, IIT Kharagpur, WB, India-721302.

Thomas Hatzenbichler Agro-Technik GmbH, Andrä, Austria. https://www.hatzenbichler.com/en/

Tian L. 2002. Development of a sensor-based precision herbicide application system. *Computers and Electronics in Agriculture* **36:** 133-149.

Turner tools pvt. Ltd. https://www.turnertools.in/

Upadhyaya MK and Blackshaw RE. 2007. *Non-Chemical Weed Management- Principles, Concepts and Technology*. Biddles Ltd, King's Lynn, U.K.

V.S.T. Tillers Tractors Ltd. http://www.vsttillers.com/

Van der Weide RY, Bleeker PO, Machten VTJ. 2008. Innovation in mechanical weed control in row crops. *Weed Research* **48:** 215–224.

Vanhala P, Kurstjens DAG, Ascard J. 2004. Guidelines for physical weed control research: flame weeding, weed harrowing and intra-row cultivation. Pp.194–225. In: *Proceedings of the 6th EWRS Workshop on Physical and Cultural Weed Control*. Lillehammer. http://orgprints.org/00002445.

Vigneault C, Benoit DL, McLaughlin. 1990. Energy aspects of weed electrocution. *Revues of Weed Science* **5:** 15-26.

White G, Bond B and Pinel M. 2000a. Steaming ahead. *Grower*, Nexus Horticulture, Swanley, UK **134(5):** 19-20.

White G, Bond B and Pinel M. 2000b. Return to the age of steam. *HDC News* No. **61:** 12-14.

Yaduraju NT and Mishra JS. 2017. Enhancing farmers' income through smart weed management. pp.5-6. In: *"Doubling Farmers' Income by 2022: The Role of Weed Science"*, Biennial Conference of the Indian Society of Weed Science on MPUA&T, Udaipur, India.

Chapter 12

Herbicide use in agriculture: An Indian perspective

Partha P. Choudhury*, Dibakar Ghosh[1], Amitava Sanyal[2], Debi Sharma
ICAR-Indian Institute of Horticultural Research,
Hesaraghatta Lake Post, Bengaluru 560 089
[1]ICAR-Directorate of Weed Research, Jabalpur, Madhya Pradesh 482004
[2]Sumitomo Chemical India Pvt. Ltd., New Delhi
**Email: Partha.Choudhury1@icar.gov.in*

Summary

Till recently, weed management in crop lands in India was almost exclusively a manual farm operation, involving women and child labour. However, since a few decades, our farmers are facing problems in weed management due to spread of obnoxious weeds and also due to higher manual labour costs. Herbicides have taken the responsibility to combat this problem. The use of herbicides for weed control was limited to plantation crops like tea in north-eastern region and some major crops like rice and wheat in the high productivity areas of north-western India. Farmers are realizing the efficiency of herbicides in controlling weeds at low cost. Low-dose high-potency herbicides of various groups with different modes of action and their mixtures are now available for broad-spectrum weed control in all major crops including the food grain crops, horticultural plantations and also non-cropped areas. Herbicide resistance in weeds can also be managed by rotating the herbicides of different modes of action or by applying combination products. The only thing, we need, is judicious use of safer herbicides that may serve our purpose to secure food along with conserving biological diversity. This chapter provides an in-depth perspective on use, regulation, marketing and fate of herbicides in India.

Key words*:* Chemical management, Herbicide consumption, Herbicide use, Indian perspective

Introduction

The importance of crop protection products in agriculture is enormous because they are considered as one of the major tools to protect crops and increase the yield to feed 2.5 billion people in the developing world depending on agriculture for their livelihoods. By 2050, small holding farmers will need to double their production to ensure rural prosperity and global food security. Small holding farmers in India, China and sub-Saharan Africa account for around 35% global grain (maize, soybean, wheat and rice) production. However, they lack access to technology, education and training, information on climate change, pests, insects and diseases in crops, which hinders their productivity. Simply, their increasing awareness towards crop protection is changing the situation. Use of crop protection products in the country has helped alleviate the estimated 37% gross loss of crops due to infestation of pests and diseases. Our country has to ensure food security for population of 1.25 billion while facing reduction in cultivable land resource and dwindling water resources.

In the tropical countries, like ours, the damaging pests and diseases are of major concern in agricultural production. Weed infestation is one of the major threats to crop production. Without any intervention for managing weeds, it is impossible to achieve the target set for crop yield. Weed infestation can lower the crop yield by about 5% in commercial agriculture, 10% in semi-commercial agriculture, and 20% in subsistence agriculture. In semi-arid tropics, weed-induced yield losses may be up to 80%. In our country, 80 different weed species out of 826 species are considered as very serious and 198 as serious weeds (Choudhury *et al.* 2015). Some weeds, *viz. Parthenium, Micania, Lantana, Mimosa etc.*, collectively known as alien invasive weeds, have made entry from their native habitat to our country. They have established themselves rapidly in their location in absence of their co-evolved predators and parasites, causing terrific harm towards crop production and biodiversity of our native plants and animals. As per Convention on Biological Diversity (CBD 1992), alien invasive species are the biggest threats to biodiversity next only to human resettlement.

Climate change is one of the major global change stressors, which drive ecosystem alterations. Climate is primarily responsible for the vegetation distribution from region to region on the globe. Rise in temperature and level of CO_2 has a direct impact on crop-weed competition influencing agricultural production systems (Howden *et al.* 2007, Hulme 2009, McDonald *et al.* 2009). In general, weed population shows greater variation and will achieve superior competitive fitness against the crop plants under the altered global climate with higher level of atmospheric carbon dioxide and temperature.

In this complex scenario of increasing weed infestation, farmers need to have improved technology to control weeds because manual weeding is going to be impractical due to many reasons. The process of rapid urbanization and industrialization is causing an acute labor shortage. Farmers are opting for herbicide application because it is less expensive than mechanical or manual operations. In our country, the use of herbicides is significantly low in comparison to that in industrialized countries. The share of herbicides was below 5% during 1970s and 1980s. But since 1990s farmers are preferring herbicide application. In India, the earliest effort for weed control with herbicides was made in 1937 in Punjab for managing *Carthamus oxycantha* by using sodium arsenite (Mukhopadhyay 1993). 2,4-D was first tested in our country in 1946. Since then a number of herbicides was imported and tested for their effectiveness in controlling many weed species. In 1952, ICAR commenced schemes for testing the field performance of herbicides in rice, wheat and sugar cane in different states. The era of herbicide-use started effectively with the import of 2,4-D during the decade of sixty. But initially for a long period, it was not very much acceptable to common Indian farmers. They used cheap labours to manage their weed problems. In fact, the organised tea planters had started herbicide application with 2,4-D in the beginning; and paraquat thereafter. Presently, the weed infestation of almost all crops is being managed by application of herbicides. Along with escalating use of herbicides, the load of these chemicals in the environment is also increasing along with the associated problems. Total load of herbicides in Indian soil from the beginning till date is negligible in comparison to insecticides. But taking the lesson from industrialized countries, where the herbicide consumption is more than 65% of total pesticides, we should be alert and should plan accordingly to minimize the toxicity due to herbicides in the future.

Herbicide registration and regulation

The events of manufacturing, vending, importing, exporting and using herbicides are regulated by the Ministry of Agriculture. The Ministry governs the entire pesticide-related affairs through the Insecticide Act, 1968 and Insecticide Rule, 1971, with a view to prevent risk to human beings or animals and for matters connected therewith. The Central Insecticides Board (CIB) constituted under Section 4 of the Act is the regulatory authority. It advises Central and State Governments on technical matters. The use of pesticides and their formulations are approved by another committee, known as the Registration Committee. Pesticides get registered by the Registration Committee after rigorous scrutiny of pesticides' chemistry, bioefficacy and toxicology. As per the CIB circular published in its website on 18.09.2018, 63 technical herbicides and 27 combination herbicides are registered for use in our country (**Table 1** and **2**).

Table 1. Herbicides and their formulations registered in India under the Insecticides Act, 1968

Name of the pesticides	Formulation registered
2,4-Dichlorophenoxy acetic acid (2,4-D sodium, amine and ester salt)	a) 2,4-D sodium salt used as tech. a.i. 80% w/w min. b) 2,4-D amine salt 58% SL 22.5% SL c) 2,4-D ethyl ester 38% EC, 4.5% Gr, 20% WP
Alachlor (ban will be implemented from December 31, 2020)	50% EC, 10% Gr
Ametryn	80%WG (FI)
Anilofos	30% EC, 18% EC
Atrazine	50% WP
Azimsulfuron	50% DF
Bensulfuron-methyl	60% DF
Bentazone	480 g/l SL
Bispyribac-sodium	10% SC
Butachlor	50% EC, 5% Gr, 50% EW
Carfentazone-ethyl	40% EC
Chlorimuron-ethyl	25% WP
Chlorpropham	50% HN
Cinmethylene	10% EC
Clodinafop-propinyl (Pyroxofop-propinyl)	15% WP
Clomazone	50% EC
Cyhalofop-butyl	10% EC
Dazomet	Dazomet technical (soil sterilant Gr)
Diclofop-methyl	28% EC
Diuron	80% WP
Ethoxysulfuron	10% EC
Fenoxaprop-p-ethyl	10% EC, 9.3% EC one time import, 6.7% EC
Fluazifop-p-butyl	13.4% EC
Fluchloralin	45% EC
Flufenacet	60% WP
Flumioxazin	50.0% w/w SC
Glufosinate-ammonium	13.5% SL
Glyphosate	41% SL, 20.2% SL, 5%SL

Name of the pesticides	Formulation registered
Glyphosate-ammonium salt	71% SG
Halosulfuron-methyl	75% WG
Haloxyfop-P-methyl	10.5% EC
Imazamox	In combination product
Imazethapyr	10% EC,
Isoproturon	50% WP, 75% WP, 50% Flow
Linuron	50% WP
Metamitron	70%SC
Methabenzthiazuron	70% WP
Methyl chlorophenoxy acetic acid	40% SL or 40% WSC (amine salt)
Metsulfuron-methyl	20% WDG, 20% WG
Metolachlor	50% EC
Metribuzin	70% WP
Orthosulfamuron	50% WDG
Oxadiazon	25% EC
Oxadiargyl	80% WP, 6% EC
Oxyfluorfen	23.5% EC, 0.35% Gr
Paraquat dichloride	24% SL
Pendimethalin	30% EC, 5% Gr., 38.7% CS
Penoxsulum	21.7% SC
Pinoxaden	5.1% EC
Pretilachlor	50% EC, 30.7% w/w EC, 37.0% EW
Propanil	35% EC
Propaquizafop	10% EC
Pyrazosulfuron-ethyl	10% WP
Pyrithiobac-sodium	10% EC
Quizalofop-ethyl	5% EC
Quizalofop-p-tefuryl	4% EC
Sulfentrazone	39.6% SC
Sulfosulfuron	75% WG
Tembotrione	34.4% SC
Thiobencarb (benthiocarb)	50% EC, 10% Gr
Triallate	50% EC
Triasulfuron	20% WG
Trifluralin	48% EC

Source: Insecticides / Pesticides Registered under section 9(3) of the Insecticides Act, 1968 for use in the Country (as on 18/09/2018), Central Insecticides Board and Registration Committee, Ministry of Agriculture, GOI.

Herbicides applied in combination either pre plant incorporated or pre-emergence or post-emergence generally increase the spectrum of weed control or the length of residual weed control. Tank-mixing herbicides may improve the spectrum of weeds controlled in a single application, which saves time and labour in a weed management programme. Mixing compatible herbicides from different chemical families may improve control of specific weed populations, such as 2,4-D applied with dicamba for broad-leaf weeds. Herbicide combinations may also provide control of several weed types at the same time, such as grassy and broad-leaf weeds. For example, the combinations of mesosulfuron and iodosulfuron, clodinafop and metsulfuron, and sulfosulfuron and metsulfuron control both grasses and broad-leaf weeds in wheat. The combination product of chlorimuron and metsulfuron controls sedges and grassy weeds in rice. In soybean, pendimethalin + imazethapyr and imazemox + imazethapyr control grasses and broad- leaf weeds. Presently, in our country, 14 combination products of two active ingredients are available (**Table 2**). This trend in herbicide combination products will likely continue in crop production.

Table 2. Combination herbicides and their formulations registered in India under the insecticides Act, 1968

Combination formulation	Combination formulation
Anilofos 24% + 2,4-D 32% EC	Indaziflam 1.65% + Glyphosate-isopropyl ammonium 44.63% SC (FI)
Bensulfuron-methyl 0.6% + Pretilachlor 6% Gr	Metsulfuron-methyl 10% + Carfentrazone-ethyl 40% DF
Carfentrazone-ethyl 20% + Sulfosulfuron 25% WG	Mesosulfuron-methyl 3% + Idosulfuron-methyl sodium 0.6% WG (FI)
Carfentrazone-ethyl 0.43% + Glyphosate 30.82% w/w EW	Metfulfuron-methyl 10% + Chlorimuron-ethyl 10% WP
Clodinafoppropargyl 9% + Metribuzin 20% WP	Metribuzin 42% + Clodinafoppropargyl 12% + WG
Clodinafop-propargyl 15% + Metsulfuran-methyl 1% WP	Oxyfluorfen 2.5% + Isopropyl amine salt of glyphosate 41% SC
Clodinafop-propargyl 16.5% + Sodium acifluorfen 8%WP	Penoxsulam 0.97% w/w + Butachlor 38.87% w/w SE
Clomazone 20% + 2,4-D ethyl ester 30% EC	Penoxsulam 1.02% + Cyhalofop-butyl 5.1 % OD
Fenoxaprop-p-ethyl 7.77%+ Metribuzin 13.6% EC	Pretilachlor 6% + Pyrazosulfuron-ethyl 0.15% GR
Fluxapyzoxad 62.5% g/L + Epoxyconazole 62.5% g/L EC	Propaquizafop 5% + Oxyfluorofen 12% EC
Fomesafen 11.1% w/w + Fluazifop-P-butyl 11.1% w/w SL	Propaquizafop 2.5% + Imazethayper 3.75% w/w ME
Hexazinone 13.2% + Diuron 46.8% WP(FI)	Sodium aceflourofen 16.5% + Clodinafop-propargyl 8% EC (FI)
Imazamox 35% + Imazethapyr 35% WG(FI)	Sulfosulfuron 75% + Metsulfuron 5% WDG
Imazethapyr 2%+ Pendimethalin 30%EC	

Source: Insecticides / Pesticides Registered under section 9(3) of the Insecticides Act, 1968 for use in the Country (as on 18/09/2018), Central Insecticides Board and Registration Committee, Ministry of Agriculture, GOI.

Pesticides already registered are reviewed for their performances on regular basis. If any pesticide does not conform the toxicological norms, it is reviewed stringently and ultimately banned. Recently, a popular herbicide alachlor has been listed for banning, which will be implemented from December 31, 2020 (**Table 3**). India has more than 800 pesticide formulators. Herbicides under 9(4) registration are formulated and marketed by many companies. A few hundreds of formulations of registered herbicides are available in Indian market.

Herbicide production and consumption

In many advanced countries, the average annual consumption of herbicides is 675 to 1350 g/ha. In Japan it is as high as 5000 g/ha. Against these high figures, in

India at present the average annual herbicide use is hardly 40 to 50 g/ha. This is largely because of poor purchasing power of most of our farmers and also due to lack of technical knowledge about use of herbicides. The cost of certain herbicides is also very high as the basic ingredients for manufacturing herbicides are imported from the developed countries. The present annual installed capacity of herbicide production in India is about 6000 tones. A large portion of the available herbicides in India are used in plantation crops. Herbicide use in field crops under our conditions is practiced in major crops like wheat, rice, soybean, maze, sugarcane, *etc.*

Crop protection market is fluctuating between US$25 and $35 billion per year over the last 15 years with herbicides representing almost 50% of this amount. In our country, the situation is totally different. Based on the market value of 2016 and 2017, the share of herbicides is only 21% (**Figure 1**, **Table 4**). In 1995, herbicide usage was just 6040 ton (technical grade), whereas in 2010, it was more than 7000 ton (**Table 5**). Due to the increased use of low-dose herbicides replacing the conventional high-dose herbicides like 2,4-D, isoproturon *etc.*, the amount of consumption of herbicides has decreased, but the acreage under weed management with the use of herbicide has been increased. Two major herbicides, butachlor in rice and isoproturon in wheat, are being substituted largely by low-dose herbicides, *viz.* pyrazosulfuron in rice, and urea herbicides like sulfosulfuron in wheat.

The consumption of butachlor has decreased from 2699 ton (technical grade) in 2005-06 to 993 ton (technical grade) in 2014-15, a reduction of 37% (**Table 6**). Pretilachlor became popular compared to butachlor in the rice market. During the

Table 3. Banned, withdrawn, refused and restricted-in-use herbicides in India

Herbicides banned in India	Nitrofen, paraquat dimethyl sulphate, metoxuron, alachlor (ban will be implemented from December 31, 2020)
Herbicides withdrawn in India	Dalapon, Simazine, Sirmate
Herbicides with refused registration	2,4,5-T, Ammonium sulphamate**, C**alcium arsenate, TCA
Herbicide restricted in use	Dazomet (Use of dazomet is not permitted on tea) Trifluralin (Use permitted only in wheat)

Source: (i) Insecticides / pesticides registered under section 9(3) of the insecticides Act, 1968 for use in the Country (as on 20/09/2015), Central Insecticides Board and Registration Committee, Ministry of Agriculture, GOI; (ii) Ministry of Agriculture and Farmers Welfare gazette notification, 08/08/2018.

Table 4. Segment wise contribution in pesticide market in India

Segment	2016		2017	
	Value (INR Mn)	Per cent	Value (INR Mn)	Per cent
Insecticides	83,111	48.28	85,396	48.83
Fungicides	44,888	26.08	42,567	24.34
Herbicides	34,754	20.19	36,985	21.15
PGR	7,490	4.35	8,132	4.65
Seed treatment	1,884	1.09	1,798	1.03
Total	172,127		174,877	

Source: Industry

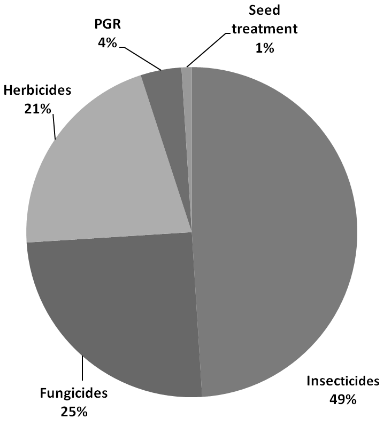


Figure 1. Pesticide use pattern in India based on market value during 2016 and 2017

Table 5. Consumption of technical grade pesticides (group-wise) in tones during 1995-96 to 2014-15

Year	Pesticide group				
	Insecticide	Fungicide	Herbicides	Others	Total
1995-96	38788	10563	6040	5869	61260
1996-97	34665	9969	7060	4420	56114
1997-98	33379	10054	7103	1703	52239
1998-99	30469	10428	7292	968	49157
1999-2000	28926	8435	7369	1465	46195
2000-01	26756	8307	7299	1222	43584
2001-02	29839	9222	6979	1308	47348
2002-03	28197	10712	7857	1398	48146
2003-04	25627	9087	5610	438	40762
2004-05	25929	6397	7364	1660	41350
2007-08	NA	NA	NA	NA	43630
2008-09	NA	NA	NA	NA	43630
2009-10	NA	NA	NA	NA	41822
2010-11	NA	NA	NA	NA	55540
2011-12	NA	NA	NA	NA	52979
2012-13	NA	NA	NA	NA	45619
2013-14	NA	NA	NA	NA	60282
2014-15	NA	NA	NA	NA	60282

Source: i.TERI Energy Data Directory and Yearbook – 2007; ii. Ministry of Statistics and Programme implementation, GOI, www.indiastat.com.

last five years, pretilachlor has a steady production of around 1900 ton per year (**Table 7**). Recent herbicides with low dose, *viz.* pyrazosulfuron-ethyl, bispyribac-sodium and orthosulfamuron are replacing the market share of butachlor and pretilachlor. Similarly, due to isoproturon resistance in *Phalaris minor*, a major weed on wheat, there is a reduction of isoproturon use by 75% within 10 years, from 2005-06 to 2014-15 (**Table 6**). Wheat growers even opt for sulfosulfuron, pinoxaden and more recently flumioxazin and combination products like mesosulfuron + iodosulfuron, *etc*.

Table 6. Consumption of herbicides during 2005-06 to 2014-15 in India (ton/technical grade)

Herbicide	2005-06	2006-07	2007-08	2008-09	2009-10	2010-11	2011-12	2012-13	2013-14	2014-15
Alachlor	50	55	35	70	117	111	218	27	29	16
Anilophos	243	255	103	253	1421	1217	1188	250	228	81
Atrazine	0.00	240	239	337	370	280	225	127	194	229
Bensulfuron-methyl	-	-	-	-	-	-	1	-	-	-
Bensulfuron + pretilachlor	-	-	-	-	-	-	-	-	17	-
Butachlor	2699	1197	1236	1246	372	1020	1020	894	997	993
Chlodinafop	-	-	-	-	-	-	47	58	50	55
Clomazone	-	-	-	-	-	-	3	1	1	1
Dalapon	34	19	11	9	3	2	1	3	1	1
2,4-D	565	446	412	555	662	403	643	606	886	1010
Diuron	29	16	10	11	333	332	376	10	63	44
Ethoxysulfuron	-	-	-	-	-	-	1	1	1	
Fluchloralin	82	98	81	49	71	40	37	20	30	9
Glyphosate	216	358	324	644	1397	433	320	220	582	718
Isoproturon	2140	1314	1126	1154	1429	1282	1414	799	757	527
Carfentrazone-ethyl	-	-	-	-	-	-	1	1	-	1
Paraquat dichloride	148	256	137	169	383	149	162	147	227	146
Propanil	16	9	17	9	75	59	62	85	58	5

Source: (i) States/UTs, Zonal conference on inputs, 2010. (In: Standing Committee on Chemicals and Fertilisers (2012-13). 2013; (ii) Production and availability of pesticides. 36th Report, 15th Lok Sabha, Dept. of Chemicals and Petrochemicals, Ministry of Chemicals and Fertilisers, Govt. of India. August, 2013.); (iii) Directorate of Plant Protection Quarantine & Storage, 2018 (http://ppqs.gov.in)

The production trend of technical grade of major herbicides has not changed much over the period from 2010 to 2015 (**Table 7**). It is due to recent innovation of low-dose herbicides imported from different countries. Technical grade materials of some of the sulfonyl ureas and imidazolinones are imported and then formulated in India. Accurate data on the import of herbicides was not available. The information obtained from the office of Commercial Intelligence and Statistics, Kolkata does not mention sulfonyl ureas and others (**Table 8**). However, the list of import (**Table 9**) and indigenously manufactured herbicides (**Table 6**) published by the Directorate of Plant Protection Quarantine and Storage, Faridabad indicates that many herbicides are being imported in the form of technical grade as well as formulation grade. In the report of Standing Committee 2013 on 'Production and availability of pesticides', it has been mentioned that our country imported 25.92, 38.99, and 22.28 ton under the head of 'Weedicides and weed killing products' and 3,775.36, 4,689.01, and 5,739.84 ton under the head of 'Other herbicides-anti-sprouting products' during 2010-11, 2011-12 and 2012-13, respectively. There was no mention of export or import value for any individual herbicide. Even the list obtained from the Zonal Conference on Inputs 2010, did not say anything about the newer herbicides actually imported from other countries.

Table 7. Production of key herbicides in India during 2005-06 to 2015-16 (ton/technical grade)

Herbicide	2005-06	2006-07	2007-08	2008-09	2009-10	2010-11	2011-12	2012-13	2013-14	2014-15	2015-16
2,4-D	329	0	270	214	NA	11517	12374	12951	17902	11620	18456
Anilophos	197	21	0	NA	0	NA	NA	NA	NA	NA	NA
Atrazine	0	93	218	263	263	248	661	652	1237	1200	1210
Butachlor	254	182	330	119	239	292	199	183	39	NA	2
Diuron	0	0	52	12	126	225	307	136	69	120	1260
Fluchloralin	119	101	0	NA	0	NA	NA	NA	NA	NA	NA
Glyphosate	1517	2100	1517	2331	1697	4860	5253	6120	8478	9690	6960
Isoproturon	4295	3150	2962	2979	2910	3684	2528	4052	2345	2430	1952
Metribuzin	NA	NA	NA	NA	NA	NA	NA	244	742	520	908
Pretilachlor	NA	NA	NA	NA	NA	1179	1650	1928	2216	1880	1941

Source: Directorate of Plant Protection Quarantine & Storage, 2015 and 2018 (http://ppqs.gov.in)

Table 8. Imports of herbicides and their CIF values (2005-06 to 2009-10)

Year	Pesticides			
	Isoproturon	MCPA	TCA	2,4-D
2005-06 Qty*	144.0	1.0	0	0.15
2005-06 CIF Value**	426.0	38.0	0	22.0
2006-07 Qty	145.0	2.0	0	1.0
2006-07 CIF value	427.0	40.0	0	24.0
2007-08 Qty	0	0	0	1.0
2007-08 CIF value	0	0	0	83.0
2008-09 Qty	0.006	8.20	-	4.1
2008-09 CIF value	0.2	8.0	-	12.4
2009-10 Qty	-	16.0	-	62.0
2009-10 CIF value	-	15.0	-	72.0

*Quantity (Qty.) in (ton/technical grade); **Cost, insurance and freight (CIF) value in Rs. lakhs
Source: Dte. General of Commercial Intelligence & Statistics, Kolkata

India earned foreign currency by exporting ‘me-too’ herbicides like 2,4-D, MCPA and isoproturon over the years (**Table 10**). Our country exported 4632.24, 4222.37 and 2589.95 ton under the head of ‘Weedicides and weed killing products’ and 10535.31, 14,971.12 and 10,048.73 t under the head of ‘Other herbicides-anti-sprouting products’ during 2010-11, 2011-12 and 2012-13, respectively (Standing Committee 2013). During the financial year of 2012-13, India exported technical grade 2,4-D to USA, Brazil, Argentina, Thailand, and Ethiopia and isoproturon to the Netherlands, Belgium and Thailand (**Table 11**). The average prices of individual herbicides have also been increased over the years mainly due to inflation (**Table 12**). During the consecutive three years from 2015 to 2017, there is no much change in the list of top herbicide formulations used in our country (**Table 13**). The demand of glyphosate for tea sector places it on top position, whereas butachlor and isoproturon are no longer of much use in rice and wheat, respectively.

Herbicide efficacy under Indian condition

In our country, weed management was started with the introduction of 2,4-D. But it took a practical shape through the management of weeds with the application

Table 9. Consumption of imported herbicides during 2005-06 to 2009-10) (ton / technical grade)

Herbicide	2005-06	2006-07	2007-08	2008-09	2009-10	2010-11	2011-12	2012-13	2013-14	2014-15
2,4-D									27	28
Anilophos									3	3
Atrazine	0.0	0.0	0.0	0.0	0.3	-	-	-	94	91
Benthiocarb	0.1	0.1	32.0	8.4	3.0	0.9	2	-	-	-
Butachlor	-	-	-	-	-	-	-	-	69	65
Fluchloralin	-	-	-	-	-	-	-	-	4	4
Glufosinate-ammonia	-	-	-	-	-	0.5	2	2		
Glyphosate	-	-	-	-	-	2	-	-	157	148
Imazathatyr	-	-	-	-	-	1	2.1	-	-	-
Methabenz-thiazuron	0	0.0	0.0	1.0	8.0	-	-	-	-	-
Metribuzin	2.0	2.0	2.0	88.0	126.0	-	-	-	-	-
Metolachlor	2.0	27.0	3.0	2.0	3.0	2	9.0	7.5	2	2
Metoxuron	-	-	-	-	-	0.5	-	0.4	25	0.2
Metribuzin	-	-	-	-	-	22.0	52.6	26	38	11
Oxadiazon	14.0	0.1	0.0	0.0	0.0	-	-	-	-	-
Oxadiargyl	12.0	90.2	3.0	5.0	7.0	-	-	-	-	-
Oxyfluorfen	26.0	26.1	4.0	16.4	33.0	12.0	14.4	2	10	3
Pendimethalin	9.0	10.0	72.0	101.5	114.3	-	-	-	-	-
Pretilachlor	0.0	0.0	8.0	95.1	209.1	167.1	147.6	57	33	29
Simazine	0.0	0.0	0.0	1.0	2.0	1	1	-	-	-
Triallates	9.0	68.3	0.0	0.0	1.0	0.5	-	1	1	
Trifluralin	7.0	6.0	0.0	42.0	3.1	-	-	-	-	-

Source: Directorate of Plant Protection Quarantine & Storage, 2015 and 2018 (http://ppqs.gov.in)

Table 10. Exports of herbicides from 2005-06 to 2009-10

Pesticides	2005-06 Qty*	2005-06 CIF Value**	2006-07 Qty	2006-07 CIF value	2007-08 Qty	2007-08 CIF value	2008-09 Qty	2008-09 CIF Value	2009-10 Qty	2009-10 CIF Value
2,4-D	4138	4719	14670	29612	739	766	3096	4349	702	8817
Isoproturon	1078	2041	1157	2191	1009	1675	1447	3542	1812	3761
MCPA	1021	2113	889	2592	554	763	195	627	95	174

*Quantity (Qty.) in (ton/technical grade)); **Cost, insurance and freight (CIF) value in ` lakhs
Source: (Dte. General of Commercial Intelligence and Statistics, Kolkata)

Table 11. Top five export destination of selected herbicides during 2012-13

Product	Country	Quantity (ton)	Value (` in lakhs)
2,4-D	USA	4315	8393
	Argentina	1566	2684
	Brazil	4194	8069
	Thailand	2700	4277
	Ethiopia	596	816
Isoproturon	Netherland	4026	12707
	Belgium	142	437
	Thailand	13	44

Table 12. Average prices* (`/kg/L) of the key herbicides during 2005-06 to 2015-16

Herbicide	2005-06	2006-07	2007-08	2008-09	2009-10	2010-11	2011-12	2012-13	2013-14	2014-15	2015-16
2,4-D sodium salt 80%	118	176	215	272	226	-	-	-	-	-	430
2,4-D Acid	-	-	-	-	-	213	253	260	570	305	320
Alachlor EC	58	284	262	300	340	331	302	177	392	331	335
Alachlor Gr	-	152	100	50	-	-	-	-	-	-	-
Anilophos 30% EC	109	264	272	249	256	307	250	341	334	329	358
Atrazine	151	289	232	259	290	281	283	332	350	373	343
Butachlor 5% Gr	52	46	198	48	163	-	-	-	-	-	-
Butachlor 50% EC	138	152	202	194	174	190	180	194	250	259	293
Carfentrazone-ethyl	-	-	-	-	-	-	2572	-	-	-	1660
Chlodinafop + metsulfuron	-	-	-	-	-	-	2800	318	-	-	-
Chlorimuron-ethyl	-	-	-	-	-	-	11320	3493	-	-	-
Diuron	-	-	-	-	-	-	465	-	-	-	718
Glyphosate	29	296	449	347	348	286	302	316	353	396	349
Imazethapyr	-	-	-	-	-	-	1576	1636	1830	1661	1421
Indoxacarb	-	-	-	-	-	3109	3069	2882	3425	3259	3902
Isoproturon 75% EC	167	266	717	287	266	240	282	390	324	368	371
Metribuzin	-	-	-	-	-	-	1231	1463	1468	1355	1413
Metsulfuron-methyl	-	-	77	3563	4558	-	-	-	-	-	-
Oxyfluorfen	-	-	-	-	-	-	1630	2050	1844	1621	1681
Paraquat dichloride	-	-	-	-	-	-	285	319	350	348	328
Pretilachlor	-	-	462	513	428	269	378	413	457	418	434

Source: (i) State Department of Agriculture. (In: Standing Committee on Chemicals and Fertilisers (2012-13). 2013. Production and vailability of pesticides. 36th Report, 15th Lok Sabha, Dept. of Chemicals and Petrochemicals, Ministry of Chemicals and Fertilisers, Govt. of India. August, 2013.); (ii) Source:States/UTs Zonal Conference on Agriculture inputs(PP); (iii) Directorate of Plant Protection Quarantine & Storage, 2018 (http://ppqs.gov.in)

* Average Price of a pesticide is the sum of all prices of the pesticide divided by number of States provided price of that pesticide.

Table 13. Top generic herbicide formulations in India for consecutive three years from 2015 to 2017

Formulation	Volume in tone or kiloliter		
	2015	2016	2017
Glyphosate 41 SL	18200	20,171	20,534
Imazethapyr 10 SL	3,200	3,366	2,459
Pretilachlor 50 EC	4,626	5,064	4,900
Clodinafop 15 WP	1,500	1,260	1,409
Paraquat 24 SL	6,600	6,053	6,476
Metribuzin 70 WP	791	821	1,324
2,4-D 58 EC (amine salt)	2,222	3039	3,522
Oxyfluorfen 23.5 EC	613	594	Not available
Pendimethalin 30 EC	1,980	2,147	1,594
Pendimethalin 38.7 ES	1359	1,414	1,933
Atrazine	Not available	4,667	4,538

Source: The information is based on the compilation of sales from industrial members of CropLife India of paraquat in tea gardens. The commercial impetus of herbicide use was gained during the late 70s or early 80s of last century. Later on herbicides like 2,4-D and butachlor in rice and isoproturon in wheat gained popularity among farmers. Recently introduced herbicides are now replacing the older ones because of their better effectiveness, *i.e.* control of weeds, their effects on succeeding crops as well as in soil microflora. Herbicide efficacy largely depends on the soil type and climate. For an example, the availability of many sulfonylurea herbicides to weeds is less in acidic soil, as the acidic condition degrades sulfonylureas fairly rapidly affecting their efficacy. However, they may persist for a longer time in saline soil. For registration of any herbicide in our country, it requires two seasons' bioefficacy studies from three different agroclimatic zones of our country. Therefore, the research on herbicide efficacy is very much essential on different crops under various soils and agro-climatic conditions available in our country. Efficacy studies for different herbicides in major crops are reviewed here (**Table 14**).

Herbicide recommendations and safety standards

In India, our farmers have the list of distinct recommendations for herbicide uses against different weeds in all important crops made by the Ministry of Agriculture. The respective department revises or updates the recommendations regularly. Recommendations are also available to farmers through the label claim attached to the formulation packages. The registrant company affirms the use of herbicide under registration in the label claim. All the details of the herbicide usage including the crop(s) and application rate(s) are mentioned in the label claim. This information of the product's usage is based on the bioefficacy data generated from the experiments conducted by SAUs or ICAR-institutes or any other recognized laboratories. Such studies also take care of their metabolism, persistence and degradation so as to develop a proper dose regime, which reduce risk to target crops and users. The Registration Committee, constituted by the Central Government published a compilation of approved uses of pesticides in the best possible way. It is available in the website of Central Insecticides Board. Herbicides have to be used on those crops where the data generation has been carried out previously. For an example, atrazine has the recommendation for weed management in maize. Farmers should not use it in other cereals or crops. Similarly, bispyribac-sodium is recommended for rice. Pesticide dealers cannot sell it for the weed management in wheat. The information on waiting period has also been generated for most of the herbicides in many crops. Waiting period is the period of time after the application of a herbicide to a crop during, which harvest of the crop is prohibited to ensure that the crop will meet the established pesticide residue tolerance. Thus, if a farmer applies quizalofop to control weeds, any part of the crop cannot be harvested before its waiting period of seven days (**Table 15**). Unfortunately, the uses of herbicides take place beyond the official recommendation in our diversified and fragmented agriculture system. We need to have strong awareness programmes among stakeholders for the utilization of label claim to avoid potential risk due to the injudicious application of herbicides.

Table 14. Crop-wise bioefficacy studies of herbicides in India

Crop	Weed management	Reference(s)
Aswagandha	Isoproturon 0.50 kg/ha + glyphosate 1.0 kg/ha pre-emergence (PE) followed by (*fb*) hand weeding (HW) at 45 days after sowing (DAS)	Kulmi and Tiwari 2005
Blackgram / greengram	Pendimethalin 0.50 kg/ha (PE) *fb* HW 45 DAS	Kumar *et al.* 2006
	Pendimethalin 0.50 kg/ha (PE) *fb* HW 60 DAS	Rathi *et al.* 2004
	Trifluralin 0.50 kg/ha (PE) *fb* HW 45 DAS	Sardana *et al.* 2006
	Oxyfluorfen 120 g/ha *fb* imazethapyr 50 g/ha	Rao *et al.* 2010
	Imazethapyr + pendimethalin 1000 g/ha	Singh *et al.* 2016a
	Imazethapyr 40 g/ha + quizalofop ethyl 37.5 g/ha as post-emergence (PoE) at 20 DAS	Pazhanivelan *et al.* 2015
Cotton	Pendimethalin 1.0 kg/ha (PE) *fb* quizalofop-ethyl 50 g/ha (PoE) 2-4 weed leaf stage *fb* one hoeing	Singh and Rathore 2015
	Pyrithiobac-sodium 62.5 g/ha + quizalofop-ethyl 50 g/ha *fb* one hoeing	Singh *et al.* 2016b
Lentil	Pendimethalin 1.0 (PE) *fb* HW 45 DAS	Lhungdim *et al.* 2013
	Pendimethalin 205 g/ha + imazethapyr 14 g/ha (PE)	Kumar *et al.* 2018
Coriander	Pendimethalin 1.0 kg/ha (PE) *fb* HW 45 DAS	Nagar *et al.* 2009
Cowpea	Pendimethalin 0.75 kg/ha (PE) *fb* HW 35DAS	Mathew *et al.* 1995
Garlic	Oxyfluorfen 0.15 kg/ha or pendimethalin 1.0 kg/ha (PE) *fb* HW 40 DAS	Porwal 1995
Groundnut	Pendimethalin or alachlor 1.0 kg/ha (PE) *fb* HW 30 DAS	Itnal *et al.* 1993
	Pendimethalin 1.0 kg/ha (PE) *fb* quizalofopp-ethyl 50 g/ha (PoE)	Sagvekar *at al.* 2015
	Imazethapyr 75 g/ha (PoE)	Sagvekar *at al.* 2015
Indian mustard	Pendimethalin 0.50 kg/ha (PE) or fluchloralin 0.50 kg/ha (PE) *fb* HW 30 DAS	Singh *et al.* 1999
	Fluchloralin 0.75 kg/ha (PE) *fb* HW 25 DAS	Singh 2006
	Oxadiargyl 0.09 kg/ha (PE)	Mankar 2015
	Oxyfluorfen 0.15 kg/ha (PE)	Mankar 2015
	Isoproturon 1.0 kg/ha (PE)	Mankar 2015
	Clodinafop 0.06 kg/ha (PoE) at 25-30 DAS	Mankar 2015
Onion	Pendimethalin 1.5 kg/ha (PE) *fb* HW 60 days after transplanting (DAT)	Rameshwar *et al.* 2002
	Oxyfluorfen 0.25 kg/ha (PE) *fb* HW 40 DAT	Nandal and Singh 2002
	Oxyfluorfen 0.15 kg/ha (PE) *fb* HW at 35 DAT	Kolhe 2001
	Fluchloralin or pendimethalin 0.9 kg/ha (PE) *fb* HW 40 DAT	Sukhadia *et al.* 2002
	Pendimethalin 1.0 kg/ha + oxyfluorfen.0.25 kg/ha (PE) *fb* HW: 30 DAT	Kalhapure and Shete 2012
Okra	Stale seed bed with glyphosate; eucalyptus mulch	Ameena *et al.* 2006
Opium Poppy	Isoproturon 375 g/ha or 500 g/ha (PE) *fb* HW: 30 DAS	Kulmi and Tiwari 2005
Pea	Pendimethalin 1.0 kg/ha (PE) *fb* HW: 30 DAS	Tewari *et al.* 2003
Pigeonpea / Ground nut intercrop	Pendimethalin 1.0 kg/ha or fluchloralin 1.0 kg/ha (PE) *fb* HW: 30,42 DAS	Vijayakumar *et al.* 1995

Crop	Weed management	Reference(s)
Chickpea and mustard	Fluchloralin 1.0 kg/ha as pre-plant incorporation (PPI); intercrop: chickpea + mustard	Kaur *et al.* 2013
Rice: transplanted rice	Butachlor 1.0 kg/ha or anilofos 0.4 kg/ha (PE)	Gogoi *et al.* 2001
	Anilophos 0.6 kg/ha at 7 DAT *fb* HW: 27 DAT	Singh and Kumar 1999
	Thiobencarb 1.5 kg/ha	Ghansham and Singh 2008
	Metsulfuron methyl 10% + chlorimuron-ethyl 10% 0.04 kg/ha mixed with butachlor 0.938 kg/ha at 3 DAT	Patra *et al.* 2011
	Pyrazosulfuron-ethyl 42.0 g/ha at 3 DAT	Banerjee *et al.* 2012
	Triasulfuron 20 WG 12 g/ha	Sajjam *et al.* 2013
	Bensulfuron methyl + Pretilachlor 0.06 + 0.60 kg/ha (PE) *fb* inter-cultivation at 40 DAS	Sunil *et al.* 2010
	Azimsulfuron at 35 g/ha (PoE)	Shapirov 2002, Saha and Rao 2012
	Pendimethalin 0.75 kg/ha *fb* bispyribac 25 g/ha or azimsulfuron 20 g/ha or 2,4-D 500 g/ha	Walia *et al.* 2008
	Penoxsulam 40 g/ha	Larella *et al.* 2003
	Pretilachlor 1.0 kg/ha	Phogat and Pandey 1998
Rice : dry-seeded	Butachlor 1.0 (PE) *fb* HW: 30 DAS	Singh and Singh 2001
	Pendimethalin 0.75 kg/ha	Tomar *et al.* 2002
	Bispyribac Na 25 g/ha	Mahajan *et al.* 2009
	Penoxsulam 25 g/ha	Mahajan *et al.* 2009
	Pyrazosulfuron-ethyl 15 g/ha	Moorthy 2002
	Ethoxysulfuron 30 g/ha	Saini *et al.* 2002
	Fenoxaprop-P-ethyl 75-90 g/ha 25 DAS	Saini *et al.* 2002
	Bispyribac Na + azimsulfuron 25+17.5 g/ha 15 DAS	Ghosh *et al.* 2017
	Cyhalofop-butyl 0.09 kg/ha	Kolhe and Tripathi 1998
	Pretilachlor 0.75 kg/ha	Singh *et al.* 2012
	Metsulfuron 0.015 kg/ha	Singh *et al.* 2012
	Clomazone 500 g/ha	Ghosh *et al.* 2016
Rice: upland	Oxadiazon 0.4 kg/ha + cyhalofobutyl 70 g/ha at two leaf stage, oxadiazon 0.4 kg/ha and butachlor 1.5 kg/ha	Dhanvate 2000
	Oxadiazon 0.4 kg/ha + HW and pretilachlor + safener 0.75 kg/ha + HW	Nikam 2003
Sesame	N: 60 + fluchloralin 1.0 PPI *fb* HW: 21 DAS	Singh *et al.* 2001
	Quizalofop-ethyl 0.05 kg/ha 20 DAS *fb* HW: 30 DAS	Bhadauria *et al.* 2012
Soybean	Butachlor 1.5 kg/ha (PE) *fb* HW: 30 DAS	Chandrakar and Urkurkar 1993
	Alachlor 1.0 kg/ha (PE)	Shekara and Nanjappa 1993
	Quizalofop-ethyl 0.05 kg/ha + chlorimuron-ethyl 0.09 kg/ha 15 DAS *fb* HW: 30 DAS	Jadhav and Gadade 2012
	Imazethapyr at 75 - 100 g/ha 15-20 DAS	Mandloi *et al.* 2000
	Fenoxaprop-p-ethyl at 70 g/ha	Mandloi *et al.* 2000
	Pendimethalin 1.0 kg/ha + hand weeding	Jain *et al.* 1985
	Metribuzin 0.75 kg/ha + hand weeding	Jain *et al.* 1985
	Pendimethalin + imazethapyr 0.75 + 0.10 kg/ha (PE)	Das and Das 2018

