Chapter 4

Weeds and Weed Management in India – A Review

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Abstract: India has a wide range of agroclimates and soil types. 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. Invasive alien weeds are a major constraint to agriculture, forestry and aquatic environment. Crop-specific problematic weeds (weedy rice in rice) are emerging as a threat to cultivation, affecting crop production, quality of product and income of farmers. Traditionally, weed control in India has been largely dependent on manual weeding. However, increased labour scarcity and costs are encouraging farmers to adopt labour and cost-saving options. These include herbicides whose market grew at an annual rate of 15%. Integrated weed management (IWM) is being practiced by Indian farmers, with the level of adoption varying from one farm to the other. The continuous application of isoproturon coupled with mono-cropping rotation of rice-wheat has led to the evolution of resistance in *Phalaris minor* Retz. In the northern part of India. Efforts to manage herbicide resistance have led to the adoption of conservation agriculture in the rice-wheat cropping system, as a component of IWM.

Research on weed management in India is mostly centred on herbicide efficacy. Herbicides, applied alone or in combinations, have been regarded as essential tools in the effective management of weeds in different ecosystems. IWM, which includes preventative, mechanical, cultural, chemical and biological methods, is advocated in crop production systems as well as aquatic and forest ecosystems. Herbicide-resistant (HR) transgenic crops have the potential to improve the weed management efficiency and facilitate adoption of CA in India, provided the risks associated with such crops are examined in detail, prior to their adoption and commercialization. Newer weed management approaches must be developed considering the threat of HR weeds appearance in addition to the recurrence and persistence of weeds and the need to bring down weed management costs to enhance profit for farmers while protecting the environment. Understanding weed ecology and biology and using information technology should be part of developing and disseminating effective, economical and ecologically advantageous IWM strategies in India. Detailed review of weeds and weed management options of the past, present and future in India is made in this chapter.

Key words: Weeds, India, hand weeding, preventive methods, cultural methods, biological control, herbicides, resistance, conservation agriculture, integrated weed management.

Introduction

India is located to the north of the equator between 8° 4′ and 37° 6′ N latitudes and between 68° 7′ and 97° 25′ E longitudes. She is the seventh largest country in the world and the second largest in Asia, with a land area of about 15,200 km and a coastline of 7,516 km. India measures 3,214 km from north to south and 2,933 km from east to west. Agriculture continues to be the backbone of the Indian economy as it employs 54.6% of the total work force. The total share of agriculture and its allied sectors (including the livestock, forestry and fishery sub-sectors) to the gross domestic product was 13.9% in 2013-14. Out of India's total cropped area of 192 million ha, less than one-half is under irrigation. The Indian agricultural production system has a challenge to feed17.5% of the global population with only 2.4% of land and 4% of the available water resources at its disposal.

India, bestowed with heterogeneous landforms and diverse climatic conditions, comprises lofty mountains, riverine deltas, high altitude forests, peninsular plateaus and various other geological formations. The country also experiences a wide range of temperatures–varying from arctic cold to equatorial hot–and rainfall from extreme aridity (< 10 cm yr^{-1}) to extreme humidity, with some areas recording the world's highest rainfall (1,120 cm). India has high plateau, open valleys, rolling upland, plains, swampy low lands and barren deserts. Depending upon soil, bio-climate and physiography, the country has 20 agro-eco regions and 60 agro-eco-subregions. Each agro-eco-subregion has further been classified into agro-eco-units at the district level for developing long term land use strategies [Gajbhiye and Mandal 2006]. Each of the agro-ecological regions and crops grown has distinct weed problems [Rao et al. 2014].

Eversince the Green Revolution, beginning the 1960s, Indian rice and wheat systems have been playing a critical role in the global food economy. The food, primarily rice, produced by India supports the local population of 1.25 billion besides other millions of people in Asian and African countries by way of exports [Burneya and Ramanathan 2014]. India has set a growth target of 4% for the agriculture sector during the 12th Plan period of 2012-2017 [Planning Commission 2013]. However, growth in agriculture and allied sectors is expected to be only 1.1% in 2014-15, down from 3.7% in 2013-14, due to the impact of low southwest monsoon on both kharif (monsoon: Apr-Oct) and rabi (winter: Nov-Mar) harvests. This emphasizes the need for constant efforts to increase crop productivity and production to meet the demands of increasing population by developing and extending climate-resilient technologies for agricultural and horticultural crops. Such efforts must take into consideration management of weeds, which adapt well to grow in both unfavourable and favourable environments and cause yield and quality loss, while competing with crops for resources [Rao and Nagamani 2010].

India is the world's second largest producer of rice, wheat and cotton after China; and the second largest producer of sugarcane, after Brazil. It is also the second largest global producer of horticultural products. Moreover, India is the world's second largest importer of vegetable oils besides being the largest producer, consumer and importer of pulses (grain legumes). However, productivity of these crops is far lower than that of developed countries and China (Table 1). To meet the demands of an increasing population and avoid food imports, crop productivity in India needs major improvements, which can be attained by identifying the constraints that hinder farmers in achieving high yields.

Table 1. Global comparison of area, production and yield of principal crops.*

Country	Area (million ha)	Production (million tonnes)	Yield (tonnes ha^{-1})	Production (% of world)
Rice				
World	163.46	718.35	4.39	100
China	30.56	206.09	6.74	28.69
India	42.50	152.60	3.59	21.24
Indonesia	13.44	69.05	5.14	9.61
Bangladesh	11.70	34.20	2.92	4.76
Vietnam	7.75	43.66	5.63	6.08
Wheat				
World	216.64	674.88	3.12	100
China	24.14	120.58	5.00	17.87
India	29.90	94.88	3.17	14.06
Russia	21.28	37.72	1.77	5.59
U.S.A.	19.83	61.76	3.11	9.15
Maize				
World	176.99	875.10	4.94	100
USA	35.36	273.83	7.74	31.29
China	34.97	208.26	5.96	23.80
Brazil	14.23	71.30	5.01	8.15
Mexico	6.92	22.07	3.19	2.52
Indonesia	3.96	19.38	4.89	2.21
India	8.40	21.06	2.51	2.41
Sugarcane				
World	25.76	1773.81	68.85	100
Brazil	9.41	670.76	71.30	37.81
India	5.09	347.87	68.34	19.61
China	1.8	124.17	68.81	7.00
Thailand	1.3	96.5	74.23	5.44
Groundnut				
World	24.63	41.27	1.68	100
China	4.73	16.88	3.57	40.71
India	4.90	5.78	1.18	14.00
Nigeria	2.42	3.07	1.27	7.44
USA	0.65	3.06	4.70	7.41
Myanmar	0.88	1.37	1.56	3.32

*Source: FAO, Regional Office for Asia and the Pacific, Bangkok.

In India, weeds are one of the major biological constraints that limit crop productivity. They compete with crops for natural and applied resources besides being responsible for reducing quantity and quality of agricultural productivity [Rao and Nagamani 2010, 2013; Rao et al. 2015], despite continuous research and extension efforts made. Bhan et al. [1999] estimated that weeds in India reduce crop yields by 31.5% (22.7% in winter and 36.5% in summer and kharif seasons). In other studies, weeds were reported to cause up to one-third of the total losses in yield, besides impairing quality of produce and causing health and environmental hazards [DWSR 2013]. In a survey, Indian weed scientists estimated losses due to weeds from 10% to 100% (Table 2). 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]. Losses of this magnitude due to weeds may occur in plantation crops, fruits, vegetables, grasslands, forestry and aquatic environments. 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.

Table 2. Potential yield loss due to weeds in different major crops of India [Rao et al. 2014].

