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Integrated Weed Management in India–Revisited*

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ABSTRACT

Integrated weed management (IWM) is a science-based decision-making process that coordinates the use of macro and micro-environment information, weed biology and ecology, and all available technologies to control weeds by the most economical and ecologically viable methods. The concept of IWM is not new and many advances have been made in recent years in India. The IWM research carried out in India during the last 20 years is reviewed in this paper. Limited ecological studies were carried out on certain problematic weeds. Majority of the research in India on IWM was herbicide-based. Economic analysis revealed that herbicides use in combination with hand weeding was most economical. Weeds are dynamic and it is required to redesign the strategies from time to time for the successful management of ever increasing problem of weeds. IWM research in India must broaden beyond herbicide-centred weed management. Future IWM research in India must focus on decision-making processes, weed biology and ecology, environmentally and economically viable components of IWM practices in cropping systems, herbicide resistance, environmental issues related to transgenic plants, and potential benefits of weeds.

Key words : Crops, economics, herbicides, India, integrated weed management, non-chemical

INTRODUCTION

Weeds are a major impediment to crop production through their ability to compete for resources and their impact on product quality. In the agro-ecosystems ideal environmental conditions provided for optimal crop productivity are being exploited by the associated weeds. Weeds are responsible for heavy yield losses in all the crops. Weeds not only cause huge reductions in crop yields but also increase cost of cultivation, reduce input efficiency, interfere with agricultural operations, impair quality, act as alternate hosts for several insect-pests, diseases, affect aesthetic look of the ecosystem, native biodiversity, as well as affect human and cattle health. Weeds are known to account for nearly one third of the losses due to various biotic stresses. In India, presence of weeds in general reduces crop yields by 31.5 and 22.7% in winter season and 36.5% in summer and **kharif** season and in some cases can cause complete devastation of the crop (Anonymous, 2007). Weed control is one of the major input costs of crop production.

During the last half-century, worldwide food production from farming has kept pace with population growth. Total projected population of India is 1,420 million peoples in 2026 (Anonymous, 1998). The agricultural growth rate has slowed down in India (Anonymous, 2010) and increased agricultural productivity is needed to meet the increasing needs of the growing population. Improved crop productivity and production must be accomplished in an environmentally sustainable way. Proper weed management technologies if adopted can result in an additional production of 103 million tonnes of food grains, 15 mt of pulses, 10 mt of oilseeds and 52 mt of commercial crops per annum, which in few cases are even equivalent to the existing annual production. This amounts to an additional income of Rs. 1,05,036 crores per annum (Anonymous, 2007), which shows that weed management technologies have the potential of significantly enhancing the share of agriculture in India's GDP by about 15%. Thus, weed management would continue to play a key role to meet the growing food and fibre demands of increasing population in India.

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The weed problems are likely to increase and with the increased public awareness on environmental pollution, the focus would shift to the development of eco-friendly weed management technologies in the years to come. As the future weed problems will be multi-pronged, a holistic multi-disciplinary approach would be imperative. In this context, integrated weed management (IWM) may provide a more sustainable approach to crop production.

IWM is a science-based decision-making process that coordinates the use of environmental information, weed biology and ecology, and all available technologies to control weeds by the most economical means, while posing the least possible risk to people and the environment (Sanyal, 2008). By using different appropriate management practices against weeds, farmers have more options for controlling weeds, thereby reducing the possibility of escapes and weed adaptation to any single weed management tactic. The concept of IWM is not new. For example, the traditional practice of puddling soil to kill existing weeds and aid water retention, transplanting rice seedlings into standing water to achieve an optimum stand density, and maintaining standing water to suppress weeds, followed by one or several periods of manual weeding, is a well established example of integrated weed management (IWM) (Rao *et al*., 2007).

Many advances have been made in recent years in India on IWM. Weeds are a constant problem in crop production because of the dynamic nature of weed populations. Because of the diversity and plasticity of weed communities, weed management needs to be viewed as a continuous process. Thus, it is required to redesign the strategies from time to time for the successful management of ever increasing problem of weeds. It is essential to review the progress so far made on IWM in India and redesign the future strategies for the successful management of ever increasing problem of weeds. The objective of this paper is to review the research work on integrated weed management in India and suggest areas of future research on integrated weed management to combat weed menace effectively, economically and ecologically.

Since the research papers published in the "Indian Journal of Weed Science (IJWS)", give a broader picture of the research work carried out in India on integrated weed management in India, the main papers published from 1992 (Volume 25 : 1 & 2) to 2009 (Volume 41: 1 & 2) of IJWS were used for this review. 685 full length papers were published during that period in IJWS. Only 27% of the total research papers were on IWM. Information collected on the research reported on integrated weed management is presented.