Crop	Weed management	Reference(s)
	Pendimethalin 0.75 kg/ha + carfentrazone-ethyl 0.02 kg/ha (PE)	Das and Das 2018
	Imazamox + imazethapyr 70 g	Pandey *et al.* 2007
Sugarcane	Metribuzin or atrazine 1.0 kg/ha + trash mulch 3.5 tons; inter-rows: 60 DAP	Singh *et al.* 2001
Wheat	Pendimethalin 0.75 kg/ha (PE) *fb* HW: 30 DAS	Singh and Singh 2004
	Cross sowing + isoproturon 1.0 kg/ha + 2,4-D 500 g/ha	Chaudhry *et al.* 2009
	Clodinafop 60g/ha (PoE)	Brar *et al.* 2003
	Isoproturon 1.0 kg (PoE)	Gautam 1982
	Fenoxaprop-P 0.69 kg (PoE)	Montazeri 1993
	Carfentrazone-ethyl 20 g/ha (PoE)	Kumar *et al.* 2017
	Metribuzin 175g (PoE)	Sardana *et al.* 2001
	Metsulfuron 4 g/ha (PoE)	Sardana *et al.* 2001
	Pinoxaden 30 g/ha (PoE)	Chhokar *et al.* 2008
	Sulfosulfuron 25 g/ha (PoE)	Chauhan *et al.* 1998
	Clodinafop + metsulfuron 60+4 g (PoE)	Om *et al.* 2006
	Sulfosulfuron + metsulfuron 30 + 2 g (PoE)	Om *et al.* 2006
	Mesosulfuron + iodosulfuron 12 + 2.4 g (PoE)	Brar and Walia 2008
Maize	Atrazine 1.0 kg/ha (PE)	Gautam *et al.* 1981
	Tembotrione 110 g/ha 20 DAS	Reddy *et al.* 2017
	Topramezone 25 g/ha 20 DAS	Reddy *et al.* 2017
	Pendimethalin 750 g/ha (PE) *fb* halosulfuron methyl 90 g/ha (PoE)	Lakshmi and Luther 2017
	Atrazine 1.0 kg/ha (PE) *fb* 2,4-D 1.0 kg/ha at 30 DAS	Ram *et al.* 2017

Pesticides invariably leave varying amounts of residues in the treated crop. The time for, which the residues of pesticide are retained in the treated substrate, is referred to as its persistence. The persistence of these residues is required to give protection to the crop up to a certain period of time. Pesticide residues responsible for keeping the pests away can be hazardous too. High residue may result from either higher dosages or application of the pesticide at the wrong time or both. The term 'pesticide residues' usually means the remnant of the applied pesticide together with its toxic metabolic product(s) and impurities, if any, in a given substrate at a given time after its use. Pesticide residues may be harmful for us depending on their toxicological properties and the degree of exposure to these residues. Therefore, there should be a definition of residues in the substrate, i.e. food commodity. That level of residues is called 'Maximum Residue Limit (MRL)'. The Codex Alimentarius defines MRL as 'the maximum concentration of a pesticide residue that is recommended by the Codex Alimentarius to be legally permitted in or on food commodity'. These limits are proposed by the FAO/WHO Joint Meetings on Pesticide Residues (JMPR) in a series of reports and are based on an estimate of the maximum residue levels expected following Good Agricultural Practices (GAP) and consideration of the Acceptable Daily Intake (ADI) for the pesticide in question. The MRL at harvest for a particular crop/pesticide combination is

Table 15. Some major recommendation of herbicides with their waiting period and toxicity

Name	Crops	Application rate (kg/ha)	Waiting Period (day)	Acute toxicity	
				$LD_{50,\text{ acute, oral,rat}}$ (mg/kg)	$LD_{50,\text{ acute, dermal,rat}}$ (mg/kg)
2,4-Dichlorophenoxy acetic acid	Rice	0.85-1.0	-	375 (amine salt) 700 (ethyl ester) 500-805 (sodium salt)	>2000
	Wheat	0.50-0.84	90		
	Maize	0.5-1.0	50-60 (dimethyl amine salt) 90-120 (sodium salt)		
	Sugarcane	3.50	-		
	Citrus	1.0-2.50	>180		
	Grapes	2.0	>90		
Acetochlor	-	-	-	1929	>2000
Alachlor				930-1350	>13300
Anilophos	Rice	0.30-0.50	30	470-830	>2000
	Soybean	1.25-1.50	100-120		
Atrazine	Maize	0.50-1.0	-	1870-3100	>3100
Benthiocarb/thiobencarb				920-1300	>2000
Bensulfuron-methyl	Rice	0.06		>5000	>2000
Bispyribac-sodium	Rice	0.02	78	4111	>2250
Butachlor	Rice	1.25-2.0	90-120	2000	>13000
Carfentazone-ethyl	Wheat	0.020	80	5000	>4000
Chlorimuron-ethyl	Rice	0.06	60	>4102	>2000
	Soybean	0.09	45		
Cinmethylene	Rice	0.075-0.100	110	4553	>2000
Clodinafop-propargyl	Wheat	0.060	110	1829	>2000
Clomazone	Rice	0.40-0.50	90	2077	>2000
	Soybean	0.75-1.0	90		
Cyhalofop-butyl	Rice	0.075-0.100	90	>5000	>2000
Diclofop-methyl	Wheat	0.70-1.0	90	563-693	>2000
Dithiopyr				>5000	>5000
Diuron	Sugarcane	1.60-3.20	-	3400	>2000
Ethoxysulfuron	Rice	0.0125-0.150	110	3270	>5000
Fenoxaprop-p-ethyl	Rice	0.0566-0.06038	61	304	>2000
	Wheat	0.10-0.12	110		
	Soybean	0.10	100		
Fluazifop-p-butyl	Soybean	0.125-0.250	90	3680	>2110
Fluchloralin	Cotton	0.90-1.20	180	>6400	>10000
	Soybean	1.0-1.50	120-150		
Flufenacet				589	>2000
Glufosinate-ammonium	Tea	0.375-0.500	15	1620-2000	>4000
Glyphosate	Tea	0.82-2.13	21 (IPAsalt) 7 (ammonium salt)	3680	>5000
Hexazinone				1690	>5278
Imazethapyr	Soybean	0.10	75	>5000	>2000

Name	Crops	Application rate (kg/ha)	Waiting Period (day)	Acute toxicity	
				LD$_{50}$, acute, oral,rat (mg/kg)	LD$_{50}$, acute, dermal,rat (mg/kg)
Imazamox + imazethapyr	Soybean	0.07	56	>5000	>4000
Isoproturon	Wheat	1.0	60	1826-3600	>2000
Linuron	Pea	0.625-1.00	80-90	4000	>2000
Mesosulfuron-methyl + Iodosulfuron-methyl sodium	Wheat	0.012 + 0.024	96	>5000	>2000
Methabenzthiazuron	Wheat	0.70-1.75	100	5000	>5000
Methyl chlorophenoxy acetic acid (MCPA)	Wheat	1.0	-	1160	>4000
Metolachlor	Soybean	1.0	-	2780	>2000
Metribuzin	Soybean	0.35-0.525	30	>2000	>20000
	Potato, Tomato, Brinjal, Chilli	0.525	-		
Metsulfuron-methyl	Wheat	0.04	76-80	>5000	>2000
	Rice	0.04	71		
Orthosulfamuron	Rice	0.060-0.075	65	>5000	>5000
Oxadiargyl	Rice	0.10	97	>5000	>2000
Oxadiazon	Rice	0.50	-	>8000	>2000
Oxyfluorfen	Rice	0.10-0.24	-	>5000	>5000
	Onion, Potato, Groundnut	0.10-0.20	-		
Paraquat dichloride				150	235-500
Pendimethalin	Soybean	0.580-1.0	40-110	1050-1250	>5000
	Sorghum, Pearlmillet, Greengram, Blackgram, Pigeonpea, Chickpea, Lentil, Sunflower, Rapeseed, Mustard, jute	0.75-1.0	-		
Pretilachlor	Rice	0.50-0.75	75-90	6099	>3964
Pinoxaden	Wheat	0.040-0.045	90	>5000	>2000
Propanil	-	-	-	>2500	>2000
Propaquizafop	Soybean	0.050-0.075	21	5000	>2000
Pyrazosulfuron-ethyl	Rice	0.010 – 0.015	95	>5000	>2000
Pyrithiobac-sodium				4000	>2000
Quizalofop-ethyl	Soybean	0.0375-0.050	95	1670	>5000
Quizalofop-P-tefuryl	Soybean	0.030-0.040	30	1012	>5000
Sulfosulfuron	Wheat	0.025	110	>5000	>5000
Triallate	Wheat	1.25	150	1100	>8200
Tribenuron	-	-	-	>5000	>5000
Trifluralin	-	-	-	>10000	>2000
Chlorimuron-ethyl + Metsulfuron-methyl	Rice	0.04	90	>4000	>2000
Anilophos + 2,4-D ethyl ester	Rice	(0.24+0.32) to (0.36+0.48)	90	>500	NA
Bensulfuron + pretilachlor	Rice	0.060 + 0.600	88	>5000	>2000
Sulfosulfuron + Metsulfuron-methyl	Wheat	0.03-0.02	110	NA	NA
Pendimethalin + Imazethapyr	-	-	-	>5000	NA
Diuron + hexazinone	-	-	-	2073	>5000
Anilophos + Ethoxysulfuron	-	-	-	>500	NA
Clomazone + 2,4-D	Rice	0.250-0.375	100-110	>500	NA
Clodinafop-propergyl + Metsulfuron-methyl	Wheat	0.06 + 0.04	100	>5000	NA
Imazamox + imazethapyr	-	-	-	NA	NA

determined from a series of carefully designed supervised field trials that represent a wide variety of good agricultural practices. Recently, Food Safety and Standards (contaminants, toxins and residues) regulations, Food Safety and Standards Authority of India, Ministry of Health and Family Welfare, GOI has developed MRL values of some herbicides in different crop commodities based on the toxicity information and bio-efficacy and residue studies conducted in our country (**Table 16**).

Herbicides in the environment

Herbicide molecules and formulations are designed in such a fashion that they stay in the target sites for a sufficient time to produce the desired effect and thereafter disintegrate into less-toxic to non-toxic components. The duration an herbicide remains active in the environment is called its ‘persistence’. Some herbicides persist for a long time in the soil, some disappear within a month. But most of the herbicides registered in India are of moderate persistence range (**Table 17**). The persistency of an herbicide is associated with its chemical nature and innate stability. But some environmental factors have major roles to interact with herbicide’s chemistry. The higher the persistence of herbicide, the higher is the chance of transportation to different distant compartments of environment, *viz.* surface water, ground water etc., creating non-point source of contamination. Each compartment has its own chemical and biological environments, which influence organic molecules to be altered. Reactive species like super oxides, singlet oxygen, hydroxyl ion, and enzymes catalyze the degradation of herbicides to some less toxic compounds, which eventually undergo mineralization. Organic matter present in soil provides the reactive chemical species under the influence of sunlight and microbial population. Due to higher soil temperature and biomass, the microbial activity in most of the Indian soil is enormous. The longer day length and higher microbial activity causes quicker degradation of herbicides in soil. The rest unaltered herbicide contaminates our environment including agricultural commodities, surface water and ground water. In fact, there is hardly any report available for ground water contamination by herbicides. Nevertheless some reports on herbicide residues contamination food grains, fruits and vegetables are available in our country. The subject including herbicide contamination in the environment and their residues in agricultural commodities is being discussed in a separate article in this book.

Risk due to herbicide application

The presence of herbicide, if any, in drinking water, food, feed, and water body may pose toxicity towards human being, domestic and wild life, and microbial world. The extent of this toxic effect for a particular organism depends on the inherent toxicity of the herbicide (expressed as LD_{50} value) and the amount of that herbicide consumed. Fortunately, most of the herbicides we are using are in the class of II (slightly hazardous) and III (slightly hazardous) under WHO’s classification of pesticides on the basis of toxicity. There is no verifiable report on

Table 16. FSSAI-defined MRL values of some herbicides

Name of Herbicide	Food / Crop	Maximum Residue Limit (MRL) in mg/kg
2,4-Dichlorophenoxy acetic acid	Sugarcane	0.05
	Food grain	Maize-0.05, Wheat-2.0 and Rice-0.1 and other food grains-0.01
	Milled food grain	0.01
	Potato	0.20
	Milk and milk products	0.05
	Meat and poultry	0.20
	Eggs	0.05 (Shell free basis)
	Fruits	2.0
Anilophos	Rice	0.10
Atrazine	Sugarcane	0.25
Bensulfuron-methyl	Rice	0.01
Bispyribac-sodium	Rice	0.05
Chlorimuron-ethyl	Rice	0.01
	Soybean seed	0.01
	Wheat	0.05
Diclosulum	Soybean	0.05
Diuron	Sugarcane	0.02
	Cottonseed	1.0
	Banana	0.10
	Maize	0.50
	Citrus (sweet orange)	1.0
	Grapes	1.0
Ethoxysulfuron	Rice	0.01
Fluazifop-P-butyl	Soybean	0.05
	Cotton seed oil	0.01
	Groundnut	0.01
	Groundnut oil	0.01
Fluchloralin	Cottonseed	0.05
	Soybean	0.05
	Rice	0.01
	Onion	0.01
	Okra	0.01
	Groundnut	0.01
	Wheat	0.01
	Potato	0.01
	Brinjal	0.01
	Cabbage	0.01
	Black Gram	0.01
Gluphosinate-ammonium	Cottonseed oil	0.05
	Tea	0.01
	Milk and milk products	0.02
Glyphosate	Tea	1.0
	Rice	0.01
	Meat and meat products	0.05
Iodosulfuron-methyl sodium	Wheat	0.01
Imazethapyr	Soybean	0.03
	Soybean oil	0.10
	Groundnut oil	0.10
Isoproturon	Wheat	0.10

Name of Herbicide	Food / Crop	Maximum Residue Limit (MRL) in mg/kg
Linuron	Pea	0.05
	Pototo	0.01
Mesosulfuron-methyl	Wheat	0.01
Methyl Chlorphenoxy Acetic Acid (MCPA)	Rice	0.05
	Wheat	0.20
	Milk and milk products	0.04
Metolachlor	Soybean oil	0.05
	Milk and milk products	0.01
Metribuzin	Tomato	0.05
	Sugarcane	0.01
	Potato	0.05
	Soybean oil	0.10
	Wheat	0.03
Metsulfuron-methyl	Rice	0.01
	Wheat	0.10
	Sugarcane	0.02
Orthosulfamuron	Paddy	0.10
Oxadiargyl	Mustard seed	0.05
	Onion	0.10
	Cumin	0.01
	Rice	0.10
	Sunflower seed	0.05
Oxyfluorfen	Rice	0.05
	Groundnut oil	0.05
	Mentha	0.01
	Tea	0.20
	Potato	0.01
	Onion	0.05
Paraquat dichloride (determined as Paraquat Cataion)	Food grains	Sorghum-0.03 and other food grains-0.10
	Milled food grains	0.03
	Potato	0.20
	Other vegetables	0.05
	Cottonseed	2.0
	Cotton seed oil (edible refined)	0.05
	Milk and milk products	0.01
	Fruits	0.05
	Tea	0.20
	Coffee	0.01
Pendimethalin	Wheat	0.05
	Rice	0.05
	Soybean oil	0.05
	Cotton seed oil	0.05
	Chilli	0.05
	Groundnut	0.01
	Onion	0.40
	Red gram	0.05
Penoxuslum	Rice	0.10
Pinoxaden	Wheat	0.70
Pretilachlor	Rice	0.05
Pyrazosulfuron-ethyl	Rice	0.01

Name of Herbicide	Food / Crop	Maximum Residue Limit (MRL) in mg/kg
Quizalofop-ethyl	Cotton seed	0.10
	Soybean seed	0.05
	Onion	0.01
	Groundnut	0.10
	Black gram	0.01
Quizalofop-P-tefuryl	Soybean seed	0.02
	Cotton seed / oil	0.05
Sulfosulfuron	Wheat	0.02
Triallate	Wheat	0.05
Triasulfuron	Wheat	0.01
Trifluralin	Wheat	0.05
Propanil	Rice	0.05
2,4-D amine salt	Tea	0.05
Ametyrene	Sugarcane	0.05
Fomesafen	Soybean	0.02
	Soybean oil	0.02
	Groundnut	0.02
	Groundnut oil	0.02
Bentazone	Soybean	0.05
	Soybean oil	0.05
	Rice	0.05
Flucetosulfuron	Rice	0.02
Haloxyfop-R-methyl	Soybean	2.0
	Soybean oil	0.02
	Soybean deoiled cake	0.02
Sulfentrazone	Soybean	0.20
	Soybean oil	0.20
	Soybean deoiled cake	0.20

Source: Gazette Notification G.S.R. No. 492, December 28, 2017

Table 17. Relative persistence of some herbicides in soil

1 month	1- 3 months	3 - 6 months	6 months
2,4-D, Glyphosate, MCPA	Alachlor, Acetochlor, Ametryn, Anilofos, Bispyribac-sodium, Butachlor, Carfentrazone-ethyl, Dalapon, Fluazifop-butyl, Halosulfuron, Metribuzin, Metamifop, Metsulfuron-methyl, Metolachlor, Oxyfluorfen, Propachlor, Pyrazosulfuron-ethyl, Tembotrione, Thiobencarb	Clomazone, Chlorimuron-ethyl, Diallate, Dithiopyr, Ethofumesate, Fluchloralin, Imazethapyr, Isoproturon, Metamitron, Oxadiazon, Linuron, Pendimethalin, Pyrazon, Sulfosulfuron	Atrazine, Bromacil, Chlorsulfuron, Diuron, Diquat, Imazapyr, Paraquat, Picloram, Sulfentrazone, Sulfometuron, Simazine, Tembotrione, Trifluralin, Triasulfuron

Source: Adopted from (i) Janaki *et al.* (2015); (ii) Pesticide Properties Data Base, University of Hertfordshire, UK

ill effect of herbicides on organisms, though some reports are available for the herbicide dependent industrialized countries. Indiscriminate use of herbicides affects not only the environment, but also influences weed biology adversely. It definitely changes the shape of plant kingdom in terms of development of resistance, shifting of weeds and effect on non-target plant flora. The continuous long-term use of herbicides of same mode of action can induce the weed physiology to detoxify the herbicide, and thus, resistance against herbicide is developed within the weed. A weed shift is the change in the composition or relative frequencies of weeds in a population in response to natural or man-made environmental changes in an agricultural system. Weed shift occurs when the application of herbicide does not control an entire weed community or population. Some species or biotypes are killed by the herbicide, others are not affected. Those unaffected species can grow, reproduce and increase in the community, resulting in a weed shift.

Minimizing the risk

As our farmers do not have any other feasible option in their hands, the escalating problems of weed infestation must be mitigated by the application of herbicides. Only option left is to shift ourselves from the conventional approach to safer alternatives. We are in fact in the transition of this shifting process. In our early days of chemical weed control, herbicides were used in high doses, *viz*. more than 1 kg per ha. Some of these herbicides are still in use, although their consumption is decreasing. New generation low dose herbicides are replacing the use of conventional herbicides, thus, reducing the environmental load. The recommended dose for sulfonyl ureas and imidazolinones is within 10 to 40 g/ha. Today, modern herbicides, such as the sulfonyl ureas and imidazolinones are low in toxicity. They also don’t persist for a long time in the environment, particularly in the environment of tropical countries. Hopefully, these safer herbicides will completely replace the conventional herbicides in near future giving a comprehensive protection of crop as well as biodiversity. The problem of resistant development in weeds can be managed by rotating herbicides of different modes of action or by applying combination formulation made from two different herbicides. With the help of good knowledge on soil-herbicide interactions and their major controlling factors it is possible to limit or eliminate environmental risk from herbicides by manipulating agricultural management systems.

Conclusion

To combat the compounded problems due to weeds, chemical control methods have become inevitable in the industrialized countries and are becoming so in developing countries like ours. The labor cost involved in mechanical and manual weed control is soaring high due to urbanisation. However, the chemical losses due to weeds cannot be ignored. Under these circumstances, our farmers have no alternative other than application of herbicides. Presently, we have many low-toxicity and low-dose herbicides in our arsenals. It is possible now to manage multifarious weeds in different crops by use of herbicides available in our market. We would have to learn to deal with safer herbicides and integrate these with other methods of weed management in order to establish clean weed management practices that lead to food security as well as conservation of biodiversity.

References

Ameena M, Kumari VLG, George S. 2006. Integrated management of purple nutsedge (*Cyperus rotundus* L.) in okra. *Indian Journal of Weed Science* **38**: 81–85.

Banerjee H, Pal S, Ghosh RK, Kundu R, Alipatra A. 2012.Effect of pyrazosulfuron-ethyl on yield of transplanted rice. *Indian Journal of Weed Science* **44**(4): 210–273.

Brar LS, Walia US, Gill BS and Seema J. 2003. Influence of paddy residue management techniques on the bioefficacy of herbicides for control of *Phalaris minor* in rice-wheat system. *Indian Journal of Weed Science* **35**(3&4): 186–189.

Brar AS and Walia US. 2008. Effect of rice residue management techniques and herbicides on nutrient uptake by *Phalaris minor* Retz. and wheat (*Triticum aestivum* L.). *Indian Journal of Weed Science* **40**(3&4): 121–127.

Bhadauria N, Yadav KS, Rajput RL, Singh VB. 2012. Integrated weed management in sesame. *Indian Journal of Weed Science* **44**(4): 235–237.

Chandrakar BL, Urkurkar JS. 1993. Efficacy and economics of weed control in soybean (*Glycine max* L.) under vertisols of Chattisgarh region. *Indian Journal of Weed Science* **25**: 32–35.

Chaudhry Sanjai, Rathi JPS, Singh RP and Chaudhry VK. 2009. Effect of seeding methods and weed management on wheat (*Triticum aestivum*). *International Journal of Agricultural Sciences* **5**(2): 469–471.

Chauhan DS, Sharma RK and Verma OS. 1998. Integrated weed management in wheat through tillage options and new molecules under rice-wheat system. pp. 263–273. In: *Proceedings, International conference on Wheat: research needs beyond 2000* AD, Karnal.

Chhokar RS, Samar Singh and Sharma RK. 2008. Herbicides for control of isoproturon-resistant Little seed Canary grass (*Phalaris minor*) in wheat. *Crop Protection* **27**(3/5): 719–726.

Choudhury PP, Singh R, Ghosh D and Sharma AR. 2015. *Herbicide Use in Indian Agriculture*. ICAR-Directorate of Weed Research, Jabalpur, Madhya Pradesh, 110 p.

Das TK and Das DK. 2018. Using chemical seed dormancy breakers with herbicides for weed management in soybean and wheat. *Weed Research* (Oxford) **58**(3): 188–199.

Dhanvate VB. 2000. Effect of row spacing and herbicides on growth and yield of direct seeded rice. Thesis submitted to Dr. B.S.K.K.V., Dapoli.

FAO Stat. 2014. http://faostat3.fao.org

Food Safety and Standards (contaminants, toxins and residues) Regulations. 2011. Food Safety and Standards Authority of India (FSSAI), Ministry of Health and Family Welfare, GOI. (www.fssai.gov.in)

Gautam KC. 1982. Weed management studies in wheat-mustard mixed crops. p. 5. In: *Abstracts, Annual Conference of Indian Society of Weed Science*.

Gautam KC, Mani VS and Yaduraju NT. 1981. Chemical weed control in relation to use of fertilizer nitrogen in maize. p. 19. In: *Abstracts, Annual conference of Indian Society of Weed Science.*

Ghansham P, Singh S. 2008. Effect of seed rate, spacing and herbicides use on weed management in direct seeded upland rice (*Oryza sativa* L.). *Indian Journal of Weed Science* **40**(1&2): 11–15.

Ghosh D, Singh UP, Brahmachari K, Singh NK and Das A. 2017. An integrated approach to weed management practices in direct-seeded rice under zero-tilled rice-wheat cropping system. *International Journal of Pest Management* **63**(3): 37–46

Ghosh D, Singh UP, Ray K and Das A. 2016. Weed management through herbicide application in direct-seeded rice and yield modeling by artificial neural network. *Spanish Journal of Agricultural Research* **14**(2), e1003, 10 pages. http://dx.doi.org/10.5424/sjar/2016142-8773.

Gogoi A, Rajkhowa DJ, Kandali R. 2001. Integrated weedcontrol in rainy season rice under medium land situation. *Indian Journal of Weed Science* **33**: 18–21.

Howden SM, Soussana JF, Tubiello Fn, Chhetri N, Unlop D and Meinke M. 2007. Adapting agriculture to climate change. pp. 19691–19696. In: *Proceedings of the National Academy of Science of the United States of America 104*.

Hulme Pe. 2009. Relative roles of life-form, land use and climate in recent dynamics of alien plant distributions in the British. *Weed Research* **49**: 19–28.

Itnal C, Lingaraju BS, Kurdikeri CB. 1993. Effect of herbicides and cultural methods on weed

control in irrigated groundnut. *Indian Journal of Weed Science* **25**: 27–31.

Jadhav AS, Gadade GD. 2012. Evaluation of post emergence herbicides in soybean. *Indian Journal of Weed Science* **44**(4): 259–260.

Jain HC, Dubley SK, Koshta LD and Raghu JS. 1985. Integrated weed management in soybean (*Glycine max* (L.) Merrill). p. 67. In: A*bstracts, Annual conference of Indian Society of Weed Science.*

Janaki P, Sharma N, Chinnusamy C, Sakthivel N and Nithya C. 2015. Herbicide residues and their management strategies. *Indian Journal of Weed Science* **47**(3): 329–344.

Kalhapure AH, Shete BT. 2012. Integrated weed management in onion. *Indian Journal of Weed Science* **44**(2): 88–91.

Kaur R, Sharma BC, Kumar A, Kour P. 2013. Nutrient uptake by chickpea + mustard intercropping system as influenced by weed management. *Indian Journal of Weed Science* **45**(3): 183–188.

Kolhe SS. 2001. Integrated weed management in onion (*Allium cepa* L.). *Indian Journal of Weed Science* **33**: 26–29.

Kolhe SS, Tripathi RS. 1998. Integrated weed management in direct seeded rice. *Indian Journal of Weed Science* **30**(1&2): 51–53.

Kulmi GS, Tiwari PN. 2005. Integrated weed management m Asgandh (*Withania somnifera* Dunal). *Indian Journal of Weed Science* **37**: 77–80.

Kumar S, Angiras NN, Singh R. 2006. Effect of planting and weed control methods on weed growth and seed yield of blackgram. *Indian Journal of Weed Science* **38**: 73–76.

Kumar Adyant, Ravi Nandan, Pandey IB, Sandeep Patil. 2018. Weed dynamics and performance of lentil as affected by weed management practices under rainfed conditions. *Indian Journal of Weed Science* **50**(1): 46–50.

Kumar Rajender, Singh J, Uppal SK. 2017. Management of weeds in sugarcane-wheat intercropping system in sub-tropical India. *Indian Journal of Weed Science* **49**(2): 139–146.

Lakshmi PV and Luther MM. 2017. Studies on influence of herbicides on nutrient uptake and yield in maize. *International Journal of Farm Sciences* **7**(1): 37–39.

Larelle D, Mann R, Cavanna S, Bernes R, Duriatti A and Mavrotas C. 2003. Penoxsulam, a new broad spectrum rice herbicide for weed control in European Union paddies. *The BCPC International Congress: Crop Science and Technology* **1&2**: 75–80.

Lhungdim ‘J, Singh Y, Pramod Kumar, Chongtham SK. 2013. Integrated weed management of lambsquarter and nut sedge in lentil. *Indian Journal of Weed Science* **45**(3): 192–197.

Mahajan G, Chauhan BS, Johnson DE. 2009. Weed management in aerobic rice in north-western Indo-Gangetic plains. *Journal of Crop Improvement* **23**(4): 366–382.

Mandloi KS, Vyas MD and Tomar VS. 2000. Effect of weed-management methods in soybean (*Glycine max*) grown in Vertisols of Madhya Pradesh. *Indian Journal of Agronomy* **45**(1): 158–161.

Mankar DD. 2015. Study on effective weed management in Indian mustard *(Brassica juncea* L.*)*. *Journal of Oilseed Brassica* **6**(2): 279–288.

Mansoor Montazeri. 1993. Evaluation of a few wheat selective grass herbicides at two times of application on canary grass (*Phalaris minor*) and wild oat (*Avena sterilis*). pp. 166-167. In: *Proceedings, Indian Society of Weed Science International Symposium on Integrated weed management for sustainable agriculture*, Hisar, India, 18-20 November 1993.

Mathew G, Sreenivasan E, Mathew J. 1995. Integrated weed management in cowpea. *Indian Journal of Weed Science* **27**: 42–44.

McDonald A, Riha S, Ditommaso A and Degaetano A. 2009. Climate change and geography of weed damage: Agriculture. *Ecosystems and Environment* **130**: 131–140.

Moorthy BTS. 2002. Evaluation of pyrazosulfuron ethyl alone and in combination with molinate for controlling weeds in rainfed direct-seeded lowland rice. *Indian Journal of Weed Science* **34**(3): 285–286.

Mukhopadhyay SK. 1993. Weed research in India and future thoughts. pp. 104-109. In: *Proceedings, 10th Australian Weeds Conf./14th Asian-Pacific Weed Sci. Soc. Conf.*, Brisbane, Queensland, Australia held during 6-10 September, 1993. Published by Weed Society of Queensland, Australia.

Nagar RK, Meena BS, Dadheech R. 2009. Effect of integrated weed and nutrient management on weed density, productivity and economics of coriander (*Coriandrum sativum*). *Indian Journal of Weed Science* **41**: 71–75.

Nandal TR, Singhal R. 2002. Integrated weed management in onion (*Allium cepa* L.) under Himachal Pradesh conditions. *Indian Journal of Weed Science* **34**: 72–75.

Nikam MS. 2003. Effect of plant population and weed control on growth and yield of direct seeded rice. Thesis submitted to Dr. B.S.K.K.V., Dapoli.

Om Hari, Nandal DP, Dhiman SD, Mangat Ram. 2006. Weed control in wheat (*Triticum aestivum*) sown by zero-tillage. *Indian Journal of Agronomy* **51**(3): 199–201.

Pandey AK, Joshi OP, Billore SD and Kumar D. 2007. Effect of weed management practices on productivity of soybean [*Glycine max* (L.) Merrill]. *Haryana Journal of Agronomy* **23**(1&2): 82–86.

Patra AK, Halder J, Mishra MM. 2011. Chemical weed control in transplanted rice in Hirakund command area of Orissa. *Indian Journal of Weed Science* **43**(3&4): 175–177.

Pazhanivelan S, Latha KR and Ramachandiran K. 2015. Effect of integrated weed management practices on weed growth, yield attributes and yield of blackgram. *Madras Agricultural Journal* **102**(476): 137–139.

Phogat BS, Pandey J. 1998. Effect of water regime and weed control on weed flora and yield of transplanted rice (*Oryza sativa*). *Indian Journal of Agronomy* **43**(1): 77–81.

Porwal MK. 1995. Integrated weed management in garlic (*Allium sativum*) under vertisols. *Indian Journal of Weed Science* **27**: 16–18.

Ram P, Sreenivas G, Rani PL, Madhavi A. 2017. Weed management to improve productivity and nutrient uptake of Rabi maize. *Indian Journal of Weed Science* **49**(1): 90–92.

Ram P, Sreenivas G, Leela Rani P. 2017. Impact of sustainable weed management practices on growth, phenology and yield of rabi grain maize (*Zea mays* L.). *International Journal of Current Microbiology and Applied Sciences* **6**(7): 701–710.

Rameshwar SC, Sharma GD, Rana S. 2002. Evaluation of herbicides for weed control and economics in onion (*Allium cepa* L.) under cold desert region of Himachal Pradesh. *Indian Journal of Weed Science* **34**: 68–71.

Rao AS, Rao GS, Ratnam M. 2010. Copies Bio-efficacy of sand mix application of pre-emergence herbicides alone and in sequence with imazathapyr on weed control in relay crop of blackgram. Pakistan *Journal of Weed Science Research* **16**(3): 279–285.

Rathi JPS, Tewari AN, Kumar M. 2004. Integrated weed management in blackgram (*Vigna mungo* L7). *Indian Journal of Weed Science* **36**: 218–220.

Reddy AS, Rao AS, Rao GS, Naidu TCM, Kumari AL and Trimurthulu N. 2017. Weed management with pre and post emergence herbicides in maize. *Journal of Research ANGRAU* **45**(2): 64–74.

Sajjam G, Jayadeva HM, Krishnamurty N. 2013. Effect of different weed control measures in transplanted rice (*Oryza sativa*). *Journal of Agriculture Research and Technology* **38**(3): 388–392.

Saini JP, Angiras NN. 2002. Evaluation of ethoxysulfuron against broad-leaved weeds and sedges in direct seeded puddled rice. *Indian Journal of Weed Science* **34**(1): 36–38.

Sardana Virender, Walia US, Gulshan Mahajan. 2001. Management of broadleaf weeds in wheat (*Triticum aestivum* L.). *Indian Journal of Weed Science* **33**(1&2): 69–71.

Sardana V, Singh S, Sheoran P. 2006. Efficacy and economics of weed management-practices in

blackgram (*Vigna mungo* L.) under rain-fed conditions. *Indian Journal of Weed Science* **38**: 77–80.

Sagvekar VV, Waghmode BD, Chavan AP and Mahadkar UV. 2015. Weed management in rabi groundnut (Arachis hypogaea) for Konkan region of Maharashtra. *Indian Journal of Agronomy* **60**(1): 116–120.

Saha S, Rao KS. 2012. Efficacy of azimsulfuron against complex weed flora in transplanted summer rice. *Oryza* **49**(3): 183–188.

Shekar, Nanjappa HV. 1993. Nutrients uptake by crop and weeds and economics of different weed control treatments in soybean. *Indian Journal of Weed Science* **25**: 40–43.

Semwal MP, Amrendra Kumar, Ramu N, Mandal Tanumay, Chandra Bhushan, Shukla Anil. 2016.

Influence of pre- and post-emergent applied herbicides on weed dynamics, nutrients uptake and yield of pigeonpea (*Cajanus cajan* L.). *International Journal of Bio-resource and Stress Management* **7**(4): 705–711.

Shinde SH, Pawar VS, Suryawanshi GB, Ahire NR, Surve US. 2003. Integrated weed management studies in pigeonpea + pearl millet intercropping (2:2) system. *Indian Journal of Weed Science* **35**: 90–92.

Singh VP, Singh G. 2001. Weed control studies in spring rice (*Oryza sativa* L.) under rainfed low valley situation of Uttaranchal. *Indian Journal of Weed Science* **33**: 52–55.

Singh PK, Om Prakash, Singh BP. 2001. Studies on the effect of N fertilization and weed control techniques on weed suppression, yield and nutrients uptake in sesame. *Indian Journal Weed Science* **33**(3&4): 139–142.

Singh R. 2006. Effect of cropping sequence, seed rate and weed management on weed growth and yield of Indian mustard in western Rajasthan. *Indian Journal of Weed Science* **38**: 69–72.

Singh R, Singh B. 2004. Effect of irrigation time and weed management practices on weeds and wheat yield. *Indian Journal Weed Science* **36**: 25–27.

Singh N, Vashist KK, Mahal SS, Sidhu AS. 2012. Bio-efficacy of pretilachlor with varying irrigation regimes in furrow transplanted and furrow irrigated rice (*Oryza sativa* L.) in Punjab. *Journal of Crop and Weed* **8**(2): 148–151.

Singh SP, Kumar RM. 1999. Efficacy of single and sequential application of herbicides on weed control in transplanted rice. *Indian Journal of Weed Science* **31**: 222–224.

Singh Kulvir, Rathore Pankaj. 2015. Efficacy evaluation of selected herbicides on weed control and productivity evaluation of Bt cotton in Punjab. *Journal of Environmental Biology* **36**(4): 993–998.

Singh VP. Singh TP, Singh SP, Kumar A, Kavita Satyawali, Banga Akshita, Bisht, Singh RP. 2016a. Weed management in blackgram with pre-mix herbicides. *Indian Journal of Weed Science* **48**(2): 178–181.

Singh Kulvir, Singh HP, Singh Kuldeep. 2016b. Weed management in cotton with pre- and post-emergence herbicides. *Indian Journal of Weed Science* **48**(3): 348–350.

Standing Committee on Chemicals and Fertilisers (2012-13). 2013. *Production and Availability of Pesticides*. 36th Report, 15th Lok Sabha, Dept. of Chemicals and Petrochemicals, Ministry of Chemicals and Fertilisers, Govt. of India. August, 2013.

Sukhadia NM, Ramani BB, Dudhatra MG. 2002. Response of onion (*Allium cepa* L.) to methods of sowing and weed management practices. *Indian Journal of Weed Science* **34**: 76-79.

Sunil CM, Kalyanamurthy KN, Shankaralingappa BC. 2010. Growth and yield of arobic rice as influenced by integrated weed management practices. *Indian Journal of Weed Sciences* **42**(3&4): 180–183.

Tewari AN, Tiwari SN, Rathi JPS, Singh B, Tripathi AK. 2003. Effect of cultural and chemical methods on weed growth and grain yield of dwarf pea. *Indian Journal of Weed Science* **35**: 49–52.

Tomar TPS, Rana NS, Kumar S, Singh R. 2002. Effect of integrated weed management on upland direct seeded rice and associated weeds. *Annals of Agricultural Research*. **23**(3): 423–429.

Vijaykumar B, Reddy MN, Shivashankar M. 1995. Integrated weed management in pigeonpea-groundnut intercropping. *Indian Journal of Weed Science* **27**: 12–15.

Walia US, Bhullar MS, Nayyar S, Walia SS. 2008. Control of complex weed flora of dry-seeded rice (*Oryza sativa* L.) with pre- and post-emergence herbicides. *Indian Journal of Weed Science* **40**(3): 161–164.

Chapter 13

Weed management in conservation agriculture in India

T.K. Das*, M.S. Bhullar[1], Suman Sen and Sarita Rani
Division of Agronomy, ICAR-Indian Agricultural Research Institute,
New Delhi 110012
[1]Department of Agronomy, Punjab Agricultural University,
Ludhiana, Punjab 141004
**Email: tkdas64@gmail.com*

Summary

Conservation agriculture (CA) with three inter-related principles such as minimum soil disturbance, permanent soil cover, crop rotations has been found to achieve higher crop and system productivities and resource-use efficiency. The CA in India although is at its infancy, has been found quite promising and successful in the irrigated rice-wheat cropping systems of the Indo-Gangetic Plains (IGP). Recently, it has also been demonstrated in parts of central India. Increased weed problems during the 'transition period' tends to be the most common hurdle in adoption of CA by farmers. Specific microclimates created by continuous residue cover and no/minimal tillage under CA influence weed emergence and interference in crop fields. Weeds cause higher reduction in crop yield than other pests and diseases under both conventional and conservation agriculture. Under the CA systems, herbicide becomes principal option for weed control but can trigger weed dynamics over time. This advocates integrated weed management (IWM) approaches as important for conventional agriculture so for CA. An IWM approach, involving herbicides (rotation, mixtures), good agronomic/ cultural practices, timeliness of operations, crop rotation, cover and inter-cropping, crop residue retention, crop competitiveness against weeds as applicable under a particular crop or cropping system need to be evaluated for economical, better, eco-friendly and longer weed management. At present, residue retention on farmer fields tends to be low. Greater awareness campaign of the benefits of residue retention than burning for improving soil health is required for the farmers of the Indian Gangatic Plane (IGP), particularly in the north-western IGP.

Keywords: Conservation agriculture, Crop diversification, Farmers' socio-economic conditions, Integrated weed management, Zero tillage

Introduction

Indian agriculture has made rapid strides in crop production in last five decades. Several challenges such as stagnation in net sown area under crops, reduction in per capita land availability, climate variability, soil degradation, lowering of water table, paucity of irrigation water, new weeds/pest insurgence/ resistance, and low input-use efficiencies yet continue to influence Indian agriculture in the coming years. Therefore, a paradigm shift in farming practices is needed to ensure future productivity gains while sustaining the natural resources. In this context, conservation agriculture (CA) has emerged as an effective strategy to enhance sustainable agriculture worldwide (Abrol and Sangar 2006). CA has three inter-related principles that include zero/minimum soil disturbance, permanent soil cover, and crop diversification with legumes. It may lead to achieve acceptable gains with high and sustained production, while concurrently preventing top soil erosion and runoff, and improving soil fertility, moisture conservation and environmental footprints. Therefore, there is need of transformations in conventional agriculture with regard to management of weeds/ pests, soil, water, nutrients, and farm machineries as there exists wider differences on methods/ practices between conventional till and CA-based production systems (**Table 1**).

Weeds cause higher reduction in crop yield than other pests and diseases under both conventional and conservation agriculture. Yaduraju (2006) reported that weeds roughly account for 37%, insects for 29%, diseases for 22% and other pests for 12% of the total annual loss of agricultural produce in India. Weed flora is in a continual state of change. They are ubiquitous and have a wide range of ecological amplitude that determines their adaptability. The disturbances in habitat (tillage, mulching, fire, flooding, drought, *etc*.) and the changes made in agronomic practices towards raising a crop have tremendous influence on the composition of weed flora and may lead to changes in weed species over time. Tillage and inter-culture in crop fields are as responsible for control of weeds so for their proliferation. Specific microclimate created by continuous residue cover and no/ minimal tillage under CA influence weed emergence and interference in crop fields. Herbicide becomes principal option for weed control in such situations, but triggers weed dynamics over time, depending on the nature and spectrum of weed control. This advocates integrated weed management approaches as important for conventional agriculture so for CA.