Crop	Yield loss (%)	Crop	Yield loss (%)
Chieckpea	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

This review provides a broad overview of weeds and their management as well as future outlook on developments in weed science in India. It includes a) major crops of India and weeds associated with them, along with the estimates of losses caused by weeds; b) important, contentious weed species in agriculture crops, water bodies, public amenity areas and methods of their management; c) invasive and parasitic weed species and their management; d) the extent, limitations and cost-benefit analysis of weed management in conservative agriculture (CA) systems; e) innovative strategies for managing weeds; f) herbicides available, herbicide residues in soil and food-chain, their mitigation and management in rotational crops; and g) herbicide resistance in weeds of India and their management. It also discusses the potential for adoption of herbicide resistant (HR) transgenic crops in India, the current status of weed research and education and extension activities besides emerging concerns/challenges and opportunities for weed management.

Important Weed Species and their Management

Weeds Associated with Crops

Major weeds associated with different crops vary with crops (Table 3) and locations [Rao et al. 2014]. The Directorate of Weed Research (DWR), Jabalpur, has developed a Weed Atlas for major weeds in major crops in 435 districts spread across 19 states of the country and published a handbook on weed identification [Naidu 2012]. Its findings revealed that a) infestations of little mallow (*Malva parviflora* L.), jangli palak (*Rumex retroflexus* Lag. ex Schult. & Schult.f.), annual bluegrass (*Poa annua* L.), lesser swinecress {*Coronopus didymus* (L.) Sm.} and rabbitfoot polypogon {*Polypogon monspliensis* (L.) Desf.} are increasing in the rice-wheat cropping zone; b) tiger foot morning glory (*Ipomoea pestigridis* L.) has become a serious weed of sugarcane in Haryana and U.P.; c) the intensity of submerged weeds is gradually increasing in the rice-rice sequence in Assam; d) ragweed (*Ambrosia artemisiifolia* L.) and parthenium (*Parthenium hysterophorus* L.) are gradually spreading beyond the non-cropped area and entering cropped and plantation areas; and e) loranthus (*Loranthus longiflorus* Desr.) is likely to be a major problem for mango orchards in the southern part of the country. In addition, weedy rice (*Oryza sativa* L.) is emerging as a major problem in direct-seeded rice [Rao and Nagamani 2007; Rao et al. 2007].

Table 3. Weeds of economic significance (in order of significance) in specific crops [Rao et al. 2014].

Wheat	Rice	Soya bean	Chickpea	Maize
Phalaris minor Retz.	*Echinochloa colona* (L.) Link	*Echinochloa colona* (L.) Link	*Chenopodium album* L.	*Echinochloa colona* (L.) Link
**Avena ludoviciana* Durieu	*Echinochloa crus-galli* (L.) Beauv.	*Cyperus rotundus* L.	*Avena fatua* L.	*Celosia argentea* L.
Chenopodium album L.	*Cyperus* spp.	*Euphorbia geniculata* Ortega	*Medicago denticulata Willd.*	*Cynotis axillaris* (L.) D. Don.
Avena fatua L.	*Alternanthera* sp.	*Commelina communis* L.	*Chicorium intybus*	*Euphorbia hirta* L.
Cichorium intybus L.	*Cyperus rotundus* L.	*Dinebra retroflexa* (Vahl) Panz	*Convolvulus arvensis* L.	*Melochia corchorifolia* L.
Medicago denticulata Willd.	*Commelina benghalensis* L.	*Physalis minima* L.	*Lathyrus aphaca* L. /*Lathyrus sativus* L.	*Cyperus* spp.

Wheat	Rice	Soya bean	Chickpea	Maize
Parthenium hysterophorous L.	*Caesulia axillaris* Roxb.	*Trianthema* spp.	*Vicia sativa*	*Spilanthes acmella* Murr.
Vicia sativa L.	*Ammannia* sp.	*Alternanthera sessilis* (L.) R. Br. ex DC.	*Cyperus rotundus* L.	*Blainvillea acmella* (L.) Philipson
Convolvulus arvensis L.	*Dinebra* sp.	*Chenopodium album* L.	*Orobanche*	*Euporbia geniculata* Ortega
Melilotus alba Medik.	*Eclipta alba* (L.) Hassk.	*Convolvulus arvensis* L.	*Phalaris minor* Rtez.	*Digera* spp.
Melilotus indica (L.) All.	*Fimbristylis miliacea* (L.) Vahl	*Cynodon dactylon* (L.) Pers.	*Avena ludoviciana*	*Ageratum* spp.
Rumex dentatus L.	*Dactyloctenium aegypticum* (L.) Willd.	*Digera arvensis* Forsk.	*Euphorbia geniculata* Orteg.	*Cyperus iria* L.

*Synonym: *Avena sterilis* L. subsp. *ludoviciana* (Durieu) Gillet & Magne [excluded].

Shifts in weed flora have also been reported. For example, due to growing rice under alternating flooding regimes and residual soil moisture conditions prevalent in the Cauvery Delta region of Tamil Nadu, red sprangletop {*Leptochloa chinensis* (L.) Nees} and European waterclover (*Marsilea quadrifolia* L.) became predominant in rice fields by replacing barnyardgrass (*Echinochloa* sp.) [Yaduraju and Kathiresan 2003]. In the eastern Indo-Gangetic Plains, adoption of zero tillage has resulted in an increase in population of globally-significant perennial weeds such as purple nutsedge (*Cyperus rotundus* L.) and Bermuda grass {*Cynodon dactylon* (L.) Pers.} [Malik and Kumar 2014]. Such shifts are likely to occur in other production systems as well, suggestmg that changes in weed flora need to be monitored continuously in all cropping systems and agro-ecological regions in order to assess emerging weed problems and plan weed management strategies accordingly.

Weed Management in Major Crops

Manual weeding has been synonymous with weed management for centuries, due to abundant availability of labour, cheaper labour costs and the nature of agriculture as an occupation. Hence, manual and mechanical methods were the prevalent weed management techniques used by farmers until the end of 1990s. During the 1990s, the nominal farm wages grew at 11.6% annually, while in the 2000s they rose at 8.9%. In the recent past, the growth was 17.8% during 2007-2008 and 2010-2011 (Source: Labour Bureau, Shimla, India). The effect of increased wages and labour costs has concomitantly increased reliance on herbicides, applied alone or as a component of integrated weed management (IWM) [Rao et al. 2014].

In the past, the herbicides most commonly used were isoproturon and 2,4-D. Currently, sulfosulfuron, clodinofop, metsulfuron, mesosulfuron+iodosulfuron and isproturon+2,4-D mixture are commonly used by wheat farmers. In rice, thiobencarb, butachlor, 2,4-D and anilophos have been used in the past. Currently, bispyribac-sodium, butachlor, fenoxaprop, chlorimuron+metsulfuron, ethoxysulfuron, oxadiargyl, pyrazosulfuron, pretilachlor and 2,4-D are more favoured by rice farmers.

The distribution of horticultural crops and weeds in India, weed management methods in fruit, vegetable, tuber, ornamental, medicinal, aromatic and plantation crops and economics were discussed by Chadha et al. [1997]. Herbicide use in combination with hand weeding was observed to be most economical by several researchers. Rao and Nagamani [2010] summarized economical weed manegement strategies for a few major crops of India (Table 4). The dynamic nature of weeds necessitates continuous redesigning of strategies from time to time for their successful management.

Table 4. Most economical weed management methods for managing weeds in certain crops of India [Rao and Nagamani 2010].