1. MAJOR THRUST AREAS OF IWM RESEARCH

Majority (92%) of the research papers published on IWM in IJWS were on herbicide-based IWM. Only 8% of the papers were on non-chemical IWM. As IWM takes into consideration the information on weed ecology and biology in managing weeds, research papers on weed flora, crop-weed competition, weed ecology and weed biology were also reviewed in this paper. They constitute around 14% of the total full length papers published in the IJWS.

2. WEED FLORA

The composition and competition by weeds is dynamic and is dependent on soil, climate, cropping and management factors. Several studies were conducted on weed flora in India which include : maize (Sandhu *et al*., 1999) in Punjab; potato in Haryana (Punia *et al*., 2007); rice-wheat system in Indo-Gangetic plains (Singh *et al*., 2005a); wheat in Punjab and Haryana (Singh *et al*., 1993a; Singh *et al*., 1995; Brar and Walia, 2007b); soybean in Madhya Pradesh and Himachal Pradesh (Jain and Tewari, 1993; Rana and Angiras, 1994); sunflower in Delhi (Wanjari *et al*., 1999); pointed guard in Assam (Barua *et al*., 2002); and tea in southern part of India (Ilango and Sharma, 2008). Weedy rice is emerging as a major problem in direct-seeded rice (Rao *et al*., 2007; Rao and Nagamani, 2007).

There is urgent need to continuously monitor the weed flora in all cropping systems and agro-ecological regions of India, to assess the emerging weed problems and to plan weed management strategies for the present and future weed problems across agro-ecological zones.

3. WEED ECOLOGY AND BIOLOGY

Autecology of weeds such as *Oxalis latifolia* (Arya, 1995; Pandey *et al*., 2000), *Echinochloa colona, E. glabrescens* and *E. crusgalli* (Raju and Reddy, 1999b) and *Cyperus rotundus* (Raju and Reddy, 1999a) was studied. Weed seed germination ecology was reported for *Trianthema portulacastrum*, *Ageratum houstonianum*, *Phalaris minor*, *Leptochloa chinensis*, *Eclipta alba*, *Malva parviflora*, *Malva neglecta*, *Rumex dentatus* and

R. spinosus (Umarani and Selvaraj, 1994; Angiras and Kumar, 1995; Chhokar and Malik, 1999; Chhokar *et al*., 1999; Yadav and Singh, 2005; Aulakh *et al*., 2006; Dhawan, 2007; Kaur *et al*., 2008; Singh and Punia, 2008). Seed biology of *Euphorbia geniculata* (Araf *et al*., 2009) was researched. Weed seed bank dynamics were analysed in maize (Jebaratnam *et al*., 2006); wheat (Walia *et al*., 2005) and rice-wheat (Mishra *et al*., 2005, Walia and Brar, 2006a, Jain *et al*., 2006) cropping system.

Ecological studies revealed that characteristics associated with better competitiveness and adaptability of weeds to agro-ecosystem include : (a) broken dormancy when conditions favour survival (Umarani and Selvaraj, 1994; Araf *et al*., 2009); (b) rapid early growth and expansion (Raju and Reddy, 1999b; Singh and Punia, 2008), early and fast root/tuber/bulbils growth (Raju and Reddy, 1999a; Pandey *et al*., 2000); efficient uptake and processing of nutrients and water (Raju and Reddy, 1999a); ability to reproduce early in life cycle (Raju and Reddy, 1999a); prolific seed production (Mishra, 2009); excess absorption of resources (Pandey *et al*., 1997; Kumawat *et al*., 2002); tolerance to low levels of resources (Singh *et al*., 1995); genetic and environmental adaptability (Dhawan *et al*., 2008) and ability to develop resistance to control measures (Malik *et al*., 1995; Walia and Brar, 2006b).

Ecological studies on *M. parviflora*, *R. dentatus* and *R. spinosus* revealed greater emergence of *R. dentatus* from shallow depths (0 to 1 cm), which can be exploited for its management by tillage manipulations (Singh and Punia, 2008). Allowing the seed on the surface after crop harvest for its predation, greater emergence in the next growing season from surface and its killing by pre-seeding herbicide application or tillage can lower the soil seed bank. Placing seed deeper than 4 cm by tillage operations will also render the seed to lower and delay emergence posing no competition to crops. Similarly, lower emergence of *M. parviflora* from surface and susceptibility of *R. spinosus* to flooding can be exploited to lower their menace (Singh and Punia, 2008).