Table 1. Some distinguishing features of conventional and conservation agriculture systems

Conventional agriculture	Conservation agriculture
Excessive tillage	No or reduced tillage but biological tillage
High wind and soil erosion	Low wind and soil erosion
Residue burning or removal (bare surface)	Residue retention (permanent cover)
Usually low water infiltration	Usually high water infiltration
Use of *ex-situ* FYM and composts	Use of *in-situ* organics and composts
Green manuring (incorporated)	Brown manuring/cover crops (surface retention)
Kills established weeds but also stimulates more weed seeds to germinate	Weeds are a problem in the early stages of adoption but decrease with time
Free-wheeling of farm machinery increases soil compaction	Controlled traffic, compaction only in tramline, but residue promotes microbes and reduces compaction
Mono cropping/culture, less efficient rotations	Diversified and more efficient rotations
Heavy reliance on manual labour, uncertainty of operations	Mechanized operations, ensure timeliness of operations
Poor adaptation to stresses, yield losses more under stress conditions	More resilience to stresses, yield losses are less under stress conditions
Productivity gains in long-run are in declining order	Productivity gains in long-run are in incremental order

(Source: Sharma *et al.* 2015b)

History of conservation agriculture in India

Conservation agriculture (CA) is being practised on about 180.4 million ha area across the globe (Kassam *et al.* 2018). It is one of the fastest-growing agricultural technologies in the world. USA, Brazil, Argentina, Canada and Australia are five major CA practising countries in the world. The spread of CA in these countries is mostly in the rain-fed regions, but in India success of CA has been achieved in irrigated rice-wheat cropping systems of the Indo-Gangetic Plains (IGP). Bhan and Behera (2014) attributed this to the non-adoption or non-promotion of CA systems in other major agro-ecological regions of India such as rainfed semi-arid tropics and the arid regions of the mountain agro-ecosystems. In India, gradual increase in the area of zero-till (ZT) wheat in the rice-wheat system of the IGP has been witnessed in last two decades, mainly, due to locally developed farm machineries and availability of effective herbicides (Jat *et al.* 2012). ZT wheat has also started to increase in the eastern IGP during the last few years (Malik *et al.* 2014). Recently, in Punjab and Haryana, dry direct-seeding of rice in un-puddled fields (DSR) has been introduced as an alternative rice establishment system. In Punjab alone, the area under DSR increased from 4200 ha in 2012 to 22,000 ha in 2013 and further to 160,000 ha in 2015; the area under DSR was <1000 ha in 2009, the first year of its introduction in this state (www.tribuneindia.com). Such rapid adoption of DSR clearly highlights the ready acceptance of CA technologies among the farmers in the region. Other CA practices including laser levelling, furrow irrigated raised-bed planting, unpuddled mechanical transplanting of rice and residue management practices are also being adopted by the farmers of the north-western region (IARI 2012, Das *et al.* 2014b). CA adoption also offers opportunities for diversification of the rice-wheat system through relay cropping of sugarcane, pulses, and vegetables as intercrop with wheat and maize. For example, many farmers are practising intercropping in raised-bed systems, where wheat is planted on raised beds and mint or sugarcane in the furrows. Gupta and Seth (2007) recorded that inter-cropping systems of potato/onion with maize; chickpea/Indian-mustard with sugarcane are becoming popular in western Uttar Pradesh.

In recent years, the CA technologies have been successfully demonstrated at farmers' fields in Madhya Pradesh under the aegis of ICAR-Directorate of Weed Research in which the yield enhancement varied from 1.5 to 2 times than conventional practices (Smart Indian Agriculture 2015). The adoption of CA has advanced sowing time of rice, maize, wheat, mustard crops by 10-15 days enabling the farmers to take third crop of green gram in the summer season. Encouraged by the success of these demonstrations, the state agriculture department has started providing subsidy for the purchase of CA machinery. The long-term study on different CA based systems, initiated under AICRP-weed management has shown promising results in case of maize-sunflower in Tamil Nadu, pearl millet-mustard in Gujarat, rice-chickpea-green gram in Karnataka pointing towards the possibilities of extending the benefits of CA to central and south India (AICRP-WM 2015).

Weed problems under CA

Buhler *et al.* (1994) reported that weeds are one of the biggest constraints for the adoption of CA. Weed species shifts/dynamics is concomitant in CA. A large number of weed seeds are present on the soil surface under CA. The CA system has inherent self-managing properties for weeds, which can render it more sustainable. Weed species, which germination is stimulated by light are likely to be more problematic under this situation. Highly disturbed ecosystems like CT systems usually favour annual weeds (more broad-leaved weeds), while less disturbed ZT systems favour perennial weeds and species that can successfully germinate on the soil surface such as annual grasses (Hume *et al.* 1991, Swanton *et al.* 1993, Moyer *et al.* 1994, Das 2001, Taa *et al.* 2004, Chauhan *et al.* 2006). The population of Indian sorrel (*Oxalis corniculata*) increased under ZT wheat following CT-TPR. Higher concentration of seeds of this weed on the soil surface might favour its proliferation (Chhokar *et al.* 2007, 2009). Its seeds are sensitive to burial depth, and seeds buried at a depth ≥ 4 cm could not emerge (Dhawan 2005). CA requires enough efforts to control weeds initially; however, after maintaining a certain threshold level, it is easier to manage weed infestations (Chauhan *et al.* 2012). Bhullar *et al.* (2012) reported that weeds like *Ipomoea* spp, which germinate well in shade under closed crop canopy and twin around the crop plants, could be a problem in residue-retained CA systems. Weed shift from typical aquatic rice weeds to aerobic grassy weeds and perennial sedges, which are difficult to control with herbicides recommended for transplanted puddled rice have been witnessed in direct-seeded rice in Punjab and Delhi. Shade tolerant and moisture loving weeds such as *Convolvulus arvensis, Malva parviflora, Medicago denticulata, Polypogon monspeliensis* are also on the increase in ZT wheat in Punjab.

Weed management options under CA

Weed prevention and herbicide-led stale seedbed

Prevention is better than intervention. Prevention aims to minimize the area of weed infestation and decrease dissemination of weed seeds. Some preventive measures include the use of clean crop seeds, the use of clean agricultural implements, and managing weeds on bunds and roads and their control before flowering and fruiting. In the stale seedbed technique, weed seeds are encouraged to germinate, and are killed by a non-selective herbicide (paraquat, glyphosate, glufosinate) before sowing. Mahajan *et al.* (1999) observed that stale seedbed significantly reduced weed pressure in ZT-wheat. Renu *et al.* (2000) reported that the stale seedbed technique is more effective under ZT, in which weeds are killed without disturbing the soil but by using non-selective herbicides than with mechanical methods. This technique is effective in reducing weed seed bank as well (Kumar and Ladha 2011, Rao *et al.* 2007, Singh *et al.* 2009). This technique is most effective against weed seeds present in topsoil; weeds having low initial dormancy; and weed seeds requiring light to germinate. Susceptible weed species includes *Cyperus iria, Digitaria ciliaris, Eclipta prostrata, Leptochloa chinensis* and *Ludwigia hyssopifolia*. Singh (2015) observed in DSR in Punjab that stale seedbed reduced weed density by 39%. With the limited options available to manage weedy rice in ZT-DSR, the stale seedbed technique is recommended as part of an IWM strategy in many weedy rice-infested areas (Rao *et al.* 2007). Singh *et al.* (2018) reported that a combination of the stale seedbed with tillage, pendimethalin and bispyribac resulted in highest rice grain yield (7.3 t/ha) and the highest economic returns ($1310/ha); the returns in this treatment was $ 260/ha higher than using the same herbicides used without a stale seedbed.

Tillage and weed control

Weed seed bank is reservoir of viable seeds in soil (Harper 1977) and plays an important role towards weeds problem in certain areas. Tillage affects infestation of weeds under different crops and cropping systems under varying agro-climatic conditions (Swanton *et al.* 2000). Kumar *et al.* (2013) reported that the shift from conventional transplanted puddled rice (TPR) to dry direct-seeded rice (DSR) with reduced or ZT influenced weed diversity and abundance. Under ZT-DSR, weed flora often shifts towards more difficult to control and competitive grasses and sedges (Kumar and Ladha 2011, Singh *et al.* 2015a,b). The shift from TPR to ZT-DSR is expected to favour grass weed species such as *Dactyloctinum aegyptium*, *Leptochloa chinensis*, *Eragrostis* spp, weedy rice (*Oryza sativa*) along with *Echinochloa crus-galli* and *E. colona*; sedges such as *Fimbristylis miliacea*, *Cyperus rotundus* and *Cyperus iria;* and broad-leaved weeds such as *Eclipta prostrata* and *Digera arvensis* also increased in DSR systems. Most of these species are able to germinate over a wide range of temperatures, but prefer moist and warm conditions, which make them well adapted to rice fields. They also establish at or close to the soil surface, where weed seeds in ZT systems typically concentrate (Chauhan and Johnson 2009). From an experiment on DSR under DSR-ZT wheat cropping system, Baghel *et al.* (2018) reported that applications of pendimethalin 1.5 kg/ha as pre-emergence followed by bispyribac-Na 25 g/ha at 25 days after sowing (DAS) along with one hand weeding at 45 DAS significantly decreased the weed dry weight and increased rice grain yield significantly. Sen *et al.* (2018) observed that the sequential applications of pendimethalin 1.0 kg/ha as pre-emergence followed by a mixture of penoxsulam + cyhalofop-butyl at 130 g/ha as post-emergence exhibited a significant reduction in weed interference, resulting in a considerable increase in weed control efficiency (84.49%) and rice productivity (3.92 t/ha). Surin *et al.* (2013) studied the effect of tillage and weed control on grain and straw yield of rice in rice-wheat sequence and found that conventional transplanted rice gave higher yields and weed management option, two hand weeding was superior, giving significantly higher yields compared to other treatments. However, highest net returns and benefit:cost were recorded with the treatment that comprised of the applications of butachlor + 2,4-D in rice followed by isoproturon + 2,4-D in wheat, mainly because of more labour cost incurred in hand weeding.

Bisen *et. al.* (2006) reported that the densities of all weed species in wheat were lower in ZT compared to reduced tillage or conventional tillage (CT), while the density of *Rumex denticulatus* was higher in ZT **(Table 2)**. Also, total weed dry matter was significantly lower in ZT. The shift from CT to ZT in wheat has resulted in a shift in weed flora. Emergence of *Phalaris minor* is lower under ZT than CT in wheat, but higher for some of the broad-leaved weeds, such as *Rumex dentatus* and Indian sorrel (Malik *et al.* 2002, Chhokar *et al.* 2007, Gathala *et al.* 2011). Franke *et al.* (2007) observed that emergence rate of all three flushes of *Phalaris minor* in wheat sown on the same date were lower in ZT compared with CT. The first emergence flush, which was the most important flush affecting crop–weed competition was about 50% lower in ZT than in CT. Chhokar *et al.* (2007) estimated 39% lower biomass of *Phalaris minor* (based on 15 field observations) under ZT compared with CT because of lower density. Further suppression of *Phalaris minor* and other weeds is achieved in wheat when ZT is combined with residue retention on the surface and early sowing. Susha *et al.* (2014) reported that ZT with maize residue caused a significant reduction on the population of grassy weeds such as *Phalaris minor, Avena ludoviciana*; broad-leaved such as *Chenopodium album, Melilotus indica* and total weeds compared to CT and ZT without residue. Several researches highlight the superiority of ZT raised bed planting over conventional flat sowing of wheat on the reduction of *Phalaris minor*. Dhillon *et al.* (2005) observed that the sowing of wheat on ZT permanent raised beds reduced weed density and biomass compared to the conventional flat seedbed. In contrast, Das and Yaduraju (2012) reported the inferior effect of furrow-irrigated raised bed system in sandy loam soil on the reduction of three-year mean population densities of grassy, broad-leaved and total weeds, total weed population density and biomass compared to a flat bed missing-row sowing.

Table 2. Effect of tillage on weed population (no./m^2) and total weed dry weight in wheat at Varanasi

Tillage	Weed populations (no./m^2)						Weed dry matter (g/m^2)
	Phalaris minor	*Cynodon dactylon*	*Cyperus rotundus*	*Rumex denticulata*	*Anagallis arvensis*	*Chenopodium album*	
Conventional	5.0	4.6	5.2	6.5	8.4	5.8	35.9
Zero	2.4	4.1	3.5	6.7	3.7	4.6	30.2
Reduced	3.9	4.8	4.6	5.9	5.8	6.4	32.9
LSD (p=0.05)							1.7

Source: Bisen *et al.* 2006

Nath *et al.* (2016, 2017) reported that ZT with crop residue retention and 75% of required N plus GreenSeeker™ (GS)-aided N management resulted in a significant reduction of weed density and dry weight compared to CT or ZT without residue**.** Mehta and Singh (2002) observed population density of *Phalaris minor* in wheat under the rice-wheat system in north-western IGP at different locations and found lesser germination in CA than CT because of less soil disturbance and lesser exposure of weed seeds to light **(Table 3)**.

Table 3. Density of *Phalaris minor* in wheat as affected by tillage at different locations

District	Year	Population / m^2		Fall in density due to ZT (%)
		ZT	CT	
Kurukshetra	1998-2001	504	709	28.9
Kaital	2002-2003	122	171	28.1
Panipat	1999-2001	826	1052	21.5
Ferozepur	2000-2002	110	264	58.3
Kapurthala	1999-2002	111	70	84.3
Nawanshahar	2001-2002	41	59	30.5
Gurudaspur	2001-2002	39	42	7.1
Mean		236	338	30.2

(Source: Mehta and Singh 2002)

Kumar *et al.* (2013) studied the effect of different levels of residue mulch on the emergence of herbicide-resistant weeds in wheat and observed least number of weeds at the highest residue level of 8 t/ha. Again, Mishra (2004) reported that ZT was superior to CT in reducing *Phalaris minor* population in different places of rice-wheat systems. He also found that the populations of *Melilotus* spp. and *Chenopodium album* were lower, while that of *Avena* spp. was higher in ZT than CT. Similarly, Farooq and Nawaz (2014) observed that ZT significantly reduced the density of *Chenopodium album* and *Rumex dentatus* over other tillage practices, but *Phalaris minor* density varied across tillage systems. Dhyani and Misra (2007) studied the effect of tillage on relative weed density of *Phalaris minor* at different stages of wheat and found that relative density of weeds was lower by almost 30% with ZT compared to CT. Malik *et al.* (2002) also highlights the long term superior effects of ZT on reducing *Phalaris minor* population and increasing wheat yield. Similar reports on the effects of planting methods/ tillages on weeds have been made in maize (Chopra and Angiras 2005); black gram (Kumar *et al.* 2006); wheat (Pandey *et al.* 2001); and rice (Yadav and Singh 2005). Das and Yaduraju (2001) found that shallow and frequent pre-sowing tillage followed by irrigation was highly useful for controlling annual weeds in soybean, whereas deep tillage during the hot summer months is beneficial for the control of perennial weeds like *Cyperus* sp., *Cynodon dactylon*. Monsefi *et al.* (2013) studied weed management under different tillage and crop establishment methods in soybean and found that CT-bed and wheat residue mulch 5 t/ha + imazethapyr 75 g/ha as post-emergence were superior in controlling weeds that gave higher soybean yield **(Table 4)**. This imparted a favourable physico-chemical environment in soybean-wheat system as well (Monsefi *et al.* 2014). Younesabadi *et al.* (2013a) reported that weed density in no-tilled (ZT) treatment was significantly lower than CT, but weed dry matter, leaf soluble protein, chlorophyll content and yield of soybean were not affected by tillage treatments. Weed management practice such as the pendimethalin 0.75 kg/ha along with one hand weeding at 30 DAS resulted in lowest weed dry weight, but the highest yield was recorded with the spray of tank-mixture of penimethalin + imazethapyr (0.5 + 0.075 kg/ha) at pre-emergence. Their similar studies in soybean-wheat system (Younesabadi *et al.* 2013b, 2014) also revealed that in soybean, ZT-ZT system was similar with CT-CT system with respect to weed control and soybean yield, but wheat yield was significantly higher in the former.

Table 4. Effect of different tillage and crop establishment methods and weed management options on weed dry weight and yields (t/ha) of soybean

Treatment	Weed dry weight ($g/0.5\ m^2$) at 60 DAS	Seed yield (t/ha)
Tillage and crop establishment		
CT-Bed	71.22	1.802
CT-Flat	115.78	1.483
ZT-Bed	92.05	1.523
ZT-Flat	131.67	1.330
LSD (p=0.05)	26.61	0.154
Weed management		
Control	355.49	0.915
Pendimethalin at 750 g/ha (PE) + HW at 20 DAS	20.07	1.922
Pendimethalin at 750 g/ha (PE) + imazethapyr at 75 g/ha (PoE)	22.65	1.607
Wheat residue mulch at 5 t/ha + imazethapyr at 75 g/ha (PoE)	17.51	1.692
LSD (p=0.05)	25.91	0.150

Source: Monsefi *et al.* 2014

Ramesh and Devasenapathy (2005) studied the effect of *in situ* soil moisture conservation practices on weeds in cowpea at Coimbatore and concluded that mulching combined with the ridge and furrow (R&F) or compartmental bunding (CB) was superior to R&F and CB alone in reducing weed interference and increasing crop yield**.** Hajebi *et al.* (2014) studied the N, P and K uptake by weeds and chilli crop under different tillage practices and found that the uptakes of N, P, and K by weed was lower in ZT compared to CT and there was no significant difference in N and P uptakes by chilli crop, while K uptake by crop was higher with CT**.** This could reveal that ZT superior to CT on weed control (Hajebi *et al.* 2016) and gave 5.2% higher chilli yield. A weed management option, the application of tank-mixture of pendimethalin + imazethapyr resulted in better weed control and 166% increase in chilli yield **(Table 5)**.

Table 5. Tillage and weed management effects on weeds and productivity of chilli

Treatment	Weed density ($no./m^2$)	Weed dry weight (g/m^2)	Yield (t/ha)
Conventional tillage (CT)	111.2	103.0	7.06
Zero-tillage (ZT)	107.8	89.3	7.43(5.2)
LSD (P=0.05)	NS	NS	NS
Pendimethalin 1.0 kg/ha	96.7	70.3	7.85
Pendimethalin 0.75 kg/ha + oxyfluorfen 0.15 kg/ha (tank mix)	94.0	70.2	7.86
Pendimethalin 0.5 kg/ha + imazethapyr 0.075 kg/ha	48.0	19.2	8.85(165.8)
Pendimethalin 0.75 + quizalofop-p-ethyl 0.025 kg/ha at 30 DAS	121.3	107.0	6.62
Pendimethalin 0.75 kg/ha + hand-weeding 30 DAS	130.7	117.3	6.36
Weedy check	276.0	289.0	3.33
Weed-free check	0.0	0.0	9.84
LSD(p=0.05)	15.3	22.7	0.59

Source: Hajebi *et al.* 2016

Residue retention/mulching and weed control

Residue retention/ mulching can suppress weeds and reduce recruitment and early growth of weeds by imposing a physical barrier to emerging weeds (Mohler 1996) and releasing allelo-chemicals in soil (Weston 1996) under both cropped and non-cropped situations. It is very effective against most annual weeds and some perennial weeds such as *Cynodon dactylon*, *Sorghum halepense*. Surface residue decreases the daily maximum soil temperature, but has little effect on the daily minimum (Teasdale and Mohler 1993), resulting in two changes: cooler average soil temperatures and less drastic fluctuations. Most agronomic crops and many weeds require soil temperatures above a certain threshold in order to germinate; lower average soil temperatures would therefore delay germination of both (Wicks *et al.* 1994). Some weed species' germination is enhanced by larger temperature fluctuations (Liebman and Mohler 2001); the buffered soil temperature could therefore reduce germination rates in addition to causing later germination. Chhokar *et al.* (2009) observed that 2.5 t/ha rice residue mulch was not effective in suppressing weeds, but 5.0 and 7.5 t/ha residue mulch reduced weed biomass by 26 to 46%, 17 to 55%, 22 to 43%, and 26 to 40% of *Phalaris minor, Oxalis corniculata, Medicago sativa* and *Setaria glauca*, respectively compared with ZT without residue. Singh *et al.* (2005a) observed that *Glyricidia* leaf mulch effectively controlled weed density compared to control in groundnut. Ramesh and Devsenpathy (2005) reported similar reductions in weed density (~69.0%) and dry weight (~70%) due to the ridge and furrow with residue mulch. Kaur and Singh (2006) observed weed density and dry weight were higher in paired row planting of pearl millet compared to regular row planting, but mulching significantly reduced weed density and dry matter compared to no mulch. There is evidence of allelopathic properties of cereal residues in inhibiting weed germination, which can be used wisely for control of weeds. Improvements in planting technology like the shredder-spreader (Turbo Happy Seeder) has made it possible to sow wheat in heavy residue mulch of up to 8 to 10 t/ha without any adverse effects on crop establishment (Kumar and Ladha 2011, Sharma *et al.* 2008). Such heavy mulch has the potential to reduce the establishment of weeds in crops. Singh *et al.* (2013) recorded 48% reduction in weed population in wheat sown with Turbo Happy Seeder compared to conventional till sown wheat in Punjab. Improved weed control with application of rice residues as straw mulch at sowing time at 6 t/ha in potato (Bhullar *et al.* 2015) and at 9 t/ha in turmeric (Kaur *et al.* 2008) than without mulch have been reported. Under ZT conditions, soil solarization using transparent polyethylene mulch during hot summer season would add another dimension in weed management in crops and cropping systems. Soil solarization leads to reductions in weed interference and other pests and diseases during both rainy and winter seasons, if soil is not tilled/disturbed (Das and Yaduraju 2001, 2008). In a soybean-wheat system, soil solarization followed by glyphosate 1.0 kg /ha controlled weeds effectively and recorded the highest system productivity (Kumar and Das 2008, Kumar *et al.* 2012). Under residue retention, weed seed predation can be important in systems where newly produced weed seeds remain on the soil surface, for example, in no-till systems. Cromar *et al.* (1999) reported post-dispersal predation of *Echinochloa crus-galli* reduced seed input from 2000 to 360 seeds/m^2. Also, ZT and residue retention enhance the activity of weed seed decay agents and could contribute to reduce weed seed bank in the long run.

Crop diversification/rotation in CA

The cropping system plays an important role in influencing weed flora in CA. Crop rotations are arguably the most effective way to control weeds. Every crop applies a unique set of biotic and abiotic constraints on the weed community; this will promote the growth of some weeds while inhibiting that of others. In this way, any given crop can be thought of as filter, only allowing certain weeds to pass through its management regime (Booth and Swanton 2002). Monocultures often lead to weed simplification with only a few dominant weeds (Blackshaw *et al.* 2001, Cardina *et al.* 2002), potentially simplifying the choice of herbicide, but potentially increasing selection pressure for herbicide resistant weeds. Rotating crops will rotate selection pressures, preventing one weed from being repeatedly successful, and thus preventing its establishment. Crop diversification based on situations/ locations provides an edge over sole cropping towards reduction of weed competition unless there operates allelopathy between crops. Corn-legume intercropping led to a higher soil canopy cover and decreased light availability for weeds, which resulted in a reduction in weed density and dry matter compared with sole crops (Kumar *et al.* 2010). Weed suppression by crops was also greater at a low-productivity site than at a high-productivity site (Bilalis *et al.* 2010). Tadesse *et al.* (2010) reported that cowpea intercropping with and without pendimethalin (1.0 kg/ha) as pre-emergence led to greater reduction in *Parthenium* growth, resulting in a significant increase in sorghum growth.

Singh *et al.* (2005) reported changes in weed flora in rice due to change in cropping system. In rice-wheat system, the relative densities of sedges, grassy and non-grassy were 61.1, 28.5 and 10.4%, respectively in rice. In sugarcane–rice system, the relative densities of sedges 50.1%, grasses 15.8%, and non-grasses 34.1%, while in rice-pea-rice system, the relative densities of sedges, grasses and non-grassy weed were 36.4 , 28 and 35.6%, respectively in rice. All these changes were due to the change in microclimate. They further reported that among non–grassy weeds, *Eclipta alba* and *Commelina benghalensis* were higher in rice–wheat, *Alternanthera sessilis* higher in rice-pea-rice system, while in rice–sugarcane, *Commelina*, *Parthenium* and *Cynotis axillaris* were higher. Among grassy weeds, *Echinochloa* spp. was higher in all three cropping patterns. *Leptochloa chinensis* in rice–wheat and rice – sugarcane, while *Ischaemum rugosum* only in rice- wheat cropping system. Among sedges, *Cyperus iria* and *Cyperus difformis* were higher in rice-pea-rice cropping pattern and *Cyperus rotundus* higher in rice–sugarcane. *Fimbrystylis miliacea* was only in rice-wheat cropping pattern. Similarly, Gill *et al.* (2005) reported that in rice-wheat cropping system, population of grasses, broad-leaved weeds and *Phalaris minor* were higher in comparison to other cropping systems tested. Singh (2006) observed that weed population and dry matter significantly lower in mungbean-mustard compared to fallow-mustard cropping sequence and higher seed rate resulted in reduced weed population and dry weight compared to normal seed rate. Rice-fallow-sugarcane- ratoon sugarcane- sunflower- rice-wheat - sugarcane is a long duration (4 year) rotation, which is common in the north-east districts of Haryana. This rotation offers little opportunity for *Phalaris minor* to proliferate (Chhokar *et al*. 2008). Other rotations include rice-potato-sunflower, rice-mustard-sugarcane and rice-potato-onion. Inclusion of berseem (*Medicago sativa*) in the rice wheat cropping system helped to reduced seed bank of *Phalaris minor* within a less period, because emerged plants of *Phalaris minor* were cut with each cutting of berseem and these were not given any opportunity to set and shed seeds in field (Singh *et al*. 1999). Similarly, in potato based rotations uprooting of germinated *Phalaris minor* plants takes place with earthing up or digging operations. Malik and Singh (1995) found fewer resistance cases of *Phalaris minor* where growers used sugarcane, sunflower and vegetables in rotation rather than a rice-wheat system. Diversification and intensification of the rice-wheat system by growing a short-duration vegetable crop (pea, potato) followed by late sown wheat can also improve weed control without increasing herbicide use (Chhokar *et al*. 2008). By replacing wheat with alternate crops such as berseem, potato, sunflower, oilseed rape for 2-3 years in rice-wheat system, seed bank of *P. minor* was significantly reduced (Brar 2002).

Competitive crops/varieties and agronomic practices in CA

Competitive crops or crops varieties are of paramount importance in CA. Breeding for CA-responsive/specific crop varieties are yet to make headway. Early maturing inbred and hybrids because of their faster early growth and ground cover are more effective in smothering weeds than medium- to long-duration cultivars (Gill *et al*. 2013, Singh *et al*. 2014). The differences in competitive abilities of crop species and varieties against weeds are well documented (Balyan and Malik 1989, Das and Yaduraju 1995 and 1996, Chahal *et al*. 2003, Kaur *et al*. 2003). The ZT helps in manipulating/advancing sowing time to favour crop growth and yield in CA. In north-western IGP, sowing wheat 2 weeks earlier than the conventional till system could stimulate/boost up early seedlings vigour in wheat over *Phalaris minor* (Singh *et al*. 1999). Narrow row spacing (15 cm) reduced *Phalaris minor* biomass by 16.5% compared with normal spacing of 22.5 cm (Mahajan and Brar 2002). Higher seed rate of 150 kg/ha was found helpful in reducing populations of *Phalaris minor*, *Oxalis corniculata*, and *Melilotus alba* compared with a normal seed rate of 125 kg/ha. Mahajan and Brar (2001) reported that November 25 and October 25 sown wheat crop significantly reduced dry matter of *Phalaris minor* as compared to November 10 sown crop because October 25 (early) sown wheat crop shown smother effect on *Phalaris minor* and in Nov-25 (late) sown crop first flush of *Phalaris minor* was destroyed during seed bed preparation and second flush was not so competitive. Das and Yaduraju (2007) reported that managing irrigations and nitrogen could reduce grassy weeds competition in wheat. Furrow-irrigated raised bed system (FIRBS), a recent introduction from CIMMYT, Mexico has been found useful in reducing overall weed including *Phalaris minor* competition in wheat, mainly on the raised bed, but the furrows remain populated with weeds (Das and Yaduraju 2012). Angiras and Sharma (1993) reported that increasing wheat plant density by way of reducing row spacing from 20 to 15 cm could reduce the dry weights of *Lolium* and *Phalaris* by 11.9 and 18.3%, respectively. Weed competition in ZT-DSR can also be reduced by optimizing seed rate and the crop geometry (Chauhan 2012). In the IGP, a seed rate of 20 to 25 kg/ha has been recommended for DSR under optimum weed control (Gill *et al.* 2013, Kumar and Ladha 2011). Das and Yaduraju (2011) reported that leaving 20% of rows unsown significantly reduced weed populations and dry weights, and increased the competitiveness of wheat plants through greater leaf area, numbers of ear-bearing tillers, and uptake of N and ultimately resulting in increased wheat yield by 10.9, 17.3, and 8.2% during first, second, and third year, respectively.

Brown manuring, cover crop and intercropping in CA

Brown manuring in CA is an alternative to green manuring practised in conventional agriculture. It imparts several ecosystem services, besides weed smothering. This has shown promise for suppressing weeds in ZT rice production system in the IGP. This involves sowing of *Sesbania bispinosa* at 20-25 kg/ha along with rice/maize. *Sesbania* is allowed to grow with rice for a small period of 25-30 DAS, which could suppress weeds as a cover crop, and, then is killed by 2,4-D. This practice could significantly improve weed control (Gupta and Seth 2007, Singh *et al.* 2007, Maity and Mukherjee 2009 and 2011, Sharma *et al.* 2010, Ramachandran *et al.* 2012, Oyeogbe *et al.* 2017 and 2018, Susha *et al.* 2018). Sen *et al.* (2018) reported moderate effects of brown manuring on weed control in DSR, which was inferior to sequential herbicides application. *Sesbania* cover crop can lead to weeds suppression by physical impedance of weed species and continued leaching of allele-chemicals into soil (Weston 1996). Singh *et al.* (2007) reported 76-83% lower broad-leaved weed densities and 20-33% lower grass weed densities with this practice compared with only a rice crop. As most rice weed species are sensitive to mulching, it could be an effective weed management strategy in ZT-DSR. However, *Sesbania* plants may interfere with rice plants, if 2,4-D application is ineffective, or delayed because of continuous rains. *Sesbania* seeds require some additional costs; and it may invite more nematodes (Baghel 2017). Integrated weed management using brown manuring in maize and herbicide mixtures in wheat increased the grain yields by 10 and 21%, respectively over the weedy check (Oyeogbe *et al.* 2018). Similar study (Oyeogbe *et al.* 2017) indicated that BM crop decreased weed interference and herbicide dose and residue in soil in maize-wheat system. This will as well reduce herbicide intake into environment.

Chemical weed control and challenges in CA

Weeds pose serious concerns/constraints, particularly during the initial/ transitional years of adopting CA. On principle, mechanical weeding, rigorous manual weeding using hand tools leading to more soil disturbances will not be permitted under CA. Besides, non-availability of labourers on time and rising labour wage across India cast doubts about manual weeding to become a viable option for weed management in the coming years. Therefore, CA system largely depends on herbicides and agronomic practices for controlling weeds. Herbicides are cheaper than traditional weeding methods, require less labour, tackle difficult-to-control weeds, and allow flexibility in weed management. In CA, the diverse weed flora present in field before crop sowing must be killed by using non-selective, less persistent herbicides like glyphosate, paraquat or glufosinate-AM, for ensuring weed-free conditions for crop germination. Besides, a pre-emergence herbicidal treatment is required to control flushes of annual weeds coming up with the germination of crops. But, crop residues may intercept 15-80% of the applied herbicides (Chauhan *et al.* 2012) and bind soil-applied herbicides and favour the weed seedlings to escape from the applied herbicides. This indicates proper selection of herbicide formulation, dose and other manipulations required to achieve greater weed control efficacy under post-sown/pre-emergence conditions of crops.

To overcome such problems, the strategies that can be adopted are: high volume rate at pre-emergence sprays; higher dose of herbicide than normal; granular herbicide formulations; broad-spectrum and non-selective herbicide for off-season perennial weeds control; and more preference to early post-emergence herbicides than pre-emergence. The 5R stewardship of herbicide use in crops may be the *sumum bonum* for achieving effective weed control under CA. The 5R stewardship are: right choice, right source, right dose, right time, and right method of application of herbicide. A large number of experiments in recent past have highlighted the effective role of herbicides towards weed control under CA (Singh *et al.* 2007, Ramachandran *et al.* 2012, Oyeogbe *et al.* 2017 and 2018, Das and Das 2018, Susha *et al.* 2018). A large number of herbicides have been recommended for different crops under CA (Sharma *et al.* 2015a). However, over reliance on herbicides leads to evolution of herbicide resistance in weeds (Das 2008, CAST 2012, Heap 2012). The low persistence, rapid degradation by sunlight, excellent bio-efficacy and low mammalian toxicity of clodinafop could provide the solution for an effective alternative for the control of isoproturon resistant *P. minor* biotypes to combat the weed flora shift in wheat fields of India (Roy *et al.* 2006). Rotating herbicides of different modes of action, herbicide mixtures may be important in avoiding or delaying the evolution of resistance. In wheat, the *Phalaris minor* has evolved multiple herbicide resistance owing to overreliance on post-emergence herbicides (Chhokar and Sharma 2008, Malik and Singh 1995, Bhullar and Walia 2004a, Bhullar *et al.* 2014, Das *et al.* 2014a). The commonly used post-emergence herbicides in wheat and direct-seeded rice are either acetolactate synthase or acetyl-CoA carboxylase inhibitors (Kumar and Ladha 2011), which are highly prone to the evolution of resistance (HRAC 2012). As the adoption of direct-seeded rice is likely to increase the load of herbicides, the herbicide resistance in weeds might be a problem along with environmental concerns in near future.

Herbicide-tolerant crops in CA

Herbicide-tolerant crops can be a promising component of the IWM schedule in CA systems. These crops are cultivated by growers in many countries of the world. Presently, herbicide tolerant crops are not available to growers in India. There are also some risks associated with the adoption of herbicide tolerant crops. Continuous use of the same herbicide such as glyphosate may result in shifts in weed flora or it may accelerate the development of glyphosate resistance in weeds. Indeed, glyphosate was successfully utilized for over two decades before a resistant biotype of rigid ryegrass (*Lolium rigidum*) was identified in Australia in 1996 (Powles *et al.* 1998). However, since the release of herbicide tolerant crops, several resistant weed biotypes have been reported in glyphosate-tolerant systems in as little as 3 years (Green 2007, Duke and Powles 2008). Therefore, herbicide tolerant crop cultivars should not be considered as a stand-alone component of weed management. An integrated weed management strategy should be used to ensure that this important weed management tool remains effective, profitable and environmentally sound over a long period of time.

Integrated weed management

Any single method of weed control used in isolation cannot provide season-long effective weed control. Secondary weeds become primary weeds in course of time due to continuous use of single herbicide or herbicides of similar mode of action. Similarly, noxious perennial weeds appear in CA systems over times. This problem can be avoided by adopting an integrated weed management (IWM) approach, involving herbicides (rotation, mixtures), good agronomic/cultural practices, timeliness of operations, crop rotation, cover and inter-cropping, crop residue retention, crop competitiveness against weeds. A comprehensive, effective and well adoptable IWM needs to be evaluated to achieve sustainable and effective weed management under CA systems for sustainable crop production **(**Raj *et al.* 2018). Majority of the researches on weed management focuses on herbicide-based IWM (Wicks *et al.* 1994, Liebman and Davis 2000, Pandey *et al.* 2001, Taa *et al.* 2004, Kaur and Singh 2006, Singh *et al.* 2007, Swanton *et al.* 2008, Singh *et al.* 2009, Ramachandran *et al.* 2012, Singh *et al.* 2015a, Oyeogbe *et al.* 2017 and 2018, Susha *et al.* 2014 and 2018, Younesabadi *et al.* 2013a,b and 2014, Baghel *et al.* 2018).

Economic analyses revealed that the use of herbicide was more economical than manual methods, and herbicide in combination with hand weeding, zero tillage, residue, nitrogen management *etc.* gave cost-effective, efficient and longer weed control. The integration of herbicides with intercropping in sugarcane (Bhullar *et al.* 2006) and with nitrogen fertilization in wheat (Bhullar and Walia 2003) improved weed control than sole cropping or herbicide alone. Due to herbicides and IWM treatments, ZT-DSR resulted in grain yield similar to CT-DSR and TPR in Ludhiana (AICRP-WM 2014). Under IWM treatment, ZT-DSR with residue retention gave 19% higher yield than CT-DSR, however, under only herbicides treatment, CT-DSR recorded 8% higher yield than ZT-DSR. Singh *et al.* (2018) reported that integrated use of a stale seedbed with shallow tillage followed by the sequential application of post sowing herbicides effectively controlled the complex weed flora in dry-seeded rice. Baghel *et al.* (2018) also reported the integration of tillage, residue and sequential herbicides leading to efficient control of weeds in DSR under a CA-based rice-wheat system. Singh *et al.* (2015a) opined that CA practices such as ZT can be an important component of integrated weed management in DSR, provided herbicide efficacy can be maintained by adjusting the rate and timing of herbicide application. Monsefi *et al.* (2013) reported that total weed density and dry matter was comparatively higher under ZT than CT, but adoption of chemical + cultural weed control methods led to 79.5 to 82.5% weed control efficiency. Oyeogbe *et al.* (2017) reported that adaptive N and integrated weed management enhance synergy between agronomic productivity, fertilizer and herbicide efficiency, and greenhouse gas mitigation in CA-based maize-wheat cropping system. Tadesse *et al.* (2010) reported that a pre-emergence treatment of atrazine (0.75 kg/ha) with wheat straw mulch (5.0 t/ha) brought about a consistent and significant reduction in the parthenium growth and, consequently, increased the sorghum yield by 90.8%. Nath *et al.* (2015) reported that ZT with 5 t/ha maize residue + 75% N + rest N-based on GreenSeeker and sequential applications of pendimethalin followed by sulfosulfuron caused a considerable reduction in the populations of narrow-leaved, broad-leaved and total weeds compared to CT. Their carry-over effect was also significant in reducing weed growth in succeeding mungbean.

Conclusion

A greater weed control challenge is usually observed under CA than CT in the initial years, but weed problems are gradually reduced in the subsequent years. Crop residue retention is essential for the success of CA in the long-run, but continued CA adoption may cause shift in weed flora, especially emergence of perennial weeds like *Cyperus rotundus, Cynodon dactylon* and *Sorgum halepense* in most crops. Restricting tillage reduces weed control options and increases reliance on herbicides. Therefore, herbicide residue, persistence and degradation pathways are to be studied periodically, particularly where same herbicides are being used over a long period. Crop residue allelopathy and weed management may be studied in depth through crop residue characterization and quantification for a long period. Allelopathic crop cultivars could be a strategy to avoid development of herbicide resistance in CA systems. Biotechnological tools may help to unveil allelopathic traits of plants, and a breeding programme to transfer allelopathic genes into modern cultivars to enhance their allelopathic activity for weed suppression may help to reduce over-reliance on herbicides in CA systems. Approaches such as brown manuring with non-selective herbicides, uniform and dense crop establishment, use of cover crops and crop residues as mulch, crop rotations, enhanced crop competitiveness against weeds with a combination of pre- and post-emergence herbicides could be integrated to develop sustainable and effective weed management strategies under CA systems. Development of integrated weed, disease or pest control strategies under CA systems would be of paramount importance.

References

Abrol IP and Sangar A. 2006. Sustaining Indian agriculture–conservation agriculture the way forward. *Current Science* **91**(8): 1020–2015.

AICRP–WM. 2014. *Annual Technical Report*. All India Coordinated Research Project on Weed Management. Department of Agronomy, Punjab Agricultural University, Ludhiana, India, 100 p.

AICRP–WM. 2015. *Annual Technical Report*. All India Coordinated Research Project on Weed Management. ICAR Directorate of Weed Research, Jabalpur, India.

Angiras NN and Sharma V. 1993. Effect of cultural manipulations and weed control methods on crop–weed competition in wheat. *Indian Journal of Weed Science* **23**(3&4): 6–10.

Aslam M, Majid A, Hashmi NI and Hobbs PR. 1993. Improving wheat yield in the rice–wheat cropping system of the Punjab through zero tillage. *Pakistan Journal of Agricultural Research* **14**: 8–11.

Baghel J. 2017. *Conservation Agriculture and Weed Control Effects on Productivity and Resource–Use Efficiency in Rice–Wheat Cropping System*. Ph.D. Thesis, Division of Agronomy, IARI, New Delhi.

Baghel JK, Das TK, Rana DS and Paul S. 2018. Effect of weed control on weed competition, soil microbial activity and rice productivity in conservation agriculture–based direct–seeded rice (*Oryza sativa*)–wheat (*Triticum aestivum*) cropping system. *Indian Journal of Agronomy* **63**(2): 129–136.

Balyan RS and Malik RK. 1989. Influence of nitrogen on competition *Phalaris minor* in wheat. *Pestology* **13**: 5–6.

Bhan S and Behera UK. 2014. Conservation agriculture in India– Problems, prospects and policy issues. *International Soil and Water Conservation Research* **2**(4): 1–12.

Bhullar MS and Walia US. 2003. Studies on integration of nitrogen and clodinafop for controlling isoproturon resistant *Phalaris minor* in wheat. *Fertilizer News* **49**(5): 41–48.

Bhullar MS and Walia US. 2004a. Classification of isoproturon resistant biotypes of *Phalaris minor* Retz. *Indian Journal of Weed Science* **36**(1&2): 112–14.

Bhullar MS, Kamboj A and Singh GP. 2006. Weed management in spring–planted sugarcane (*Saccharum officinarum*)–based intercropping systems. *Indian Journal of Agronomy* **51**(3): 183–85.

Bhullar MS, Kaur S, Kaur T and Jhala AJ. 2015. Integrated weed management in potato (*Solanum tuberosum*) using straw mulch and atrazine. *Horticultural Technology* **25**(3): 335–339.

Bhullar MS, Punia SS, Tomar SS, Singh VP and Sharma JD. 2014. Development of cross resistance in little seed canary grass to clodinafop in Punjab: Farmers' Perspective. *Indian Journal of Weed Science* **46**(3): 237–240.

Bhullar MS, Walia US, Singh S, Singh M, and Jhala AJ. 2012. Control of morning glories (*Ipomoea* spp.) in sugarcane (*Saccharum* spp.). *Weed Technology* **26**: 77–82.

Bilalis D, Panayiota P, Aristidis K, Sotiria P, Anestis K and Aspasia, E. 2010. Weed suppressive effects of maize–legume intercropping in organic farming. *International Journal of Pest Management* **56**: 173–181.

Bisen PK, Singh RK and Singh RP. 2006. Relative composition of weeds and wheat yield as influenced by different weed control and tillage practices. *Indian Journal of Weed Science* **38** (1&2): 9–11.

Blackshaw R, Larney F, Lindwall C, Watson P, and Derkse D. 2001. Tillage intensity and crop rotation affect weed community dynamics in a winter wheat cropping system. *Canadian Journal of Plant Science* **81**, 805–813.

Booth BD, Swanton CJ. 2002. Assembly theory applied to weed communities. *Weed Sci*ence 50, 2–13.

Buhler DD, Stoltenberg DE, Becker RL and Gunsolus JL. 1994. Perennial weed populations after 14 years of variable tillage and cropping practices. *Weed Science* **42**: 205–209.

Cardina J, Herms CP, Doohan DJ. 2002. Crop rotation and tillage system effects on weed seed banks. *Weed Science* **50**: 448–460.

CAST. 2012. *Herbicide–resistant Weeds Threaten Soil Conservation Gains: Finding a Balance for Soil and Farm Sustainability*. *Issue Paper 49*. 16 p. Ames, IA. Council for Agricultural Science and Technology.

Chahal PS, Brar HS and Walia US. 2003. Management of *Phalaris minor* in wheat through integrated approach. *Indian Journal of Weed Science* **35**: 1–5.