Crop*	Weed management	Reference
Asgandh (*Withania somnifera* Dunal)	Isoproturon 0.50+glyphosate 1.0 Pre; HW 45 DAS.	Kulmi and Tiwari 2005
Blackgram	Pendimethalin 0.50; HW 45 DAS Pendimethalin 0.50; Pre; HW 60 DAS Trifluralin 0.50 Pre; HW 45 DAS	Kumar et al. 2006 Rathi et al. 2004 Sardana et al. 2006
Lentil	Pendimethalin 1.0 Pre; HW 45 DAS	Lhungdim et al. 2013
Coriander	Pendimethalin 1.0 Pre; HW 45 DAS	Nagar et al. 2009
Cowpea	Pendimethalin 0.75 Pre: HW 35DAS	Mathew et al. 1995
Garlic	Oxyfluorfen 0.15 or pendimethalin 1.0 Pre; HW 40 DAS	Porwal 1995
Groundnut	Pendimethalin or alachlor 1.0 Pre; HW 30 DAS	Itnal et al. 1993
Indian mustard	Pendimethalin 0.50 or fluchloralin 0.50 Pre; HW 30 DAS Fluchloralin 0.75 Pre; HW: 25 DAS	Singh et al. 1999 Singh 2006
Onion	Pedimethalin1.5 Pre; HW: 60 DAT Oxyfluorfen 0.25 Pre; HW: 40 DAT Oxyfluorfen 0.15 Pre; HW: 35 DAT Fluchloralin or pendimethalin 0.9 Pre; HW: 40 DAT Pendimethalin 1.0+oxyfluorfen 0.25 Pre; HW: 30DAT	Rameshwar et al. 2002 Nandal and Singh 2002 Kolhe 2001 Sukhadia et al. 2002 Kalhapure and Shete 2012

Crop*	Weed management	Reference
Okra	Stale seed bed with glyphosate; eucalyptus mulch	Ameena et al. 2006
Opium Poppy**	Isoproturon (375 g) or (500 g) Pre; HW: 30 DAS	Kulmi and Tiwari 2004
Pea, Dwarf	Pendipmethaln 1.0 Pre; HW: 30 DAS	Tewari et al. 2003
Pigeonpea/ Groungnut intercrop	Pendimethalin 1.0 or fluchloralin 1.0 Pre; HW: 30, 42 DAS	Vijayakumar et al. 1995
Pigeonpea/ pearlmillet intercrop	Pendimethalin 1.50 Pre; HW: 40 DAS	Shinde et al. 2003
Chickpea and mustard	Fluchloralin 1.0 PPI; intercrop: chickpea+mustard	Kaur et al. 2013
Rice; transplanted rice	Butachlor 1.0 or anilofos 0.4: close planting Anilophos 0.6: 7 DAT; HW: 27 DAT	Gogoi et al. 2001 Singh and Kumar 1999
Rice: dry-seeded	Butachlor 1.0 Pre; HW: 30 DAS	Singh and Singh 2001
Sesame	N: 60 +fluchloralin 1.0 PPI; HW: 21 DAS quizalofop-ethyl 0.05 Post 20 DAS; HW: 30 DAS	Singh et al. 2001 Bhadauria et al. 2012
Soya bean	Butachlor 1.5 Pre; HW: 30 DAS rows spacing: 22.5 cm, alachlor 1.0 Pre Quizalofop-ethyl 0.05 +chlorimuron-ethyl 0.009 Post 15 DAS; HW: 30 DAS	Chandrakar and Urkurkar 1993; Shekara and Nanjappa 1993 Jadhav 2013
Sugarcane	Metribuzin or atrazine 1.0+trash mulch 3.5 tons; inter-rows: 60 DAP	Singh et al. 2001a
Wheat	Pendimethalin 0.75 Pre; HW: 30 DAS Cross sowing+isoproturon 1.0 +2,4-D 500 g	Singh and Singh, 2004 Chaudhary et al. 2013

*Crop: The crops are mentioned alphabetically, not according to their economic importance; **Opium Poppy: *Papaver somniferum* L.); DAS = days after seeding; DAP = days after planting; DAT = days after transplanting; PPI: preplant incorporation; Pre: preemergence; HW=Hand weeding; Herbicide rate: kg ha^{-1} or g ha^{-1}.

Weeds of Forest Lands

Weeds, particularly the invasive ones growing in forests, are characterized as forest invasive species (FIS) and these include both indigenous and exotic (introduced) taxa. The Asia-Pacific Forest Invasive Species Network (APFISN) has listed (http://apfisn.net/countryreports) 49 species as forest invasive species in India, which are nationally-distributed. The following species have a special mention as major weeds:

- Lantana (*Lantana camara* L.) is one of the most obnoxious weeds that has encroached most of the areas under community and reserve forestlands;
- Crofton weed {*Ageratina adenophora* (Spreng.) R. M. King & H. Rob.} (Synonym: *Eupatorium glandulosum* Michx.) is found in the temperate region of the south and the north;
- Gorse (*Ulex europaeus* L.) represents a fire hazard to private property in the Western Ghats;
- Black Wattle (*Acacia mearnsii* De Wild.) was introduced in the Western Ghats, particularly in the Nilgiri Hills (South-central India), to provide fuel wood to rural people and to save the shola forests in Kerala. But these forests were degraded by human activities. This species has also been planted in tea plantations to provide shade to tea plants but now it has covered most of the shola forests and become menace in the Nilgiris besides spreading to waste lands and road-sides in several states. Regeneration of shola forests is affected by profuse regeneration and invasive nature of this species;
- Mikania (*Mikania micrantha* Kunth), a perennial fast growing weed of Neotropical origin, has become a major menace to natural forests, plantations and agricultural systems in North-east and South-west India. This climbing weed spreads very fast in areas where canopy is open;
- Broom {*Cytisus scoparius* (L.) Link}, introduced from European countries in the Western Ghats for ornamental purposes, has become a menace in the Nilgiri Hills, particularly in the shola forests and grazing lands; and
- Royle's Spurge (*Euphorbia royleana* Boiss) in the Himalayan zones has spread extensively, covering thousands of hectares of land.

Besides, other species viz., common wormwood (*Artemisia vulgaris* L.), karonda (*Carrisa carandas* L.), and hopbush (*Dodonaea viscosa* Jacq.), have also spread over large areas in the Himalayan zone.

The actions being considered by APFISN to prevent introduction of such forest invaders include: a) limiting soil disturbances; b) immediate re-vegetation of disturbed sites; c) use of certified "weed-free" seeds for re-vegetation of disturbed sites; d) cleaning equipment and materials before and after use to ensure they are free of invasive plant seeds and plant parts before arriving and leaving the site; e) use of "weed-free" hay bales for erosion control and feed; f) early detection and eradication by training field staff in the identification of restricted and noxious invasive plants, collection of survey information, destruction of individual invasive plants and reporting new infestations in a timely manner; g) conducting invasive plant survey prior to commencement of any land-disturbing activity to identify potential problem areas; h) communication between various stakeholders and provincial and municipal government agencies information transfer to promote regional awareness; i) incorporation of invasive plant management in planning phase; j) education and awareness; and k) controlling invasive weeds by utilizing their raw materials for economic purpose.

There are many examples of utilization of weeds in India. For instance, water hyacinth {*Eichhornia crassipes* (Mart.) Solms} is being utilized for electricity generation [Gopal 1987] and *Eupatorium*{ *Chromolaena odorata* (L.) King and Robinson} for preparation of compost [Nawaz and George 2004]. Forest Research Institute has made furniture and buckets from Lantana wood (http://apfisn.net/ country reports).

Weeds of Aquatics and Public Amenity Areas

Aquatic plants are an essential component of aquatic ecosystems, and as some of them may reach excessive proportions they pose a serious threat to fishery industry [Gupta 1987]. Aquatic weeds compete with fish for water, nutrients, light, niche and oxygen, and thus reduce fish yields [Varshney and Singh 1976; Wiley et al. 1984]. The major aquatic weed species such as water hyacinth, water spinach (*Ipomoea aquatica* Forssk.), bullrush (*Typha angustata* Bory&Chaub.), hornwort (*Ceratophyllum demersum* J.G. Klein ex Cham.), salvinia (*Salvinia molesta* D.S. Mitchell), lotus (*Nelumbo nucifera* Gaertn.), alligator weed {*Alternanthera philoxeroides* (Mart.) Griseb.}, *Hydrilla verticillata* F. Muell., *Vallisneria spiralis* L., *Chara* spp., *Nitella* spp. and *Potamogeton* spp. are a primary concern in India [Sushilkumar 2011]. The aquatic weed problems vary from one State to the other. For example, the major aquatic weeds in Kerala include water hyacinth, *Salvinia* sp., *E. crassipes*, *Pistia stratiotes* L., *Alternanthera* sp., *Azolla*, *Lemna minor* L. and *H. verticillata* [Jayan and Sathyanathan 2012]. In Madhya Pradesh, predominant aquatic weeds include *Vallisneria* sp., *Potamogeton* sp., *Ipomoea* sp., *Lemna* sp., *Azolla* sp., *Pistia* sp., *Hydrilla* sp., *Chara* sp. and *Myriophyllum* sp. [Singh and Nigam 2014]. The aquatic weed problems and their management in India have been reviewed from time to time [Jain 1975; Mani et al. 1976; Varshney and Singh 1976; Mukhopadhyay 1986; Nandeesha et al. 1989; Gopal and Zutshi 1998; Sushilkumar 2011; Datta et al. 2014].