Much more research effort is needed on weed ecology and biology. Out of the total 826 weed species reported in the country, 80 are considered as very serious and 198 as serious weeds (Anonymous, 2007). Ecology and biology of very serious and serious weeds need to be studied in relation to their management for incorporating the knowledge in IWM. Current information about weed biology and ecology is very limited and largely descriptive. Even limited information is available about mechanisms of weed interactions with crops and responses of weeds to various production systems. Future research must focus on mechanisms of weed interactions with crops and cultural, physical and biological factors operating in agro-ecosystems. IWM should have a primary focus on practices that affect propagule production, survival and the propagule-seedling transition within the crop land.

4. YIELD LOSSES DUE TO WEED COMPETITION AND THE CRITICAL PERIOD OF CROP-WEED COMPETITION

The losses caused by weeds in various crops and cropping systems were quantified, indicating the need for weed management for realising optimal crop yields (Table 1). On-farm studies on yield losses caused by weeds were limited. An on-farm study indicated that the yield loss from weeds in unweeded plots was highest in the rice-wheat system followed by rice-pea-rice, and was least in the sugarcane system (Singh *et al*., 2005a). Assuming a regular distribution of weeds when predicting yield losses, probably, resulted in an overestimation of weed-related yield losses. In addition, the distribution of weeds within agricultural fields is rarely uniform, weeds typically are found in patches having a high relative density surrounded by areas with a few plants.

The critical period for weed control is a period in the crop growth cycle during which weeds must be controlled to prevent yield losses (Zimdahl, 1988). The critical period has two components : (1) the length of time weed control is required to prevent crop yield losses, and (2) the length of time crops can tolerate weeds before resulting in yield losses. These components combined define the critical weed-free period (Zimdahl, 2004). Thus, knowledge of weed emergence patterns becomes essential for successful implementation of this concept. Several studies on critical period of crop weed competition were conducted in India (Table 2). However, studies on weed emergence patterns in different cropping systems and agro-ecological regions of India are limited.

5. NON-CHEMICAL IWM

Limited number of studies were reported on non-chemical methods of IWM. In rice/wheat cropping system, inclusion of greengram in summer or summer cowpea for fodder or Sesbania for green manuring, resulted in lowest grasses and sedges (Singh *et al.,* 2008).

Table 1. Estimated yield losses caused by weeds in different crops and cropping systems in India

Crop	Weeds	Per cent reduction in yield due to weeds	Reference
Fababean	Unchecked weeds growth	60 to 70	Nehra and Malik (1999)
Grain cowpea	Unchecked weeds growth	62	Mathew *et al*. (1995)
(i) Lentil	Season long weed competition	(i) 46.6	Pandey *et al*. (1998)
(ii) Wheat		(ii) 40.6	
(iii) Toria		(iii) 40.1	
(iv) Barley		(iv) 28.1	
(v) Field pea		(v) 24.7	
(i) Greengram	Cuscuta 1 to 10/m^2	(i) 27.7 to 88.3	Moorthy *et al*. (2003, 2004)
(ii) Niger		(ii) 39.3 to 98.4	
(iii) Lentil		(iii) 20 to 95	
(iv) Chickpea		(iv) 28 to 100	
Maize	(i) Grasses	(i) 77.4	Pandey *et al*. (2002)
	(ii) Non-grassy	(ii) 44.2	
	(iii) Sedges	(iii) 38.4	
Maize	(i) A unit increase in weed density/m^2	(i) 0.79 q/ha	Parmeet *et al*. (2007)
	(ii) A unit increase in weed dry weght/m^2	(ii) 1.418 q/ha	
Rice-wheat cropping system	In farmers' fields	13.1 to 22.4	Singh *et al*. (2005b)
Sunflower	Season long weed competition in		Wanjari *et al.* (1999)
	(i) Kharif	(i) 54.6	
	(ii) Spring	(ii) 25.7	
Soybean-chickpea cropping system	*Euphorbia*		
	geniculata at	(i) 12-30 of soybean	Mishra and Singh (2003)
	10 to 120/m^2 plants	(ii) 18-53 of chickpea	
Wheat	*Rumex spinosus* at		Walia *et al.* (2004)
	1 plant/m^2	2.5	
	2 plans/m^2	6.1	
	3 plants/m^2	20.1	
	5 plants/m^2	30.1	
	10 plants/m^2	49.0	
	30 plants/m^2	116.1	
Wheat	Competition of		Walia and Brar (2001)
	(i) only broadleaf weeds	(i) 17.0	
	(ii) only wild oats	(ii) 36.6	
	(iii) both	(iii) 45.1	