Chauhan BS and Johnson DE. 2009. Seed germination ecology of junglerice (*Echinochloa colona*): a major weed of rice. *Weed Science* **57**: 235–240.

Chauhan BS, Gill GS and Preston C. 2006. Influence of tillage systems on vertical distribution, seedling recruitment and persistence of rigid ryegrass (*Lolium rigidum*). *Weed Science* **54** (4): 669–676.

Chauhan BS, Singh BG and Mahajan G. 2012. Ecology and management of weeds under conservation agriculture: A review. *Crop Protection* **38**: 57–65

Chauhan BS. 2012. Weed ecology and weed management strategies for dry–seeded rice in Asia. *Weed Technology* **26**:1–13.

Chhokar RS, Sharma RK, Jat GR, Pundir AK and Gathala MK. 2007. Effect of tillage and herbicides on weeds and productivity of wheat under rice–wheat growing system. *Crop Protection* **26**(11): 1689–1696.

Chhokar RS, Sharma RK, Singh RK, and Gill SC. 2008. Herbicide resistance in littleseed canarygrass (*Phalaris minor*) and its management. P.106. In: *Proceedings of the 14th Australian Agronomy Conference*. Adelaide, South Australia: Australian Society of Agronomy.

Chhokar RS, Singh S, Sharma RK, and Singh M. 2009. Influence of straw management on *Phalaris minor* control. *Indian Journal of Weed Science* **41**: 150–156.

Chopra P and Angiras NN. 2005. Integrated effect of tillage and weed control methods on weed dynamics in maize under rain fed conditions in Himachal Pradesh. Pp 150–151. In: *Proceedings of National Biennial Conference,* ISWS, PAU, Ludhiana, April 6–9,2005

Cromar HE, Murphy SD and Swanton CJ. 1999. Influence of tillage and crop residue on post dispersal predation of weed seeds. *Weed Science* **47**: 184–194.

Das TK and Das DK. 2018. Using chemical seed dormancy breakers with herbicides for weed management in soyabean and wheat. *Weed Research* **58**(3): 188–199.

Das TK and Yaduraju NT. 1995. Crop–weed competition studies in some *Kharif* crops: ll, nutrient uptake and yield reduction. *Annals of Plant Protection Sciences* **3**(2): 95–99.

Das TK and Yaduraju NT. 1996. Crop–weed competition studies in some *Karif* crops: l, physiological parameters. *Indian Journal of Agricultural Research* **30**(4): 235–241.

Das TK and Yaduraju NT. 2001. Comparing several crop husbandry practices with soil solarization for weed control and crop yield in soybean (*Glycine max*) – broccoli (*Brassica oleracea convar botrytis* var *italica*) cropping system. *Indian Journal of Agricultural Sciences* **71**(4): 284–286.

Das TK and Yaduraju NT. 2007. Effect of irrigation and nitrogen levels on grassy weed competition in wheat and comparative eco–physiology of *Phalaris minor* Retz. and *Avena sterilis* ssp *ludoviciana* Dur. in wheat. *Indian Journal of Weed Science* **39**(3&4): 178–184.

Das TK and Yaduraju NT. 2008. Effect of soil solarization and crop husbandry practices on weed species competition and dynamics in soybean–wheat cropping system. *Indian Journal of Weed Science* **40**(1&2): 1–5.

Das TK and Yaduraju NT. 2011. Effects of missing–row sowing supplemented with row spacing and nitrogen on weed competition and growth and yield of wheat. *Crop and Pasture Science* **62**(1): 48–57.

Das TK and Yaduraju NT. 2012. The effects of combining modified sowing methods with herbicide mixtures on weed interference in wheat. *International Journal of Pest Management* **58**(4): 311–320.

Das TK, Ahlawat IPS and Yaduraju NT. 2014a. Littleseed canarygrass (*Phalaris minor*) resistance to clodinafop–propargyl in wheat fields in north–western India: Appraisal and management. *Weed Biology and Management* **14**(1): 11–20.

Das TK, Sepat S, Singh P, Bhattacharyya R and Pathak H. 2014b. Conservation agriculture for enhancing crop productivity and resource–use efficiency. *Indian Farming* **64**(1): 18–21.

Das TK. 2001. Overview weed dynamics in crop field. *Pesticide Information* **27**(3): 35–46.

Das TK. 2008. *Weed Science: Basics and Applications*. Jain Brothers Publishers, New Delhi, India, 901p.

Dhawan R. 2005. Studies on germination and emergence of *Rumex maritimus*. *Indian Journal of Weed Science* **37**:144–146.

Dhillon SS, Prashar A and Thaman S. 2005. Comparative studies on the effect of weed management practices on *Phalaris minor* in bed and conventionally planted wheat (*Triticum aestivum* L.). *Indian Journal of Ecology* **32**: 72–75.

Dhyani VC and Misra RD. 2007. Dynamics of weeds and their management through herbicides in zero tilled wheat (*Triticum aestivum*). *Indian Journal of Agricultural Sciences* **77**(5): 314–316.

Duke SO and Powles SB. 2008. Glyphosate: a once–in–a–century herbicide. *Pest Management Science* **64**: 319"325.

Farooq M and Nawaz A. 2014. Weed dynamics and productivity of wheat in conventional and conservation rice–based cropping systems. *Soil and Tillage Research* **141**:1–9.

Franke AC, Singh S, Mcroberts N, Nehra AS, Godara S, Malik RK and Marshall G. 2007. *Phalaris minor* seed bank studies: longevity, seedling emergence and seed production as affected by tillage regime. *Weed Research* **47**: 73–83.

Gathala MK, Ladha JK, Saharawat YS, Kumar V and Sharma PK. 2011. Effect of tillage and crop establishment methods on physical properties of a medium–textured soil under a seven–year rice–wheat rotation. *Soil Science Society of America Journal* **75**: 1851–1862.

Gill G, Bhullar MS, Yadav A and Yadav DB. 2013. Technology for successful production of direct seeded rice. In : *Training Manual*, University of Adelaide, South Australia; PAU Ludhiana, Punjab; CCSHAU, Hissar, Haryana.

Gill MS, Walia SS and Singh S. 2005. Weed dynamics in relation to crop diversification and intensification through various cropping system. Pp 190–191. *Proceedings of National Biennial Conference*, ISWS, PAU, Ludhiana April 6–9, 2005,.

Green JM. 2007. Review of glyphosate and ALS–inhibiting herbicide crop resistance and resistant weed management. *Weed Technology* **21**(2): 547–558.

Gupta R and Seth A. 2007. Areview of resource conserving technologies for sustainable management of the rice–wheat cropping systems of the Indo–Gangetic Plains. *Crop Protection* **26**: 436–447.

Hajebi A, Das TK, Arora A, Singh SB and Hajebi F. 2016. Herbicides tank–mixes effects on weeds and productivity and profitability of chilli (*Capsicum annuum* L.) under conventional and zero tillage. *Scientia horticulturae* **198**: 191–196.

Hajebi A, Das TK, Vyas AK, Rana DS and Pooniya V. 2014. Effect of tillage and tank–mix herbicide application on weed management in chilli (*Capsicum annuum*). *Indian Journal of Agronomy* **59**(4): 651–656.

Harper JL. 1977. *The Population Biology of Plants*. Academic Press, London, U. K. 892 p.

Heap I. 2012. *International Survey of Herbicide Resistant Weeds*. (www.weedscience.com)

HRAC. 2012. Herbicide Resistance Action Committee. (http://www.hracglobal.com)

Hume L, Tessier S and Dyck F. 1991. Tillage and rotation influences on weed community composition in wheat (*Triticum aestivum* L.) in southwestern Saskatchewan. *Canadian Journal of Plant Science* **71**: 783–789.

IARI. 2012. *Crop Residue Management with Conservation Agriculture: Potential, Constraints and Policy Needs*. TB–ICN 100/2012. Indian Agricultural Research Institute, New Delhi, vii + 32 p.

Jat ML, Malik RK, Saharawat YS, Gupta R, Bhag M and Paroda R. 2012. *Proceedings of Regional Dialogue on Conservation Agriculture in South Asia*. New Delhi, India, APAARI, CIMMYT, ICAR,.p 32 p.

Kassam A, Friedrich T and Derpsch R. 2018. Global spread of conservation agriculture. *International Journal of Environmental Studies* https://doi.org/ 10.1080/ 00207233. 2018.1494927.

Kaur A and Singh VP. 2006. Weed dynamics as influenced by planting methods, mulching and weed control in rainfed hybrid pearlmillet (*Pennisetum glaucum* L.). *Indian Journal of Weed Science* **38** (1&2): 135–136.

Kaur H, Brar HS and Walia US. 2003. Competitive ability of wheat cultivars sown on different dates with littleseed canarygrass (*Phalaris minor* Retz.). *Indian Journal of Weed Science* **35**: 21–23.

Kaur K, Bhullar MS, Jagmohan Kaur and Walia US. 2008. Weed management in turmeric (*Curcuma longa*) through integrated approaches. *Indian Journal of Agronomy* **53** (3): 229–234.

Kumar M and Das TK. 2008. Integrated weed management for system productivity and economics in soybean (*Glycine max*)–wheat (*Triticum aestivum*) system. *Indian Journal of Agronomy* **53**(3): 189–194.

Kumar M, Das TK and Yaduraju NT. 2012. An integrated approach for management of *Cyperus rotundus* (purple nutsedge) in soybean – wheat cropping system. *Crop Protection* **33**: 74–81.

Kumar R, Gopal R, Jat ML and Gupta, RK. 2010. Conservation agriculture based strategies for sustainable weed management in maize (*Zea mays*). In: *Training Manual*. Directorate of Maize Research, New Delhi, India.

Kumar Suresh, Angiras, NN and Singh R. 2006. Effect of planting and weed control methods on weed growth and seed yield of black gram. *Indian Journal of Weed Science* **38** (1&2): 73–76.

Kumar V and Ladha JK. 2011. Direct seeding of rice: recent developments and future research needs. *Advances in Agronomy* **111**: 299–413.

Kumar V, Singh S, Chhokar S, Ram K, Malik S, Daniel C and Ladha JK. 2013. Weed management strategies to reduce herbicide use in zero–till rice–wheat cropping systems of the IGP. *Weed Technology* **27**: 241–254.

Liebman M and Davis A. 2000. Integration of soil, crop and weed management in low–external–input farming systems. *Weed Research* **40**, 27–48.

Liebman M, Mohler CL and Staver CP. 2003. Ecological management of agricultural weeds. *Annals of Botony* **91**(4): 499–500.

Mahajan G and Brar LS. 2001. Integrated management of *Phalaris minor* in wheat. *Indian Journal of Weed Science* **33**(1&2): 9–17.

Mahajan G and Brar LS. 2002. Integrated management of *Phalaris minor* in wheat: rationale and approaches–A review. *Agricultural Reviews* **23**(4): 241–251.

Mahajan G, Brar LS and Sardana V. 1999. Effect of tillage and time of sowing on the efficacy of herbicides against Phalaris minor in wheat. pp. 193–198. In: *The Proceeding of 17th Asian Pacific Weed Science Society Conference.* Organisation of the 17th APWSS Conference, Bangkok, Thailand

Maity SK and Mukherjee PK. 2009. Effect of brown manuring on grain yield and partial factor productivity of nutrients in dry–direct seeded summer rice (*Oryza sativa* L.) under *Terai* agro–ecological region of West Bengal. *Journal of Crop and Weed* **5**(2): 31–35.

Maity SK and Mukherjee PK. 2011. Effect of brown manuring on grain yield and nutrient use efficiency in dry direct seeded *kharif* rice (*Oryza sativa* L.). *Indian Journal of Weed Science* **43**(1&2): 61–66.

Malik RK and Singh S. 1995. Littleseed Canarygrass (*Phalaris minor*) resistance to isoproturon in India. *Weed Technology* **9(3)**: 419–425.

Malik RK, Kumar V, Yadav A and McDonald A. 2014. Conservation agriculture and weed management in south Asia: perspective and development. *Indian Journal of Weed Science* **46**(1): 31–35.

Malik RK, Yadav A, Singh A, Malik RS, Balyan RS, Banga RS, Sardana PK, Jaipal S, Hobbs PR, Gill G, Singh S, Gupta RK and Bellinder R. 2002. Herbicide resistance management and evolution of zero–tillage – A success story. *Research Bulletin.* CCS HAU Hissar, India, 43 p.

Mehta AK and Singh R. 2002. *Zero–Tillage Sowing of Wheat– A Profitable Technology*. Zonal Coordinating Unit, Zone–I, PAU Campus, Ludhiana.14 p.

Mishra JS. 2004. Tillage and Weed Management. NRCWS, *Technical Bulletin* N*o*.1, 14 p.

Mohler CL. 1996. Ecological bases for the cultural control of annual weeds. *Journal of Production Agriculture* **9**(4): 468–474.

Monsefi A, Sharma AR and Das TK. 2013. Conservation tillage and weed management for improving productivity, nutrient uptake and profitability of soybean (*Glycine max*) grown after wheat (*Triticum aestivum*). *Indian Journal of Agronomy* **58**(4): 570–577.

Monsefi A, Sharma AR, Rang Zanc N, Behera UK and Das TK. 2014. Effect of tillage and residue management on productivity of soybean and physico–chemical properties of soil in soybean–wheat cropping system. *International Journal of Plant Production* **8**(3): 429–440.

Moyer JR, Roman SR, Lindwall CW and Blackshaw RE. 1994. Weed management in conservation tillage systems for wheat production in North and South America. *Crop Protection* **13**(4): 243–259.

Nath CP, Das TK and Rana KS. 2016. Effects of herbicides and tillage practices on weeds and summer mungbean (*Vigna radiata*) in wheat (*Triticum aestivum*)–mungbean cropping sequence. *Indian Journal of Agricultural Sciences* **86**(7): 860–864.

Nath CP, Das TK, Rana KS, Bhattacharyya R, Pathak H, Paul S, Meena MC and Singh SB. 2017. Weed and nitrogen management effects on weed infestation and crop productivity of wheat–mungbean sequence in conventional and conservation tillage practices. *Agricultural Research* **6**(1): 33–46.

Nath CP, Das TK, Rana KS, Pathak H, Bhattacharyya R, Paul S, Singh SB and Meena MC. 2015. Weed–management and wheat productivity in a conservation agriculture–based maize (*Zea mays*)–wheat (*Triticum aestivum*)–mungbean (*Vigna radiata*) system in north–western Indo–Gangetic plains of India. *Indian Journal of Agronomy* **60**(4): 554–563.

Oyeogbe AI, Das TK and Bandyopadhyay KK. 2018. Agronomic productivity, nitrogen fertilizer savings and soil organic carbon in conservation agriculture: Efficient nitrogen and weed management in maize–wheat system. *Archives of Agronomy and Soil Science* **64**(12): 1635–1645.

Oyeogbe AI, Das TK, Bhatia A and Singh SB. 2017. Adaptive nitrogen and integrated weed management in conservation agriculture: impacts on agronomic productivity, greenhouse gas emissions, and herbicide residues. *Environmental Monitoring and Assessment* **189**(4): 198.

Pandey IB, Sharma SL, Tiwari S and Bharti V. 2001. Effect of tillage and weed management practices on grain yield and nutrient removal by wheat and weeds. *Indian Journal of Weed Science* **33** (3&4): 107–111.

Powles SB, Lorraine–Colwill DF, Dellow JJ and Preston C. 1998. Evolved resistance to glyphosate in rigid ryegrass (*Lolium rigidum*) in Australia. *Weed Sci*ence **46**: 604–607.

Raj R, Das TK, Kaur R, Singh R and Shekhawat K. 2018. Invasive noxious weed management research in India with special reference to *Cyperus rotundus*, *Eichhornia crassipes* and *Lantana camara*. *Indian Journal of Agricultural Sciences* **88**(2): 181–196.

Ramachandran A, Veeramani A and Prema P. 2012. Effect of brown manuring on weed growth, yield and economics of irrigated maize. *Indian Journal of Weed Science* **44**(3): 204–206.

Ramesh T and Devsenpathy. 2005. Influence of *in situ* soil moisture conservation practices on weed dynamics and grain yield in rainfed cowpea. pp. 136–137. *Proceedings* of *National Biennial Conference*, ISWS, PAU, Ludhiana April 6–9, 2005.

Rao AN, Johnson DE, Sivaprasad B, Ladha JK and Mortimer AM. 2007. Weed management in direct–seeded rice. *Advances in Agronomy* **93**:153–255.

Renu S, Thomas CG and Abraham CT. 2000. Stale seedbed technique for the management of *Sacciolepis interrupta* in semi–dry rice. *Indian Journal of Weed Science* **32**:140–145.

Roy S, Das TK and Singh SB. 2006. Persistence of clodinafop in soil, wheat crop and *Phalaris minor*. *Pesticide Research Journal* **18**(1): 87–91.

Sen S, Kaur R, Das TK, Shivay YS and Sahoo PM. 2018. Bio–efficacy of sequentially applied herbicides on weed competition and crop performance in dry direct–seeded rice (*Oryza sativa*). *Indian Journal of Agronomy* **63**(2): 230–233.

Sharma AR, Behera UK and Das TK. 2015b. Conventional and conservation agriculture systems. pp. 321–335. In: Weed *Science For Sustainable Agriculture, Environment and Biodiversity*. (Eds. Yadueraju NT, Rao AN and Yaduraju, 25th APWSS Conference, Hyderabad, India.

Sharma AR, Das TK and Behera UK. 2015a. Conservation agriculture systems and weed management. *Indian Farming* **65**(7): 07–13.

Sharma AR, Singh R, Dhyani SK and Dube RK. 2010. Effect of live mulching with annual legumes on performance of maize (*Zea mays*) and residual effect on following wheat (*Triticum aestivum*). *Indian Journal of Agronomy* **55**(3): 177–183.

Sharma KL, Grace JK, Mandal UK, Gajbhiye PN, Srinivas K, Korwar GR, Bindu VH, Ramesh V, Ramachandran K and Yadav SK. 2008. Evaluation of long–term soil management practices using key indicators and soil quality indices in a semi–arid tropical Alfisol. *Australian Journal of Soil Research* **46**(4): 368–377.

Singh A, Kang JS, Kaur M and Goel A. 2013. Root parameters, weeds, economics and productivity of wheat (*Triticum aestivum*) as affected by methods of planting in–situ paddy straw. *International Journal of Current Microbiology and Applied Sciences* **2**(10): 396–405.

Singh G, Singh VP, Singh V, Singh SP, Kumar A, Mortimer M and Johnson DE. 2005. Characterization of weed flora and weed management practices in rice under different cropping system in western Gangetic plain in India – A case study. *Indian Journal of Weed Science* **37** (1&2): 45–57.

Singh M, Bhullar MS and Chauhan BS. 2015a. Influence of tillage, cover cropping, and herbicides on weeds and productivity of dry direct–seeded rice. *Soil and Tillage Research* **147**: 39–49.

Singh M, Bhullar MS and Chauhan BS. 2015b. Seed bank dynamics and emergence pattern of weeds as affected by tillage systems in dry direct–seeded rice. *Crop Protection* **67**: 168–177.

Singh M. 2015. *Weed management in Direct Seeded rice (Oryza sativa L.) under different stale seed bed Methods and Herbicides*. M.Sc. Thesis, Punjab Agricultural University, Ludhaina, India 70 p.

Singh NP, Datta M and Mitra S. 2005a. Efficacy of mulching to minimize weed density in crops grown in Tripura.P.128. *Proceedings of National Biennial Conference*, ISWS, PAU, Ludhiana April 6–9, 2005.

Singh RK, Singh A and Pandey CB. 2014. Agro–biodiversity in rice–wheat–based agro ecosystems of eastern Uttar Pradesh, India: Implications for conservation and sustainable management. *International Journal of Sustainable Development & World Ecology* **21**: 46–59.

Singh M, Bhullar MS and Gill G. 2018. Integrated weed management in dry–seeded rice using stale seedbeds and post sowing herbicides. *Field Crops Research* 224:182–191.

Singh RP and Singh RK. 2006. Ecological approaches in weed management. pp 301–304. In : *Extended Summaries* (*Voluntary Articles*), *Golden Jubilee National Symposium on Conservation Agriculture and Environment.* ISA, New Delhi and BHU, Varanasi, India, October 26–28 at Varanasi.

Singh S, Chhokar RS, Gopal R, Ladha JK, Gupta RK, Kumar V and Singh M. 2009. Integrated weed management: a key to success for direct–seeded rice in the Indo–Gangetic plains. Pp. 261–278. In: *Integrated Crop and Resource Management in the Rice–Wheat System of South Asia*. (Eds. JK Ladha, Y Singh, O Erenstein and B Hardy Los Banos). Philippines: International Rice Research Institute.

Singh S, Kirkwood RC, and G Marshall. 1999. A review of the biology and control of *Phalaris minor* Retz. (littleseed canarygrass) in cereals. *Crop Protection* **18**: 1–16.

Singh S, Ladha JK, Gupta RK, Bhusan L, Rao AN, Sivaprasad B, and Singh P. 2007. Evaluation of mulching, intercropping with *Sesbania* and herbicide use for weed management in dry–seeded rice (*Oryza sativa* L.). *Crop Protection* **26**: 518–524.

Smart Indian Agriculture. 2015. http://www.smartindianagriculture.in/its–not–a–fad–its–the–fastest–spreading–ag–technology–in Madhya–Pradesh/. Accessed on 27 December 2015.

Surin SS, Singh MK, Upasani RR, Thakur R and Pal SK. 2013. Weed management in rice (*Oryza sativa*)–wheat (*Triticum aestivum*) cropping system under conservation tillage. *Indian Journal of Agronomy* **58**(3): 288–291.

Susha VS, Das TK, Nath CP, Pandey R, Paul S. and Ghosh S. 2018. Impacts of tillage and herbicide mixture on weed interference, agronomic productivity and profitability of a maize–wheat system in the North–western Indo–Gangetic Plains. *Field Crops Research* **219**: 180–191.

Susha VS, Das TK, Sharma AR and Nath CP. 2014. Carry–over effect of weed management practices of maize (*Zea mays*) on weed dynamics and productivity of succeeding zero and conventional till wheat (*Triticum aestivum*). *Indian Journal of Agronomy* **59**(1): 41–47.

Swanton CJ, Clements DR and Derksen DA.1993. Weed succession under conservation tillage: A hierarchical framework for research and management. *Weed Technology* **7**: 286–297.

Swanton CJ, Mahoney KJ, Chandler K and Gulden RH. 2008. Integrated weed management: Knowledge–based weed management systems. *Weed Science* **56:** 168–172.

Swanton CJ, Shrestha A, Knezevic SZ, Roy RC and Ball–Coelho BR. 2000. Influence of tillage type on vertical seed bank distribution in a sandy soil. *Canadian Journal of Plant Science* **80**: 455–457.

Taa A, Tanner D, Bennie AT. 2004. Effects of stubble management, tillage and cropping sequence on wheat production in the south–eastern highlands of Ethiopia. *Soil and Tillage Research* **76**: 69–82.

Tadesse B, Das TK and Yaduraju NT. 2010. Effect of some integrated management options on *Parthenium* interference in sorghum. *Weed Biology and Management* **10**(3): 160–169.

Teasdale JR and Mohler C. 1993. Light transmittance, soil temperature, and soil moisture under residue of hairy vetch and rye. *Agronomy Journal* **85**: 673–680.

Weston LA. 1996. Utilization of allelopathy for weed management in agroecosystems. *Agronomy Journal* **88**(6): 860–866.

Wicks GA, Crutchfield DA and Burnside OC, 1994. Influence of wheat (*Triticum aestivum*) straw mulch and metolachlor on corn (*Zea mays*) growth and yield. *Weed Science* **42**: 141–147.

www.tribuneindia.com/2014/20140929/punjab. Accessed on 08 Aug 2015.

Yadav SK and Singh G. 2005. Studies on the depth and periodicity of *Phalaris minor* emergence in wheat under different crop establishment methods. *Indian Journal of Weed Science* **37:** (1&2): 29–32.

Yaduraju NT. 2006. Herbicide resistant crops in weed management. P. 297–98. In: *The Extended Summaries, Golden Jubilee National Symposium on Conservation Agriculture and Environment.* October 26–28, Banaras Hindu University, Banaras,.

Younesabadi M, Das TK and Paul S. 2014. Tillage and weed management effect on weeds, non target toxicity in soil and yield of soybean. *International Journal of Farming and Allied Sciences* **3**(9): 962–969.

Younesabadi M, Das TK and Pandey R. 2013a. Effect of herbicide tank–mixes on weed control, yield and physiological parameters of soybean (*Glycine max*) under tilled and no–tilled conditions. *Indian Journal of Plant Physiology* **18**(3): 290–294.

Younesabadi M, Das TK and Sharma AR. 2013b. Effect of tillage and tank–mix herbicide application on weed management in soybean (*Glycine max*). *Indian Journal of Agronomy* **58**(3): 372–378.

Chapter 14

Herbicide resistant weeds in India and their management

R.S. Chhokar*, Ankur Chaudhary[1] and R.K. Sharma
ICAR- Indian Institute of Wheat and Barley Research, Karnal, Haryana 132 001
[1]CCS HAU Regional Research Station, Uchani, Karnal, Haryana 132 001
**Email: rs_chhokar@yahoo.co.in*

Summary

In India, the dependence on herbicide as tool for weed management is increasing. The over reliance on herbicides because of non-feasibility of mechanical interculture due to close spaced crops (rice and wheat) or continuous rains during rainy season (soybean and rice) has led to recently increased cases of herbicide resistance in weeds. In wheat, five weeds (*Phalaris minor*, *Avena ludoviciana*, *Polypogon monspeliensis*, *Chenopodium album* and *Rumex dentatus*) have evolved resistance against acetolactate synthase (ALS) inhibitor herbicides (sulfosulfuron, mesosulfuron, pyroxsulam). Among these, two weeds (*Phalaris minor* and *Avena ludoviciana*) have also evolved resistance against acetyl-coA carboxylase (ACCase) inhibitor herbicides (clodinafop, fenoxaprop and pinoxaden). While in rice, two weeds species (*Cyperus difformis* and *Echinochloa crusgalli*) have evolved resistance to ALS inhibitor herbicides (Bispyribac Na, penoxsulam, ethoxysulfuron, metsulfuron). Also in soyabean, *Echinochloa* spp. is escaping the control with imazethapyr. These increased cases of herbicide resistance require concerted efforts to have timely integrated weed management strategies to contain the yield reductions for sustainable crop production.

Key words: Chemical management, Herbicde resistance, Over use, Weed management

Introduction

Since the cultivation of the crops, weeds have been recognized as the most detrimental biotic factor that reduces quantity and quality of crops. The losses caused by weeds vary depending on their types, density and emergence time in relation to crop. Weeds emerging along with crop or before crop are generally more competitive than those emerging after crop establishment. Globally, weeds are responsible for decreasing the production of the world's eight most important food and cash crops by 13.2% (Oerke, 2006). The evolution of herbicide resistance in weeds have further aggravated yield losses. In India, weeds cause about one third of losses in crop yield. The introduction of herbicides made weed control less labor-intensive and more energy efficient. Due to its cost and time effectiveness, the chemical weed control method has rapidly extended all over the world and become one of the most used tools to control weeds. Unfortunately, this useful tool has been challenged by the evolution of herbicide resistance in current scenario.

In India, there are 60 different modes of action herbicides are registered along with more than 700 formulations thatare available in the market. Herbicides are being used on more than 20 mha in India (DWR 2015) with a share of 20% of total pesticides used. Herbicide consumption (technical grade) increased in India from 1995 (6040 t) to 2010 (7000 t). However, rate of herbicide use or consumed is very less and decreased due to increased use of low-dose herbicides (penoxsulam, pyrazosulfuron, and bispyribac-sodium in rice;clodinafop, metsulfuron, carfentrazone and sulfosulfuron in wheat) that replaced the conventional high-dose herbicides like butachlor, isoproturon 2,4-D, *etc*., that reduced amount of consumed herbicides (Choudhury *et al*., 2016). Punjab topped the list regarding highest consumption of herbicides followed by Uttar Pradesh, Andhra Pradesh, and Maharastra. Soybean farmers of Madhya Pradesh are very fascinated by fenoxaprop-P-ethyl (ACCase inhibitors) and imazethapyr (ALS inhibitors) and consumed higher rate of herbicides while, in Gujarat pendimethalin is very popular amongst cotton farmers for weed management (Choudhury *et al.*, 2016). In India, rice and wheat accounts for about 20 and 28%, respectively of the total herbicide consumption and followed by soybean (9%) and sugarcane (7%) (Yaduraju2012). Due to higher rate of herbicide consumption coupled with monotonous cropping system *i.e*., rice-wheat in north western Indian plains and soybean-wheat in central India,the herbicide resistance in weeds associated with these crops has been observed.

Globally, at present, there are 495 unique cases (species x site of action) of herbicide resistant weeds, with 255 species (148 dicots and 107 monocots). Weeds have evolved resistance to 23 of the 26 known herbicide sites of action and to 163 different herbicides (Heap 2018). Moreover, just in eight years 60 unique cases are added in list of HR weeds, where in 2010 species are 195 (Heap 2010). Further, aggravation of the crisis is that during last three decades no new herbicide site of action or innovative chemistry has been discovered or developed (Duke 2012) and the reasons might be huge cost of development (more than 250 million dollar from discovery to development), more fund diversion towards development of new molecules for insecticides and fungicides development perspectives, industry consolidation, hostile properties of new candidate as a herbicide coupled with very short market buzz due to accelerated development of herbicide resistance (Duke 2012, Reddy and Nandula 2012).

Herbicide resistance (HR) status in India

The three crops namely wheat, rice and soybean, which accounts for the major share of herbicide consumption are facing the problem of herbicide resistant weeds. The resistance cases being reported in these crops are discussed here under.

Herbicide resistant weeds in wheat

Wheat is recognized as most valuable crop for food security as it contributes about 20% protein, 21% food calories and 36% food for global population (Kumar *et al.* 2013, Braun *et al.* 2010). Wheat production has increased tremendously near to nine fold from 11.0 Mt during 1960-61 to 97 Mt during 2017-18 in India. This magic result from the pleiotropic effect associated with adoption of high yielding short statured varieties, increased use of fertilizers and irrigation facilities along with improved pest and weed control measures. Moreover, intensive cultivation of these high yielding input responsive dwarf varieties with less competitiveness provided congenial environment for growth and development of weeds compared to earlier conventional taller cultivars. Among various factors limiting wheat production and productivity, weed infestation is major one.

Weed infestation across different growing regions of wheat causes average yield loss about 20-30% and may up to 66% (Mongia *et al.* 2005, Chhokar *et al.* 2008). While, losses depends upon weed species or type of weed flora, weed density, time of emergence or nature of weed flush, type of weed flora, duration of infestation, wheat cultivar growth habits, cropping system, soil and environmental factors and time of herbicidal application (Chhokar *et al.* 2012). Weed flora of wheat differ from regions to regions and field to field, depending on environmental conditions, cropping sequences or nature of crop grown in rotation, type of tillage operation performed, irrigation availability, type of soil and nature of weed control practices adopted (Saavedra *et al.* 1990, Chhokar *et al.* 2007, 2012). The predominant weeds associated with conventional till wheat are *Phalaris minor, Avena ludoviciana, Poa annua, Polypogon monspeliensis, Rumex dentatus, R. spinosus, Chenopodium album, Anagallis arvensis, Convolvulus arvensis, Medicago denticulate, Malvaparviflora, Vicia sativa, Lathyrus aphaca, Circium arvense, Melilotus alba, Coronopus didymus, Polygonum plebejum* and *Spergula arvensis*. *P. minor, P. monspliensis* and *P. annua* are more important grassy weeds of wheat based irrigated area of Haryana where rice-wheat is predominant cropping system, whereas *Avena fatua, M. indica, R. spinosus, F. parviflora* and *A. tenuifolius* under drier situation especially in cotton/peralmillet-wheat system (Punia *et al.* 2017). No-till system in wheat under rice-wheat system reduced the *Phalaris minor* (littleseed canarygrass) infestation (*Chhokar et al.* 2007, Singh 2007) due to higher soil strength but favoured the infestation of broad-leaved weeds like *Rumex dentatus* (toothed dock)*, Malva parviflora* (little mallow) and *Medicago denticulate* (burclover). Punia *et al.* (2016) reported that in case of rice, density of *E. crusgalli, Echinochloa colona, Leptochloa chinensis, Cyperus* spp, *Ammania baccifera* and *Ecliptaalba* is increased in zero and minimum tillage transplanting system, while, for wheat density of *Chenopodium album, Melilotus indica* and *Rumex dentatus* dominated in zero tillage system. Wild oats showed higher tendency of infestation in non-rice system. However, *C. album* emergence declined remarkably with the adoption of zero tillage over the years. It has been observed that zero tillage in both rice and wheat crops increases the infestation of *Polypogon monsplensis* among grassy weeds **(**Chhokar unpublished data**).** So in future, under double zero (ZT rice-ZT wheat) system such weeds likely to be cause higher yield losses, may exacerbated problem further if the same also shows resistance to applied herbicides as that is what happened with it in recent scenario.

Herbicides offers convenient, flexible and an efficient option of weed control in wheat. However, continuous and intensive use of herbicides with similar chemistry and mechanisms of action in crops/cropping systems over a period of time leads to development of resistant biotypes within the weed community besides undesirable shifts in weed flora towards “difficult to control weed flora”. Gradually the resistant biotypes develop multiple resistances posing a greater threat to the production systems. The development of resistance in weeds is a result of a combination of number of factors which include biology of weed species (seed dormancy, germination, mode of pollination, seed production capacity) and weed seed bank in soil, type of herbicide in use and application methods (Hall *et al.* 1994, Beckie *et al.* 2000). The weed itself, herbicide and cultivation/crop practices modulate development of herbicide resistance.

Current status of herbicide resistance in wheat associated weeds

The herbicide resistance studies done at IIWBR, Karnal have observed five weeds in festing wheat have evolved herbicide resistance (**Table 1**). The increased cases of herbicide resistant weeds are threat to wheat production in India and ultimately food security. The first case of herbicide resistance development in India is resistance to isopropturon (substituted phenyl urea) herbicide reported in *Phalaris minor* due to heavy reliance of mono cropping system (rice-wheat) and sole dependence on isoproturon (Malik and Singh 1995, Chhokar and Malik 2002) during early 1990s. But further problem is being aggravated by the emergence of four new cases of herbicide resistant weeds of *Avana ludvicinana*, *Rumex dentatus*, *Chenopodium album* and *Polypogon monspeliensis* (Chhokar *et al.* 2017, Singh 2016, Singh *et al.* 2017) in rice-wheat system. Now these five weed species showed various level of resistance to applied herbicide and became nuisance for farmers in northern India. The accelerated development of herbicide resistance in wheat associated weeds in short period of time (20 years) against most of wheat herbicides possess serious threat to wheat production in India. However, gravity of fact is that last four species (*Avana ludvicinana*, *Rumex dentatus* Linn, *Chenopodium album*and *Polypogon monspeliensis* (Linn) Desf.) defying herbicidal action against best herbicides chemistry (ACCase and ALS)reported just within last five years. Now, the situation is critical due to absence of effective alternative herbicides to mitigate problem of multiple herbicide resistant population as new species brewing resistance every few season. This horrible burst of resistant escalates the cost of their management as farmers have to apply higher doses of chemicals to modulate weed infestation or pressure to desirable level. Globally, about 75 weed species are reported resistant in wheat. *Phalaris minor* reported resistant to ACCase inhibitors, PSII inhibitor, ALS inhibitors in eight countries with multiple resistant from India and South Africa. *Avena fatua* reported resistant in 17 countries with 14 cases of multiple and most devastating in United States against herbicidal chemistries (ACCase inhibitors, ALS inhibitors, anti-microtubule mitotic disrupter, lipid Inhibitors, cell elongation inhibitors, lipid Inhibitors). *Chenopodium album* reported resistant in 20 countries against ALS inhibitors (B/2), synthetic auxins but more against Photosystem II inhibitors and greater distribution in United States. While, only one case of resistant was reported in Israel against Photosystem II inhibitors (atrazine, and simazine) in *Polypogon monspeliensis* (Heap 2018).

***Phalaris minor* (littleseed canarygrass):** It is a C_3 monocot weed having similar morphological characters as that of wheat that makes it difficult in its early

Table 1. Herbicide resistant weeds of wheat in India and their control

Weeds	Resistance	Susceptible
Littleseedcanarygrass (*Phalaris minor)*	Phenyl urea (Isoproturon), Sulfonylurea (sulfosulfuron, mesosulfuron), Aryloxyphenoxypropionic (Clodinafop), Cyclohexene oxime (Tralkoxydim), Phenylpyrazole (pinoxaden) and Triazolopyrimidine sulfonamide (pyroxsulam)	Flumioxazin, Pendimethalin, Metribuzin, Terbutryn, Flufenacet, and pyroxasulfone
Rabbitfoot grass (*Polypogon monspeliensis*)	Sulfonylurea (sulfosulfuron, mesosulfuron), Triazolopyrimidine sulfonamide (pyroxsulam)	Pendimethalin, Metribuzin Clodinafop, Fenoxaprop, Pinoxaden, Flufenacet and Pyroxasulfone
Toothed dock (*Rumex dentatus*)	Sulfonylurea (metsulfuron, triasulfuron, iodosulfuron), Triazolopyrimidine sulfonamide (pyroxsulam, florasulam)	2,4-D, Carfentrazone, Pendimethalin, FlumioxazinMetribuzin & Terbutryn
Chenopodium album	Sulfonylurea (sulfosulfuron, metsulfuron)	2,4-D, Carfentrazone, Flumioxazin
Avena ludoviciana	Aryloxyphenoxypropionic (Clodinafop) Sulfonylurea (sulfosulfuron, mesosulfuron),	Pyroxasulfone, Flufenacet

discrimination and restrict desirable adoption of mechanical and manual weeding control measures. It has emerged as single dominant grassy weed in wheat fields of north-western Indo Gangetic Plains (IGP), where rice-wheat is more prevalent (Singh *et al*, 1995, Punia *et al.* 2017) due to its greater ability to tolerate/survive anaerobic conditions executed during rice season (Hari *et al.* 2003, Chhokar *et al.* 2012). Furthermore, intensive ploughing performed to make good seed bed for wheat sowing also enhanced germination of *P. minor* due to light stimulation (Franke *et al.* 2007). Moreover, in rice-wheat system, majority of seedling emerged from seeds within depth of one cm and the same declined significantly with increasing seeding depth (Hari *et al.* 2003). Conventional tillage also accelerated the diffusion of gases *i.e.*, O_2 into and CO_2 out of the soil with greater temperature fluctuation, provides brief flush of light during tillage and favors more nitrogen mineralization. These factors consequently help to overcome dormancy and stimulate more germination. After the evolution of isoproturon resistance in *P. minor* during early nineties, farmers faced significant yield reduction in absence of effective alternative herbicides. To halt the diminishing productivity of wheat associated with enhanced herbicide degradation mechanism based biotype of *P minor*, new herbicidal chemistries (acetyl co-A carboxylase (ACCase) and acetolactate synthase (ALS) inhibitors) were screened out and widely promoted for its effective management during 1997-98 (Yadav *et al.* 1997, Chhokar and Malik 2002, Singh 2006 and 2007). The resistant biotypes may develop cross resistance *i.e.*, resistance to two or more herbicide molecules having similar mode of action (Bechie and Rebound 2009) over a period of time due to intensive selection pressure of herbicides on weed population. This is what happened with *P minor*, as sole dependence on ACCase (clodinafoppropargyl, fenoxaprop-p-ethyl) and ALS (sulfosulfuron, mesosulfuron, pyroxsulam) inhibitors based formulations for 10-15 years led to further aggravation of resistance gravity towards these novel chemistries (Chhokar and Sharma 2008, Singh *et al.* 2007) besides, resulted in weed flora shift. Some of *P. minor* resistant biotype showed GR_{50} values for clodinafop and sulfosulfuron greater than 20 times compared to susceptible one but sensitive to pendimethalin, flufenacet, pyroxasulfone, metribuzin, terbutryn, oxyfluorfen and flumioxazin (Chhokar *et al.* 2017). Now management of this multiple herbicide resistant *P. minor* has become quite tedious in Haryana and Punjab. A recent survey conducted in three states revealed wide spread multiple herbicide resistance in *P. minor* in Haryana and Punjab (**Figure 1**).

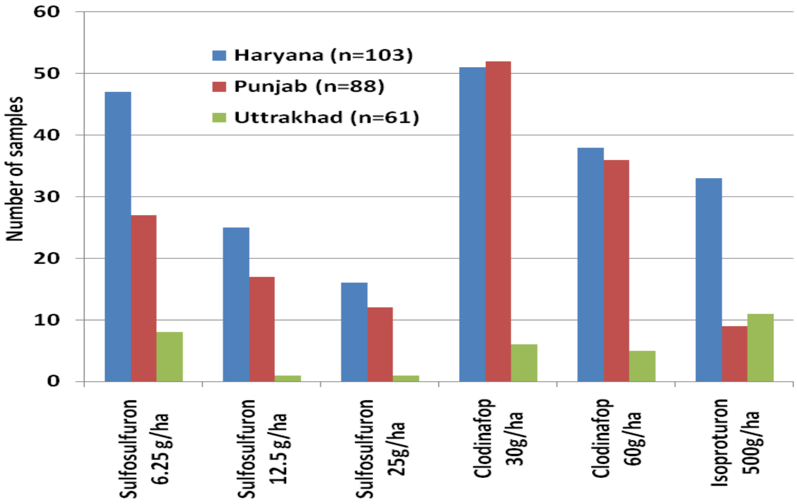


Figure1. *P. minor* populations having a relative growth of more than 50% in comparison to control at a particular dose of herbicide

***Avena ludoviciana* (wild oat):** It is a self-pollinated C_3 allohexaploid species of the Poaceae family and recognized as one of the ten worst annual weeds that halts productivity of various crops. *Avena* spp. are the most important herbicide-resistant weed species worldwide Globally, wild oat showed resistance against seven multiple herbicides site of action (Heap 2018). Wild oat is more elastic and competitive compared to another grassy counterpart *P. minor* due to its early emergence and tremendous competitive capacity against wheat for resources acquisition *viz.*, nutrient and water. Also, wild oat seedlings can emerge from near surface to a depth of more than 10 cm. Clodinafop, fenoxaprop and sulfosulfuron along with pre-mix of mesosulfuron + iodosulfuron were recommended for the control of this grassy weed in the late nineties. Now in India, *A. ludoviciana*has evolved multiple herbicide resistance (ACCase and ALS inhibitor herbicides) in non-rice wheat system (Singh 2016). The alternative herbicides pendimethalin and flumioxazin effective against MHR P minor are not effective against wild oat. However, pyroxasulfone, metribuzin and flufenacet provide control of MHR wild oat.