The herbicides recommended for managing aquatic weeds are given in Table 5. The utilisation of aquatic weeds for waste water treatment has also been suggested [Trivedi 1998; Kathiresan 2012; Dolui et al. 2014]. Water hyacinth has been successfully used for the extraction of nano-fibres using chemical (alkali and peroxide) and mechanical treatments (2, 2, 6, 6-tetramethylpiperidine-1-oxyl radical–TEMPO–mediated oxidation treatment) [Kathiresan 2012]. We suggest an integrated approach as the best method for managing aquatic weeds in India, and this should include examining options for utilization of their biomass whenever and wherever there are beneficial opportunities.

Table 5. Herbicides used for aquatic weed control in India [Jayan and Sathyanathan 2012].

Herbicide	Type of weeds	Rate
Sodium arsenite	Submerged weeds	5-8 ml L^{-1}
Copper sulphate	Submerged weeds + algae	0.5-2.0 mg L^{-1}

Herbicide	Type of weeds	Rate
Hydrogen peroxide	Submerged weeds	10-20 mg L^{-1}
Dalapon	Emergent grass weeds	18-25 kg^{-1}
2,4-D	Free floating and emergent weeds	2-10 kg^{-1}
2,4-D	Submerged weeds	1.0 mg L^{-1}
Dichlobenil	Submerged and emerged floating weeds	1.0 to 2.0 mg L^{-1}
Diuron	Algae; submerged floating and emerged weeds	0.5 to 1.5 mg L^{-1}
Triazines	Algae; submerged and free floating weeds	0.5 to 1.0 mg L^{-1}
Paraquat	Submerged and floating weeds	0.5 mg L^{-1}
Diquat	Floating and emerged weeds	1.0 kg^{-1}
Endothall	Submerged weeds	0.5-2.5 mg L^{-1}
Fluridone	Submerged and floating weeds	0.1-1.0 mg L^{-1}
Glyphosate	Emergent and floating weeds	1.8-2.1 kg^{-1}

Weeds of Wastelands and Roadsides

Owing to the growing economic conditions in India, there is a visible increase in lands being kept fallow (in addition to the existing wastelands). The process of road construction spreads weeds to road-side lands adjacent to highways. In the Himalayan region of Uttarakhand state, a study on the distribution of invasive species (163 invasive alien species under 105 genera), based on habitat, showed that the highest number of species is found in wastelands (48%), followed by cultivated fields (20%), roadsides (14%) and forests (8%) [Sekar et al. 2012]. Reviewing the weed research in India, Mukhopadyay [1993] reported parthenium as a new weed becoming apparent in India by its presence in waste lands all over the country. Bhan et al. [1999] also reported parthenium as a waste land weed. Currently, it is a major weed of dry land crops, causing yield declines in several crops [Tanveer et al. 2015]. Thus, its management in un-used wastelands and roadsides is essential to arrest them from becoming a serious weed problem in agro-ecosystems and to prevent allergies to humans.

Roadsides provide suitable conditions for the establishment and growth of exotic species and their spread. Of the 71 species infesting roadsides in the central highlands of India, 55 were non-native ones, whose propagules spread from roadsides to the interior forest landscapes, indicating the need to restrict their spread [Sharma and Raghubanshi 2009]. A study on the roadside distribution patterns of invasive alien plants along an altitudinal gradient in the Himalayas of Arunachal Pradesh, indicated that the most common plants, by both frequency and coverage (> 50%) were: goatweed (*Ageratum conyzoides* L.), Siam weed (*C. odorata*) and

Mikania. Composition of species changed with altitude [Kosaka et al. 2010]. Thirteen species grew in the tropical, 10 in the subtropical, six in the temperate and one (*Taraxacum officinale* F.H. Wigg) in the subalpine zones. Kosaka et al. [2010] suggested that low temperature and snowfall in the highlands prevented establishment of non-adapted tropical species and that recent construction of highways facilitated the establishment of invasive alien plants. A serious attempt to enumerate weeds of wastelands and road sides, in different parts of India, needs to be made, and we observe that such an effort is yet to materialise. Proper monitoring and reporting of infestations and spread of new and naturalized weeds is required for early detection and management.

Invasive and Parasitic Species

Invasive Species

Some of the introduced (alien) plants are cultivated for economic purposes (food, forage, timber, ornamental, etc.). Some of these species, after becoming locally dominant, invade natural communities and come to be regarded as Invasive Alien Species (IAS). These often exhibit morphological, physiological and demographic plasticity to flourish in a variety of habitats [Meekins and McCarthy 2001]. Invasive alien species, defined as those non-native species that threaten ecosystems, habitats or species [CBD 2008], are key drivers of human-caused global environmental change [Vitousek et al. 1997]. They also inflict serious impact on the ecosystem processes that have global consequences for well-being [MES 2005], including the wholesale loss or alteration of goods (e.g., fisheries, agricultural and forest products) and services (e.g., clean and plentiful drinking water, climate stabilization, pollination, culture and recreation) [Daily et al. 1997; Mooney 2005].

Of the 45,000 plants that have been identified [Sharma et al. 1993], 40% are alien or introduced [Saxena 1991] while 20% being invasive [Raghubanshi et al. 2005]. Reddy [2005] has documented 173 IAS belonging to 117 genera and 44 families. About 80% of them have been introduced from neotropics. Tropical America (74%) and tropical Africa (11%) contributed a majority of the invasive alien flora now present in India. A habit-wise analysis showed that 151 were herbaceous species, followed by shrubs (14), climbers (5) and trees (3). Some of the prominent invasive alien weeds include *Lantana camara*, *C. odorata*, *E. crassipes*, *Opuntia dillenii* Haw. *Mimosa pudica* Mill., *Lippia geminate* Kunth and *Jatropha gossypiifolia* L. [Viraktamath 2002]. Other species like *Parthenium hysterophorus* L. *Phalaris minor* Retz., *Eupatorium glandulosum* Michx., *Ulex europaeus* L., *Acacia mearnsii* De Willd, *Cytisus scoparius* (L.) Link, *Opuntia vulgaris* auct. non P. Mill., *Prosopis chilensis* (Molina) Stuntz and *Euphorbia royleana* Boiss [Dakar 2003; Srivastava and Singh 2009] are also invasive.

Mikania, discussed earlier, was introduced in India after the Second World War and its profuse growth in Kerala and Assam over the years affected forests and tea plantations causing damage to the ecosystem and economy of the country [Banerjee et al. 2012]. Since the 1980s, it began spreading and invading other Indian states and there is an urgent need to map and monitor its spread. The perennial shrub *L. camara* is considered as one of the 10 worst weeds in the world and in India it is a weed of fence lines, pastures, rangelands, waste places and cultivated lands [Nanjappa et al. 2005]. Another worst invasive species is *C. odorata*. These two species were introduced to India through the Calcutta Botanical Garden in the last century [Muniappan and Viraktamath 1993]. To prevent predominance of such invasive weeds, the National Invasive Weed Surveillance (NIWS) Program was launched in 2008 to detect their establishment. Extensive surveys and rigorous monitoring have led to the detection of five quarantine weeds: *Cenchrus tribuloides* L., *Solanum carolinense* L., *Cynoglossum officinale* L., *Ambrosia trifida* L., and *Viola arvensis* Murray in several parts of the country [Yaduraju 2012].