Virk *et al*. (2003) reported that combination of early sowing (October 25) with quick growing wheat variety (PBW 154 or PBW 343 or WH 542) significantly smothered *P. minor*. In baby corn, thorough land preparation and irrigation upto field capacity for solarization was found effective in suppressing weeds followed by one ploughing + harrowing and 40 mm of irrigation fb one hand weeding at 30 days was crucial (Thimmegouda *et al*., 2007). Soil solarization was also observed to record the highest system productivity in the soybean-wheat cropping system closely followed by wheat straw incorporation and repeated tillage with irrigation (Das and Yaduraju, 2008).

In transplanted rice, the reduction in weed growth was observed with (a) intensive puddling and shallow depth submergence (Reddy and Reddy, 1999) and (b) higher dosage rate of fertilizer i. e. 180 kg N/ha and plant density of 41 plants/m^2 (Brar and Walia, 2001).

6. IWM WITH HERBICIDES AS A COMPONENT

In India, about 6000 tonnes of herbicides are currently used for weed control, mainly in irrigated crops (about 77% on wheat and rice) and on plantations (about

Table 2. Critical period of crop-weed competition (CPCWC) for different crops and cropping systems in India

Crop/Cropping system	CPCWC	Reference
Rice-transplanted rice (TPR) and Wet-seeded rice (WSR)	TPR–20 to 40 DAT and WSR–15 to 60 DAS	Mukherjee *et al*. (2008)
Rice-TPR (between *Caesulia axillaris* and TPR)	The initial period of 40–70 DAT	Brar *et al*. (1995)
Wheat	First 32 to 40 DAS	Chopra *et al*. (1999)
Soybean	27 to 40 DAS	Chhokar *et al*. (1995)
Sunflower	25 to 43 DAS	Wanjari *et al*. (2000)
Cumin	22-39 DAS	Kumar (2001)
Pigeonpea/Mungbean	Upto 30 DAS	Varshney (1992)
Pigeonpea/Sesame	Pigeonpea : 30 and 45 DAS Sesame: 15 and 30 DAS	Singh *et al*. (1993b)

DAS–Days after seeding, DAT–Days after transplanting.

10%). However, herbicides form only 12% of the pesticides used on crops in India (Saksena, 2003; Bhat and Chopra, 2006). Continuous use of some 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* has developed resistance against isoproturon (Malik and Singh, 1995; Yaduraju and Ahuja, 1995; Walia *et al*., 1997). Research on IWM was carried out to use herbicide as a component of weed management rather than using herbicides alone.

(a) Crop Rotations, Cropping Systems and Herbicides

Crop rotation is an important component of IWM. The choice and sequencing of crops affect long-term weed population dynamics, and consequently weed management. In traditional farming, rotations comprising crops with different life cycles were a key component of weed management. Different planting and harvest dates among these crops provide more opportunities for farmers to prevent either plant establishment or seed production by weeds.

In rice/wheat cropping system, sequences involving summer cowpea for fodder or *Sesbania* for green manuring, resulted in significantly lowest population of grasses and sedges (Singh *et al*., 2008). However, the different cropping sequences failed to affect broadleaf weeds. Rice-lentil+mustard (3 : 1)-cowpea, rice-maize + pea (1 : 1)-cowpea and rice-potato-greengram gave high yield (Singh *et al*., 2008).

Effective weed control in terms of reduced weed density and dry weight was achieved by pretilachlor with safener at 400 g/ha combined with *Sesbania* (Dhaincha) intercropping and azolla dual cropping in wet-seeded rice (Subramanian and Martin, 2006). The conoweeder incorporation of daincha and azolla resulted in higher weed control during early stages. Mungbean-mustard cropping sequence resulted in higher net return and benefit : cost ratio than fallow-mustard (Singh, 2006).

The effectiveness of crop rotation in weed suppression may be enhanced by crop sequences that create varying patterns of resource competition, allelopathy, soil disturbance and mechanical damage to certain weed species. Many aspects of crop rotation and intercropping and their effects on weeds are yet to be explored.