***Rumex dentatus* (toothed dock):** It is a C_3 dicot weed of *Rabi* season of the Polygonaceae family and is a serious problem of irrigated wheat particularly of rice-wheat based system. This weed is highly competitive and besides reducing the yield also interferes with combine harvesting. Moreover, *Rumex dentatus* L. with long and extensive deep root system showed greater photosynthetic and resource use efficiency *i.e.*, photosynthetic nitrogen and energy use efficiency along with higher specific leaf area, leaf mass per unit area and outcompete *Phalaris mino*r in resource acquisition. These ecophysiological resilient traits likely to benefit more the *Rumex dentatus* compared to *P. mino*r under both limited/assured availability of nitrogen and advocated that former likely to be more precarious (Singh and Singh 2017). Metsulfuron, a sulfonylurea herbicide was recommended for broadleaf weed control in wheat during 1998. This herbicide provided effective control of majority of broad-leaf weeds at a very low dose rate (2-4 g/ha). *Rumex dentatus* is highly sensitive to metsulfuron and this herbicide is providing effective control of this weed for the last 15 years in wheat in India. While, now *Rumex dentatus* has shown a very high level of resistance against metsulfuron (ALS inhibitors herbicides) and resistant biotype showed cross resistance to iodosulfuron, triasulfuron, florasulam, iodosulfuron-methyl-sodium, mesosulfuron-methyl, halauxifen + florasulam and pyroxsulam. But resistant population are sensitive to 2,4-D, carfentrazone, metribuzin, pendimethalin and isoproturon (Chhokar *et al.* 2013). These alternate herbicides along with proper spray techniques can be employed to avoid or delay in development of multiple/cross resistance in *Rumex dentatus*. Globally, it is the first case of resistant in *R. dentatus*, second case of herbicide resistant weed in India while, first among broad-leaf weeds. This is the second *Rumex* species found resistant, as earlier in 2011, *Rumex acetosella* showed resistant against Photosystem II inhibitors (hexazinone) in Canada (Heap, 2018). However, the mechanism of resistance seems to be target based but yet to require detailed analysis and confirmation.

***Polypogon monspeliensis* (rabbitfoot grass)**: It is a major C_3 weed of Poaceae family and a native of Great Britain and Europe (Montenegro *et al.* 1991). It is an important grassy weed of rabi season crops of northern India and reported as third most important weed in irrigated rice-wheat system (Singh *et al.* 1995). This weed shows tremendous capacity of seed production with very light seeds that easily blow away by winds and translocated to one field to another. Longer and delayed emergence of this imparts escape mechanism to it against applied herbicides. Farmers shift from puddle transplanting (PTR) to ZT-DSR or ZT transplanting in rice followed by zero tillage in wheat (double zero) increases infestation of *Polypogon monsplensis* (Chhokar unpublished data). This weed has also evolved resistance against ALS inhibitor herbicides (**Table 1**) but can be controlled with fenoxaprop, clodinafop and pinoxaden herbicides (Chhokar *et al.* 2008, Singh 2009). But development of resistance in *P. minor* and *A. ludoviciana* against these herbicides limits their use for controlling this weed. Flumioxazin and pyroxasulfone were also found effective for control of this weed.

Chenopodium album **(lamb's quarters)**: It is one of the most important C_3 weed of Chenopodiaceae family. This weed also got its presence in the list of worst weeds in the world (Holm *et al.* 1977b) as it infest various crops of dissimilar life cycle, *viz.* wheat, mustard, soybean, corn, garlic, pea, potato, maize, cauliflower, fennel. *Chenopodium album* shows characteristics of climate and stress resilient weeds due to various attributes, *viz.* rapid canopy and growth development, withstand hardest condition such as nutrient and moisture stress or toxicity of metals, indeterminate growth habits, tremendous plasticity with prolific seed production, longer seed viability, delayed germination that imparts escape mechanism against pre or early post emergent herbicides, complex polymorphism, staggered germination and variable dormancy (Chu *et al.* 1978, Hilgenfield *et al.* 2004, Holm *et al.* 1977a, Kurashige and Agarwal 2005, Clemants and Mosyakin 2004). Moreover, this weed having traits that makes it adapted to depleted photosynthetic photon flux density and red to far red light ratio by delaying in seed set, taller growth with greater leaf production per plant (Mahoney and Swanton, 2008). *Chenopodium album* is one among the top ten resistant weeds reflected by presence of its resistant biotype in 20 countries against ALS inhibitors (B/2), synthetic auxins, photosystem II inhibitors, ureas and amides (Heap 2018). In India, recently this weed has shown resistance against ALS inhibitor herbicides (sulfosulfuron, metsulfuron iodosulfuron, triasuluron) and cross resistance to penoxsulam (**Table 1**). However, it can be controlled with 2,4-D, carfentrazone, flumioxazin and pendimethalin.

Herbicide resistant weeds in rice

In India, rice is grown over an area of about 40 mha. The most of the rice is under puddle transplanting (PT) conditions. However, due shortage of water and labour, the alternative crop establishment method (direct dry seeding) is being evaluated and adopted in specific regions having the heavy soil type. The adoption of DSR (direct-seeded rice) has shifted the weed flora and weed is higher in this system as compared to puddle system (Chhokar *et al.* 2014). Weeds, including *Cyperus rotundus* L., *Dactyloctenium aegyptium* (L.) Willd., *Digera arvensis* Forsk., *Phyllanthus niruri* L., and *Trianthema portulacastrum* L. which were found in the un-puddled DSR treatments were absent in the puddled plots, particularly the PT treatments. The yield losses due to weeds in the DSR treatments ranged from 91.4 to 99.0%, compared to 16.0 and 42.0% in the transplanting treatments (PT and NTT) (Chhokar *et al.* 2014). For management of diverse weed flora in DSR application of multiple herbicides either in combination or sequence are required. Recently, acetoacetate synthase (ALS) and ACCase inhibitor herbicides are being extensively promoted for weed management in DSR (Kumar and Ladha, 2011). Bispyribac and penoxsulam are being widely used to control grasses, broad-leaved and sedges weeds in DSR as well as puddle transplanted rice. In light soil, where water does not stagnate for longer time and water is in shortage some of the weeds escape the control with application of pre-emergence herbicides. Recently, some of the biotypes of *Cyperus difformis* have evolved resistance against bispyribac and penoxsulam. These biotypes are showing the cross-resistance against metsulfuron+chlorimuron as well as ethoxysulfuron and flucetosulfuron. However, it can be controlled by nebtazone or 2,4-D as well as pretilachlor application. *Echinochloa crus-galli* is also escaping the control with bispyribac and penoxsulam . These biotypes can be controlled by fenoxaprop or cyhalofop application. These cases are being from the direct-seeded rice fields or the fields, where period of water stagnation on surface is less due to higher infiltration rate. The lack of resistance in conventional rice cultivation might be due to incorporation of various tactics *viz.*, intensive puddling, transplanting of seedlings impart competitive advantage against weeds and also continuous flooding of more than a month. But, in case of DSR there is as such no support of these synergistic practices which provides competitive benefit to crop against weeds. In DSR, as emerging seedlings are less competitive against simultaneously emerging weeds for initial resources acquisition along with absence of flooding that failed to control early flush (Kumar *et al* 2008, Rao *et al.* 2007). Shift from CT PTR to ZT DSR resulted in greater emergence of grassy (*Dactyloctenum aegyptium*, *Echinochloa colon*, (L.) P. Beauv, *Leptochloa chinensis* (L.), *Ischaemum rugosum* Salisb, weedy rice along with *Echinochloa crusgalli*), annual sedges (*Cyperus difformis* L. and *Fimbristylis miliacea* L.)Vahl, broad-leaved weeds (*Digera arevensis* and *Eclipta prostrate*), perennial species (*Paspalum distichum* L., *Cynodon dactylon* (L.) Pers., *Cyperus rotundus* L (Ho 1996, Timsina *et al.* 2010; Singh *et al.*2005a, Kumar and Ladha 2011). So herbicide resistance could become a problem in direct-seeding scenario as in wheat, where sole reliance on herbicides, especially post emergent.

Global view of HR in *Echinochloa colona* and *Cyperus difformis*

Worldwide, more than 51 weed species of rice have shown various level of resistant with 25 cases in various countries, where resistant is multiple in nature and mostly confined to *Echinochloa* species. Resistant in *Echinochloa* species against propanil and bispyribac-sodium (ALS/AHAS) herbicides have been reported earlier (Fischer *et al*. 1993,Valverde2007, El-Nady*et al.* 2012). Globally, *Echinochloa colona* found resistant EPSP synthase inhibitors (glyphosate), photosystem II inhibitors (atrazine, ureas and amides), ACCase inhibitors (cyhalofop-butyl, fenoxaprop-P-ethyl, fluazifop-P-butyl, haloxyfop-P-methyl), ALS inhibitors (bispyribac-sodium), synthetic auxins (quinclorac) and with five cases of multiple resistant. While, *Echinochloa crusgalli* found resistant to above mentioned chemistries along with long chain fatty acid inhibitors (butachlor), microtubule inhibitors (pendimethalin), DOXP inhibitors (clomazone) and 10 cases of multiple resistant (Heap 2018). Global resistant data shown that *Cyperus difformis* found resistant mostly to ALS (B/2) chemistry (bensulfuron-methyl, cyclosulfamuron, pyrazosulfuron-ethyl, azimsulfuron, cinosulfuron, ethoxysulfuron, halosulfuron-methyl, imazosulfuron, and penoxsulam) and only one PSII inhibitor (propanil) (Heap 2018).

Echinochloa colona (jungle rice) is one of the most problematic grass weed of Indian origin with C_4 photosynthetic pathway. This weed aggressively interferes in DSR compared to puddled transplanted rice (PTR) and reported to be infested more than 24 countries (Rao *et al.* 2007). It is an annual weed and propagates mainly through seeds with seed bearing capacity of more than 4000-6000 seeds per plant. Flowering starts from 30-35 days after emergence and reaches maturity within 50-55 days (Awan *et al.* 2014). Due to its close morphological mimicry with rice during seedling stage, laborers failed to discriminate or recognize it with rice and sometimes transplant it instead of rice seedlings during manual transplanting, subsequently compete with rice crop in field. If initially, it is not controlled well then increasing density of this weed may dominate the crop. Variable level of losses is caused by this weed in different rice establishment scenario as about 20-25% in puddle transplanted, 30-35% in wet seeded and greater than 50% in case of dry DSR (Mukherjee *et al.* 2009).

C. difformis known as small flower umbrella-sedge/rice sedge with C_3 photosynthetic pathway and mark its presence in world's worst weeds (Holm *et al.* 1977b). The weed mostly confined in sugarcane, rice (more dominant in DSR), maize and tea. Ephemeral nature (relatively short generation) of this weed *i.e.*, seed to seed just takes 4-6weeks with massive seed production potential imparts escape mechanism to it against various stresses and that could be a valuable trait for its reoccurrence and significant yield losses in crops. *C. difformis* alone could reduce rice grain yields upto12-50% (Ampong-Nyarko and DeDatta 1991).

Seed ecology of these weeds revealed that *C. difformis* germination inhibited 50% at NaCl concentration of 23 mM and osmotic potential -0.12 MPa, while, for *Echinochloa colona* ,it was recorded 106 mM and -0.46 MPa (OP) so tolerate better water and salt stresses which are likely to be more under future climate change scenario (Pérez-López *et al.* 2010). In case of *Cyperus difformis,* about 58% seedling emergence has been recorded when seed on soil surface while, only 0.3% when seed placed to a depth of 0.5 cm and failed to emerge if further depth is increased. *Cyperus difformis, Echinochloa colona* and *Echinochloa crusgalli* showed light preference (photoblastic in nature) and emerged more than 70-80% in light while, negligible in dark (Chauhan and Johnson 2009abc, Chauhan *et al.* 2006). Seed size and light plays an important role in germination of weed species as small seeds tend to germinate more from the surface while, large seeds more under deeper depth based on seed energy reserves. So both the weeds would be a problem or more prevalent in continuous no till due to greater emergence as compared to conventional planting system. Furthermore, initial germination inhibition of photoblastic weed seeds with surface mulch or residue and later close crop canopy imposed significant competition for light, nutrients and water may reduce their interference with crop and subsequent, weed seed bank. Moreover, for effective control of *C. difformis* deeper flooding is required (Moody 1990), which may be a limiting factor in future water scarcity.

Herbicide resistant weeds in soybean

Soybean, pigeonpea and maize are alternative to rice for providing the diversification of rice-wheat system. Soybean (*Glycine max* .) known as "miracle crop" has significantly lower water requirement compared to rice. Self-sustaining nutrient efficient soybean could meet more than 50% of its nitrogen (N) requirement from biologically N_2 fixation (Salvagiotti *et al*. 2008). Studies are going on to standardize on soybean production technology to replace a part of area under rice-wheat with soybean-wheat (SW) cultivation under irrigated situation that also help in enhancing edible oil production and mitigate edible oil crisis. Being a rainy season crop, it suffers severely due to weed infestation. Weed infestation could reduce grain yield by 30 to 85% in soybean if not controlled during critical period of crop-weed competition, depending upon nature, density of weeds and crop management practices (Kachroo *et al.* 2003, Kewat *et al.* 2000). Panda *et al.* (2015) reported that in soybean mainly *Echinochloa colona* (33%) and *Dinebra retroflexa* (24%) were the predominant weeds along with *Alternanthera philoxeroides, Cynodon dactylon*, *Cyperus rotundus*, *Mollugo pentaphylla* and *Eclipta alba.* In India, the major soybean area is in central India.

Chemical control of weeds is now entirely confined to imazethapyr (post-emergence) herbicide to get the satisfactory weed control in soybean (Patel *et al.* 2009, Panda *et al.* 2015). During past 2-3 years *Echinochloa* spp. and *Commelina benghalensis* are escaping the control with imazethapyr with increased doses. There is likely chances of evolution of herbicide resistance and needs to be confirmed and to devise the alternative weed management strategies for sustainability of *Kharif* crops.

Future perspectives

Climate change and behavior of resistant weeds: Climate change bound to influence the ecology of weeds with possible implications for their management. Weeds by virtue of their greater genetic diversity have better adaptability to the changing climate as compared to crops. Weed management is likely to become more complex in future due to increase in their invasiveness, weed shifts, greater development of herbicides resistance in weeds under changing climate. Under the condition of high CO_2 concentration, C_3 plants are likely to become more water-efficient, potentially allowing C_3 weeds to move into drier territories.

Chemical control: Elevated CO_2 and temperature likely to influence biological fitness, herbicides efficacy and management practices employed to control these weed species. Elevated CO_2 induced anatomical and morpho-physiological changes in plants that affect the uptake rate and herbicides translocation in plants (Manea *et al*. 2011, Rodenburg *et al*. 2011). At biochemical level, differential uptake, translocation and metabolism of the herbicide decides the fate of resistance development. C_3 plants reduced their stomata number and conductance while, cuticle thickness increased with more starch accumulation on the surface likely to interfere with selectivity and efficacy of foliar applied herbicides as well as uptake of soil active herbicides due to reduced transpiration (Ainsworth and Long 2005, Patterson 1995, Bailey 2004). Perennial weeds will invade more because of greater vegetative growth stimulated by greater photosynthetic rate results in higher allocation of photosynthates to belowground parts *i.e.*, greater root-shoot ratio (Ziska *et al.* 2004) and subsequently results in "dilution effect" on applied systemic herbicides accompanied with greater conjugation of active chemical. Hence, perennial weeds likely to cause significant problem in no till situation. Metzrafi *et al.* (2016) revealed that global warming reduced herbicide efficacy and increase the incidence of non-target site or metabolic based herbicide resistance. Furthermore, due to attenuation in protein content per gram of plant tissue accompanied with lower requirement of amino acids may interfere with efficacy of amino acids/protein synthesis inhibitor [ALS/AHAS, shikimate acid (EPSP) pathway (glyphosate), glufosinate]efficacy under elevated CO_2 (Bowes 1996) besides, most vulnerable stage to herbicide action *i.e.*, seedling stage would be curtailed or shortened (Ziska *et al.* 1999). Hence, in near future problem of weeds (*Phalaris minor, Avana ludvicinana*, *Rumex dentatus*, *Chenopodium album* and *Polypogon monspeliensis*) due to their C_3 mechanism along with greater plasticity these likely to compete with wheat crop more and may offsets CO_2 fertilization effect in wheat especially during resources limited scenario.

Conservation agriculture and resistant weed behavior: Weed control in CA is a greater challenge than in conventional agriculture because of no tillage coupled with no use of pre-plant incorporation of herbicides. Shift from intensive tillage to no till dramatically affect dynamics of weed population and seed distribution in the soil. Zero tillage scenario most of the seasonal weed seeds remain on the soil surface that enrich the weed seed bank and it acts as the main source of annual weed infestation. That's why under zero tillage the infestation of weeds is more especially during initial years. It has been observed that no-till favours the buildup of *Rumex dentatus* and *Polypogon monspeliensis* but reduces the *P. minor* population associated with higher upper soil strength (Chhokar *et al.* 2007). Higher emergence of these species because of more seeds concentrate near the soil surface rather than when buried deep into the soil (Chhokar *et al.* 2007, 2009), that may be the reason for their higher weed density under NT conditions. *R. dentatus* seeds are light with a perianth due to that these float and accumulate on the soil surface after puddling in rice and while remain on soil surface when zero till sowing is performed in wheat (Chhokar *et al.* 2007). Moreover, under conventional tillage in wheat, seeds of *R. dentatus* are buried deep and failed to emerge if buried to a depth greater than 4 cm (Dhawan 2005). Surface residues can affect seed germination via physical aspects (reduction in light interception and soil surface insulation subsequent, less drastic fluctuations in temperature *i.e.*, thermo moderation along with more entrapment of moisture) and chemical modification in the seed environment (Teasdale and Mohler 1993). Bullied *et al.* (2003) reported that conservation tillage promoted earlier emergence of *A. fatua* and *C. album* compared to conventional tillage.

The germination response of weeds to residue depends on the quantity (amount of residue present on surface), position (vertical or flat and below or above weed seeds), and allelopathic potential (important characteristics of cover crops) of the residue. Emergence of *Phalaris minor*, *Chenopodium album,* and *Rumex dentatus* was inhibited by 45, 83 and 88%, respectively at 6 t/ha rice residue load compared to without residue mulch (Kumar *et al.* 2013). Dhima *et al.* (2006) also reported that the plant residues of barley, rye, and triticale retained in a maize field showed their allelopathic effect against *E. crusgalli* and decreased its emergence by 27-80% compared with the non-mulched treatment, however maize plants received no harmful effect from the applied mulches. When zero tillage is practiced with residue retention then weed infestation will be lesser. This is because crop residues alter environmental conditions related to weed seed germination, physically impede seedling growth, or inhibit germination and growth by allelopathy (Crutchfield *et al.* 1986).Chhokar *et al.* (2009**)** observed that 2.5 t/ha rice residue mulch was not effective in suppressing weeds, but 5.0 and 7.5 t/ ha residue mulch reduced weed biomass by 26 to 46%, 17 to 55%, 22 to 43%, and 26 to 40% of little seed canary grass, Indian sorrel, bur clover and foxtail grass, respectively, compared with ZT without residue. Besides, modulating emergence of weeds, presence of surface residue enhances weed seed predation rate and helps in depleting seed bank. Kumar *et al.* (2013) reported that *P. minor* seed predation (post dispersal) was more under zero tillage with residue (50-60%) compared to conventional tilled wheat (10%).

Since weeds are not physically controlled in the zero-tillage system, reliance on efficacy of herbicides is increased. However, due to negligible option for effective post emergent herbicides with greater vulnerability to herbicide resistance makes pre-emergence (PRE) herbicides the best solution. PRE herbicides are less effective in the conservation system due to presence crop stubble/residue load that intercept and trap huge amount of applied herbicides (Chauhan and Abugho 2012) and absence of soil incorporation that prompt losses through volatilization/ photodecomposition. So to enhance efficacy of PRE herbicides, research should be focused on optimizing spray volume and time of application (projecting PREs as EPOE) along with droplet size. Moreover, detailed analysis is required to upsurge penetration capacity of applied herbicides with and without surfactant for weed control. Another unhealthy alternative practice of residue management *i.e.*, residue burning has its own problem. Burning of rice straw increases the germination of littleseed canarygrass besides reducing the efficacy of soil-active herbicides like isoproturon, pendimethalin and pyroxasulfone (Chhokar *et al.,* 2009). New herbicidal chemistries with novel and multiple modes of action *viz.*, pyraxasulfone, flumioxazin (inhibition of protoporphyrinogen oxidase), diflufenican (phytoenedesaturase inhibiotrs), flufenacet (inhibition of cell division/ very long chain fatty acids) should be integrated with other management strategies for effective control of these resistant weeds. But for effective control of all cohorts PREs should be integrated with resilient (less vulnerable to resistance development) post emergent herbicides.A study revealed that synergistic integration of zero tillage + residue retention (8 t/ha) along with higher seed rate (125 kg/h) coupled with pre-emergence herbicide mixture (pendimethalin 1.5 + metribuzin 0.210 kg/ha) beneath the mulch dramatically reduced weed population to about zero (Sindhu *et al*. 2017). Proper selection of herbicide formulations and spray volume for application under heavy residue may be necessary to increase its efficacy.

Management perspectives

Preventive measures

In view of increased cases of herbicide resistance, there is need to give more emphasis on preventive control measure to contain the spread of resistant weeds. For this, focus should be on use of weed-free crop seeds and adoption of cultural and mechanical measures to minimize the weed infested area and decrease the dissemination of weed seeds from one area to another or from one crop to another. Besides use of weed-free clean crop seed the other strategies include, use of well-decomposed manure/compost to destroy viability of seeds in fields, use of clean agricultural implements, and managing weeds on irrigation ditches, bunds or levees and roads along with prevention of weed seed rain by mechanically cutting the reproductive part prior to seed setting, Implement quarantine laws to prevent the entry of alien invasive and obnoxious weed seeds having the herbicide resistance.

Stale seedbed

This practice can be a valuable measure to reduce weed pressure in till or no-till systems having the problem of herbicide resistance. The main advantage of the stale seedbed practice is that the crop emerges in weed-free environments and it will have a competitive advantage over late-emerging weed seedlings. It depletes the seed bank in the surface layer of the soil and reduces subsequent weed emergence. This practice involves lightly irrigation in field 10–15 days prior to actual seeding which favour and encourages the germination of weed seeds lying on the soil surface. As most of the weed seeds remain in the topsoil layer in case of no till and weed seeds mostly germinate and emerge from the upper soil layer, a flush of weed seedlings will appear within a week after irrigation. Emerged weeds are then destroyed by the application of non-selective herbicides like glyphosate or paraquat in no till system or by ploughing in till system.

Weed seed predation

It can be altered with nature and amount of crop residue, tillage adoption (Cromar *et al.* 1999) as with adoption of no till in soybean results in about 30% predation of *Echinochloa crusgalli* and *Chenopodium album* seed. Muthukumar *et al.* (2013) reported that no till leads to seed predation of Red rice and Barnyard grass of about 80-85 and 49-77% respectively, in soybean. So there is need to screen and identify the suitable weed seed predators and congenial environment for their multiplication especially in case of rice-wheat system, where the resistance development in weeds is being occurring in quicker rate. Furthermore, this may be enhanced by adopting direct seeding of rice along with retention of residue of wheat, moongbean or *sesbania* or other crops that can be fitted in intensive rice-wheat cropping system.

Competitive crop cultivars

Crop cultivars vary in their growth behavior and competitiveness.Plant characteristics associated with weed competitiveness are more plant height, early canopy cover, high tiller density, high leaf area (leaf area index) leading to more light interception and shading, vertical leaf orientation, rapid biomass accumulation at the early crop growth stage, high shoot dry weight, large root biomass, and root volume (Ni *et al.* 2000, Mason *et al.* 2007, Saito *et al.* 2010). In the wake of herbicide resistance evolution and changing weed flora in response to management practices, crop competition is a valuable weed management option. In Future, there is need to focus on the breeding for crop cultivars having fast germination, early growth and high biomass which can help in better weed management by providing the competitive advantage over weeds. Further, better understanding of biology and ecology of weeds would certainly aid in efficient weed management using crop competitiveness. Competitive crop cultivars have special importance in case of direct seeded rice (DSR) to module crop weed competition. There is need to design or incorporate competitive traits in DSR as conventional puddled cultivars do not fit ecologically in former scenario.

Diversified crop rotation

Regardless of herbicides, crop rotation is an important measure for diversifying weed communities and rotating selection pressure (Radosevich *et al.* 1997, Nicholass *et al.* 2015). The mechanisms by which crop rotation reduces the size of weed seed banks and opportunities for weed emergence and growth with diverse selection pressure and that can be harmonized with adopting crop sequences that employs spatio and temporal variation for resource competition (Liebman and Dyck 1993), niche disruption, rotating crop with dissimilar planting and harvest dates (Nicholas *et al.* 2015), growth habit, competitive ability (Buhler 2003, Buhler *et al.* 1997), soil disturbance, mechanical damage, allelopathy (Sosnoskie *et al.* 2009) that ultimately interfere with growth and development of weed and subsequently determines level of weed association with crop. Furthermore, diverse crop rotation also affects species communities by determining the type of tillage, tillage frequency, time of tillage events relative to crop and weed emergence, herbicide programme (availability and dose) besides cropping practices, such as, crop seed rate, fertilization and irrigation practices.

Herbicide mixture, rotation and spray technology

Herbicide rotation or mixing of different herbicides of diverse modes of action with variable selection pressure may help in delay herbicide resistance in weeds and conserve susceptible gene in weed population that subsequently, prolong the commercial life of herbicides. There is need to optimize spray volume, nozzle spray pattern, formulation as well as time of spray so that a synergy can be built under mulch or residue condition with herbicides that effectively control the weeds with minimum herbicide environmental leakage. Further there is need to assemble spraying component on the combine harvester, especially having the straw management system (SMS) that prolong the effect of herbicidal action on weeds with minimum interception. In view of lesser availability of new mode of action herbicides focus should also be given on the development of herbicide tolerant and resistant cultivars to manage the resistance problem in weeds. However, recognized as two edge sword "herbicide tolerant crop"adoption require preconscious knowledge bank due to variable risk associated with these in the form of shrinkage in crop genetic diversity, tremendous resistance build up in weed against employed herbicide over the years, gene flow or flow to similar weed species, undesirable weed shift along with poor biological diversity (Kumar *et al.* 2008b)

Weed seed bank dynamics

Studies should be conducted to quantify the seed predation rate, seed emergence pattern, seed viability, period of dormancy *etc*. Further, there is need to establish niche development for specific weed seed predators and should promote no till with optimum residue retention to enhance the activity and diversity of the seed predators. Weed seed destructor can also be employed to deplete or preventing development of weed seed bank. In this regards, machineries like Harrington seed destructor (HSD), narrow windrow burningchaff carts, and bale direct can be utilsed which are based on the principle of weed seed collection during harvesting period of grain crop that limits the replenishment and enrichment of the seed bank. Walsh *et al.* (2012) reported that with Harrington seed destructor has given astonishing results by seed control of different weeds species *viz*., wild radish, wild oat, brome grass and annual ryegrass by 93, 99, 99 and 95% seed control**,** besides providing soil protection from erosion and enhancement of fertility. So these weed seed target based strategies can be employed for the sustainable weed management. Further, there is need to understand biological fitness of resistant biotype along with future scenario (elevated CO_2, temperature under limited resources availability *i.e*., nutrient and moisture in comparison to normal/susceptible one.

Adopting and integrating best management practices like closer spacing, bidirectional sowing, early planting, higher seed rate, competitive crop cultivars, optimum rate of fertilizer and irrigation, avoid straw burning rather using it as surface mulch, strategic crop rotation involving crops such sorghum, sugarcane or sunflower or other crops with some allelopathic potential with alternative herbicides can contribute significantly in reducing the resistance problem and sustaining the crop production.

References

Ainsworth EA and Long SP. 2005. What have we learned from 15 years of free–air CO_2 enrichment (FACE)? A meta–analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO_2. *New Phytologist* **165**: 351–372.

Alberto A, Ziska L, Cervancia C and Manalo P. 1996. The influence of increasing carbon dioxide and temperature on competitive interactions between a C_3 crop, rice (*Oryza sativa*) and a C_4 weed (*Echinochloa glabrescens*). *Functional Plant Biology* 23(6): 795–802

Ampong–Nyarko K and DeDatta SK. 1991. *A Handbook for Weed Control in Rice*. Manila, Philippines: International Rice Research Institute.

Awan TH, Chauhan BS and Cruz PCS. 2014. Growth plasticity of jungle rice (*Echinochloa colona*) for resource use when grown with different rice (*Oryza sativa*) planting densities and nitrogen rates in dry–Seeded conditions. *Weed Science* **62**: 571–587.

Bailey SW. 2004. Climate change and decreasing herbicide persistence. *Pest Management Science* **60**: 158–162.

Beckie H J, Heap I M, Smeda R J and Hall LM. 2000. Screening for herbicide resistance in weeds. *Weed Technology* **14**: 428–445.

Bowes G. 1996. Phtosythestic responses to changing atmospheric carbon dioxide concentrations. Pp 397–407. In: *Photosynthesis and the environment.* (Ed. Baker NR), Kluwer Academic Publishers, The Netherlands.

Braun HJ, Atlin G and Payne T. 2010.Multi location testing as a tool to identify plant response to global climatic change. In: *Climate Change and Crop Production* (Ed. Reynolds CRP) CABI, London, U.K.

Buhler DD, Hartzler RG and Forcella F. 1997. Weed seed bank dynamics– implications to weed management. *Journal of Crop Production* **1**: 145–168.

Buhler DD. 2003. Weed biology, cropping systems, and weed management. *Journal of Crop Production* **8**: 245–270.

Bullied WJ, Marginet AM and Van Acker RC. 2003. Conventional– and conservation–tillage systems influence emergence periodicity of annual weed species in canola. *Weed Science* **51**: 886–897.

Chauhan BS and Abugho SB. 2012.Interaction of rice residue and *PRE* herbicides on emergence and biomass of four weed species. *Weed Technology* **26**: 627–632.

Chauhan BS and Johnson DE. 2009a. Ecological studies on *Cyperus difformis, C. iria* and *Fimbristylis miliacea*: Three troublesome annual sedge weeds of rice. *Annals of Applied Biology* **155**: 103–112.

Chauhan BS and Johnson DE. 2009b. Influence of tillage systems on weed seedling emergence pattern in rainfed rice. *Soil & Tillage Research* **106**: 15–21.

Chauhan BS and Johnson DE. 2009c. Seed germination ecology of jungle rice (*Echinochloa colona*): A major weed of rice. *Weed Science* **57**: 235–240.

Chauhan BS, Gill G and Preston C. 2006. Tillage system effects on weed ecology, herbicide activity and persistence: A review. *Australian Journal of Experimental Agriculture* **46**: 1557–1570.

Chhokar RS and Malik RK. 2002. Isoproturon resistant *Phalaris minor* and its response to alternate herbicides. *Weed Technology* **16**: 116–123.

Chhokar RS and Sharma RK. 2008. Multiple herbicide resistance in little seed canary grass (*Phalaris minor*); A threat to wheat production in India. *Weed Biology and Management* **8**: 112–123.

Chhokar RS, Sharma RK, Garg R and Sharma Indu. 2013. Metsulfuron resistance in *Rumex dentatus*. *Wheat Barley Newsletter* **7**(2): 11.

Chhokar RS, Sharma RK, Gill SC, Singh R and Singh GP. 2017. Management of herbicide resistant weeds for sustainable wheat production. P. 32. In: *Proceedings of Biennial Conference on "Doubling Farmers' Income by 2022: The Role of Weed Science"*, 1–3 March, 2017, Udaipur. Indian Society of Weed Science, Jabalpur, India. 322 p.

Chhokar RS, Sharma RK, Jat GR, Pundir AK and Gathala MK. 2007.Effect of tillage and herbicides on weeds and productivity of wheat under rice–wheat growing system. *Crop Protection* **26**: 1689–1696.

Chhokar RS, Sharma RS, and Sharma I. 2012. Weed management strategies in wheat–A review. *Journal of Wheat Research* **4**(2): 1–21.

Chhokar RS, Singh S and Sharma RK. 2008. Herbicides for control of isoproturon–resistant little seed canary grass (*Phalaris minor*) in wheat. *Crop Protection* **27**: 719–726.

Chhokar RS, Singh S, Sharma RK and Singh M. 2009. Influence of straw management on *Phalaris minor* control. *Indian Journal of Weed Science* **41**: 150–156.

Chhokar, RS, Sharma RK and Verma RPS. 2008. Pinoxaden for controlling grass weeds in wheat and barley. *Indian Journal of Weed Science* **40**: 41–46.

Chhokar, RS, Sharma RK, Gathala MK and Pundir AK. 2014. Effect of crop establishment techniques on weeds and rice yield. *Crop Protection* **64**: 7–12.

Choudhury PP, Singh R, Ghosh D and Sharma AR. 2016. *Herbicide Use in Indian Agriculture*. ICAR – Directorate of Weed Research, Jabalpur, Madhya Pradesh, 110 p.

Chu C, Ludford PM, Ozbun JL and Sweet RD. 1978. Effects of temperature and competition on the establishment and growth of redroot pigweed and common lambsquarters.*Crop Science* **18**: 308–310.

Cromar HE, Murphy SD and Swanton CJ. 1999. Influence of tillage and crop residue on post–dispersal predation of weed seeds. *Weed Science* 47: 184–194.

Crutchfield DA, Wicks GA and Burnside OC. 1986.Effect of winter wheat (*Triticum aestivum*) straw mulch level on weed control. *Weed Science* **34**: 110–114.

Dhawan R. 2005. Studies on germination and emergence of *Rumex maritimus*. *Indian Journal of Weed Science* **37**: 144–146.

Dhima K, Vasilakoglou I, Eleftherohorinos I and Lithourgidis A. 2006. Allelopathic potential of winter cereals and their cover crop mulch effect on grass weed suppression and corn development. *Crop Science* **46**: 345–352.

Duke SO. 2012. Why have no new herbicide mode of action appeared in recent years? *Pest Management Science* **68**: 505–512.

DWR. 2015.*Vision 2050*. Directorate of weed Research. Indian Council of Agricultural Research, Jabalpur 482004, Madhya Pradesh.

El–Nady M, Hamza A and Derbalah A. 2012.*Echinochloa colonum* resistance to bispyribac–sodium in Egypt—occurrence and identification. *Journal ofPlant Protection Research* **52**: 139–145.

Fischer AJ, Granados E and Trujillo D. 1993.Propanil resistance in populations of jungle rice (*Echinochloa colona*) in Colombian rice fields. *Weed Sci*ence **41**:201–206.

Franke AC, Singh S, McRoberts N, Nehra AS, Godara S, Malik RK and Marshall G. 2007. *Phalaris minor* seed bank studies: Longevity, seedling emergence and seed production as affected by tillage regime. *Weed Research* **47**: 73–83.

Hall LM, Holtum JAM and Powles SB. 1994. Mechanisms responsible for cross resistance and multiple resistance. Pp. 243–261. In: *Herbicide Resistance in Plants: Biology and Biochemistry* (Eds. Holtum JAM and Powles SB). Lewis Publishers, Boca Raton, FL, USA.

Hari Om, Dhiman SD, Hemant K and Sajjan K. 2003. Biology and management of *Phalaris minor* in wheat under a rice–wheat system. *Weed Research* **43**: 59–67.

Heap I. 2010. The International Survey of Herbicide Resistant Weeds. Online. Internet.. Available *www.weedscience.com*

HeapI. 2018 The International Survey of Herbicide Resistant Weeds. *www.weedscience.org* (01.11.2018).

Hilgenfield KL, Martin AR, Mortensen DA and Mason SC. 2004. Weed management in glyphosate resistant soybean system: weed species shifts. *Weed Technology* **18**: 284–291.

Ho Nai–Kin. 1996. Current status of rice herbicides use in the tropics. Pp.77–86. In: JIRCAS *International Symposium.*No.**4**:.

Holm LG, Plucknett DL, Pancho JV and Herberger JP. 1977b. The *World's Worst Weeds. Distribution and Biology*. Honolulu, Hawaii, USA: University Press of Hawaii.

Holm LG, Plucknett DL, Pancho JV and Herberger JP.1977a. *Chenopodium album* L. Chenopodiaceae, goosefoot family. Pp 84–91. In: *The World's Worst Weeds: Distribution and Ecology.* Honolulu, HI: University Press of Hawaii.

Kachroo D, Dixit AK and Bali AS. 2003. Weed management in oilseed crops– A Review. *Shair A Kashmir University of Agricultural Science and Technology Journal of Research* **2**(1): 1–12.

Kelley, J.P., 1998. *Impact of Cultural Practices on Jointed Goatgrass (Aegilops Cylindrica) in Wheat (Triticum aestivum).*MS thesis. Oklahoma State University, Stillwater, OK, 35 p.

Kewat ML, Pandey J, Yaduraju NT and Kulshreshtha G. 2000. Economic and ecofriendly weed management in soybean. *Indian Journal of Weed Science* **32**(3&4): 135–139

Koscelny, J.A., Peeper, T.F., Solie, J.B., Solomon Jr., S.G., 1990. Effect of wheat (*Triticum aestivum*) row spacing, seeding rate, and cultivar on yield loss from cheat(*Bromus secalinus*). *Weed Technology* **4**, 487–492.

Kumar V and Ladha JK. 2011. Direct–seeding of rice: recent developments and future research needs. *Advances in Agronomy* **111**: 297–413.

Kumar V, Bellinder RR, Gupta RK, Malik RK and Brainard DC. 2008. Role of herbicide–resistant rice in promoting resource conservation technologies in rice–wheat cropping systems of India: A review. *Crop Protection* **27**: 290–301.

Kumar V, Singh S, Chhokar RS, Malik RK, Brainard DC and Ladha JK. 2013. Weed management strategies to reduce herbicide use in zero–till rice–wheat cropping systems of the Indo–Gangetic Plains. *Weed Technology* 27: 241–254.

Kurashinge NS and Agarwal AA. 2005. Phenotypic plasticity to light competition and herbivory in *Chenopodium album* (Chenopodiaceae). *American Journal of Botany***92**(1): 21–26.

Liebman M and Dyck E. 1993. Crop rotation and intercropping strategies for weed management. *Ecological Applications* **3**: 92–122.

Mahoney KJ and Swanton CJ.2008. Exploring *Chenopodium album* adaptive traits in response to light and temperature stresses. *Weed research* **48**(6): 552–60.

Malik RK and Singh S. 1995. Little seed canary grass (*Phalaris minor*) resistance to isoproturon in India. *Weed Technology* **9**: 419–425.

Manea A, Leishman MR and Downey PO. 2011. Exotic C_4 grasses have increased tolerance to glyphosate under elevated carbon dioxide. *Weed Science* **59**: 28–36.

Matzrafi M, Seiwert B, Reemtsma T, Rubin B and Peleg Z. 2016. Climate change increases the risk of herbicide–resistant weeds due to enhanced detoxification. *Planta* **244**: 1217–27

Mongia AD, Sharma RK, Kharub AS, Tripathi SC, Chhokar RS and Shoran J. 2005.Coordinated research on wheat production technology in India. Karnal, India: *Research Bulletin No.*20, Directorate of Wheat Research. p 40.

Montenegro CS, Teillier P, Arce and Poblete V.1991.Introduction of plants into the mediterranean–type climate area of Chile. Pp. 103–114. In: *Biogeography of Mediterranean Invasions,* Groves, R. and F. Di Castri (eds.). Cambridge Univ. Press, Cambridge. 485 p.

Moody K. 1990.Pest interaction in rice in the Philippines. Pp. 269–299. In:*Pest Management in Rice* (Eds. Grayson BT, Green MB, and Copping LG.),.New York Society of Chemistry Industry, New York.

Mukherjee J, Kaur R, Kaur M andMahey RK. 2009. Production potential of rice (*Oryza sativa*) as affected by varying population densities of *Echinochloa crusgalli*. *Indian Journal of Weed Science* **41**: 32–37.

Muthukumar V, Bagavathiannan and Norsworthy JK. 2013. Post–dispersal loss of important arable weed seeds in the midsouthern United States. *Weed Science* **61**:570–579.

Nichols V, Verhulst N, Cox R and Govaerts B. 2015. Weed dynamics and conservation agriculture principles: A review. *Field Crop Research* **183**:56–68.

Oerke EC. 2006. Crop losses to pests. *Journal of Agricultural Science* **144**: 31–43.

Panda S, Lal S, Kewat ML, Sharma JK and Saini MK. 2015. Weed control in soybean with propaquizafop alone and in mixture with imazethapyr. *Indian Journal of Weed Science* **47**(1): 31–33.

Patel RK, Sondhia S and Dwivedi AK. 2009. Residues of imazethapyr in soybean grain, straw and soil under application of long term fertilizers in typichaplustert. *Indian Journal of Weed Science* **41**(1&2): 90–92.

Patterson DT. 1995. Weeds in a changing climate. *Weed Science* **43**: 685–701.

Pérez–López U, Robredo A, Lacuesta M, Muñoz–Rueda A and Mena–Petite A .2010. Atmospheric CO_2 concentration influences the contributions of osmolyte accumulation and cell wall elasticity to salt tolerance in barley cultivars. *Journal of Plant Physiology***167**(1): 15–22.

Punia SS, Singh S, Yadav A, Yadav DB and Malik RK. 2016. Long–term impact of crop establishment methods on weed dynamics, water use and productivity in rice–wheat cropping system. *Indian Journal of Weed Science* **48**(2): 158–63.

Punia SS, Yadav DB, Kaur M and Sindhu VK. 2017. Investigations on weed flora of wheat in Haryana. *Agriculture Research Journal* **54** (1): 136–138

Radosevich S, Holt J and Ghresa C. 1997. *Weed Ecology: Implications for Management,* 2nd. John Wiley & Sons, NY, USA, 589 p..

Rao AN, Johnson DE, Sivaprasad B, Ladha JK and Mortimer AM. 2007. Weed management in direct–seeded rice. *Advances in Agronomy* **93**: 153–255.

Reddy KN and Nandula VK .2012. Herbicide resistant crops: History, development and current technologies. *Indian Journal of Agronomy* **57** (1): 1–7.

Rodenburg J, Meinke H and Johnson DE. 2011. Challenges for weed management in African rice systems in a changing climate. *Journal of Agricultural Science* **149**: 427–435.

Saavedra K, Torres LG, Bermejo EH and Hildago B. 1990. Influence of environmental factors on the weed flora in crop in the Guadalquivir Valley. *Weed Research* **30**: 363–374.

Salvagiotti F, Cassman KG, Specht JE, Walters DT, Weiss A and Dobermann A. 2008. Nitrogen uptake, fixation and response to fertilizer N in soybean: a review. *Field Crops Research* **108:** 1–13.

Sindhu VK, Singh S, Punia SS and Singh S. 2017. Pre–emergence herbicides can tactically fit into conservation agriculture systems with various benefits. In: "*Doubling Farmers' Income by 2022: The Role of Weed Science*", Biennial Conference of the Indian Society of Weed Science on MPUA&T, Udaipur, India during 1–3 March, 2017.

Singh G, Singh Y, Singh VP, Johnson DE and Mortimer M. 2005a. System–level effects in weed management in rice–wheat cropping in India. pp. 545–550. In: *Proceedings of the BCPC International Congress on Crop Science and Technology*, Vol. 1, The British Crop Protection Council, Glasgow, Scotland, UK.

Singh S, Dhillon A, Gowda P, Irfan M and Kumar P. 2017. Strategies to manage multiple resistant wheat weeds in India to herbicides of several sites of action. P. 169 In: The 26th Asian Pacific Weed Science Society Conference–Weed Science for People, Agriculture and Nature September19–22, 2017 Kyoto Japan pp.