Reviews on the biology and management of invasive weeds, including Lantana [Pimentel et al. 2001; Nanjappa et al. 2005] suggested that the economic losses caused by IAS in Indian crops and pastures were in the order of US$ 37.8 and US$ 0.92 billion, respectively. Lantana was introduced from Australia as an ornamental plant. This perennial shrub, belonging to Verbanaceae, had invaded the majority of Indian pasture lands over 13 million and other areas [Singh et al. 1996]. Known to be toxic to cattle, the cost of Lantana control was estimated to be US$ 70 ha^{-1} [Singh et al. 1996]. As 4% of India's land area is under pastures, the damage caused by it was estimated to be US$ 924 million. If other introduced weeds like parthenium are also taken into consideration, the losses caused by alien weeds to pastures would be much higher.

The Government of India introduced a statutory element–Plant Quarantine Order 2003–to synchronize India's regulatory framework with the Agreement (WTO-SPS Agreement) on application of Sanitary and Phyto-Sanitary Measures adopted by the International Plant Protection Convention and The World Trade Organization. A permit requirement is now enforced on imports of seeds, including flower, seeds, propagating materials and mushroom spawn cultures. Declarations have also been specified for import of 144 agricultural commodities [Mandal 2011]. A scientific legal and institutional approach to the country's bio-security threat needs to be strengthened for long-term success against invasive weeds.

Parasitic Species

Globally, about 2,500 species of angiosperms are reported to be parasitic plants. These largely belong to Loranthaceae, Convolvulaceae, Scrophulariaceae, Orobanchaceae, Balanophoraceae Lauraceae and Santalaceae families. Parasitic weeds such as field dodder (*Cuscuta campestris* Yuncker); Striga, broomrape and Loranthus are serious problems in some of the major crops and cropping systems of India.

Dodder is an annual obligate stem parasite belonging to Cuscutaceae. The genus *Cuscuta* is comprised of about 175 species worldwide. Of the 12 species reported in India, *C. campestris* and *C. reflexa* Roxb. are the most common ones. Cuscuta is a major limitation for cultivation of niger {*Guizotia abyssinica* (L.f.) Cass.} in radiata Odisha; lucerne in Gujarat; blackgram {*Vigna mungo* (L.) Hepper} and greengram {*Vigna radiata* (L.) R. Wilczek} in rice-fallows of Andhra Pradesh; and niger, berseem (*Trifolium alexandrinum* L.), lentil (*Lens culinaris* Medikus), linseed (*Linum usitatissimum* L.), and chickpea (*Cicer arietinum* L.) in parts of Madhya Pradesh and Chhattisgarh. Some species of Cuscuta also infest ornamental plants, hedges and trees [Mishra 2009].

Broomrapes (*Phelipanche* spp. and *Orobanche* spp.) are obligate root parasites belonging to Orobanchaceae. Of the 90 genera in this family, *Phelipanche ramosa* L. and *Phelipanche aegyptiaca* (Pers.) Pomel severely infest Brassica [Rathore et al. 2014]. Infestation of Orobanche is largely confined to major mustard growing states of northern Rajasthan, Haryana, Punjab, Western UP and northeast Madhya Pradesh [Punia 2014]. It is a major root parasite in tobacco, tomato and potato in parts of Karnataka, Andhra Pradesh, Tamil Nadu and Gujarat [DWSR 2013]. In Andhra Pradesh and Karnataka, 50% of the area under tobacco (40,000 ha) is infested by Orobanche, causing 50-60% yield loss. Tomato is also infested by it in Mewat and Bhiwani districts of Haryana. The extent of crop failure due to Orobanche depends on the extent of infestation, environmental factors, soil fertility and the crop competitiveness [Dhanapal et al. 1996]. Many farmers have even abandoned cultivation of mustard under the threat of this parasitic weed [Punia 2014].

Cultural, chemical and preventive methods used in an integrated approach to manage these parasitic weeds in mustard include, a) crop rotations with non-host crops, such as wheat, barley and chickpea, depending on the irrigation facilities; b) delayed sowing (25 October-10 November) of mustard supplemented with higher seed rate; c) use of organic manures, in combination with increased N fertilizer, to enhance crop vigour; d) two applications of glyphosate at 25 g ha^{-1} at 30 DAS and 50 g ha^{-1} 55 DAS, provided the crop is not under moisture stress at the time of spray; and e) hand removal/pulling of left-over emerging shoots before flowering to prevent weed seed bank build-up in the soil [Punia 2014].

Striga infests mostly sugarcane, maize, sorghum and pearl millet grown in dry areas in some parts of Karnataka, Madhya Pradesh and Chhattisgarh. Loranthus is noticed in economically useful tree crops such as mango, neem (*Azadirachta indica* A.Juss), teak, *Cassia* spp., rosewood (*Dalbergia nigra* Fr. All.), Dalbergia (*Dalbergia sissoo* Roxb.), Albizia {*Albizia lebbeck* (L.) Benth.}, Terminalia (*Terminalia acuminata* Eichler), rain tree (*Albizia saman* F.Muell.), pongamia {*Millettia pinnata* (L.) Panigrahi}, gulmohar {*Delonix regia* (Boj. ex Hook.) Raf.}, Madhuca {*Madhuca longifolia* (J. Konig) J.F. Macbr}, Ficus (*Ficus religiosa* L.), etc. It is necessary to develop effective and economical management technologies for these weeds, which are fast spreading to newer areas and parasitizing many other host plants. As Parker [1993] concluded "while difficult, the control of parasitic weeds is not impossible".

Weed Management in Conservation Agriculture Systems

Conservation Agriculture (CA) is considered an efficient crop management technology, which uses less inputs and improves production and income [Gupta and Seth 2007; Chauhan et al. 2012a]. Reduced costs, increased profitability and better use of resources (e.g., labour and water) are the main factors responsible for the adoption of CA in India [Hobbs and Gupta 2004]. Impending changes in climate and sustainability of cropping systems are also important reasons for adoption of CA systems in India. In the Indo-Gangetic Plains, the resource conservation technologies are being practiced in > 3 million ha under the rice-wheat based systems [Sharma and Singh 2014].

Despite several benefits CA offers, weeds continue to be one of the biggest constraints to its adoption. After adoption of zero-till wheat in Northwest India, weed flora shifted towards broadleaf weeds including toothed dock (*Rumex dentatus* L.). Similarly, in the vertisols of Jabalpur, infestation of common vetch (garden vetch: *Vicia sativa* L.) increased in zero-till system compared to conventional tillage system [Mishra and Singh 2011]. As adoption of CA practices has been increasing [Hobbs 2007], there is a need to gain better understanding on weed management in CA crop production systems. Various approaches, including the use of preventive measures, intercropping, cover cropping, crop residue as mulches, competitive crop cultivars, optimum planting geometry, optimum sowing time, herbicide-tolerant (HT) cultivars and herbicides, (components of integrated method) need to be followed to successfully manage weeds [Chauhan et al. 2012, 2012a; Sharma and Singh 2014]. Weedy rice (*Oryza sativa* L.) has become a serious problem in India, and its spread is largely through the use of contaminated rice seeds [Chauhan and Mahajan 2012]. The authors have discussed preventive measures, such as the use of clean crop seeds and clean machine, which are much cheaper and easier options in reducing weedy rice infestation in CA systems.

In CA system, crop residues are left behind on the soil surface. In addition to moisture and soil conservation, the residues act as mulch and suppress weed seedling emergence [Chauhan et al. 2012a; Chauhan 2012]. Inclusion of a cover crop between two main crops also helps reduce weed density in CA cropping system. In this, the cover crop can be killed by using a non-selective herbicide and its dead mulch be used to suppress weed germination by releasing allelochemicals and/or reducing light transmittance to soil surface. Growing *Sesbania rostrata* Bremek. & Oberm as a cover crop was found to control most of the weeds, leaving the field almost weed-free in rice-wheat cropping systems [Mahapatra et al. 2004]. Similarly, mungbean can be grown as a cover crop in rice-wheat cropping system.