Singh S, Malik R K, Balyan R S and Singh Samar.1995. Distribution of weed flora of wheat in Haryana. *Indian Journal of Weed Science* 27: 114–121.

Singh S. 2006. Herbicide resistance mechanism in *Phalaris minor* and its consequences on management strategies. *Indian Journal of Weed Science* **38**: 183–193.

Singh S. 2007. Role of management practices on control of isoproturon resistant little seed canary grass (*Phalaris minor*) in India. *Weed Technology* **21**: 339–346.

Singh S. 2009. Evaluation of some graminicides against *Polypogon monspeliensis* (L.)Desf. *Indian Journal of Weed Science* **41**(1&2): 96–98.

Singh S. 2016. FOPS resistance in *Avena ludoviciana*– first case from India. Pp 13–17. In: Jan–June, ISWS Newsletter.

Singh V and Singh H. 2017.Effect of nitrogen application on biomass and ecophysiology of *Phalaris minor* and *Rumex dentatus* in wheat field of Indo–Gangetic plains**.** pp. 37–38. *Proceedings, Volume III (Poster Papers)*. 25th Asian–Pacific Weed Science Society Conference, Hyderabad, India. Indian Society of Weed Science, Jabalpur.

Sosnoskie LM, Herms CP, Cardina J and Webster TM. 2009. Seed bank and emerged weed communities following adoption of glyphosate–resistant crops in a long–term tillage and rotation study. *Weed Science* **57**: 261–270.

Teasdale JR and Mohler CL. 1993. Light transmittance, soil temperature, and soil moisture under residue of hairy vetch and rye. *Agronomy Journal* **85**: 673–680.

Timsina J, Haque, Chauhan BS, Johnson DE. 2010. Impact of tillage and rice establishment methods on rice and weed growth in the rice–maize–mungbean rotation in northern Bangladesh. In: *28th International Rice Research Conference*, 8–12 November 2010. Hanoi, Vietnam OP09: Pest, Disease, and Weed Management.

Valverde BE. 2007. Status and management of grass–weed herbicide resistance in Latin America. *Weed Technol*ogy **21**: 310–323.

Walsh MJ, Harrington RB and Powles SB.2012. Harrington seed destructor: a new nonchemical weed control tool for global grain crops. *Crop Science* **52**: 1343–1347.

Yadav A, Malik RK and Balyan RS. 1997. Studies on alternate herbicides to control isoproturon–resistant little seed canary grass. *Pestology* **21**: 26–28.

Yaduraju NT. 2012. Weed management perspectives for India in changing agriculture scenario in country. *Pakistan Journal of Weed Science and Research* **18**: 703–710.

Ziska LH, Faulkner SS and Lydon J. 2004. Changes in biomass and root: shoot ratio of field–grown Canada thistle (*Cirsium arvense*), a noxious, invasive weed, with elevated CO_2: implications for control with glyphosate. *Weed Science* **52**: 584–588.

Ziska LH, Teasdale JR and Bunce JA. 1999. Future atmospheric carbon dioxide may increase tolerance to glyphosate. *Weed Science* **47**: 608–615.

Chapter 15

Weed utilization for phytoremediation

P.J. Khankhane* and Sushil Kumar[1]
ICAR-National Bureau of Soil Survey and Land Use Planning Regional Centre,
New Delhi 110 012
[1]ICAR-Directorate of Weed Research, Maharajpur, Jabalpur,
Madhya Pradesh 4820 04
**Email: pjkhankhane@yahoo.com.ph*

Summary

In context to water purification purposes, some fast growing weedy plants with high biomass have shown potential in removing contaminants from waste water. The use of such specially selected metal accumulating plants for environmental cleanup is termed as phytoremediation. Phytoremediation is a promising technology for remediating contaminated soils or water by metal hyper-accumulation in certain plants. The oxidation pond or activated sludge process are the two most commonly used wastewater treatment technologies in India. Being expensive and requiring complex operations and maintenance for these processes, macrophyte assisted wetland technology has been receiving greater attention in recent years. Macrophyte based bioremediation technologies are very promising and are applicable to prevent, control and remediate the contaminated water using aquatic weedy plants. In order to clean up the water, sediment or soil through various approaches of phytoremediation, selection of suitable plants is of prime importance. Depending on the macrophyte based treatment, floating aquatic plants in free water surface wetland and emergent weedy plants in sub-surface wetland are capable for increasing of water quality parameters like biological oxygen demand, chemical oxygen demand, nitrates to the levels that allow the use of the purified water for discharging in surface water bodies. More aquatic plants and porous media requires to be tested for heavy metals and phosphorus removal. Metal contaminated weedy plant biomass is still a challenge. Higher proportion of heavy metals are stored in roots than in shoot part of aquatic plants. To delay metal entry into food chain, possible uses of metal rich weed biomass as a raw material for biogas, paper pulp and ethanol production are also discussed. This chapter review the use of weed plants for purify the water for its use in other activities.

Key words: Macrophytes, Bioremediation, Containments, Heavy metal, Phytoremediation, Utilizable products

Introduction

The waste water generated as sewage from class I and class II towns together is estimated to be about 38,254 million liters /day (MLD) out of which only 11,787 MLD (35%) is being treated with a capacity gap of 26,467 MLD which needs urgent attention of all concerned (CPCB 2010). Due to lack of inadequate treatment facility in many cities, millions of tons of untreated sewage and industrial effluents are being discharged in surface water bodies like rivers, ponds and lakes. This has resulted in deterioration of water quality of surface water bodies in the form of eutrophication. Due to rapid industrial development and rapid urbanization during the last two decades in India, disposal of industrial effluents has become serious problem. The application of water from waste water carrying drains to agricultural lands is a general practice in peri-urban areas that received renewed attention with the increasing scarcity of freshwater resources in many arid and semiarid regions (Chhonkar *et al,* 2000a,b). Sewage effluents from municipal origin are rich in organic matter and also contain appreciable amounts of major and micronutrients (Brar *et al*. 2000). Recently it is estimated that growing Indian cities have the potential to support their peri-urban futures by providing irrigation water for food production. Over 1.1 million ha of land could be irrigated, if the city waters are rendered safe for use. While the practice of peri-urban agriculture using city water is not a new phenomenon in India, its full potential has not been fully explored, due to poor/ marginal quality (Amerasinghe *et al*. 2012). Chhonkar *et al* (2005) reported that farmers in Bakarwala village using sewage effluents for irrigation revealed that the crop yields had gone up without matching increase in fertilizer use.

Besides plant nutrients these effluents often contain high amounts of various organic and inorganic materials and heavy metals as well, depending upon the industry from where these have been originating. During dry season, cultivated areas under peri-urban agriculture are worst affected by this problem. Heavy metals can not be destroyed or changed to forms that are harmless accumulates in soil unlike organic pollutants. The use of sewage and industrial effluents has been observed to enhance the available metal status of agricultural soils by 2 to 100 times (Samra 2007). Rattan *et al (*2006) found a considerable accumulation of heavy metals in soils irrigated with sewage effluents discharged from Keshopur Sewage Treatment Plants, Delhi. According to Khankhane and Varshney (2015), soils collected from farmers field in Jabalpur and adjoining areas found higher accumulation of cadmium and lead above the critical limit of phyto-toxicity. Excessive heavy metal accumulation can be toxic to most plants leading to reduced seed germination, root elongation and biomass production, inhibition of chlorophyll biosynthesis. Besides adversely influencing plant growth, the toxic effect of heavy metals gets amplified along the food chain at each stage of food web. The heavy metals like Cd, Zn, Pb, Cu, Ni, Mn and Fe get entry into the human and animal food chain, which have been widely reported (Paulose *et al*, 2007).

In respect of water purification purpose, some fast growing weedy plants with high biomass have shown potential in removing contaminants from waste water. The use of specially selected and engineered metal accumulating plants for environmental cleanup is termed as phytoremediation, which describes a system wherein plants in association with microorganisms can remove or transform contaminants into harmless and often valuable forms (Purakayastha and Chhonkar 2010). Phytoremediation is a promising technology for remediating contaminated soils by metal hyperaccumulation in certain plants (Salt *et al*. 1995, McGrath 1998). Phytoremediation takes advantage of inherent ability of plants to take up water and soluble mineral nutrients and associated contaminants though roots, to transpire though leaves, and to act as a transformation system to absorb and bioaccumulate toxic trace elements including heavy metals or to metabolize organic compounds.

Threshold levels of trace element in water

The principal objective of waste water treatment is generally to allow human and industrial effluents to be disposed without damage to human health or unacceptable damage to the natural environment. Irrigation with waste water is both disposal and utilization and indeed is a effective form of waste water disposal (Pescod 1992). However, some degree of treatment must normally be provided to raw municipal waste water before it can be discharged in surface water bodies especially where aquaculture is practiced or used for agricultural or landscape irrigation. A threshold level of trace elements in water (FAO 1985, National Academy of Science 1972) as a source of irrigation for crop production is given (**Table 1**).

The waste water treatment can categorized as preliminary, primary, secondary and tertiary or advanced in order of increasing treatment level. These processes are

Table 1. Threshold levels of trace elements in water as a source of irrigation for crop production

Element	Concentration (mg/l)	Remarks
Arsenic	0.10	Toxicity to plants varies widely, ranging from 12 mg/l for Sudan grass to less than 0.05 mg/l for rice
Aluminum	5.0	Can cause non-productivity in acid soils (pH less than 5.5) but more alkaline soils at pH > 7 will precipitate the ions and eliminate any toxicity.
Cadmium	0.01	Toxic to beans, beets and turnip at concentration as low as 0.1 mg/l in nutrient solutions. Conservative limits recommended due to its potential for accumulation in plants and soils to concentrations that may be harmful to humans
Copper	0.20	Toxic to number of plants at 0.1 to 1.0 mg/l in nutrient solutions
Fluoride	1.0	Inactivated by neutral and alkaline soils
Iron	5.0	Not toxic to plants in aerated soils, but can contribute to soil acidification and loss of availability of essential phosphorus and molybdenum. Overhead sprinkling may result in unsightly deposits on plants, equipment and buildings.
Manganese	0.20	Toxic to a number of crops at a few tenths to a few mg/l, but usually only in acid soils.
Molybdenum	0.01	Not toxic to plants at normal concentrations in soil and water. Can be toxic to livestock if forage is grown in soils with high concentrations of available molybdenum.
Nickel	0.20	Toxic to a number of plants at 0.5 mg/l to 1mg/l : reduced toxicity at neutral or alkaline pH.
Lead	5.0	Can inhibit plant cell growth at very high concentrations.
Selenium	0.02	Toxic to plants at high concentrations as low as 0.025 mg/l and toxic to livestock if forage is grown in soils with relatively high levels of added selenium.
Zinc	2.0	Toxic to many plants at widely varying concentrations; reduced toxicity at pH > 6-0 in fine textured or organic soils

Source: FAO 1985, National Academy of Sciences (1972) operated to remove solids, organic matter, and sometimes nutrients from waste water. However, these approaches are cost intensive and more sophisticated in operation and maintenance. Waste stabilization ponds have been the treatment system favored for the majority of the application in developing countries especially those located in tropical climates (Pescod 1992). These include a wide range of shallow ponds with treatment mechanism that may vary from anaerobic fermentation to aerobic mineralization relying on sunlight to promote a symbiotic relationship of algae and bacteria. These are the most important method of sewage treatment in hot climate where sufficient land is normally available and where the temperature is most favorable for their operation (Mara 1978, Mara and Cairncross 1989). In many cases, however, the reasoning behind their use was disposal, rather than treatment. Although ponds have been in use for centuries to treat domestic waste water, no engineering design or research went into the construction of most of the ponds in developing countries including India. However, some reports suggest that in the majority of cases water effluents even from stabilized ponds do not meet stringent effluent standards. As a result stabilization, ponds are under pressure and needs to upgrade their effluent quality (Thomas and Phelps 1987). This has forced researchers to think of using aquatic plants for cleaning of their own support system.

Plants are more suited to absorb nutrients like nitrates, phosphates, sulfates and to accumulate heavy metals from water due to higher rate of phytoremediation. Plants ideal for phytoremediation must be fast growing, have high biomass, deep roots, should be easy to harvest and should tolerate and accumulate a range of metals. Metal hyperaccumulator plants though useful for phytoremediation of heavy metals, have many shortcomings such as low biomass, edible nature and difficult to harvest. Aquatic weeds grow fast, which produce high biomass and are resistant to insect and plant diseases and most of which are harmless. Moreover, such weeds do not need fertilizers or plant protection measures to enhance its growth. The first experiments for wastewater treatment were carried out using weed species such as *Scirpus lacustris* in Germany in the early 1950s. Since then, macrophyte based constructed wetlands have evolved into a reliable wastewater treatment technology for various types of wastewater. On the basis of type of growth of weedy plants, the artificial constructed wetlands are classified as emergent, submerged, floating leaved, and free-floating wetlands (Vymazal 2010, Abou-Elela 2017).

Plant species for phytoremediation

The term phytoremediation ("phyto" meaning plant, and the Latin suffix "remedium" meaning to clean or restore) actually refers to a diverse collection of plant-based technologies that use either naturally occurring or genetically engineered plants for cleaning contaminated environments (Cunningham *et al.* 1997, Flathman and Lanza 1998). An appropriate selection of plant species capable of producing adequate biomass is vital during phytoremediation. Such selection is generally based on the ability of species to withstand elevated levels of metal concentration. Plants have three basic strategies for growth on metal contaminated medium as follows:

Metal excluders: Such plants prevent metal from entering their aerial parts or maintain low and constant metal concentration over a broad range of metal concentration in soil, they mainly restrict metal in their roots. The plant may alter its membrane permeability, change metal binding capacity of cell walls or exclude more chelating substances. Using the field pot-culture and sample-analysis method, Wei *et al.* (2005**)** examined 54 weed species belonging to 20 families and 31 weed species belonging to 17 families to find whether they can exclude the uptake of heavy metals. After a systematic identification, it was determined that *Oenothera biennis* and *Commelina communis* were Cd-excluders and *Taraxacum mongolicum* was a Zn-excluder. *O. biennis* is a potential Cd-excluder, but also a potential Cu-excluder. The research raises the possibility of making a major breakthrough in the application of metal excluders for safe agro-production in the future.

Metal indicator: The species which aggressively accumulate metal in their aerial tissues and generally reflect metal level in the soil/water. They tolerate the existing concentration level of metals by producing intracellular metal binding compounds (chelators), or alter metal compartmentalization pattern by storing metals in non-sensitive parts. Many such plants, often listed as weeds, have proved useful indicators of metals in the geological substrata and the environment. Such plants concentrate specific metals in their tissues in excess of their concentrations present in the environment, such plants are: *Salsolanitrata* (for boron), *Crotalaria cobalta* (for cobalt), *Acalypha* and *Commelina* spp. (for copper), *Acacia patens* (for iron), *Crotalaria florida* (for manganese), *Artemisia tridenta* (for gold, cadmium and uranium), and *Eichhornia crassipes* (for copper, lead, zinc, and cadmium in water bodies). This helps geologist using satellite imaging in locating distribution of such plants to indicate the presence of diverse metals in earth (or water).

Hyperaccumulators: They can concentrate metals in their aerial parts, to levels far above than soil. Hyperaccumualtors are plants that can absorb high levels of contaminants level of metals either in roots, shoots and/or leaves. The plant species of water hyacinth (*Eichhornia crassipes*), water dropwort (*Oenanthe javanica*), sharp dock (*Polygonum amphibium*), duckweed (*Lemna minor*) and calmus (*Lepironia articulata*) are good candidates for phytoremediation of polluted waters (Wangel *et al.* 2003). They found that the water hyacinth and duckweed are hyperaccumulator of cadmium, water dropwort as an hyperaccumulator of Hg, *Calamus* as hyperaccumulator of lead and sharp dock through accumulation of nitrogen and phosphorus in its shoots. Lu (2004) recorded maximum values of bioconcentration factor (BCF) for Cd and Zn as 622.3 and 788.9, respectively, suggesting that water hyacinth was a moderate accumulator of Cd and Zn and could be used to treat water contaminated with low Cd and Zn concentrations. It is observed that root possesses sites free for cadmium and with time it bounds to root which is translocated to root tissues. Zarangika and Ndapwadza (1995) found that metal concentration of Ni, Zn, Co, Cr, Pb, and Cd in water hyacinth plants were much higher than in water and bioconcentration factor of 1 to 4 orders of magnitude were obtained depending on element. Levels of most elements studied were higher in roots than top of plants. Das *et al*. (1916) conducted a study with Eichhornia in 5, 10, 15, and 20 mg/L CdCl2 in a hydroponic system for 21 days, and the Cd concentrations in the roots, shoots, and leaves were estimated. The plant showed tolerance, but at high Cd concentrations decline was observed in biomass, root length, and leaf area. Cd uptake gradually increased in all the plant tissues up to 15 mg/L exposure, but at 20 mg/L, the accumulation declined. Shoot tissues accumulated more Cd than root and leaf tissues. The highest accumulation by the plant was 1927.83 µg/g/. This study suggested that water hyacinth tolerated phytotoxic concentrations of up to 15 mg/L and efficiently hyperaccumulated Cd in its above-ground tissues.

Barman *et al.,* (2000) observed high accumulation of metals of iron and chromium in *Alternanthera sessilis* and *Cynodon dactylon.* Barman *et al* (2001) observed that elevated accumulation of metals in *Eichhornia crassipes* and *Marsilea* species growing along the effluent channel has been identified as a potential source of biomonitoring of metals particularly of copper and cadmium and can be utilized for the removal of heavy metals from the waste water. They also showed that higher accumulation of metals was found in plant parts in naturally growing weeds and cultivated crop plant irrigated with treated effluent. Phytoremediation potential of various plants of Brassicae to decontaminate heavy metal polluted soils due to irrigation with untreated sewage water for over 20 years have been demonstrated (Chhonkar *et al.* 2005, Purakaystha *et al.* 2008).

Mishra *et al.* (2000) stated that the waste water discharges from the Najafgarh power house and Kalkaji drains of river Yamuna in Delhi increases the elemental concentrations of over bank soils downstream of discharges. They found that water hyacinth growing along the bank receiving wastewater from Najafgarh and Barapula drains were unhealthy and reduced in population, which was attributed to a combination of alkali pH of growth medium and metal toxicity and high BOD at the site receiving effluents from Najafgarh drain and same with the turbid conditions of water with fly ash particle deposition on the plant surfaces at the site receiving effluent from Barapula drain. There were marked differences on water hyacinth on over bank and flood plain of river. The roots of these plants growing on bank soils were accumulators of all elements except Co, Al, and Fe. *Lemna minor* plants were exposed to nickel concentration at 1, 3, 5 and 7 mg /L and analyzed after 24, 48, and 72 hours indicated that *L. minor* can be used to remove nickel from waste waters *(*Kara *et al.* 2003).

Approaches of phytoremediation

The different approaches of phytoremedition can be divided into the various processes: phytoextraction, where plants absorb contaminants from soil, sediment/ water or gravel and translocate them to the harvestable shoots where they accumulate; phytodegradation is the breakdown of contaminated surrounding by the plant through the effect of compounds (such as enzymes) produced by the plant roots.; phytovolatilization, which involves the use of plants to extract certain metals from soil and then release them into the atmosphere through volatilization; phytostabilization, where plants are used to stabilize rather than clean contaminated sediment/soil and rhizofiltration, which involves the use of plant root to clean various aquatic environments. Although, plants show some ability to reduce the hazards of organic pollutants (Carman *et al.*, 1998), the maximum work in phytoremediation has been made with nutrients and metals. Among these different processes, phytoextaction and rhizofiltration play important roles in aquatic medium for removal of contaminants.

Phytoextraction: Phytoextraction is the most commonly recognized of all phytoremediation technologies. The terms phytoremediation and phytoextraction are sometimes incorrectly used as synonyms, but phytoremediation is a concept while phyto-extraction is a specific cleanup process. The phytoextraction process involves the use of plants to facilitate the removal of metal contaminants from a soil /gravel matrix (Kumar *et al.*1995). In practice, metal-accumulating plants are seeded or transplanted into metal-polluted medium. The roots of established plants absorb metal elements from the contaminated medium and translocate them to above-ground shoots where they accumulate. After sufficient plant growth and metal accumulation, the above-ground portions of the plant are harvested and removed, resulting the permanent removal of metals from the site. Many factors determine the effectiveness of phytoextraction in remediating metal-polluted sites. As a plant-based process, the success of phytoextraction is inherently dependent upon several plant characteristics. The two most important characters include the ability to accumulate large quantities of biomass rapidly and the ability to accumulate large quantities of environmentally important metals in the shoot tissue (McGrath 1998). It is the combination of high metal accumulation and high biomass production that result in the most metal removal. The emergent type of plants growing in contaminated water are more suited for phytoextraction. Additionally, plants being considered for phytoextraction must be tolerant of the targeted metal, or metals, and be efficient at translocating them from roots to the harvestable above-ground portions of the plant (Blaylock and Huang 2000). Although some plants show promise for phytoextraction, there is no plant which possesses all of these desirable traits.

Srivastava and Chhonkar (2000) observed that weedy plant like Sudan grass removed higher metals than oat crop under un-amended as well as amended mine soil. In order to assess maximum hyper-accumulating capacities of various *Brassica* species, a sand culture experiment was carried out at National Phytotron facility at IARI by Chhonkar *et al.* (2005), where Hoagland solutions were loaded with Zn, Cu, Pb and Ni at medium and high levels of toxicity. They found that the uptake of all the metals exhibited increase due to application of metals through Hoagland solution . In case of zinc, maximum uptake was observed with *B. Carinata* while *B. campestris* showed highest tissue concentrations. The *B. napus* not only contained highest concentrations of Cu, Ni, and Pb but also showed highest uptake of these metals over other species.

Khankhane and Varshney (2011) reported that higher concentration of heavy metals were observed in weeds of wheat and cauliflower under waste water irrigation as compared to tube well water. Among the weed species, *Avena ludoviciana* removed higher copper and manganese; *Chenopodium album* followed by *Avena ludoviciana* extracted higher cadmium where as *Parthenium hysterophorus* retained higher iron content in their shoot parts. They observed that as compared with the mustard hyperaccumulator, wild oat (*Avena ludoviciana)* found more effective in extracting copper, manganese and cadmium metals from the contaminated soil. Ghosh and Singh (2005) examined and compared five weed species (*Ipomoea carnia, Dhatura innoxia, Phragmites karka, Cassia tora* and *Lantana camera*) with two accumulator plants *Brassica juncea* and *Brassica campestris* for chromium removal in a pot study. The results indicated that *P. karka* showed much greater tolerance to metals than other plants, though the uptake was low. It was more effective in translocating Cr from soil to plant shoots. The order of Cr extraction was *Ipomoea carnia>Dhaturainnoxia> Cassia tora>Phragmites karka>Brassica juncea>L. camers> Brassica campestris* . Other than *L. camera,* all the tested weeds were better for chromium extraction than the accumulator *Brassica* species. To save the *Brassica* species infested by army moth, pesticide application was required, where as weeds required no care.

To elucidate the growth response of *Arundo donax,* irrigated with different levels of cadmium (0, 100, 200, 400, 800 and 1200 mg/L), Khankhane *et al.* (2017) tested ethylene diaminetetraacetate (EDTA) aqueous solution at three rates (0, 3 and 6mg/L applied to the plant. The results indicated that the *A. donex* tolerated Cd upto 400 mg/L without showing any adverse effect in terms of plant height, number of tillers, leaf area and total chlorophyll. The plant accumulated cadmium from spiked medium to shoot and root with bioconcentration factor (BC) of 1.44 and 1.96, respectively, at 200 mg/L Cd exposure. EDTA significantly enhanced 12.8% dry weight of shoot and enhanced 2-3 times cadmium accumulation in root as compared to control (No EDTA). At elevated cadmium concentration (400 mg/L), the BC factor of 7.74 in root and 0.89 in shoot was recorded under EDTA application of 3 mg/L. Except root length, no adverse effect of EDTA was observed on plant growth. Having high tolerance ability, *A. donex* combine with optimum dose of EDTA (3 mg/L) has a implications for phytoremediation of less bio-available cadmium contaminated sites. Krishnasamy *et al.* (2004) observed that some weeds such as *Amaranthus* species for Ni, *Arundo donax* for lead and *Colocasia* for chromium have the potential for phytoextration of heavy metals from contaminated soil. In a survey of weeds grown at contaminated sites, among plant species, *Vetiver zyzinoides, Arundo donax* removed higher lead and manganese (Khankhane and Varshney 2015).

Phytodegradation: Phytodegradation is the breakdown of contaminated surrounding by the plant through the effect of compounds (such as enzymes) produced by the plant roots. Organic contaminants (especially hydrocarbons that contain carbon and hydrogen atoms) are common environmental pollutants. Some enzymes breakdown and convert ammunition wastes, others dgrade chlorinated solvents such as trichloroethylene (TCE), and others degrade herbicides. Unterbrunner *et al.* (2007) tested the potential of weed species common reed (*Phragmites australis)* and tree plant poplar in fertilized and non-fertilized control treatments. Among the treatments, common reed without fertilizer enhanced crude oil degradation. whereas, fertilized plants did not enhance crude oil degradation in the higher molecular weight crude oil fraction (C_{20} to C_{40}). It was likely due to consequence of decreased phosphorous availability for microorganisms in the plant rhizosphere.

Phytostabilization: The water erosion leads to loss of the fertile top soil. In course of the movement of soil and water in a catchment, silting or deposition of soil load is inevitable, particularly in lower reaches of the catchment. Due to high intensity of rainfall, water erosion often may be so severe that considering silting takes place of dams and reservoirs in the catchment area. Plant nutrients are carried along with the soil lost in the runoff, which result increase in weed infestation in the reservoirs due to merging of the eutrophic waters from the urban and agricultural lands. India has a total area of about 7 million hectares under different kind of water bodies such as reservoirs, tanks, lakes, ponds, oxbow lakes, derelict water and brackish water other than the rivers and canals area (MoWR 2018). These water bodies are infested with aquatic weeds. In urban areas, the runoff water as well as house hold waters find the way in the surface water bodies like ponds, lakes causing deterioration of water quality due to weeds. To prevent and control the runoff and house hold water into the water bodies, phytostabilization with suitable grassy weeds at the entry points or at the end point of catchment area can prevent and control weed infestation problem in the water bodies. In the non-cropped areas, mining causes the land degradation resulting movement of silt, clay and organic carbon including heavy metals in runoff water, which ultimately deteriorates the water quality. Juyal *et al.* (2007) reported that among the control measures, grasses and weedy shrubs like *Ipomoea carnea* also have the potential to perform well in ravaged area of north-west Himalayas.

Rhizofiltration: Rhizoûltration can be deûned as the use of plant roots to absorb, concentrate, and/or precipitate hazardous compounds, particularly heavy metals or radionuclides, from aqueous solutions (Prasad 2000). Hydroponically cultivated plants rapidly remove heavy metals from water and concentrate them in the roots

Table 2. Grasses recommended for ravaged areas of north-west Himalayas

Vegetation	Weed species
Grasses	*Crysopogonfuvus, Eulaliopsisbinata, Pennisetum purpureum, Saccharum* spp., *Pueraria hirsute*
Shrubs	*Ipomoea carnea, Vitex nigunlo, Agave americana,*
Trees	*Leucana luucehapla, Salix tetrasperma, Acacia catechu, Cedrela toona, Bahunia* spp., *Erythrina suberosa, Lannea grandis*

Source: Juyal *et al.* (2007)

and shoots. Rhizoûltration is effective in cases where wetlands can be created and all of the contaminated water is allowed to come in contact with roots. Contaminants should be those that adsorb strongly to roots, such as lead, chromium (III), uranium, and arsenic (V). Roots of plants are capable of absorbing large quantities of heavy metals including lead and chromium from soil water or from water that is passed through the root zone of densely growing vegetation. Plants are regularly harvested and incinerated. Root exudates make changes in rhizosphere and pH also may cause metals to precipitate onto root surfaces. As they become saturated with the metal contaminants, roots or whole plants are harvested for disposal. This technology works best with water tolerant plants having fibrous root system. This system is a cost-competitive for treatment of surface or groundwater containing low, but significant concentrations of heavy metals such as Cr, Pb, and Zn *etc*. Proper plant selection is the key to ensuring the success of rhizofiltration as a water cleanup strategy. In few studies weeds have been tried for removing heavy metal uptake from water. Among floating plants, some work has been carried out (Jain *et al.* 1989) on and duck weed (*Lemna minor*), water hyacinth (*Eichhornia crassipes*). An active uptake of nickel and zinc by water hyacinth in 40% concentration of the electroplating effluent was observed, however, absorption capacity of plant gradually declined in 80 and 100% concentration, indicating that higher concentration of effluent curtails the growth and development of plants (Sridevi *et al.* 2003). Basu *et al.* (2003) observed reduction of arsenic by *Pistia stratiotes* which could effectively absorb arsenic between a range of 0.25 to 5.0 mg/l with removal efficiency of 87.5% at pH 6.5.

Plants should be able to accumulate and tolerate significant amounts of the target metals in conjunction with easy handling, low maintenance cost, and a minimum of secondary waste requiring disposal. It is also desirable plants to produce significant amounts of root biomass or root surface area (Dushenkov and Kapulnik 2000). Several aquatic species have the ability to remove heavy metals from water, including water hyacinth (*Eichhornia crassipes*, pennywort (*Hydrocotyl eumbellata*), and duckweed (*Lemna minor*). However, these plants have limited potential for rhizofiltration, because they are not efficient at metal removal, a result of their small, slow-growing roots (Dushenkov *et al.* 1995). These authors also pointed out that the high water content of aquatic plants complicates their drying, composting, or incineration. Despite limitations, Zhu *et al.* (1999) indicated that water hyacinth is effective in removing trace elements in waste streams. Terrestrial plants are thought to be more suitable for rhizofiltration because they produce longer, more substantial, often fibrous root systems with large surface areas for metal sorption (Billore 1999).

In a pond sites where *Eicchornia crassipes* was grown in Ranital and Gulluwa pond, *Alternanthera philozeroides* in Mansing and Mahanaddaand *Canna indica* in Mahanadda and Adhartal pond of Jabalpur, marked differences were observed in metal uptake by weed these species. Among the weeds, *Eichhornia crassipes* 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 elevated metal accumulation in *Eichhornia crassipes* growing in the pond waters indicated as a potential source of bio-monitoring of copper. The higher accumulation of nickel, iron and manganese by water hyacinth may be due to its strong metal absorbing ability.

Macrophytes assisted constructed wetlands

Plants are major components of constructed wetlands used for waste water treatment. Rhizofiltration in artificial constructed wetland is applied for treating various types of waste water. In an aquatic macrophyte based waste water treatment systems, the pollutants are removed by variety of complex, biological, chemical and physical processes. The aquatic macrophytes are the most obvious biological component of the systems.The macrophytes plays an important role for providing surface and substrates for bacterial growth, and by altering the physico-chemical environment in the water and in the rhizosphere. According to Vymazal (2010), the aquatic macrophytes could be grouped into two major categories for the treatment of waste water treatments are free water surface wetland and emergent macrophyte wetland.

Free water surface macrophyte treatment systems: Free floating macrophytes are highly diverse in form and habit, ranging from large plants with rosettes of aerial and /or floating leaves and well developed submerged roots (example, water hyacinth) to minute surface floating plants with few or no roots (*e.g. Lemna*, *Spirodella*, *Wolffia* sp.). In colder regions, these floating species do not reach a large size and their production of biomass is limited, which reduces their absolute water treatment value. However, in tropical regions, water hyacinth doubles in mass about every 6 days and a macrophyte pond can produce more than 250 kg/ha dry weight. Nitrogen and phosphorus reductions up to 80 and 50% have been achieved. Orth *et al*. (1987) examined the applicability of water hyacinth systems for the treatment of raw waste water discharged by small factories and housing areas of industrial estate observed that nitrogen was eliminated to a great extent, BOD and COD was dropped to a level satisfying secondary treatment standards. Subsequent harvest of the plant biomass results in permanent removal of stored contaminants from the pond treatment system.

The nutrient assimilation capacity of aquatic macrophytes is directly related to growth rate, standing crop and tissue composition. The potential rate of pollutant storage by an aquatic plant is limited by the growth rate and standing crop of biomass per unit area. Water hyacinth, for example, was found to reach a standing crop level of 30 tones (dry weight)/ha in Florida, resulting in a maximum storage of 900 kg N/ha and 180 kg P/ha (Reddy and DeBusk 1987). Fly and mosquito breeding is a problem in floating macrophyte ponds, but this can be partially alleviated by introducing larvae-eating fish species such as *Gambusia* and *Peocelia* into the ponds. It should be recognized that pathogen die-off is poor in macrophyte ponds as a result of light shading and the lower dissolved oxygen and pH compared with algal maturation ponds. In their favor, macrophyte ponds can serve a useful purpose in stripping pond effluents of nutrients and algae and at the same time produce a harvestable biomass.

Waste water containing metals (Cr, Ni and Zn) and nutrients from a tool factory was treated in a free water surface wetland in Santo Tomé, Santa Fe, Argentina using aquatic plant (Maine *et al,* 2007). *Eichhornia crassipes* became dominant and covered about 80% of the surface during first year, and decreased progressively until its disappearance. When water depth was lowered *Typha domingensis* steadily increased plant cover and attained 30% of the surface by the end of the study. While *E. crassipes* was dominant, the wetland retained 62% of the incoming Cr and 48% of the Ni. NO3- and NO2-, were also removed (65 and 78%, respectively), while dissolved inorganic phosphate (i-P (diss)) and NH4 + were not removed. During the period of *E. crassipes* decline, the wetland retained 49% of the incoming Cr, 45% of Ni, 58% NO3-, 94% NO2-, 58% NH4+ and 47% i-P(diss). Since *T. domingensis* became dominant, retention was 58% Cr, 48% Ni and 64% i-P(diss), while 79% NO3-, 84% NO2- and 13% NH4+ were removed.

Khankhane et al. (2018) tested the performance of aquatic weeds, water hyacinth *Eichhornia crassipes, Pistia stratiotes* and *Typha latifolia* in a pilot scale wetland of 5000 liter capacity during winter months of 2015 and 2016, respectively in Panagar locality of Jabalpur, Madhya Pradesh. The treatment system comprised of the collection tank, settling tank followed by treatments zone having 3 tanks each of 1200 litre capacity. The water samples were collected from inlet and outlet zone of each tank. The various water parameters were analyzed by multi-parameter water analyzer model Photolab RS12A (WTW make) and heavy metals by AAS (Thermo SOLAR S4). Results indicated that during 2^{nd} run of the pilot scale system, except slight change in electrical conductivity, no change in pH, temperature and total hardness was recorded in water treated with *Pistia stratiotes* and *Eichhornia crassipes*. However, as compared with the turbidity of drain water (64.2 Ntu), lower turbidty of 20.4 and 6.9 Ntu was recorded in water treated with *Pistia* and *Eichhornia,* respectively. Besides turbidity other parameters *viz,* total dissolved salts (TDS), sodium, sulphate, chloride and chromium in water were reduced to the extent of 24.1, 33.1, 68.7, 43.0 and 76.3% after 5 days treatment with *Eichhornia,* respectively. As far as *Typha latifolia* for heavy metals was concerned, it reduced higher Cr, Ni and Pb to the extent of 91.54, 79.52 , 46.18%, respectively. Besides heavy metals, it also reduced 91.22 and 21.06% of turbidity and EC, respectively.

Submerged plants procure all of their nutrients from the water or the substrate, and they draw the required oxygen and carbon dioxide strictly from the water. The production of submerged plants is generally limited because their metabolism is adjusted to low light conditions. There is potential for use of submerged plants for absorbing nutrients, metals, and some trace organics in a polishing phase of treatment (Eighmy *et al.* 1987, Reed *et al.* 1988). It is believed that the major removal mechanism of nutrients and trace organics is by bacterial degradation rather than plant uptake. Of the many species tested, several showed relatively aggressive growth rates in wastewater and are capable of withstanding interspecific competition. Some of these are *Elodea canadensis, E. nutallii, Egeria densa, Ceratophyllum demersum, Potamogeton foliosus* in warmer climates. *Elodea* spp. is found in tropical and temperate regions throughout the world, while

Hydrilla spp. is present in most "warm regions" (Dinges 1982). One main problem with these plants is that even the cold-region species experience a severe die back during the winter months when water temperatures approach freezing. In warmer areas, mortality may not occur, but active growth will probably cease (Dinges 1982).

In Tamil Nadu, India, studies have indicated that the coontail, *Ceratophyllum demersum,* a submerged macrophyte, is very efficient at removing ammonia (97 %) and phosphorus (96 %) from raw sewage and also removes 95% of the biological oxygen demand (BOD). It has a lower growth rate than water hyacinth, which allows less frequent harvesting. In such macrophyte pond systems, apart from any physical removal, the aquatic vascular plants serve as living substrates for microbial activity, which removes BOD and nitrogen, and achieves reductions in phosphorus, heavy metals and some organics through plant uptake. The basic function of the aquatic weeds in the latter mechanism is to assimilate, concentrate and store contaminants on a short-term basis (Pescod 1992).

Emergent macrophyte treatment systems: The rooted emergent macrophytes are the most commonly found species in constructed wetland for waste water treatment. The key features of such reed bed treatment systems are: i) rhizomes of the reeds grow vertically and horizontally in the soil or gravel bed, opening up hydraulic pathways; ii) wastewater biological oxygen demand (BOD) and nitrogen are removed by bacterial activity; aerobic treatment takes place in the rhizosphere, with anoxic and anaerobic treatment taking place in the surrounding soil; iii) oxygen passes from the atmosphere to the rhizosphere via the leaves and stems of the reeds through the hollow rhizomes and out through the roots; iv) suspended solids in the sewage are aerobically composted in the above-ground layer of vegetation formed from dead leaves and stems; v) nutrients and heavy metals are removed by plant uptake.

The growth rate and pollutant assimilative capacity of emergent macrophytes such as *Phragmites communis* and *Scirpus lacstris* are limited by the culture system, waste water loading rate, plant density, climate and management factors. Higher tissue N concentrations have been found in plants cultured in nutrient enriched (wastewater) systems and in plants analyzed in the early stages of growth. Maximum storage of nutrients by emergent macrophytes was found to be in the range 200-1560 kg N/ha and 40-375 kg P/ha in Florida (Reddy and DeBusk 1987). More than 50% of the nutrients were stored in below-ground portions of the plants, tissues difficult to harvest to achieve effective nutrient removal. However, because emergent macrophytes have more supportive tissue than floating macrophytes, they might have greater potential for storing the nutrients over a longer period. Consequently, frequent harvesting might not be so necessary to achieve maximum nutrient removal, although harvesting above-ground biomass once a year improve overall nutrient removal efficiency.

The study of the efficiency of a pilot horizontal subsurface flow system was carried out for treatment of urban wastewater from a small town in the West of Sicily by Claudio Leto *et al.* (2013) in Italy using horizontal sub-surface wetland. The pilot system had a total surface area of 100 m^2 with two units. Unit A was planted with *Arundo donax* and unit B with *Cyperus alternifolius*. The results showed excellent organic pollutant removal (BOD5 70–72%, COD 61–67%), while macronutrient removal was found to be lower (TKN 47–50%, TP 43–45%). Pathogen load removal was found to be approximately 90%, but *Escherichia coli* concentrations at outflow were not within Italian legislative limits. Giant reed showed higher nitrogen content in the biomass (an average 28.9 ± 1.8 g/m^2/year and 63.8 ±1.8 $g/m^{2/}$ year for the above ground and below ground parts, respectively) than umbrella sedge. The treated wastewater was used to irrigate parkland areas.

Shaharah *et al.* (2012) established *Arundo donax* in experimental subsurface flow, gravel-based constructedwetlands (CWs) receiving untreated re-circulating aquaculture system wastewater in Australia. The BOD, TSS, TP, TN, TAN, and *E. coli* removal in the *A. donax* and *P. australis* beds was 94, 67, 96, 97, 99.6% and 100% and 95, 87, 95, 98, 99.7%, and effectively 100%, respectively, with no significant difference ($p>0.007$) in performance between the *A. donax* and *P. australis* CWs. These monitored water quality parameters removed efficiently by the CWs, to the extent that the CW effluent was suitable for use on human food crops grown for raw produce consumption under Victorian state regulations and also suitable for reuse within aquaculture systems. In this study, the above ground yield of *A. donax* top growth (stems + leaves) (15.0±3.4 kg wet weight) was considerably more than the *P. australis* beds (7.4±2.8 kg wet weight). The standing crop produced in 14-week trial equates to an estimated 125 and 77 t/ ha/year biomass (dry weight) for *A. donax* and *P. australis*, respectively (assuming that plant growth is similar across a 250-day (September–April) growing season and a single cut, annual harvest. The similarity of the performance of the *A. donax* and *P. australis*-planted beds indicated that either may be used in horizontal subsurface flow wetlands treating aquaculture wastewater, although the planting of *A. donax* provides additional opportunities for secondary income streams through utilization of the energy-rich biomass produced.

Hamouri *et al.* (2007) reported the performance and behavior of a subsurface-horizontal flow constructed wetlands (SSF-h CW) used for sewage post-treatment behind an up-flow anaerobic reactor under Moroccan climate conditions. Kinetic first order constant, K (20 °C) for BOD5 removal was calculated using the tracer study results. K values were 1.384, 1.284 and 0.904 d”1 for *Arundo, Phragmites* and for the control, respectively. Compared to the control, K value increased by 53 and 42% for *Arundo* and *Phragmites*, respectively, clearly showing the impact of planting the beds. A satisfactory COD removal pattern was achieved. It was found 70, 85 and 130 mg/L, for the effluents of *Arundo*, *Phragmites* and the control, respectively. However, no similar removal pattern was found for nitrogen and for phosphorus. In addition, faecal coliforms removal rate was small and did not exceed 1 Log Unit in the best case.

A rectangular sub surface horizontal model was developed for removal of pollutants such as nitrates, phosphates and heavy metals in waste water for irrigation purposes at ICAR-DWR Jabalpur. Gravels of different sizes including 1.5-

3", 0.5-1" and 0.37-0.5" were used as a media filled in the treatment zone in which the rhizomes of *Arundo donax* were planted. After well spreading of roots entangled with media in a bed zone, a treatment of drain water was given. As compared with the untreated waste water, the rhizofilter model performed in reduction of the concentrations of nickel, copper, nitrate and phosphate to the extent of 55.8, 40.6, 70.0 and 42.8%, respectively after the treatment. As far as water flow through gravel medium was concerned, no clogging was occurred in treatment zone resulting free discharge of water through the outlet. The characters of exuberant root and good adaptability of *Arundodonax* suggested its potential in rhizofiltration of waste water (Khankhane and Varshney 2015).

In Central India (Ujjain, Madhya Pradesh, subtropical climate), *Phragmites karka* was planted in a horizontal subsurface flow gravel bed for treatment of primary municipal waste water (Billore 1999). The pollutant removal performance for TSS, BOD was 78% (mean influent conc.: 701 mg/L) and 65% (mean influent conc.: 79 mg/L), respectively. TSS concentrations corresponded to extremely high strength municipal wastewaters. A further study conducted in Bandung, Indonesia (tropical climate, $\approx$ 6.5 °S) where *Phragmites karka* was planted in a vertical flow wetland for the treatment of mechanically pre-treated sewage from a private household, showed high efficiencies in BOD and COD removal and the treated wastewater was used again for irrigation purposes in gardening (Kurniadie 2000). The two-staged wetland system in Dhulikhel, Nepal showed also a high ammonia removal performance (mainly due to nitrification in the vertical flow bed), but the phosphorus removal rate was relatively poor. Removal efficiencies for NH4+-N and PO4—P: were 80-99% (mean influent conc.: 33.3 mg/L) and 5 - 69 % (mean influent conc.: 8 mg/L), respectively. The high range in the phosphorus reduction was due to decreasing absorption capacity of the soil with increasing age (Laber 1999, Shrestha 2001). The CW for the treatment of greywater in Kathmandu, Nepal showed a similar performance in ammonia and phosphorus removal (Shrestha 2001). *Phragmites karka* appeared to have root zone oxygenation capacity as effective and high as *Phragmites australis*. This was showed by Billore (1999) who found an increasing DO concentration in the effluent of the CW (34%) that is unusual for horizontal subsurface flow beds. This effect resulted in relatively high ammonium reductions to the extent of 78.7 % (mean influent conc.: 34 mg/L).

Typha latifolia is tolerant to high organic loadings (Brändle 1996), showed a good performance in cold/boreal climates. In case of domestic wastewater treatment, the mean BOD removal efficiency of *Typha latifolia* in a vertical flow wetland (Mander 1997) was 82% (influent conc.: 27 - 460 mg/L BOD in Estonia (cold/boreal climate, $\approx$ 58 °N):,). The BOD and TSS removal efficiencies of a pilot multi-stage constructed wetland system near Murmansk in the Russian Arctic (sub-arctic climate, $\approx$ 68 °N) planted with *Typha latifolia, Carexa quatilis* and *Phragmites australis* were more than 81% (Vasilevskaya and Usoltseva 2004). The BOD treatment performance of several multi-stage systems in Norway (cold/boreal climate, $\approx$ 60 °N) planted with *Typha latifolia* amounted up to > 80 % (BOD influent conc.: about 200 mg/L), (Jenssen 1993, Maehlum 1995 1999). In respect to treatment of eutrophic water, it was high tolerance to eutrophic conditions (Brändle 1996). *Typha* was found tolerant to high ammonium exposure (Clarke 2002). The same study showed that flooded conditions (0.1 m) did not significantly increase ammonium toxicity to *T. latifolia* compared to non-flooded conditions. Whereas in an another study, Surrency (1993) reported an inhibited growth at 160-170 mg/L ammonium concentrations.

In a batch fed (<1-day HRT, hydraulic retention time) vertical sub surface flow wetland based municipal waste water treatment plant of 1500-LPD capacity was developed at the sewage plot site of the Indian Agricultural Research farm, New Delhi (Kaur 2015). The pilot plant is still in operation since November 2009 and is being continuously monitored for nutrient/heavy metal (pollutant) mass reduction efficiencies. Long term average pollutant mass reduction efficiency of the pilot system illustrated its capacity to reduce wastewater turbidity and nitrate, phosphate, potassium concentrations by up to 81, 68, 48 and 47%, respectively. Planted wetland systems, in general, seemed to be having an edge over the unplanted ones. Nutrient removal efficiencies seemed to be higher for the *P. karka* based wetland systems. The *Typha latifolia* based systems, on the other hand, were observed to be associated with higher oxidation potential and thus higher sulphate reduction efficiencies (50.5%). These systems also seemed to be associated with significantly higher Ni (62%), Fe (45%), Pb (58%), Co (62%) and Cd (50%) removal efficiencies.

According to Liao (2000), *Vetiveria zizanioides* was able to grow at COD of 2,800 mg/L concentrations. It was tolerant to high-loaded organic wastewaters. In a study conducted by Kantawanichkul (1999) in subtropical Thailand, *Vetiveria zizanioides* was planted in a vertical flow constructed wetland (CW) treating diluted settled pig farm waste water having a mean COD influent conc. of 601 mg/L with a removal performance of 78.7% under HLR of 18.5 mm/d. *Vetiveria* grass proved to be tolerant to eutrophic conditions and was able to grow at high strength NH3-N concentrations of about 390 mg/L (Liao 2000).

In the study conducted by Klomjek (2005) in Thailand, *V. ziz*anioides showed a good NH3-N treatment performance for medium strength municipal wastewater. Mean reduction: 76.5 % (mean influent conc.: 19.5 mg/L). In another study in subtropical South China, *V. zizanioides* was planted in an experimental culture system without a soil medium treating relatively high strength pig farm wastewaters (Liao 2003). - Mean COD influent conc.: 825 mg/L, removal rate: 64 %, - mean BOD influent conc.: 510 mg/L, removal rate: 68 %. (HRT: 4 d). In vertical flow systems, vetiver grass proved to be tolerant to eutrophic conditions and was able to grow at high strength NH3-N concentrations of about 390 mg/L (Liao 2000). In the study conducted by Klomjek (2005) in Thailand, *Vetiveria zizanioides* showed a good NH3-N treatment performance for medium strength municipal wastewater having mean influent concentrations of 19.5 mg/L resulted 76.5 % reduction of ammonia.

Utilization of post harvest wetland plant biomass: The nutrient rich floating macrophytes are easily collected by floating harvesters. The harvested plants can be converted into composting aerobically to produce a fertilizer and soil conditioner, might be fed to cattle, used as a green manure in agriculture, or can be converted into biogas in an anaerobic digester, in which case the residual sludge can then be applied as a fertilizer and soil conditioner (UNESCAPE 1981) Maximum removal by water hyacinth was 5850 kg N/ha/year, compared with 1200 kg N/ha/ year by duckweed. Composting was proposed as post harvest plant biomass treatment (Kumar *et al.* 1995, Raskin *et al.* 1997, Garbisu and Alkorta 2001).

Total (above ground and below ground) biomass production of *Phragmites karka* was resulted in 121 t/ha in the constructed wetland system in Central India within a period of 10 months Billore (1999). Very high production could be due to ideal environmental conditions of warm climate, availability of unlimited nutrients and year-round growth in wastewater. The versatile utilization options for *P. karka* are supposed to be similar to those of *P. australis, e.g.* high potential as a renewable fuel and energy source, building material (thatching, roof materials), paper making (Kiviat 2013), raw material for making of mats and baskets, *etc*. the leaves are used as fertilizer for paddy fields in Philippines (Bodner 1988). Vetiver grass shows highly versatile utilization options like use for soil stabilization and erosion control due to the extensive and deep root system. Leaves and stems can be used as raw material for handicrafts (*e.g.* weaving of hats, mats, baskets, etc.), construction and building material (*e.g.* thatching). *Vetiveria* is also as energy source for ethanol production and “green” fuel (a proportional mix of vetiver grass and water hyacinth biomass serves as a high-quality source of “green” fuel). The raw material is also used for paper making, compost (Vetiver Network 2005).

Comparative studies has indicated that *A. donax* is the most productive non-food biomass species reported so far in the Mediterranean area (Lewandowski *et al.* 2003), with an average above ground dry matter yield of about 40 tons per hectare, which is comparable or, in some cases, higher than that of C_4 species (Angelini *et al.* 2009). Giant reed may also act as chemically activated carbon (Basso *et al.* 2006) for re-cycle nutrients and water, and produce value added products (Mavrogianopoulos *et al.* 2002). The high annual growth and cellulose content make the giant reed a potential weed for converting solar energy to industrial fiber or biofuels.When cultivated this fast-growing introduced crop attains a potentially high yielding non-food crop (Papazoglou *et al.* 2005) that can meet requirements for energy, paper pulp production, biofuels and construction of building materials (Papazoglou *et al.* 2005).

Conclusion

Phytoremediation is cost and energy intensive and no sludge is generated like other STP methods. In most of studies, *Typha latifolia* are *Phragmites karka, Arundo donax, Vetiveria zizinoides, Echhornia crassipes* tested in surface and sub-surface constructed wetlands are promising phyto-remediating agents for control of pollution. Use of constructed wetlands is spreading rapidly in developed nations however, in tropical subtropical climate countries like India there is considerable scope of use of aquatic weedy plants due to rich plant diversity for treatment of waste water from human habitation and dairies. As a part of solving wastewater treatment problems in urban or industrial areas using these macrophytes if plants economic value is explored through composting, power plant energy (briquette), ethanol, biogas, and fibre-board making this technology can become more feasible and attractive. New methods are required to be developed for management of metal contaminated biomass. More plants are required to be identified for absorbing different type of pollutants from multi-contaminated sites.

In temperate and winter climate of sub-tropical areas where plant growth is slow resulting low biomass production and less efficiency of plants, there is vast scope of research to enhance the phytoremediation using chemical molecules like EDTA for better results. Moreover, testing of microbes and bio-molecules can also be explored for enhancement of phytoremediation.

References

Amerasinghe P, Bhardwaj RM, Scott C, Jella K and Marshall F. 2012. Urban wastewater and agricultural reuse challenges in India. Colombo, Sri Lanka: International Water Management Institute (IWMI). *Research Report 147*.

Angelini LG, Ceccarini L, Nassi o Di Nasso N and Bonari E. 2008. Comparison of *Arundo donax* L. and *Miscanthus giganteus* in a long–term ûeld experiment in Central Italy: Analysis of productive characteristics and energy balance. *Biomass and Bioenergy* **33**(4): 635-643.

Barman SC, Kisku GC, Salve PR and Mishra D, Sahu RK, Ramteke DK and Bhargava SK. 2001. Assessment of industrial effluents and its impact on soil and plants. *Journal of Environmental Biology* **22**(4): 251–256.

Barman SC, Sahu RK, Bhargava SK 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

Basu A, Sunil Kumar and Mukherjee S. 2003. Arsenic reduction from aquatic environment by water lettuce (*Pistia stratiotes*). *Indian Journal of Environmental Health* **45**(1): 143–150

Billore SK, Singh N, Sharma JK. 1999. Horizontal subsurface flow gravel bed constructed wetland with *Phragmites karka* in central India. *Water Science & Technology* **40**(3): 163–171.

Bodner CC, Gereau RE. 1988. A contribution to Bontoc ethnobotany. *Economic Botany* **42**(3): 307–369.

Brändle R, Pokorny J, Kvet, J. 1996. Wetland plants as a subject of interdisciplinary research. *Folia Geobotanica et Phytotaxonomica* **31**(1): 1–6.

Carman EP, Crossman TL and Gatlife EG. 1998. Phytoremediation of No. 2 fuel oil contaminated soil. *Journal of Soil Contamination* **7**:455–466.

Chhonkar PK, Bhadraray S and Purakayastha TJ. 2005. *Phytoremediation of Heavy Metal Contaminated Soils*, Monograph IARI, New Delhi: 34 p.

Chhonkar PK, Datta SP, Joshi SC, Pathak H. 2000a. Impact of industrial effluents on soil health and agriculture I. Distillery and paper mill effluent. *Journal of Scientific Industrial Research* **59**: 350–361.

Chhonkar PK, Datta SP, Joshi SC, Pathak H. 2000b. Impact of industrial effluents on soil health and agriculture II. Tannery and textile industrial effluents. *Journal of Scientific Industrial Research* **59**: 446–454

Claudio Leto, Teresa Tuttolomondo, Salvatore La Bella, Raffaele Leone and Mario Licata. 2013. Growth of *Arundo donax* L. and *Cyperus alternifolius* L. in a horizontal subsurface flow constructed wetland using pre–treated urban wastewater—a case study in Sicily (Italy) *Desalination and Water Treatment*, **51**: 7447–7459.

CPCB. 2010. Status of water supply, waste water generation and treatment in Class–I cities and Class–II towns of India. *Control of Urban Pollution Series*: CUPS/70/2009–10.

Cunningham SD, Shann JR, Crowley DE and Anderson TA. 1997. Phytoremediation of contaminated water and soil. pp. 2–19. In: *Phytoremediation of Soil and Water Contaminants*. (Eds. Kruger EL, Anderson TA and Coays JR.). ACS symposium series 664 Washington DC, American Chemical Society.

Das S, Goswami Sunayana, Das Anupam Talukdar. 2016. Physiological responses of water hyacinth, *Eichhornia crassipes* (Mart.) Solms, to cadmium and its phytoremediation potential. *Turkish Journal of Biology* **40**: 84–94.

Dinges R. 1982. *Natural Systems For Water Pollution Control*. Van Nostrand Reinhold Company

Dushenkov S and Kapulnik Y. 2000. Phytofilitration of metals. Pp.89–106. In: *Phytoremediation of Toxic Metals – Using Plants to Clean–up the Environment*. (Eds. Raskin I and Ensley BD). New York, John Wiley & Sons, Inc.

Dushenkov V, Kumar PBAN, Motto H and Raskin, I. 1995. Rhizofiltration: the use of plants to remove heavy metals from aqueous streams. *Environmental. Science and Technology* **29**:1239–1245.

Eighmy TT, Jahnke LS and Bishop PL. 1987. Productivity and photosynthetic characteristics of *Elodea nuttallii* grown in aquatic treatment systems. In: *Aquatic Plants for Water Treatment and Resource Recovery*. (Eds. Reddy KR and Smith WH). Magnolia Publishers Inc.

FAO. 1988. *Irrigation Practice and Water Management*. Paper 1, Rev. 1. FAO, Rome. 71 p.

Flathman PE and Lanza GR.1998. Phytoremediation: Current view on an emerging green technology. *Journal of Soil Contamination* **7**(4): 415–432.

Garbisu C and Alkorta I. 2001: Phytoextraction: a cost–effective plant–based technology for the removal of metals from the environment. *Bioresource Technology* **77**: 229–236.

Ghosh M and Singh SP. 2005. A review on phytoremediation of heavy metals and utilization of its byproduct. *Applied Ecology and Environmental Research* **3**(1): 1–18.

Hamouri BE, Lahjouj J and Nazih J. 2007. Subsurface–horizontal flow constructed wetland for sewage treatment under Moroccan climate conditions. *Desalination* **215**: 153–158.

Jain SK, Vasudevan P and Jha NK. 1989. Removal of some heavy metals from polluted by aquatic plantrs: Studies on duckweed and water velvet. *Biological Wastes* **28**(2): 115–16.

Jenssen PD, Maehlum T, Krogstad T. 1993. Potential use of constructed wetlands for wastewater treatment in northern environments. *Water Science &Technology* **28**(10): 149– 157.

Juyal GP, Katiyar VS, Dadhwal KS, Joshie P, Arya R. 2007. Mined area rehabilitation in Himalayas: Sahastradhara experience. *Bulletin No.T–53/D–34.* , CSWCRTI, Dehradun.

Kantawanichkul S, Pilaila S, Tanapiyawanich W.1999.Wastewater treatment by tropical plants in vertical–flow constructed wetlands. *Water Science & Technology* **40**(3): 173 –178.

Kara I, Zeytanluoglu A, and Genc H. 2003. Bioaccumulation of nickel by aquatic macrophyta *Lemna minor* (duckweed) aquatic weed. *International Journal of Agriculture and Biology* **5**(3): 281–283.

Kaur R. 2016. Eco–friendly wastewater treatment for reuse in agriculture (India). pp. 139–155. In: *Safe Use of Wastewater in Agriculture: Good Practice Examples*. (Eds. Hiroshan Hettiarachchi and Reza Ardakanian). United Nations University Institute for Integrated Management of Material Fluxes and of Resources (UNU–FLORES)

Khankhane PJ and Varshney Jay G. 2015. Performance of sub–surface horizontal wetland model using*Arundo donax* for rhizofiltration of drain water. *International Journal of Sciences and Applied Reserch 2*(10): 53–59.

Khankhane PJ and Varshney JG. 2011. Lead and manganese accumulation by weeds at heavy metal contaminated sites in Jabalpur. *Indian Journal of Weed Science* **43** (3&4): 224–225.

Khankhane PJ, Singh DK, Kaur R, Sondhia Shobha, Patel Akhilesh and AasfaTabassum. 2018. *Performance of aquatic plant species for contaminants removal from wste water in artificial wetland*. In : *Proceedings of Weeds and Society: Challenges and Opportunities*. ISWS Golden Jubilee International Conference. 21–24 November, 2018 . ICAR–Directorate of Weed Research Jabalpur, India.

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

Khankhane PJ, AasfaTabassum and Akhilesh Patel. 2015. Cadmium tolerance and its enhanced accumulation potential of *Arundo donax* by EDTA. p. 22. In: *Proceedings of* "*Weed Science for Sustainable Agriculture, Environment and Biodiversity*". 25th Asian–Pacific Weed Science Society Conference. Hyderabad, India during 13–16 October, 2015.

Kiviat Erik. 2013. Ecosystem services of *Phragmites* in North America with emphasis on habitat functions. *AoB Plants* **5**:1–29. DOI:10.1093/aobpla/plt00

Klomjek P and Nitisoravut S. 2005. Constructed treatment wetlands: A study of eight plant species under saline conditions. *Chemosphere* **58**: 585–593.

Kumar PBAN, Dushenkov V, Motto H and Raskin I. 1995. Phytoextraction: The use of plants to remove heavy metals from soils. *Environmental Science and Technology* **29**(5): 1232–1238.

Kurniadie D and Kunze C. 2000: Constructed wetlands to treat house wastewater in Bandung. *Indonesia Journal of Applied Biotechnology* **74**(1/2): 87–91.

Laber J, Haberl R and Shrestha R. 1999. Two–stage constructed wetland for treating hospital wastewater in Nepal. *Water Science & Technology* **40** (3): 317–324.

Lewandowski I, Scurlock JMO, Lindvall E and Christou M. 2003. The development and current status of perennial rhizomatous grasses as energy crops in the US and Europe. *Biomass Bioenergy* **25**: 335–361.

Liao X, Luo S and Wu Y. 2003. Studies on the abilities of *Vetiveria zizanioides* and *Cyperus alternifolius* for pig farm wastewater treatment. *Proceedings of the third International Vetiver Conference*, Guangzhou, China. available on: URL:http://www.vetiver.com/ICV3–Proceedings/CHN_pigwaste2.pdf.

LiaoX. 2000. *Studies on Plant Ecology and System Mechanism of Constructed Wetland For Pig Farm in South China* Ph.D. Thesis, South China Agricultural University, Guangzhou, Guangdong, China

Lu Xiaomei, Kruatrachue Maleeya, Pokethitiyookb Prayad and Homyokb Kunaporn. 2004. Removal of cadmium and zinc by water hyacinth, *Eichhornia crassipes*. *Science Asia* **30**: 93–103.

Maehlum T and Stälnacke P. 1999. Removal efficiency of three cold–climate constructed wetlands treating domestic wastewater: effects of temperature, seasons, loading rates and input concentrations. *Water Science & Technology* **40**(3): 273–281.

Maehlum T, Jenssen PD and Warner WS.1995. Cold–climate constructed wetlands. *Water Science & Technology* **32**(3): 95–101.

Maine MA, Sun N, Hadad H, Sanchez G and Bonetto C. 2007. Removal efficiency of a constructed wetland for wastewater treatment according to vegetation dominance. *Chemosphere* **68**: 1105–1113.

Mander Ü and Mauring T. 1997. Constructed wetlands for wastewater treatment in Estonia *Water Science & Technology* **35**(5): 323–330.

Mara DD and Cairncross S. 1989. *Guidelines for the Safe Use of Wastewater and Excreta in Agriculture and Aquaculture–Measures for Public Health Protection*. World Health Organization, Geneva.

Mara DD. 1976. *Sewage Treatment in Hot Climates*. John Wiley, London.

Mavrogianopoulos G, Vogli, V and Kyritsis S. 2002. Use of wastewater as a nutrient solution in a closed gravel hydroponic culture of giant reed (*Arundo donax*). *Bioresource & Technology* **82**(2): 103–107.

McGrath SP. 1998. Phytoextraction for soil remediation. pp. 261–288. In: *Plants thathyperaccumulate Heavy Metals: Their Role in Phytoremediation, Microbiology, Archaeology, Mineral Exploration and Phytomining*. (Ed. Brooks RR). New York, CAB International.

Mishra A, Farago ME, Bannerjee DK. 2000. A study of *Eichhornia crassipes* growing in the overbank and flood plain soils of the river Yamuna in Delhi, India. *Environmental Monitoring and Assessment* **60**(1): 25–45.

Nakayama FS. 1982. Water analysis and treatment techniques to control emitter plugging. *Proceedings of Irrigation Association Conference*, 21–24 February 1982. Portland, Oregan.

National Academy of Sciences and National Academy of Engineering. 1972. *Water Quality Criteria*. US Environmental Protection Agency, Washington DC. Report No. EPA–R373–033. 592 p.

Orth H, Kritiya L and Wildere PA. 1987. Wastewater treatment for industrial estates in south–east Asia using water hyacinths. *Water Science & Technology* **19**: 85–96.

Papazoglou EG, Karantounias GA and Bouranis DL 2005. Growth and biomass allocation of *Arundodonax* L. under heavy metal application. In: *Proceedings of the 9th International Conference on Environmental Science and Technology*, September 1"3, Rhodes Island (Greece). Available at http://www.srcosmos.gr/srcosmos/ showpub.aspx?aa=6670.

Paulose Bibin, Dutta SP, Rattan RK and Chhonkar PK. 2007. Effect of amendments on extractability, retention and plant uptake of metals on a sewage irrigated soil. *Environmental Pollution* **146**:19–24.

Pescod MB.1992. *Waste Water Treatment and Use in Agriculture. FAO Irrigation and Drainage Paper* 47. Scientific Publishers, Jodhpur.

Prasad MNV.2000. *A State–of–the–Art Report on Bioremediation, its Applications to Contaminated Sites in India. Ministry of Environment & Forests*, Government of India, 88 p.

Purakayastha TJ and Chhonkar PK. 2010. Phytoremediation of heavy metal contaminated soils. pp. 389–429. In: *Soil Heavy Metals: Soil Heavy Metals* (Eds. Sherameti and Varma A).

Purakayastha TJ, Thulasi V, Bhadraray S, Chhonkar PK, Adhikari PP and Suribabu K. 2008. of zinc, copper, nickle and lead from contaminated soils by different species of Brassicas. *International Journal of Phytoremediation* **10**: 63–74.

Raskin I, Smith RD and Salt DE. 1997. Phytoremediation of metals: Using plants to remove pollutants from the environment. *Current Opinion on Biotechnology* **8**(2): 221–226.

Rattan RK, Datta SP, Chhonkar SP and Singh AK. 2006. Heavy metal contamination through sewage irrigation in periurban areas of national capital territory of Delhi. *Technical Bulletin*, IARI, New Delhi. 51 p.

Reddy KR and De Busk WF. 1987. Nutrient storage capabilities of aquatic and wetland plants. pp. 337–357. In: *Aquatic Plants for Water Treatment and Resource Recovery*. (Eds. Reddy KR and Smith WF). Mongolia Publishers, Orlando, Florida.

Reed SC, Middlebrooks EJ and Crites. 1988. *Natural Systems for Waste Management and Treatment.* McGraw–Hill, Inc.

RR, Haberl R and Laber J. 2001. Constructed wetl and technology transfer to Nepal. *Water Science & Technology* **44**(11/12): 345–350.

Salt DE, Blaylock M, Kumar NPBA, Dushenkov V, Ensley D, Chet I and Raskin I. 1995. Phytoremediation: a novel strategy for the removal of toxic metals from the environment using plants. *Biotechnology* **13**: 468–474.

Samra JS. 2007. Heavy metal contaminated waters and their remediation for food safty. pp. 6–11. In: *Souvenir of 10th Inter–Regional Conference on water and Environment.* Indian Society of Water Management during October 17–20, at IARI, New Delhi

Shaharah, Mohd Idris., Paul L. Jones., Scott A. Salzman., George Croatto. and Graeme Allinson. 2012. Evaluation of the giant reed (*Arundo donax*) in horizontal subsurface flow wetlands for the treatment of recirculating aquaculture system effluent. *Environmental Science and Pollution Research* **19**: 1159–1170.

Shrestha RR, Haberl R and Laber J. 2001. Application of constructed wetlands for wastewater treatment in Nepal. *Water Science & Technology* **44**(11/12):381–386.

Sridevi B, Sharief SD, Dawood N, Noorjahan CM and Prabakar K. 2003. Bioabsorption of nickel and zinc by water hyacinth–*Eichhornia* sp. *Ecology, Environment and Conservation* **9**(3): 361–365.

Srivastava Ajay and Chhonkar PK. 2000. Influence of fly ash application on micro nutrient availability and uptake by sudan grass and oats grown on coal mine spoils. *Journal of Indian Society of Soil Science* **48**(4):859–861.

Surrency D. 1993. Evaluation of aquatic plants for constructed wetlands. pp. 349 –357. In: *Constructed Wetlands for Water Quality Improvement.* (Ed. Moshiri G.A). CRC Press, Boca Raton, Florida, USA

Thomas PR and Phelps HO. 1987. Study of upgrading waste stabilization ponds. *Water Science & Technology* **19**: 77–83.

UNESCAPE. 1981. UN Economic Commission for Asia and Pacific**. h**ttps://en.wikipedia.org/wiki/United_Nations_Economic_and_Social_Commission_for_Asia_and_the_Pacific.

Unterbrunner R, Wieshammer G, Hollender U, Felderer B, Zivkovic MW, Puschenreiter M and Walter MV. 2007. Plant and fertilizer effects on rhizodegradation of crude oil in two soils with different nutrient status. *Plant and Soil* **300**(1–2): 117–126.

Vasilevskaya N and Usoltseva A. 2004. Plant communities of the constructed wetland in Russian Arctic (Murmansk region) with high level of organic matter. *Proceeding of the 7th. International Wetlands Conference.* Utrecht, The Netherlands, Abstract: Poster VIII–811.

Vetiver Network, 2005. *The Vetiver Network Homepage* – The Vetiver System for on farm soil and water conservation, land rehabilitation, embankment stabilization, disaster mitigation, water quality enhancement, and pollution control. Access:08/2018. http://www.vetiver.org/index.html

Vymazal J. 2010. Review on constructed wetlands for waste water treatment. *Water* **2**(3): 530–549. doi:10.3390/w2030530 water ISSN 2073–4441.

Wangel Q, Cui Y and Dong Y. 2002. Phytoremediation of polluted waters potentials and prospects of wetland plants. *Acta Biotechnologica* **22**(1&2): 199–208.

Wei Shuhe, Zhou Qixing and Wanga Xin. 2005. Identification of weed plants excluding the uptake of heavy metals. *Environment International* **31**: 829–834

Zarangika MF and Ndapwadza T. 1995. Uptake of Ni, Zn, Fe, Co, Cr, Pb, Cu and Cd by water hyacinth (*Eichhornia crassipes*) in Mukuvisi and Manyame rivers, Zimbabwe. *Journal of Environmental Sciences and Health* Part A. **30**(1): 157–169.

Zhu YL, Zayed AM. Quian JH, De Souza M. and Terry N. 1999. Phytoaccumulation of Trace Elements by Wetland Plants: II. Water Hyacinth. *Journal of Environmental Quality* **28**: 339–344.

Chapter 16

Weed biological control research in India: Progress and prospects

Sushilkumar* and Puja Ray[1]
ICAR-Directorate of Weed Research, Jabalpur, Madhya Pradesh 482 004
[1]Multitrophic Interactions and Biocontrol Research Laboratory, Department of Life Sciences, Presidency University, Kolkata, West Bengal 700 073
**Email: sknrcws@gmail.com*

Summary

The introduction and spread of invasive alien plant species has become a global ecological and conservation catastrophe causing cascading socio-economic effects. Biological control using insects, plant pathogens and other living organisms has been considered as eco-friendly and sustainable alternative to the management of weeds. First unintentional biological control in the world happened in India when cochineal insect, *Dactylopius ceylonicus* was mistakenly introduced from Brazil in place of *D. cacti* to produce dye from *Opuntia vulgaris* during 1795. In due course, it started to control *Opuntia*, which led the foundation of biological control of weeds in future. First intentional introduction of bioagent *D. ceylonicus* was also done from India to Sri Lanka in 1865. Several biological control agents have provided excellent control in many locations around the world including India. In India, although biological control has been much neglected in last two decades especially in terms of release of new natural enemies of weeds, much of the work on weed biological control has been done using phytophagous insects and mites, but use of microorganisms has always taken a back seat. So far in India, about 31 exotic biological control agents have been introduced against weeds, of which six could not be released in the field, 3 could not be recovered after release while 22 were recovered and established. From these established bioagents, 7 are providing excellent control, 4 substantial control and 9 partial control. More efforts in terms of skill strengthening through training, capacity building, networking and collaborative projects especially with the industries, studies on new biological control agents and improving field application technologies needs to be reassessed in the country.

Keywords: Aquatic weed, Biological control, Bioagent impact, History, Invasive weeds, Terrestrial weed

Introduction

Biological invasions are one of the key biotic stressors to ecosystem functioning and have emerged as the second biggest threat to biodiversity after habitat destruction and ecosystem degradation (Gaertner *et al.* 2009) causing enormous economic and environmental damage worldwide. Estimates show that about 80% extinctions of endangered species occur due to invasion of non-native species (Pimentel *et al.* 2005). Non-native invasive plant species have emerged as major group of invaders in many countries including India. The invasive plants change the ecology of the habitat they invade by changing the nutrient cycle and soil pH rendering the soil less fit for native foliage, which in turn negatively impact the dependent or interacting organisms including arthropods and microorganisms. India with 2.45% of the world's area, has 8.10% of the world's total biodiversity with a species count of over 1,35,261. In terms of plant diversity, India ranks tenth in the world and fourth in Asia. About 40% of the species in the Indian flora are alien, of which 25% are invasive (Raghubanshi *et al.* 2005). Some of the major invasive species in India include carrot weed *Parthenium hysterophorus* (Asteraceae), water hyacinth *Eichhornia crassipes* (Pontederiaceae), *Lantana camara* (Verbenaceae), mile-a-minute weed *Mikania micrantha* (Asteraceae Kunth.), billygoat-weed *Ageratum conyzoides* (Asteraceae), purple nutsedge *Cyperus rotundus* (Cyperaceae), *etc*. Recent studies by Gharde *et al.* (2018) estimated that total actual economic loss of about USD 11 billion due to weeds alone in 10 major crops in India.

Several control mechanisms have been implemented for preventing the spread of or eradication of invasive weeds, which prominently includes the physical, chemical and biological control strategies. Each has its benefits and drawbacks. Physical control, using mechanical mowers, dredgers or manual extraction methods, is used widely, but it is not suitable for large infestations and is generally regarded as a short-term costly solution. Although chemical control methods are available that offer quick solution to the unwanted vegetation, but they have their own limitations due to their non-target environmental impact (Visalakshy 1992, Jayanth and Bali 1993, Wyss and Muller-Scharer 200, Kannan and Kathiresan 2002, Ray *et al.* 2008c, Sushilkumar *et al.* 2008). Such environmental concerns have fuelled the upsurge of interest in biological control of weeds, which is considered a cost effective, permanent and environmental friendly method. Many times questions are raised about the safety of biological control agents against non-targeted economically important plant species. After an systematic, statistical based analysis of large data, Suckling and Sforza (2014) found that large number of biocontrol agents introduced for classical biological control of weeds in the world (>99% of 512 agents released) had no known significant adverse effects on non-target plants. Most direct non-target impacts on plants (91.6%) were categorized as minimal or minor in magnitude with no known adverse long-term impact on non-target plant populations.

Biological control agents as potential and eco-friendly resource in weed management

Over the last six decades, biological control has prominently gained lot of importance (Van Driesche *et al.* 2010). A biological control agent may be a virus, bacterium, fungi, nematode, or living insect, fish, bird, and other animal, existing naturally or released in large number for immediate effect. The natural enemies of weeds like insects, pathogens, *etc*, that regulate the weed’s population in its homeland, may be introduced in the weed invaded territory to reduce and stabilize target plant density at sub-economic levels. A microorganism as biological control agent in general has a narrow target range and a very specific mode of action. They have relatively critical application times and with have limited field persistence and a short shelf life, which present no residue problems. they safer to humans and the environment than the conventional pesticide (Menaria 2007). Biological control agents provides a more eco-friendly, self-sustaining and cost-effective alternative to chemical control. They suppress, rather than eliminate, a pest population. Success stories of these agents and the expectation of obtaining perfect analogues of chemical herbicides have opened a new vista for weed management.

Biological control is especially useful in natural areas, forests, and rangelands, where very high specificity, low costs, and permanent control are needed to reduce populations of an invasive exotic weed without harming the native species. International use of biological control agent was first used around within the country (India) with increasing frequency since about 1960 (Julien 1987, Schroeder 1992). Interestingly much later the term "biological control" was first introduced by H.S. Smith in 1919 (DeBach, 1964) to signify the use of natural enemies to control insect pest. There are some promising bioagents, which have made success stories for the management of some important weeds in several countries including India. In 2014, Suckling and Sforza (2014), analysed the release of biogents against weeds since 1865 and concluded that upto 2012, total 512 organisms were released for weed biological control world over. In context to India, some attempts have been made to review the biological control of agricultural, forest and aquatic weeds. (Sen-Sarma and Mishra 1986, Ahmad 1991, Singh 1989, Jayanth 1994, Singh 2004, Sushilkumar 1993, 2009, 2011, 2014, 2015; Kaur *et al.* 2014).

Arthropods in biological control of weeds

The first documentation of outstanding success in biological weed control in the world was recorded in India itself through the unintentional release of an imported cochineal insect, *Dactylopius ceylonicus* (Green) in 1795 for biological control of cactus, *Opuntia vulgaris* in north India mistaken to be the carmine dye producing *D. coccus* that feeds on spineless prickly pear cactus, *Opuntia ficus-indica*. Once the control potential of *D. ceylonicus* was realized, it was intentionally introduced into south India during 1836 to 1838 and to Sri Lanka around 1865 to 1968, resulting in magnificent successful control of the weed in the entire region (Moran and Zimmerman 1984, Sushilkumar 1993). *D. opuntiae* contributed to extensive successful biological control of *O. stricta* in Australia (Dodd 1940) and *O. ficus-indica* in South Africa (Pettey 1948). Several other success narrations include the use of French chrysomelid leaf beetle *Chrysolina quadrigemina* for the control of St. John's wort *Hypericum perforatum* L. in Australia and United State and later to other parts of the world as well (Harris *et al.* 1969, Julian 1987, Campbell and McCaffrey 1991, Morrison 1998). Worldwide success of the Argentine pyralid moth *Cactoblastis cactorum* against prickly pear cactus *Opuntia* sp. in Australia since 1920s and in Africa (south of the Sahara) since 1930s (Dodd 1940, Julien and Griffiths 1998, Fullaway 1954) is worth mentioning. Spectacular success has also been achieved for management of some aquatic weeds by the introduction of some exotic insects. A flee beetle, *Agasicles hygrophila,* first insect ever studied for biological control of an aquatic weed has been successfully introduced into US from Argentina for controlling alligator weed, *Alternanthera philoxeroides*

(Amaranthaceae) (Thomas and Room 1986, Tipping and Center 2003, Tipping *et al.* 2008). Release of *Cyrtobagous salviniae* caused successful control of water fern, *Salvinia molesta* DS Mitchell (Jayanth 1987, Storrs and Julien 1996) in many countries of warmer parts of the world. Other than insects, several species of mites (Acarina) including *Tetranychus opuntiae* and *Orthogalumna terebrantis* have been successfully used in management of prickly pear cacti and water hyacinth, respectively. Nematodes have been well known plant pests in general also include few species extensively useful for biological control of weeds as *Paranguina pictidis* for biological control of Russian Knapweed, *Centaurea repens*.

Weed biological control history in India

Although first deliberate introduction of *Dactylopius celonicus* was done from India to Sri Lanka in 1865 against *Opuntia vulgaris*, but, systematic biological control research in India started in 1957 with the establishment of Commonwealth Institute of Biological Control (CIBC) at Bangalore with substations in different parts of the country. This was followed by establishment of All-India Co-ordinated Research Project on Biological Control of Crop Pests and Weeds (AICRP-BC&W) in 1977 and the Project Directorate of Biological control (PDBC) under the Indian Council of Agricultural Research (ICAR) (Sushilkumar 2015). Further during the XIth and XIIth five year plans, the PDBC was upgraded as National Bureau of Agriculturally Important Insects (NBAII), which was renamed as National Bureau of Agricultural Insect Resources (NBAIR). Meanwhile, National Research Center for Weed Science (NRCWS), now named as Directorate of Weed Research (DWR) came into existence in 1989 at Jabalpur with a modest beginning of biologiocal control of weeds in 1990s. Now with the change in mandate of NBAIR, the DWR shall deal on issues related to weed management including biological control of weeds in India (Sushilkumar 2015).

Progress on classical biological control of weeds in India

Under classical biological control, exotic natural enemies are introduced against inadvertently introduced alien organisms, which have become pests in the lack of natural checks in the new environment. Work on biological control of weeds in India has been dealt by Sushilkumar (1993) and Singh (2004) and Sushilkumar (2009, 2011, 2015; Kaur 2014). So far in India, about 31 exotic biological control agents have been introduced against weeds, of which 22 were recovered and established, six could not be released in the field while 4 could not be recovered after release. From these established bioagents, 7 are providing excellent control, 4 substantial and 9 partial control (Singh 2004, Sushilkumar 2015). It was concluded by Singh (2004) that under classical biological control in India, highest degree of success was achieved in biological control of aquatic weeds (55.5%) followed by homopterous pests (46.7%) of crop pests and terrestrial weeds (23.8%). Sushilkumar (2015) has listed the introduction, failure or success of various biocontrol agents from different countries in India (**Table 1**).

Table 1. Name of bioagents , source of country, year of introudciton in India and thier current status

Sl. No.	Exotic natural enemies (Order: Family) imported in India	Source country/year of introduction and weed plant	Current status/Reference
1	*Dactylopius ceylonicus* (Hemiptera: Dactylopiidae)	Brazil, 1795, prickly pear	It was mistakenly introduced in the belief to produce good quality carmine dye but it was the species of *D. coccus*. It readily established on pear, *Opuntia vulgaris* (its natural host) in North and Central India and resulted spectacular suppression. Later on, introduced in South India during 1836-38 and Sri Lanka during1965-68, where it also did excellent control of prickly pear (Sushilkumar 1993, Singh 2004).
2	*Dactylopius opuntiae* (Hemiptera: Dactylopiidae)	USA via Sri Lanka via Australia, 1926; pricly pear	Caused spectacular suppression of *Opuntia stricta* and related *O. elatior* (Singh 2004).
3	*Pareuchaetus pseudoinsulata* (Lepidoptera: Arctiidae)	Trinidad, West Indies via Sri Lanka, 1984 ; against weed species *Chromolaena odorata*	Established in 1988 in Dakshina Kannada district (Karnataka). Good suppression was recorded by 1990. Also recovered from Kerala and Tamil Nadu; partially successful (Ahmad 1991, Thakur *et al.* 1992, Sushilkumar 1993, Singh 2004).
4	*Procecidochares utilis* (Diptera: Tephritidae)	From Mexico via Hawaii, USA via Australia via New Zealand, 1963 ; against Crofton weed *Ageratina adenophora*	Released in the Nilgiris (Tamil Nadu), Darjeeling and Kalimpong areas (West Bengal) against Crofton weed; established and is spreading naturally, but efficacy hampered by indigenous parasitoids; has spread to Nepal, where it has become well distributed; partially successful (Swaminathan and Raman 1981, Bennet and Vanstaden 1986, Sushilkumar 1993, Singh 2004).
5	*Zygogramma bicolorata* (Coleoptera; Chrysomelidae)	From Mexico, 1983; against *Parthenium hysterophorus*	Released for control of *Parthenium;* established by natural spread and by concentrated efforts of Directorate of Weed Research (Jabalpur), established well in many states of India; naturally entered from India to Nepal and Pakistan; successful bioagent (Jayanth 1982; Sushilkumar 2005, 2009, 2014).
6	*Neochetina bruchi* (Coleoptera: Curculionidae)	Argentina via USA, 1982/1983; against water hyacinth	Well distributed and established on water hyacinth, spread to different parts of the country; doing good control of weed along with *N. eichhorniae* (Jayanth 1988, Singh 2004, Sushilkumar 2011).
7	*Neochetina eichhorniae* (Coleoptera: Curculionidae)	Argentina via USA, 1983 agaisnt water hyacinth	Well distributed and established throughout India in different water bodies. It is successful in stagnated ponds and lakes but not effective in running water like river

Sl. No.	Exotic natural enemies (Order: Family) imported in India	Source country/year of introduction and weed plant	Current status/Reference
8	*Orthogalumna terebrantis* (Acari: Orthogalumnidae)	Argentina via USA, 1986; against water hycienth	Well established in all released sites and is spreading on its own; doing good control of weed along with *Neochetina* spp. (Jayanth 1996, Singh 2004, Sushilkumar 2011).
9	*Epinotia lantanae* (Lepidoptera: Tortricidae)	Mexico, unintentional accidental introduction in 1919 on *Lantana*	Established on *Lantana camara* in several places, partially effective (Sushilkumar 2001, Singh 2004).
10	*Lantanophaga pusillidactyla* (Lepidoptera: Pterophoridae)	Mexico, unintentional accidental introduction, 1919 against *Lantana*	Established on *Lantana* but not effective (Sushilkumar 2001, Singh 2004).
11	*Octotoma scabripennis* (Coleoptera: Chrysomelidae)	Mexico via Hawaii via Australia, 197; against *Lantana*	Established on *Lantana* but not effective (Sushilkumar 2001, Singh 2004).
12	*Ophiomyia lantanae* (Diptera: Agromyzidae)	Mexico via Hawaii, 1921; against *Lantana*	Established on *Lantana* at several places, but not effective (Sushilkumar 2001, Singh 2004).
13	*Orthezia insignis* (Hemiptera: Ortheziidae)	Mexico, unintentional accidental introduction, **1915l** against *Lantana*	Established on *Lantana* at several places, partially effective (Sushilkumar 2001, Singh 2004).
14	*Teleonemia scrupulosa* (Hemiptera: Tingidae)	Mexico via Hawaii via Australia, 1941; against *Lantana*	Reported to feed on teak flowers at Dehradun, hence culture was destroyed in quarantine. But the insect 'escaped' quarantine and presently found on all *Lantana* stands in India; partially effective.
15	*Uroplata girardi* (Coleoptera: Chrysomelidae)	Brazil via Hawaii via Australia, 1969 to 1971; against *Lantana*	Established on *Lantana*, not effective (Sushilkumar 2001, Singh 2004).
16	*Cyrtobagous salviniae* (Coleoptera: Curculionidae)	Brazil via Australia, 1982/1983; against *Salvinia molesta*	Initially released in Bengaluru; later released at Kuttanad (Kerala), well established, did excellent control (Jayanth 1996, Singh 2004, Sushilkumar 2011).
17	*Ctenopharyngodon idella* (Pisces: Cyprinidae)	China via Hong Kong & Japan, 1959/1962; against submerged aquatic weeds	Introduced to control submerged aquatic weeds such as *Vallisneria* spp. and *Hydrilla verticillata* in fishponds; established in different parts of the country; very effective (Singh 2004, Sushilkumar 2011).