Crop rotations and diversification not only improve soil health but also reduce build-up of pests, including weeds [Chauhan and Mahajan 2012]. Different crops require different management programmes to prevent selection of resistant weed species in CA systems. In

India, fewer cases of resistance in *P. minor* were found when growers included sunflower and sugarcane in rotation than following a continuous rice-wheat cropping system [Malik and Singh 1995]. Similarly, replacing wheat with a crop, such as berseem clover (*Trifolium alexandrinum* L.), potato and oilseed rape (*Brassica napus* L.) for 2-3 yr period in a rice-wheat cropping system reduced the population of *P. minor* significantly [Brar 2002]. Instead of continuous monoculture cultivation of rice, Chauhan et al. [2012] also suggested rotating one rice crop with an upland crop as a method to reduce the problem of weedy rice.

Herbicides play an important part in managing weeds in CA. However, due to presence of crop residues on the soil surface, pre-emergence herbicides may not be very effective [Chauhan et al. 2006]. Residues are known to intercept up to 80% of the applied pre-emergence herbicides. Therefore, there is a need to better understand the efficacy of different pre-emergence herbicides when applied in different crops in India. Because of the efficacy issue of preemergence herbicides, timing of postemergence herbicides is critical in CA. Herbicide rotations and mixtures may improve the weed control spectrum.

As discussed earlier, there are several weed management approaches now available to manage weeds in CA. However, there is a need to integrate different weed management strategies for widening the weed control spectrum and maintaining the sustainability of CA.

Innovative Strategies for Managing Weeds

There has been a significant amount of research in India on innovative strategies to manage weeds in cropping systems. For instance, in some early research in the early 1980s, Rae and Settee [1981] showed that the inclusion of fast growing, short-duration cowpea {*Vigna unguiculata* (L.) Walp.} or mungbean as weed-smothering intercrop (smother crop) in inter-rows of sorghum reduced one round of hand weeding in sorghum due to the smothering effect. Similar work [Rao et al. 1982; Kondap et al. 1983] demonstrated the use of competitive crops for managing perennial weeds including purple nutsedge (*Cyperus rotundus*). These results [Rao and Shetty 1983; Rao and Ladha 2011; Rao and Nagamani 2013] suggested that ecological approaches need to be more widely adopted to manage weeds in semi-arid tropic crops.

In another example, Kumar et al. [1993] reported that soil solarisation, in which the soil surface is heated by placing plastic sheets for 32 d on a moist soil to trap the solar radiation, decreased the emergence of crowfootgrass {*Dactyloctenium aegyptium* (L.) *Willd.*}, goosegrass {*Acrachne racemosa* (Roem. & Schult.) Ohwi}, horse purslane (*Trianthema portulacastrum* L.) and *C. rotundus* by more than 90%. Other studies suggested that the main effect of solarisation was restricted to the 0-5 cm soil layer [Kumar et al. 1993]. Patel et al. [2005] reviewed the role of soil solarisation in weed management. Soil solarisation may help in managing weeds economically in commercial and horticultural crops.

Simple cultural practices such as adjusting sowing time of some crops were found to minimize weed infestation. In North India, the adoption of zero-till and early planting of wheat resulted in reduced *P. minor* problems and increased grower profits because early planting provided a competitive advantage to the crop compared to weed [Chauhan and Mahajan 2012].

Competitive replacement of Parthenium can be achieved by planting plants like *Cassia sericea* SW., senna tora (*Cassia tora* L.), tanner's cassia (*Cassia auriculata* L.), Bonpland's croton (*Croton bonplandianum* Baill.), spiny amaranth (*Amaranthus spinosus* L.), fish poison {*Tephrosia purpurea* (L.) Pers.}, pignut {*Hyptis suaveolens* (L.) Poit.}, prickly fanpetals (*Sida spinosa* L.), and Marvel of Peru (*Mirabilis jalapa* L.) which are capable of effectively suppressing the natural habitats of Parthenium in [Wahab 2005]. A 52.5% reduction in Parthenium population by *Cassia sericea* Sw. was reported [Kandasamy and Sankaran 1997]. Aqueous extracts from cogongrass {*Imperata cylindrica* (L.) P. Beauv.}, sacrificial grass {*Desmostachya bipinnata* (L.) Stapf.}, Kleberg bluestem {*Dichanthium annulatum* (Forssk.) *Stapf.*}, and Johnsongrass {*Sorghum halepense* (L.) Pers.} markedly suppressed germination and seedling growth of Parthenium [Javaid et al. 2005]. In India, crop rotation using marigold (*Tagetes* spp.) during rainy season, instead of the usual crop, has been found to be effective in reducing Parthenium infestation in cultivated areas [Kaur et al. 2014].

Ample research has been published on allelopathic interactions of crops and weeds in India [Rao et al. 1977; Narwal 1994; Das et al. 2012]. Allelopathy has been suggested as a potential method for inclusion as component of IWM [Rizvi and Rizvi 1992; Sangeetha and Bhaskar 2015]. However, the application of Koch's postulates was required to establish proof of allelopathy [Williamson 1990] and only when such critical experiments are undertaken, the practical application of allelopathy in IWM would become a reality.

The innovative biological control of weeds in India was first documented in 1795 [Muniappan et al. 2009]. It involved the invasive plant common prickly pear {*Opuntia monacantha* (Wildenow) Haworth} (Cactaceae), which was controlled serendipitously due to the inadvertent introduction of *Dactylopius ceylonicus* (Green) (Hemiptera: Dactylopiidae) from Brazil in the mistaken identity for *Dactylopius coccus* Costa (Hemiptera: Dactylopidae) [Muniappan et al. 2009]. Biological control with Mexican beetle *Zygogramma bicolorata* Pallister (Coleoptera: Chrysomelidae) was found effective and economical [Sushilkumar 2006; Sushilkumar and Ray 2011].

The integration of the insect biocontrol agent with the use of dried plant materials of the medicinal herb Mexican mint (*Coleus amboinicus* Lour) was envisaged for managing water hyacinth as it is allelopathic on this aquatic weed. It works through membrane disruption and electrolyte leakage. The dried plant powder easily gets absorbed into the water hyacinth through the leaf scrapings made by the insects [Kathiresan 2014].

Herbicide Use, Residues, Resistance and Tolerant Crops in India

Herbicides are among the most widely used agrochemical products globally, followed by insecticides and fungicides [FICCI 2013]. However, the Indian crop protection market is largely dominated by insecticides, which account for 65% of the total. The agrochemical consumption in India was estimated to be 0.58 kg ha^{-1} as against 13 kg ha^{-1} in China and 7 kg ha^{-1} in the USA [FICCI 2013]. This indicates the growth potential of India's pesticide industry as farmers continue to adopt improved crop production technologies. Herbicides constitute the largest growing segment, and currently they account for 16% of the gross pesticide market. The market doubled between 2005 and 2010, and in 2012 it rose by 35% [Gianessi 2013].

Traditionally, weed control depended on manual weeding. The National Rural Employment Guarantee Act 2005, which mandated guaranteed employment and wages to rural population, has contributed to creating labour shortage and enhancing labour wages for weeding. This has led to manual weeding becoming an unsustainable practice in several states. As labour for manual weeding became expensive and scarce, farmers initiated adoption of herbicide-based weed management. Furthermore, research has consistently proved that herbicides provide more effective and economical weed control leading to higher crop yields [Rao and Ladha 2011; 2013; Rao et al. 2014]. One study [Govindarajan et al. 2009] reported that labour usage was about 43 hr, 33 hr and 80 hr lower in rice, maize and sugarcane, respectively, when herbicides were used. Rice and cotton are the major crops that use crop protection chemicals, accounting for 28% and 20%, respectively. The three states of Andhra Pradesh, Maharashtra and Punjab account for ~50% of the total pesticide consumption in India. Rice and wheat crops consume a major share of herbicides. Increasing costs of farm labour are likely to drive sales of herbicides further.