Sl. No.	Exotic natural enemies (Order: Family) imported in India	Source/year of introduction and weed plant	Current status
18	*Hypophthalmichthysmo litrix* (Pisces: Cyprinidae)	China via Hong Kong & Japan, 1959/1962	Released and established in different water bodies and feeds on various aquatic weeds and algae.
19	*Oreochromismoss ambicus* (Pisces: Cichlidae)	Africa, 1953; against submerged aquatic weeds	Established in different water bodies and feeds on various aquatic weeds and algae; partially effective (Singh 2004).
20	*Osphronemus goramy* (Pisces: Osphronemidae)	Java, Indonesia; Mauritius, 1916; against submerged aquatic weeds	Established in different water bodies and feeds on various aquatic weeds and algae partially effective (Singh 2004).
21	*Paulinia acuminata* West Indies, 1983 (Orthoptera: Acrididae)	West Indies, 1983; against *Salvinia molesta*	Released and recovered from water fern, *Salvinia molesta* in Thiruvananthapuram (Kerala); not effective (Singh 2004).
22	*Cecidochares connexa* (Diptera: Tephritidae)	South America via Indonesia, 2003 against *Chromolaena odorata*	Established at Bengaluru (Karnataka), Thrissur (Kerala); also released at Jagdalpur (Chhattisgarh); partially successful (Bhumannavar and Ramani 2007, Sushilkumar personal observations)
23	*Phytomyza orobanchia* (Diptera: Agromyzidae)	Yugoslavia, 1982; against broomrape *Orobanche* sp	Recovered occasionally. partially established (Singh 2004, Kannan *et al*, 2014).
24	*Dactylopius confuses* (Hemiptera: Dactylopiidae)	South America via South Africa, 1836; against prickly pear	Introduced but not recovered on *Opuntia vulgaris* (Singh 2004).
25	*Apion brunneonigrum* (Coleoptera: Apionidae)	Trinidad, West Indies, 1972-1983; against *Chromolaena odorata*	Introduced but not recovered on *Chromolaena odorata* (Singh 204).
26	*Salbia haemorrhoidalis* (Lepidoptera: Pyralidae)	Trinidad, West Indies, 1972-1983; against *Lanatana*	Introduced but not recovered on *Lantana camara* (Sushilkumar 2001, Singh 2004).
27	*Mescinia parvula* (Lepidoptera: Pyralidae)	Trinidad, West Indies, 1986 Mexico via Australia, 1985; *Chromolaena odorata*	Imported but failed in host specificity test; culture destroyed (Singh 2004)
28	*Epiblema strenuana* (Lepidoptera: Tortricidae)	Mexico, 1983; against *P. hysterophorus*	Did not breed in laboratory (Singh 1989, Sushilkumar 2005, 2009)
29	*Smicronyx lutulentus* (Coleoptera: Curculionidae)	Mexico, 1983; against *P. hysterophorus*	Failed in host specificity test hence culture destroyed (Singh 1989, Sushilkumar 2005, 2009)
30	*Leptobyrsa decora* (Hemiptera: Tingidae)	Peru & Colombia via Australia, 1971; against *Lantana*	Failed in host specificity test, culture destroyed (Mishra and Sen-Sarma 1986, Sushilkumar

Source: Sushilkumar 2015

Success stories of biological control in India

Against terrestrial weeds

First success story of biological control in terrestrial situation in India dates back in 1865 using *Dactylopius ceylonicus* agaisnt *Opuntia vulgaris,* which lead the world to use bioagents to manage weeds. Spectacular biological control success against *L. camara* in Hawaii, Fiji and Australia between 1902-1910 opened the ways for biological control of the weeds in other parts of the world. Biological control attempts in India against terrestrial weeds have been reviewed and discussed (Sushilkumar 2015). Release of biological control agent *Zygogramma bicolorata* in 1983 against *Parthenium hysterophrous* may be considered another success story of biological control in India. This has been reviewed and discussed in details by Sushilkumar (2009, 2014). Recently, again, seed weevil Smicronyx lutulentus has been imported for biological control of *Parthenium* at Bengaluru and testing for its host specificity are being done (Sreeram *et al.* 2018).

Partial effective or non-effective bioagent in India

As many as nine insect species including Tingid lace bug, *Teleonemia scrupulosa* has been introduced into India against lantana, but none has been proved successful except partial effective *T. scrupulosa* (Sushilkumar 1993, 2002, 2015).

Similarly, insect agents released against siam weed *Chromolaena odorata* (Asteraceae), crofton weed *Ageratina adenophora* (*Eupatorium adenophorum*) (Asteraceae) and Mikania *Mikania micrantha* (Asteraceae) have proved to be unsuccessful due to various reasons including heavy parasitism by native parasitoids (Singh 2004, Sushilkumar 2015). A gall fly *Cecidochares connexa* was introduced from Indonesia in 2002 against *C. oddorata* . It was released at 2 locations in Bengaluru, Karnataka during July-October 2005. Significant reduction in number of branches per plant (35.6%), number of panicles per plant (45.4%) , number of capitula per panicle (12.07%), and number of seeds per head (10.89%) was evident in galled plants over the control due to oviposition (Bhumannavar *et al.* 2007). The gall fly was also introduced in Kerala and Chhattisgarh (Sushilkumar, personal observations; Annual Report 2015). In Kerala, it had been well established in dense patches and galls occurrence was common after 8 years of its introductions, Survey in 2017 revealed its presence in campus of Kerala university and nearby area only. Small number of galls were recorded at Jagdalpur (Chhattisgarh) after three years of its introduction (Sushilkumar, personal observations). Survey made by the authors in Bengaluru and Thrissur revealed good number of galls on each plants but complete killing of plants was not observed. It was concluded that although gall flyies are able to reduce branch formation and flower produciton up to some extent but are not able to bring substantial suppression of *C. odorata*.

The microcyclic rust fungus, *Puccinia spegazzinii,* was identified as a potential classical biological control agent to replace the unsustainable or even hazardous conventional control methods. Following a successful risk analysis under quarantine at CABI (UK), a pathotype of the fungus (IMI 393067) from Trinidad and Tobago was imported into India. Prior to its release in the open field, the rust was further evaluated under strict quarantine conditions to ascertain the susceptibility of *M. micrantha* populations from three regions in India where the weed is invasive, and to confirm the safety of economically important plant species and indigenous flora. Results of host-specificity screening of 90 plant species belonging to 32 families ensured that the Trinidadian pathotype of *P. spegazzinii* was highly host- specific and could not infect any of the test plant species, though it was highly pathogenic to most of the target weed populations from Assam, Kerala and the Andaman and Nicobar Islands. The rust was released in Assam and Kerala but failed to establish at the time. However, due to the apparent success of this rust at controlling *M. micrantha* in the Pacific region, further releases in India are recommended (Sreerama 2016).

Fresh attempt has been made to reintroduce seed weevil Smicronyx lutulentus into India in April 2018 by importing 90 adults from Biosequrity Queensland, Australia. These are being tested for their host specificty tests under quarantine facilitites at Bengaluru (Sreerama 2018).

Against aquatic weeds

One of the outstanding success stories in biological control of weeds in India came in with the introduction of insect *Cyrtobagous salviniae* Calder and Sands (Coleoptera: Curculionidae), imported from Australia in 1982 and released in Bengaluru in 1983-84. Within 11 months of the release of the weevil, *Salvinia* plants collapsed (Jayanth 1987a). The cultures of *C. salviniae* supplied to Kerala met with similar success. Bioagent was established in all the released sites and in some areas resulting 99% suppression of the weed in 12-16 months. The weevil cleared over 1000 sqkm of water surface in Kuttanad area within two years of its introduction (Joy 1986).

In India, biological control of *E. crassipes* was initiated in 1982 with the introduction of 2 species of weevils, *Neochetina eichhorniae* in March 1982 and *N. bruchi* in October 1982 imported from USA. (Jayanth 1987b). In India, spectacular success has been achieved at Hebbal tank in Bangalore causing 95% control within a span of two years (Jayanth 1988), Loktak lake in Manipur (Jayanth and Visalakshi 1989) and several ponds in Jabalpur (Sushilkumar 2011, 2015). However, there were several instances where weevil releases have been a total failure, for example Kengeri tank in Bangalore (Anon. 1994). The success of these bioagens have been observed in perennial type of ponds, where chances of population build-up in future are good. In rivers and those lakes, where aquatic weed can be washed away during rainy season, chances of success are meagre.

Kannan and Kathiresan (1999) reported varied numbers of weevils required to control different growth stages of water hyacinth. Ray *et al.* (2009) studied minimum required inoculation load of weevils of *Neochetina* spp. on three growth stages of water hyacinth, based on fresh biomass, plant height and number of leaves. Impact studies of different number of inoculation load of *Neochetina* spp. after release unequivocally revealed significant reduction in flower production, plant height and dry weight after one year of release and subsequently complete control (Annual Report 2017). Biological control status of aquatic weeds in India has been reviewed by Sushilkumar (1993), Bhan and Sushilkumar (1996), Jayanth (1996), Singh (1989, 2004) and Sushilkumar (2011, 2015). Singh (2004) considered maximum degree of success (55.5%) in biological control of aquatic weeds under biological control programme in India.

Use of fish grass carp, native of large river systems of Eastern Asia (China, Siberia) has been used worldwide for biological control of aquatic weeds. Successful management of submerged aquatic weeds by fishes was demonstrated by Tyagi and Gireesha (1996) in the power canal and Hampi Foreway of the Tungbhadra Project. Grass carp feeds voraciously on *Hydrilla, Azolla, Nechamandra* and *Lemna* spp. in India. In general, grass carp prefers submerged aquatic macrophytes such as *Hydrilla verticillata*, *Chara* spp., *Najas guadalupensis*, *Potamogeton* spp., *Myriophyllum* spp. and *Vallisneria*. Among floating weeds it may feed *Wolffia* spp., *Lemna* spp., *Spirodela* spp., *Azolla caroliniana*, and many grass species.

Biological control using *Neochetina* spp. alone take considerable long time ranging from two to three years, however, chemical and biological integration may significantly reduce the time of control. This was demonstrated by Sushilkumar (2011) in a pond at Jabalpur (Madhya Pradesh) by releasing of about 1000 adults of *Neochetina* spp. in one part of the pond and spraying of herbicides in other parts of the pond in 15% area. First cycle of control was achieved within 9 months. This early collapse of weed within a period of 9 month could be possible due to integration of herbicide and bioagents, which would otherwise have taken minimum 24-36 month by the bioagents alone.

Chemical formulations may have harmful effect on non-target organisms including on biocontrol agents like *Neochetina* spp. Deleterious effects of commonly used herbicides on non-targeted organism (Visalakshy 1992, Kannan and Kathiresan 2002, Chattopadhyay *et al.* 2006, Praveena *et al.* 2007, Sushilkumar *et al.* 2008 and Ray *et al.* 2008.) and water quality (Sushilkumar *et al.* 2005, Sushilkumar 2008, Sushilkumar *et al.* 2008a) have been studied by many workers in India. Sushilkumar (2011) has reviewed the effect of herbicides on non-target organisms like bioagents and fishes and water quality. Persistence and residue of herbicides in water and sediments has been dealt in details in other chapter of the book.

Microbial control of weeds

Some microbes like fungi, bacteria, viruses and virus like agents are also being used for biological control of weeds. Among thesse, fungi have been used to a greater extent than bacteria, virus or nematodes. In some cases, it has been possible to isolate, culture, formulate and disseminate fungal propagules as mycoherbicides. Successful employment of this approach is still lacking in India against any aquatic or terrestrial weeds in spite of many reports of fungal pathogen infesting many weeds severely (Aneja *et al*. 1993, Kauraw and Bhan 1994a, Ray *et al*. 2008b). The work on microbial approaches in India has been reviewed on *Parthenium* (Sushilkumar 2009) and aquatic weeds (Sushilkumar 2011).

Fungi are particularly superior biological control agents because they have a high reproductive ability, a short generation time and are often able to survive as resting structures or as saprophytes during periods when host plants are not available. Often, isolates can be selected that have a highly specific host range. Additionally, contrasting to bacteria or viruses, which have limited abilities to pierce substrates, the mycelial growth habit of fungi enables them to break in surfaces very effectively (Ogle and Brown 1997). Several microbial products have been patented and commercialized in well-advanced countries (Templeton and Heiny 1989, Watson 1989, Boyette 2000, Charudattan and Dinoor 2000). DeVine, developed by Abbott Laboratories, USA, was the first commercial mycoherbicide derived from fungi *Phytophthora palmivora*, a facultative parasite that produces lethal root and collar rot of its host plant stangler wine *Morrenia odorata* and persists in soil saprophytically for extended period giving a long term control (Templeton 1987). Some of the other bioherbicides commercially released include Collego (based on *Colletotrichum gloeosporioides* f. sp. *Aeschynomene*) to control Northern Jointvetch *Aeschynomene virginica*, ABG5003 (*Cercospora rodmani*) against *E. crassipes*, BioMal® (*Colletotrichum gloeosporioides* f. sp. *malvae*) against Round-leaved Mallow *Malva pusilla. Alternaria cassiae* against sicklepod *Cassia obtuifolia* and a bacterial product Stumpout® (*Cylindrobasidium laeve*) for suppressing regrowth from cut stumps of bigleaf maple *Acer macrophyllum* Pursh (Boyette, 2000).

While most of the earlier work in various parts of the world, in biological control of weeds was confined to the studies of insects and mites, the Indian scientists at the Bangalore Station of Common Wealth Institute of Biological Control, were the earliest in the world to study the phytopathogens associated with several weeds (Gopal 1987).

Phytotoxic metabolites from microbes

Host specific microorganisms especially fungi have been known for their mycoherbicidal potential. Fungal culture itself have shown great efficacy for weed management but in many instances, several environmental restrains, such as adverse temperature, soil or water pH, humidity, *etc* are responsible for reduced disease incidence and severity (Auld and Morin 1995). Furthermore, environmental conditions are ever-changing, and are difficult to predict or duplicate growth-chamber studies. To overcome this problem, these days lot of concentration is being done on the secondary metabolites produced by the pathogens. Plant pathogenic fungi and bacteria produce a wide array of metabolites including alkaloids, glycosides, peptides, phenolics, terpenoids with wide range of ecological and industrial utility (Vurro 2007). These metabolites vary not only in chemical structure but also in their biological activity, mechanism of action and specificity. The increasing exploitation of secondary metabolites to synthesize new eco-friendly agrochemicals is getting popularized day by day in the arena of IPM phase. These metabolites are one of the most effective biologically based alternatives to chemical herbicides with low specificity and biodegradability. Fungal species like *Alternaria*, *Penicilium* and *Fusarium* biosynthesizes more than 130 bioactive compounds. Several workers including Charudattan and Rao (1982), Maity and Samaddar (1977), Stevens *et al*. (1979) isolated a toxin from *Alternaria eichhorniae* and obtained leaf necrosis on waterhyacinth. In contrast to efforts in other parts of the world, potential of plant pathogens as biological control agents of weeds have been very much neglected in India. Although, a few companies in India claim the successful formulation of the product from the isolates of fungi against *Parthenium* and water hyacinth (reference), but large scale field application is still awaited.

Phytotoxins from plants as bioherbicides

Plants produce an incredible diversity of low molecular weight organic compounds known as secondary metabolites (Pichersky and Gang 2000). These metabolites are referred to as allelochemicals or phytotoxins. Many allelochemicals produced by plants that inhibit the growth of other plants have been discovered (Putnam, 1988). There are several crop varieties like rice, wheat, sorghum, which has the ability to suppress weed by allelopathy (Bhowmik and Inderjit 2003). The phenomenon of allelopathy can be practically utilized for weed control in the form of crop rotations, intercropping, allelopathic mulches, and spray of allelopathic plant water extracts (Bhowmik and Inderjit 2003, Singh *et al*. 2003,Jabran *et al*. 2010a; Farooq *et al*. 2011). Sorghum (*Sorghum bicolor* and sunflower (*Helianthus annus*) are well known allelopathic crops, which contain a number of allelochemicals, which are toxic to weeds (Jabran *et al*. 2010a, b). Application of sorghum and sunflower water extracts reduced weed biomass by 33–53% and increased wheat yield (7–14%), according to Cheema *et al*. (1997). Similar observations were made in other crops (Bhatti *et al*. 2000, Khaliq *et al*.1999). Kathiresan and Dhavabharati (2008) reported allelopathic potential of 60 rice cultivars against water hyacinth.

The majority of past allelopathic research has focused upon the detrimental effects of living plants or their residues on plant growth. Recent researches on identifying novel secondary products isolated from plants, as phytochemicals with allelopathic potential (Duke 1986, Duke *et al*. 2000, Duke *et al*. 2002) offer promising scope for the control of weeds as well. The synthetic herbicides mesotrione (Callisto®) is derived from leptospermone, a compound isolated from the bottle brush plant (*Callistemon citrinus*) (Weston and Inderjit 2009). The ability to develop more herbicides from allelopathic compounds is limited by several factors.

Conclusion

There has been a quiet unjustified and unfortunate negative view commonly prevailing regarding biological control inspite of long list of success in biological control of weeds around the world. There is always discussion among the proponents and opponents about the success of biological control of weeds. Proponents of biological control advocate that biological control is an effective method to control many problematic weeds besides being economical and eco-friendly. On the other hand, opponents believe that biological control is too slow, not able to control all weeds, involves costly and cumbersome process for import of a biocontrol agent, require test of its host specificity, high rate of failure of bioagents, and may involve risk for non-target plants. Kluge (2000) discussed the false paranoia associated with weed biological control. There has been an element of fear that the biological control agent itself will become a pest or a threat to non-target plants after it has destroyed the weed. But a well host specificity verified biological control agent under quarantine conditions has no probability to shift its host even if the target host is completely eradicated from the vicinity. Classical biological control agents are self-perpetuating, self-contained and self-regulating; once they are established, therefore, further investments in control are not necessary (Pimentel 1989). In this way biological control agents differ from the use of pesticides, which usually require repeated annual applications. Also in contrast to pesticides, which cause numerous grim environmental and public health problems, biological control agents are eco-friendly Problem with using biological control agent is their often slow and uncertain nature. The gall-forming rust fungus, *Uromycladium tepperianum* was introduced into South Africa from Australia to control a noxious weed Port Jackson willow *Acacia saligna*. After an 8-10 year lag phase, the rust is now responsible for a 90-95% reduction in the weed populations and the native biodiversity is getting eventually restored without the need for reapplication of the pathogen (Morris 1997).

Sushilkumar and Yaduraju (2015) has discussed in detail, how successful is biological control of weeds? Based on the successful examples of biological weed control all over the world, they believed that still biological control approaches have big future world over. In India efforts on biological control has diminished over last two decades especially in terms of introducing new biological control agents of weeds. Often efforts to manage plant invasions have, in the past, been diluted by the ambivalence of managers attempting to find beneficial uses for these species without understanding their increasing negative impact on native biodiversity. Further the lack of a national coordinated effort for invasive species monitoring, research, and management largely results in failure of biological control agents. Over time, additional improvement needs to be brought about in methods of selection of biological control agents, especially phytopathogens, which have narrow environmental requirements and success obtained under laboratory studies should correspond with success under field conditions. In coming times, progress in terms of host-specificity studies and test plant selection for such studies may also be crucial, especially looking in changing environmental condition.

Many aspects of the activity of the bioherbicides can be tremendously improved specially for the pathogens such as increased virulence, improved toxin production, altered host range, resistance to chemical herbicides *etc*., using genetic and other biotechnological techniques.

Genetic engineering has made possible the transfer of genes across the species to overcome the reproductive barriers, the critical problem faced with gene transfer by conventional breeding. For example, the NEP 1 gene encodes for an extracellular fungal protein that causes necrosis when applied to many dicotyledonous plants, including invasive weed species. The NEP 1 gene successfully conferred hypervirulence to about nine-fold when transformed into *Colletotrichum coccodes* attacking *Abutilon theophrasti*. It also enhanced pathogenicity of *Fusarium* species to *Orobanche aegyptiaca*. parasitizing crops (Meir *et al*. 2009, Amsellem *et al*. 2002).

Although rate of success of classical biological control in India is low but still there are well founded hopes that the rate of success will increase in future projects. In many countries, introduction of multiple species of bioagents against a single weed species has shown encouraging results. For example, introduction of 9 bioagents against *Parthenium* in Australia contributes to suppress the weed significantly at different time of the year. Therefore, we have also to adopt this approche atleast for the most problematic weeds like *Parthenium, , Chromolaena, Mikenia,* water hyacinth, *Pistia* and alligator.

References

Abraham M, Abraham CT and Joy PJ. 2002. Natural enemies on *Mikania micrantha* H.B.K. in Kerala. *Journal of Tropical Agriculture* **40**: 39–41.

Ahmad M. 1991. Attempts on biological control of *Chromolaena odorata* in India. *Myforest* **27**: 179–186.

Amsellem Z, Cohen BA and Gressel J. 2002. Engineering hypervirulence in a mycoherbicidal fungus for efficient weed control. *Nature Biotechnology* **20**: 1035–1039.

Aneja KR and Singh K. 1989. *Alternaria alternata* (Fr.) Keissler a pathogen of waterhyacinth with biocontrol potential. *Tropical Pest Management* 35: 354–356.

Aneja KR, Srinvas B and Manpreet K. 1993. Evaluation of *Fusarium chlamydosporium* as a biocontrol agent of water hyacinth (*Eichhornia crassipes)* (Mart.) Solms. In: Integrated Weed Management of Sustainable Agriculture. Proceeding of Indian Society of Weed Science International Symposium, Hisra, India. 3: pp 145–149.

Annual Report. 2015. Directorate of Weed Research, Jabalpur

Annual Report. 2017. Directorate of Weed Research, Jabalpur

Anonymous. 1971 Use grass carp for weed control. *Indian Farming* **21**(5): 45–47.

Anonymous. 1987–2002. *Annual Reports for 1987–2002*. Project Directorate of Biological Control, Bangalore, India.

Anonymous. 1994. *Annual Progress Report*. Project Directorate of Biological Control, Bangalore, India.

Auld B.A. and Morin L. (1995). Constraints in the development of bioherbicides. *Weed Technology* **9**: 638–652.

Bhan VM and Sushilkumar. 1996. Eco–friendly approaches in aquatic weed management. 191–201. In: *Proceedings of Workshop on Aquatic Weeds–Problems and Management* (Ed. Varma, CVJ) held at Bangalore (Karnataka), 5–7 June 1996.

Bhatti MQL, Cheema ZA and Mahmood T. 2000. Efficacy of sorghum water extract as a natural weed inhibitor in Raya. *Pakistan Journal of Biological Sciences* **3**: 1128–1130.

Bhowmik PC and Inderjit. 2003. Challenges and opportunities in implementing allelopathy for natural weed management. *Crop Protection* **22**(4): 661–671.

Bhumannavar BS, Ramani S, Rajeshwari SK. 2007. Field release and impact of *Cecidochares connexa* (Macquart) (Diptera: Tephritidae) on *Chromolaena odorata* (L.) King and Robinson. *Journal of Biological Control* **21**(1): 59–64.

Boyette CD. 2000. The bioherbicide approach: using phytopathogens to control weeds. In: Cobb AH, Kirkwood RC, editors. Herbicides and their mechanisms of action. CRC Press, Boca Raton, FL, 134–152.

Campbell CL and McCaffrey JP. 1991. Population trends, seasonal phenology, and impact of *Chrysolina quadrigemina*, *C. hyperici* (Coleoptera: Chrysomelidae), and *Agrilis hyperici* (Coleoptera: Buprestidae) associated with *Hypericum perforatum* in northern Idaho. *Environmental Entomology* **20**: 303–315.

Charudattan R and Dinoor A. 2000. Biological control of weeds using plant pathogens: accomplishments and limitations. *Crop Protection* **19**: 691–695.

Charudattan R and Rao KV. 1982. Bostrycin and 4– Deoxybostrycin: Two nonspecific phytotoxins produced by *Alternaria eichhorniae. Applied and Environmental Microbiology* **43**(4): 846–849.

Cheema ZA, Luqman M, Khaliq A. 1997. Use of allelopathic extracts of sorghum and sunflower herbage for weed control in wheat. *Journal of Animal and Plant Science*. **7**: 91–93.

DeBach P. 1964. The scope of biological control. In Biological control of insect pests and weed. Reinhold, New York. (ed. DeBach P.). pp 1–20.

Dodd AP. 1940. The biological campaign against prickly pear. Commonwealth Prickly Pear Board Bulletin, Brisbane, Australia.

Duke SO, Dayan FE and Romagni J. 2000. Natural products as sources for new mechanisms of herbicidal action. *Crop Protection* **19**: 572–575.

Duke SO, Dayan FE, Rimando AM, Shrader K, Aliotta G, Oliva A and Romagni JG. 2002. Chemicals from nature for weed management. *Weed Science* **50**: 138–151.

Duke SO. 1986. Naturally occurring chemical compounds as herbicides. *Reviews in Weed Science* **2**: 15–44.

Farooq M, Jabran K, Cheema ZA, Wahid A, and Siddique KHM. 2011). Role of allelopathy in agricultural pest management. *Pest Management Science* **67**: 494–506.

Fullaway DT. 1954. Biological control of cactus in Hawaii. *Journal of Economic Entomology* **47**: 696–700.

Gaertner M, Breeyen AD, Hui C and Richardson DM. 2009. Impacts of alien plant invasions on species richness in Mediterranean–type ecosystems: a meta–analysis. *Progress in Physical Geography* **33**: 319–338.

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

Gopal B. 1987. Water hyacinth. Elsevier, Amsterdam– Oxford– New York–Tokyo. 471 pp.

Harris PD, Peschken, and Milroy J. 1969. The status of biological control of the weed *Hypericum perforatum* in British Columbia. *Canadian Entomology* **101**: 1–15.

Jabran K, Cheema ZA, Farooq M and Hussain M. 2010a Lower doses of pendimethalin mixed with allelopathic crop water extracts for weed management in canola (*Brassica napus* L.). *International Journal of Agriculture and Biology* **12**(3): 335–340.

Jabran K, Farooq M, Hussain M, Rehman H, Ali MA. 2010b. Wild oat (*Avena fatua* L.) and canary grass (*Phalaris minor* Ritz.) management through allelopathy. *Journal of Plant Protection Research* **50**(1): 32–35.

Jayanth KP and Bali G. 1993. Effect of commonly used weedicides on the Parthenium beetle *Zygogramma bicolorata* Pallister (Coleoptera: Chrysomelidae). Journal of *Biological control* **7**(1): 53–56.

Jayanth KP. 1987. Suppression of water hyacinth by the exotic insect Neochetina eichhoriae in Bangalore, India. *Current Science* **56**: 494–495.

Jayanth KP. 1987a. Biological control of the water fern *Salvinia molesta* infesting a lily pond in Bangalore (India) by *Cyrtobagous salviniae*. *Entomophaga* **32**: 163–165.

Jayanth KP. 1987b. Biological control of water hyacinth in India. *Technical Bulletin No. 3*, Indian Institute of Horticultural Research, Bangalore, India 28.

Jayanth KP. 1996. Biological control of aquatic weeds in India–progress and prospect. 122–129. In: *Proceedings of Workshop on "Aquatic Weed–Problem and Management*" (Ed. Varma, CVJ) held at Bangalore (Karnataka), 5–7 June 1996.

Joy PJ. 1986. Salvinia control in India. *Biocontrol News Information* **7**: 142.

Julian MH 1987. Biological control of weeds. World catalogue of agents and their target weeds. Second Edition. C.A.B International, London, 150 p.

Julien MH and Griffiths MW. eds 1998 Biological control of weeds. A world catalogue of agents and their target weeds, 4th edn. CABI Publishing, Wallingford.

Kannan C and Kathiresan RM. 1999. Biological control at different growth stages of water hyacinth. 1–8. In: *Proceedings of the First IOBC Global Working Group Meeting for Biological and Integrated Control of Water Hyacinth*. (Eds. M.P. Hill, M.H. Julian, T.D. Center). Harare, Zimbabwe, November16–19, 1998. PPRI Pretoria South Africa

Kannan C. and Kathiresan RM. 2002. Herbicidal control of water hyacinth and its impact on fish growth and water quality. *Indian Journal of Weed Science* **34**: 92–95.

Kathiresan RM and Dhavabharathi J. 2008. Rice allelopathy for water management in aquatic ecosystems. *Allelopathy Journal*. **22**: 413–416

Kaur Manpreet, Aggarwal Neeraj Kumar, , Kumar Vikas, and Dhiman Romika. 2014. Effects and management of *Parthenium hysterophorus*: A weed of global significance. *International Scholarly Research Notices* 12 : Article ID 368647, 12 pages. http://dx.doi.org/10.1155/2014/368647

Kauraw LP and Bhan VM. 1994. Efficacy of Cassytha powder to water hyacinth and of marigold to Parthenium population. *Weednews* **1**(2): 3–6.

Khaliq A, Cheema ZA, Mukhtar MA and Vasra SMA. 1999. Evaluation of sorghum (*Sorghum bicolor*) water extracts for weed control in soybean. *International Journal of Agricultural Biology*. **1**: 23–26.

Kluge RL. 2000. The future of biological control of weeds with insects: No more 'paranoia', no more 'honeymoon'. Proceedings of X International Symposium on Biological Control of Weeds. 4–19 July 1999, Montana State University, Bozeman, Montana, USA. (Ed Spencer NR). pp 459–467.

Maity BB. and Samaddar KR. 1977. A toxic metabolite from *Alternaria eichhorniae. Phytopathology* **88**: 78–84.

McFadyen REC. 2000. Success in biological control of weeds. Proceedings of X International Symposium on Biological Control of Weeds. 4–19 July 1999, Montana State University, Bozeman, Montana, USA. (Ed. Spencer NR.). pp 3–14.

Meir S, Amsellem Z, Al–Ahmad H, Safran E and Gresse J. 2009. Transforming a *NEP*1 toxin gene into two *Fusarium* spp. to enhance mycoherbicide activity on *Orobanche*—failure and success. *Pest Management Science* **65**: 588–595

Menaria BL. 2007. Bioherbicides: An eco–friendly approach to weed management. *Current Science.* **92**(1): 10–11.

Moran VC and Zimmerman HG. 1984. The biological control of cactus weeds: achievements and prospects. *Biocontrol News and Information* **5**: 297–320.

Morris MJ. 1997. Impact of the gall–forming rust fungus *Uromycladium tepperianum* on the invasive tree *Acacia saligna* in South Africa. *Biological Control* **10**: 75–82.

Morrison KD, Reekie EG and Jensen KIN. 1998. Biocontrol of Common St. Johnswort (*Hypericum perforatum*) with *Chrysolina hyperici* and a Host–Specific *Colletotrichum gloeosporioide*. *Weed Technology* **12**: 426–435.

Ogle HJ and Brown JF. 1997. Biocontrol of weeds using plant pathogens In: Plant Pathogens and Plant Diseases (Eds Brown JF and Ogle HJ). *Australasian Plant Pathology Society Inc.* 330.

Pettey FW. 1948 The biological control of prickly pears in South Africa. Union of South Africa, Department of Agriculture Science Bulletin, Entomology Series, 22: 1– 163.

Pichersky E and Gang DR. 2000 Genetics and biochemistry of secondary metabolites in plants: an evolutionary perspective. *Trends in Plant Science* **5**: 439–445.

Piementel D. 1989. Diversification of biological control strategies in agriculture. *Crop Protection.* **10**: 243–253.

Pimentel D, Zuniga R and Morrison D. 2005. Update on the environmental and economic costs associated with alieninvasive species in the United States. *Ecological Economics* **52**:273–288.

Praveena R and Naseema A. 2004. Fungi occurring on water hyacinth [*Eichhornia crassipes* (Mart.) Solms] in Kerala. *Journal of Tropical Agriculture* **42**: 21–23.

Raghubanshi AS, Rai LC, Gaur JP and Singh JS. 2005. Invasive alien species and biodiversity in India. *Current Science* **88**(4): 539–540.

Ray P, Sushilkumar and Pandey AK. 2008d. Deleterious effect of herbicides on waterhyacinth biocontrol agents Neochetina bruchi and Alternaria alternata. Biocontrol Sci. and Technol., 18 (5): 523–533.

Ray P, Sushilkumar and Pandey AK. 2009. Impact evaluation of Neochetina spp. on different growth stages of waterhyacinth. *Journal of Plant Protection Research* **49**(1): 7–13.

Ray P, Sushilkumar, Pandey AK 2008c. Deleterious effect of herbicides on waterhyacinth biocontrol agents *Neochetina bruchi* and *Alternaria alternata*. *Biocontrol Science and Technology* **18**(5): 523–533.

Ray P, Sushilkumar, Pandey AK. 2008b. Efficacy of pathogens of water hyacinth (*Eichhornia crassipes*), singly and in combinations for its biological control. *Journal of Biological Control* **22**: 173–177.

Ray P, Sushilkumar, Pandey AK. 2008a. Survey and selection of potential pathogens for biological control of water hyacinth. *Indian Journal of Weed Science* **40**: 75–78.

Schroeder D. 1992. Biological control of weeds: A review of Principles and trends. *Pesquisa Agropecuária Brasileira,* Brasília (Pesq. agropec. bras., Brasilia),**27**: 191–212.

Sen–Sarma PK and Mishra SC. 1986. Biological control of forest weeds in india–retrospect and prospects. *Indian Forester* **112**: 1088–1093

Singh HP, Batish DR and Kohli RK. 2003. Allelopathic interactions and allelochemicals: new possibilities for sustainable weed management. *Critical Reviews in Plant Science* **22**: (3–4): 239–311.

Singh SP. 1989. Biological suppression of weeds. NCIPM, Faridabad: *Technical Bulletin No.1*. 15–16.

Singh SP. 2004. *Some Success Stories in Classical Biological Control in India.* Asian and Pacific Coconut Community.

Stevens KL, Badar–Ud–Din, Ahmad A and Ahmad M. 1979. The antibiotic bostrycin from *Alternaria eichhorniae*. *Phytochemistry* **18**: 1579–1580.

Storrs MJ and Julien MH. 1996 Salvinia: A handbook for the integrated control of *Salvinia molesta* in Kakadu National Park. Northern Landscapes Occasional Papers No. 1. Australian Nature Conservation Agency, Darwin, Australia. p. 58.

Suckling DM, Sforza RFH.2014. What magnitude are observed non–target mpacts from weed biocontrol? *PLoS ONE* **9**(1): e84847. https://doi.org/10.1371/journal.pone.0084847

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

Sushilkumar and Yaduraju N.T. 2015. How successful is biological control of weeds?Pp. 30–34. In *Souvenir. Souvenir. 2015. 25 Asian–Pacific Weed Science Society Conference. Indian Society of Weed Science, Jabalpur, India.*

Sushilkumar, Kamlesh Vishwakarma and Ray P. 2008. Non–target effect of herbicides on Neochetina spp, a biological control agent of waterhyacinth. *Indian Journal of Weed Science* **40**(3&4): 200–202

Sushilkumar, Sondhia Shobha and Vishwakarma K. 2008a Evaluation of herbicides in context to regrowth against terrestrial form of alligatorweed Indian J.Weed Sci., 40 (3&4) : 180–187. Sushilkumar, Shobha Sondhia and Vishwakarma K. 2008. Evaluation of herbicide persistence in sediment to control alligator weed. *Indian Journal of Weed Science* **40**(1&2): 46–49.

Sushilkumar, Vishwakarma K and Yaduraju NT. 2005. Chemical control of lotus (Nelumbo nucifera Gaertn) in fish culture pond and its impact on water quality. *Indian Journal of Weed Science* **37**(3&4): 293–295.

Sushilkumar. 2008 Annual Report. National Research Centre for Weed Science, Jabalpur.

Sushilkumar. 2009. Biological control of *Parthenium*in India: status and prospects. *Indian Journal of Weed Science* **41**(1&2): 1–18.

Sushilkumar. 2011. Aquatic weeds problems and management in India. *Indian Journal of Weed Science* **43**(3&4): 118–138.

Sushilkumar. 2014. Spread, menace and management of Parthenium. *Indian Journal of Weed Science* **46**(3): 205–219.

Sushilkumar. 1993. Biological control of forests and waste land weeds in India. *Annals of Entomology* **11**(2): 131–153.

Sreerama Kumar Prakya, Dev Usha , Carol A. Ellison, Puzari KC, Sankaran KV and Nidhi Joshi. 2016. Exotic rust fungus to manage the invasive mile-a-minute weed in India: Pre-release evaluation and status of establishment in the field. *Indian Journal of Weed Science* **48**(2): 206–214.

Sreerama Kumar Prakya, Kumar MS, Shylesha AN, Ballal CR, Dhileepan K, Shi Boyang and Callender JT. 2018. P. 209. In: Proceedings of 1st International Biological Control ' Approaches and applications. 27-29 September 2018, Bengaluru, India.

Templeton GE and Heiny DK. 1989. Improvement of fungi to enhance mycoherbicide potential. pp. 127– 151. In: (Whipps, J.M. and Lumsden, R.D. (Eds.), Biotechnology of Fungi for Improving Plant Growth. Cambridge University press, Cambridge, UK.

Thomas PA and Room PM 1986 Taxonomy and control of *Salvinia molesta*. *Nature* **320**: 581–584.

Tipping PW, Martin MR, Center TD and Davern TM. 2008 Suppression of *Salvinia molesta* Mitchell in Texas and Louisiana by *Cyrtobagous salviniae* Calder and Sands. *Aquatic Botany* **88**: 196–202.

Tipping PW and Center TD. 2003 *Cyrtobagous salviniae* successfully overwinters in Texas and Lousiana. *Florida Entomologist* **86**: 92–93.

Tyagi AC and Gireesha O. 1996. Successful management of submerged weeds in the power canal and Hampi foreway pf the Tungabhadra board. pp.185–190. In: *Proceedings of Workshop on "Aquatic Weed–Problem and Management* (Ed. Varma, CVJ) held at Bangalore (Karnataka), 5–7 June 1996.

Van Driesche RG, Carruthers RI, Center T, Hoddle MS, Hough–Goldstein J, Morin L, Smith L, Wagner DL, Blossey B, Brancatini V, Casagrande R, Causton CE, Coetzee JA, Cuda J, Ding J, Fowler SV, Frank JH, Fuester R, Goolsby J, Grodowitz M, Heard TA, Hill MP, Hoffmann JH, Huber J, Julien M, Kairo MTK, Kenis M, Mason P, Medal J, Messing R, Miller R, Moore A, Neuenschwander P, Newman R, Norambuena H, Palmer WA, Pemberton R, Perez–Panduro A, Pratt PD, Rayamajhi M, Salom S, Sands D, Schooler S, Schwarzländer M, Sheppard A, Shaw R, Tipping PW, and van Klinken RD. 2010. Classical biological control for the protection of natural ecosystems. *Biological Control* **54**: S2–S33.

Visalakshy PNG. 1992. Effect of commonly used weedicides and mosquito larvicides on exotic waterhyacinth mite, *Orthogalumna terebrantis* Wallwork (Acarina: Galumnidae). *Journal of Biological Control* **6**(1): 35–37.

Vurro M. 2007. Benefits and risks of using fungal toxins in biological control. In: (Eds. Vurro M. and Gressel J) Novel Biotechnologies for Biocontrol Agent Enhancement and Management. NATO Security through Science Series. Springer, Dordrecht

Watson AK. 1989. Current advances in bioherbicide research. Brighton Crop Protection Conference–Weeds **3**: 987–996.

Weston LA and Inderjit 2009. Non–chemical weed management: synopsis, integration and the future. pp. 201–209. In: (Eds. Upadhyaya MK and Blackshaw RE) Non–chemical Weed Management: Principles, Concepts and Technology. CAB International.

Wyss GS, Muller–Scjarer H. 2001. Effects of selected herbicides on the germination and infection process of *Puccinia lagenophora*, a biocontrol pathogen of *Scnecio vulgaris*. *Biological Control* **20**: 160–166.

National Bank for Agriculture and Rural Development

NABARD

Our Mission: Promotion of sustainable and equitable agriculture and rural prosperity through effective credit support, related services, institution development and other innovative initiatives.

Research and Development on matter of importance pertaining to agriculture, agricultural operations and rural development including the provision of training and research facilities.

Consultancy services related to Agriculture & Rural Development through subsidiary (NABCONS).

Our Functions:

Provide Credit/Refinance for production credit and investment credit to eligible banks and financing institutions.

Development functions undertaken through Farm Sector Promotion Fund (FSPF), Financial Inclusion Fund (FIF), Watershed Development Fund (WDF), Tribal Development Fund (TDF) Rural Infrastructure Development Fund,(RIDF) etc.

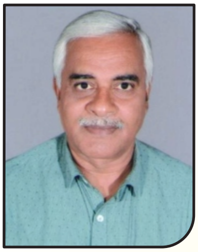
Supervisory functions in respect of Cooperative Banks and Regional Rural Banks.

Head Office Plot C-24, 'G' Block Bandra Kurla Complex, Bandra (East) Mumbai - 400 051

www.nabard.org **YouTube /nabardonline** **Taking Rural India >> Forward**

Editors

Dr. Sushil Kumar obtained his M. Sc (Entomology) from Meerut University in 1981 and Ph.D. from Forest Research Institute, Dehradun in 1986. He started his service career as Research Assistant from Forest Research Institute, Dehradun (1983-1991) and joined Agricultural Research Service (ARS) in December 1991. During his ARS services, he served in Potato Research Institute, Shimla for about two years before joining the then National Research Center for Weed Science (NRCWS). At Forest Research Institute, he made significant contribution in understanding the behavior of termites and their management besides many other insect pests of forestry and agroforestry importance. In his brief period at Potato Research Institute in Shimla, he contributed mainly to assess the losses caused by rodents and slugs in potato fields. He has worked extensively on biological based integrated management of terrestrial and aquatic weeds besides their utilization. His most pioneering contributions are for the management of *Parthenium* and Water hyacinth besides making public aware about them. He has been recipient of many awards like AZRA Young Scientist Award (1998), DWR Best Scientist Award (2004 and 2014), Fellow of Indian Society of Entomology (2008), ISWS Recognition Award (2008), ISWS Best Book Award (2008), Fellow of AZRA (2011), ICAR Extension Award (2011), Crystal National Agri Award (2014) etc. He served ISWS as Secretary (2008-2011 and 2017-2018) and as Chief Editor of Indian Journal of Weed Science (2013-2016).



Dr. J.S. Mishra obtained his M. Sc. (Ag.) from NDUAT, Faizabad and Ph. D. from JNKVV, Jabalpur. He started his service career as scientist from DWR, Jabalpur (1992-2008) and also served at IIMR, Hyderabad (2008-2014) before joining as Head, Division of Crop Research, ICAR Research Complex for Eastern Region, Patna in 2014. He has made outstanding contributions in the field of weed management research and popularization of sorghum cultivation in rice-fallows of coastal Andhra Pradesh. His pioneering contributions are in the area of biology of parasitic weed *Cuscuta campestris* and its management, conservation tillage and weed management in rice/soybean-based cropping systems, weed seedbank dynamics, popularization of sorghum hybrids in rice-fallows; and development and popularization of CA practices in rice-based cropping system in Eastern region. He has been honored with ISA PS Deshmukh Young Agronomist Award (1999), DWR Best Scientist Award (2007), Fellow of Indian Society of Weed Science (2007), Indian Society of Agronomy (2010) and Society for Upliftment of Rural Economy (2015), ISWS Gold Medal (2014) and ISA Gold Medal (2016) for his significant contributions.