The herbicides available in India, crops in which they are recommended, available formulations and their trade names are summarized bythe Directorate of Weed Research (DWR), Jabalpur. These were published in three books: i) herbicides [Sondhia and Varshney 2009]; ii) herbicides used in field crops [Dixit and Varshney 2009], and iii) herbicide recommendations [Dixit and Varshney 2009a].

Herbicide Residues in Soil and Food-chain

Increased herbicide usage may result in retention of herbicide residues in soil, residual phytotoxicity to crops grown in rotation and adverse effects on non-target organisms including human and farm animals[Sondhia 2014]. Several of the herbicides used in India get adsorbed to soil particles, making them unavailable to control weeds, and also causing possible contamination of the soils in the ecosystems they were used. Adsorption, volatilization, leaching, runoff, photo-decomposition and degradation by microbial and chemical processes determine the fate of herbicides in the soil, water and the ecosystem [Jannali et al. 2013; Sondhia 2014].

Research in India indicated the half-lives of imadazoline, phenylureas, sulfonylureas, triazines, chloroacetinalides, dinitroanilines, diethyl ethers, thiocarbamates, and 'fop' (arylphenoxy propionate) herbicides (cyhalofop-butyl; quizalofop-ethyl) in soil to be 57-71 d, 13-60 d, 13-147 d, 12-58 d, 5-60 d, 12-77 d, 19-29 d, 19-24 d, and 8-24 d, respectively [Sondhia and Varshney 2009]. Herbicides with long half-lives include chlorosulfuron (31-93 d) and metsulfuron-methyl (70-147 d), while those with short half-lives include: butachlor (5-24 d); flufenacet (9-22 d); pretilachlor (10-11 d); sulfosulfuron and (3-27 d); 2,4-D (7-22 d) [Sondhia 2014].

At harvest, residues of herbicides (e.g., cyhalofop-butyl in direct-seeded rice; quizalofop-ethyl in jute; fentrazamide in rice; pendimethalin in cabbage; trifluralin in blackgram; pendimethalin, trifluralin and oxyfluorfen in carrot) were found to be either below the maximum or detectable residue limits in soil and crop plants [Arora and Gopal 2004; Mukherjee and Gopal 2005; Banerjee 2008; Singh et al. 2010]. For example, residues of ethoxysulfuron applied at 15 to 20 g ha^{-1} were found below <0.001 μg g^{-1} in rice soil at harvest [Sondhia and Dixit 2012]. In other studies [Singh et al. 2013a], no detectable residues of fenoxaprop-ethyl acid were detected in soil, wheat grain and straw when recommended doses were used.

In a long term study (2000 to 2010) involving long-term herbicide applications integrated with nitrogen management in transplanted rice-rice cropping system, Chinnusamy et al. [2012] reported that residues of butachlor (0.75 kg ha^{-1}), pretilachlor (0.75 kg ha^{-1}), and 2,4-D (0.4 kg ha^{-1}) were below the detectable level at 45 d after application in soil and crop in consecutive seasons. At the same time, there was an increase in the abundance of soil actinomycetes, fungi and bacteria [Chinnusamy et al. 2012].

Most of the herbicides were also found to be non-toxic to the crops grown in rotation in majority of the cases [Babu et al. 2013; Sondhia 2014]. However, there have been reports of residual phytotoxicity too. For example, growth of sorghum planted after wheat was significantly affected by the residues of chlorsulfuron at 30 g ha^{-1} (which controlled weeds and increased wheat yields) followed by metribuzin at 400 g ha^{-1} [Sharma et al. 2002]. In a recent paper, Sondhia [2014] discussed the Indian perspectives of herbicides residues in soil, water, plants and non-targeted organisms and human health implications.

Herbicide-Tolerant Transgenic Crops

Herbicide-tolerant transgenic crops, commonly known as genetically modified (GM) crops, are grown on 181.5 million ha in 29 countries, involving over 17 million farmers of which about 15 million are small and resource-poor. India with 11.6 million ha is ranked fifth in terms of total area under GM crops. However, herbicide-tolerant (HT) crops are yet to be introduced in India.

Chauhan and Mahajan [2012] expressed the view that in CA, the use of HT crops may prove to be a useful tool in managing problematic weeds. Compared with conventional crop cultivars, the use of HT cultivars offers several advantages such as the application of fewer herbicides, reduced soil compaction, ability to eliminate hard-to-control weeds and higher crop yields by eliminating damage caused to the crop by herbicides, drought or low temperatures, besides being benign environmentally [Chauhan et al. 2012]. Whilst some of these aspects are advantageous, continuous use of a herbicides may result in shifts to some problematic weed species and growers may lose this important tool for weed management, if improperly used. Therefore, we feel that without proper stewardship programmes and stringent guidelines, HT crops should not be used. Currently, Indian farmers are being deprived of such modern innovations due to unfounded apprehensions [Sharma and Singh 2014].

In India, HT crop technology is at initial stages of field evaluation. It is likely to be brought to the farming community in the near future, keeping in view of potential benefits in specific situations. Farmers need to be adequately trained on the proper use of HT cultivars before they are introduced. The likely introduction of GM crops has also prompted concerns about the potential transfer of herbicide tolerance to weed populations via crop-to-weed gene flow. Strong measures to prevent possible transfer of genes to weeds need to be taken prior to the release of HT cultivars in India, based on well-developed guidelines.

Herbicide Resistance in Weeds

The continuous use of isoproturon, coupled with mono-cropping of rice-wheat, led to the evolution of resistance in *P. minor* in the states of Haryana and Punjab [Malik and Singh 1995]. The problem of resistance was so serious that farmers there began growing sunflower to exhaust the seed bank of this annual grass. The efforts of herbicide resistance management have led to the adoption of CA in the rice-wheat cropping system, as a component of IWM. Details of resistance development and its management using integrated approach with focused attention on zero-tillage have been published [Malik et al. 2002; Franke et al. 2007].

There are no other cases of herbicide resistance reported in India so far. However, continuous monitoring is needed and all efforts are to be made to prevent the occurrence of HR weeds when herbicide usage is increasing at a fast pace in several states of the country.

Weed Science Research in India

Even though farmers' experimentation to manage weeds may have begun with the initiation of agriculture, weed research in India commenced with adoption of herbicide technology. The earliest attempt to control weeds by herbicides was made in 1937 in the state of Punjab to control wild safflower (*Carthamus oxyacantha* M. Bieb.) by using sodium arsenite. After the discovery of 2,4-D as a plant growth regulator, it was first tested in India in 1946 [Mukhopadhyay 1993]. Since then a number of herbicides have been imported and tested for their effectiveness in controlling many weed species. In 1952, Indian Council of Agriculture Research (ICAR) initiated schemes for testing the field performance of herbicides in rice, wheat and sugarcane in different states of India. In the early period, the largest user of herbicides (50-60%) was the tea plantation sector.

ICAR recognized the need for strengthening weed research in India by setting up, in 1978, an All India Coordinated Research Programme on Weed Control (AICRPWC) in collaboration with the United States Department of Agriculture (USDA). This programme is now being implemented by 22 centres across the country. Prior to its establishment, weed science was considered as a sub-discipline of agronomy. This trend is still being continued, and many agricultural institutions in India are without a separate department of weed science.

The National Research Centre for Weed Science, established in 1989 at Jabalpur, was upgraded to become the Directorate of Weed Science Research (DWSR) in 2009. It is now being called as the Directorate of Weed Research (DWR) since 2014. It is engaged in basic and strategic research. It also coordinates the applied and location-specific research conducted at the 22 coordinating units, located in different parts of the country. The botany departments of several traditional universities and central universities in India are also engaged in teaching basic aspects of weed science, particularly the taxonomic, ecological and physiological aspects of weeds. Rao et al. [2014] summarized the details of weed science research conducted so far in India and future directions.

Emerging Challenges and Opportunities for Weed Management

Challenges

Weeds are a major biotic constraint to crop production all over the world, and India is no exception. Transplantation method of rice is being replaced by direct-seeding in several regions due to non-availability and increased cost of labour [Chauhan and Johnson 2010], water scarcity and increased cost for pumping water [Rodell et al. 2009; Mahajan et al. 2012a]. However, the risk of crop yield losses due to weeds in direct-seeded rice systems is more than in flooded transplanted rice system because of the absence of the suppressive effect of standing water on weed emergence and the absence of the size differential between the rice and weed seedlings [Rao et al. 2007]. Therefore, the change in crop establishment methods is likely to be associated with a shift in the weed flora towards hard-to-control weeds [Chauhan and Johnson 2010].

Herbicide use is increasing dramatically in different crops and this trend is expected to continue. Increased use of herbicides has been associated with the evolution of herbicide resistance in weeds, shifts in weed population, increased costs of chemical control measures and concerns over the environment [Buhler et al. 2002; Chauhan and Johnson 2010]. One of the best known examples of herbicide resistance development in India is resistance to isoproturon demonstrated by *Phalaris minor* in wheat due to heavy reliance of the cropping system on this substituted phenyl urea herbicide [Malik and Singh 1995]. In direct-seeded rice, acetolactate synthase (ALS) inhibitor herbicides are being widely advocated for weed management. However, evolution of resistance in weeds to ALS inhibitors is being reported more frequently than other herbicide groups [Chauhan et al. 2012]. In addition, there is evidence of weeds developing multiple resistance to herbicides of different modes of action [Chhokar and Sharma 2008], risking the sustainability of herbicides. Prevention of weeds developing resistance in farmers' field is emerging as a major challenge, as new herbicides are increasingly being introduced in India.

Another emerging challenge for weed management in India is the problem of feral crops, such as weedy rice and wild oats [Chauhan and Johnson 2010; Singh et al. 2013]. Control of such weeds has become very challenging due to the similarity in morphological and physiological traits between crop (rice) and its weedy relative (weedy rice). Weedy rice has variable seed dormancy and it displays early shattering of grain [Chauhan 2013]. Accessions of such weeds have also been found to have greater nitrogen-use efficiency for shoot biomass than cultivated rice [Chauhan and Johnson 2011].

There is a general acceptance that climate change is becoming a reality in India. Increase in temperature, atmospheric greenhouse gases and water shortage have multiple impacts on different cropping systems practiced in the country. Under high temperature, weeds will have a competitive advantage over C_3 crops [Mahajan et al. 2012]. Under water-limited conditions, Naidu and Varshney [2011] found *P. minor* having an advantage over wheat at elevated CO_2 concentration; both species have the C_3 photosynthetic pathway. In the USA, weedy rice responded more strongly than cultivated rice to rising CO_2 concentration with greater competitive ability [Ziska et al. 2010], suggesting that weedy rice may become more problematic in future in India [Chauhan et al. 2014].

Climate change may increase the adoption of CA systems in India, in which glyphosate is widely used as a pre-plant herbicide. A study by Ziska et al. [1999] found that the effectiveness of glyphosate was reduced at elevated CO_2 concentrations, suggesting that its efficacy in future may be reduced with CO_2 increments. Furthermore, changes in temperature and CO_2 concentration may affect absorption, translocation and efficacy of different herbicides. Increased CO_2 concentrations may also stimulate below-ground plant growth, suggesting that the problem of perennial weeds may increase with climate change [Mahajan et al. 2012]. Broadly, there is a need to increase research on how weeds and weed management practices may respond to the impending changes in climate.

Opportunities

Although weeds are a challenge in the current cropping systems in India, there are many opportunities to develop sustainable and effective weed management programmes. More studies are needed on weed ecology and biology, especially in understanding the seed bank dynamics in different locations and cropping systems. Better understanding of weed seed germination is needed to manage weeds effectively. There is limited information available on the persistence of weed seed banks under Indian conditions, especially in CA systems.

Weeds can be suppressed by manipulating crop density and geometry. The use of narrow row spacing and high seeding rates, for example, can help to suppress weeds [Chauhan 2012]. However, in India, the agronomic aspects of crop competitiveness are yet to be determined as components of IWM. Therefore, future research needs to focus on evaluation of the effect of agronomic approaches (i.e. cultural weed control methods, such as narrow rows, high seeding rates, weed-competitive cultivars, etc.) on weed management and crop productivity in different regions, especially where herbicide use is limited or less effective. In addition to developing weed-competitive cultivars, allelopathic crop cultivars may be identified and evaluated. Allelopathy holds promise as a possible component of IWM because sorghum and pearl millet{*Pennisetum glaucum* (L.) R. Br.} showed allelpathic ability to reduce weed population.

Rotations must be included in the tools to manage weeds. These could be rotation of establishment methods (e.g., direct-seeding and transplanted rice), tillage systems (e.g., no-till, reduced-till and conventional tillage), crops (having different management practices) or herbicides. Greater herbicide efficacy may be achieved when crops and herbicides are rotated. However, information on the role of different rotations in suppressing the build-up of weed populations in different cropping systems is very limited. Research on such topics will improve weed management.

As mentioned earlier, climate change is a reality in India. Research should focus on understanding the interaction of climate change (change in temperature, water availability and CO_2 concentrations) with weeds. Better understanding of weed response to climate change will help improving weed management in the future.

Herbicide-tolerant (HT) crops may play a promising role in weed management. There is a need to develop and evaluate transgenic and non-transgenic HT crops. Such crops may be used to control weeds like *Cyperus rotundus* in CA systems. Parasitic weeds may also be managed by using HT crops. In addition, there is a need to develop risk management strategies associated with the use of HT crops.

Several weed management methods are available in different regions. However, IWM programmes are rarely used in actual on-farm situations. In India, there is a great opportunity for weed scientists to conduct research participated by farmers to develop IWM programs for different crops grown in different geographical and agro-climatic regions.

Future Outlook on Developments in Weed Science

As discussed earlier, the major future challenges Indian weed scientists currently face include developing innovative, effective, economical, resilient and environmentally safe weed management technologies to successfully manage weeds, particularly at a time when the effects of climate change are being felt. In this regard, greater emphasis needs to be given to the following.

1. **Assessment of on-farm losses caused by weeds:** This should be scientifically pursued in different crops and cropping systems on farmers' fields in different agro-ecological regions to quantify crop losses caused by weeds.
2. **Weed ecology:** Research should focus more on weed ecology, genetics and physiology to increase the understanding of the processes that regulate weed-crop interactions, weed population dynamics, adaptation and persistence under various management practices.
3. **Inter-disciplinary efforts:** In order to tackle the complex weed problems, research must involve systems analysis, weed community analysis, weed traits eco-physiology, molecular biology and genetics, assessment of pre- and post-control shifts in weed community, herbicide resistance, issues related to transgenic plants, impact on environment and potential benefits of weeds.
4. **Integrated weed management approaches:** Herbicide technology must be made economically and ecologically affordable to farmers by innovatively integrating it with other components of IWM.
5. **Extension activity on proper herbicide use:** Even though the research in India is herbicide-based, the majority of farmers have not been benefited by herbicides. There is a need to step up coordinated extension efforts to educate farmers on the judicious use of herbicides in India and to integrate other weed management methods [Rao et al. 2014a]. The recent advances in information technology may be effectively used for transferring of technology to farmers.
6. **On-farm assessment of available IWM options:** The IWM options identified by researchers must be tested in the farmers' fields to assess their effectiveness and economic viability. Closer linkage between research and extension is needed to popularize effective and economical options for the benefit of farming community and to improve them with the feedback from it.
7. **Knowledge-based decision making tools:** There is a need to develop a larger database of weed ecology and biology characteristics; develop, improve and refine integrated weed management system simulation models; and determine the utility of these models to be used by farmers and extension personnel in IWM and to predict areas of future research.

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