(b) Tillage and Herbicides as Components of IWM

Tillage prior to crop establishment serves mainly to prepare a weed free seed bed. It eliminates established and emerged weeds prior to crop seeding and also moves weed seeds near the soil surface vertically, resulting in weed seed burial. Deep/inverted tillage with mould board plough+POE application of clodinafop 60 g/ha, sulfosulfuron 25 g/ha and fenoxaprop ethyl 100 g/ha was found to be equally effective against *P*. *minor* in wheat (Walia *et al*., 2005). However, seed bank recorded was less in clodinafop, sulfosulfuron as compared to fenoxaprop ethyl treated plots. The number of seeds of *P minor* in the top 0-15 cm soil depth was found to be significantly less in these treatments as compared to the plots of continuous zero till sown crop (Walia *et al*., 2005). The crop sown with zero tillage continuously produced significantly less grain yield than the zero tillage techniques followed after giving deep tillage for one year which indicates that with inverted tillage majority of seeds of *P. minor* were buried in the deep soil layer which were unable to germinate and consequently there was less infestation of *P. minor* in this treatment.

Soybean sowing, using stale seed bed technique, by killing the first or second flush of weeds and supplementing it with 1.0 kg/ha oxadiazon spray resulted in higher soybean yield (Jain and Tiwari, 1995). In transplanted rice, frequent cultivations were better than growing green manure or keeping field undisturbed after wheat harvest (Aulakh and Mehra, 2006). They also observed that application of pyrazosulfuron 0.015 kg/ha or two HW controlled *L. chinensis* and produced higher rice grain yield. Integration of inter-cultivation with 5 t/ha FYM +1.5 kg/ha molybdenum+HW at 20 and 40 DAS and oxadiargyl @ 0.075 kg/ha recorded minimum density and dry weight of weeds in chickpea (Patel *et al*., 2006).

Appropriate IWM strategies involving development of suitable implements for the tillage operations need to be developed for different crops and agro-ecological regions.

(c) Integration of Crop Competitiveness with Herbicides

Farmers normally prefer high yielding varieties. Using high yielding crop variety competitive against weeds in combination with other methods of weed control is one of the most economical approaches to attain optimal crop yield.

Rice cultivar 'Gautam' (high yielder) and cultivar 'Prabhat' (better weed minimizer) + butachlor at 1.5 kg/ha PE +2,4-D at 0.5 kg/ha POE recorded highest yield with minimum weed dry weight (Singh *et al*., 2004). Mahajan *et al*. (2004) observed that wheat cv. PBW-343 (with more tillers) caused maximum suppression in dry matter of *P. minor* over WH-542 and PDW-233. They also found least weed growth and higher wheat yield with wheat cv. PBW-343 and WH-542 + closer spacing (15 cm) + clodinafop at 45 g/ha or 60 g/ha.

Enhanced dry-seeded rice competitiveness against weeds was observed with 100 kg/ha seed rate + oxyfluorfen 0.25 kg/ha (3 DAS) + *halod* (Angiras and Sharma, 1998). The increase in transplanted rice density from 22 to 44 hills/m^2+application of pyrazosulfuron 0.015 kg/ha was found to be significantly better in controlling *L. chinensis* (Aulakh and Mehra, 2006).

Sunflower at a closer spacing of 45 x 30 cm (than 60 x 22.5 cm)+fluchloralin 0.5 kg/ha+pendimethalin 0.5 kg/ha supplemented with HW at 40 DAS recorded least weed weight and higher sunflower seed yield (Sumathi *et al*., 2009). In wheat, interaction of bidirectional row orientation+120 kg/ha seed rate + 15 cm or 20 cm row spacing and isoproturon 0.75 kg/ha resulted in lesser weed growth and higher wheat yield (Angiras and Sharma, 1993).

Improved crop competitiveness against weeds and higher crop yield were observed with raised beds planting of : (a) blackgram integrated with pendimethalin at 0.75 kg/ha fb one hand weeding at 45 DAS or pendimethalin 1.5 kg/ha (Kumar *et al*., 2006) and (b) maize integrated with application of atrazine 1.5 kg/ha or acetachlor 1.25 kg/ha (Chopra and Angiras, 2008).

(d) Integration of Herbicides with Mulching

Covering or mulching the soil surface can reduce weed problems by preventing weed seed germination or by suppressing the growth of emerging seedlings. Mulches can be made from a number of materials: a living plant ground cover, loose particles of organic or inorganic matter spread over soil and sheets of artificial or natural materials laid on the soil surface.

In wheat crop of rice/wheat system, surface placement of rice residues at 6 and 7 t/ha+POE of clodinafop 60 g/ha, sulfosulfuron 25 g/ha and mesosulfuron+iodosulfuron 14.4 g/ha significantly reduced the *P. minor* dry weight and nutrient uptake (Brar and Walia, 2008). Metribuzin or atrazine (PE) both at 1.0 kg/ha fb trash intra row mulching at 3.5 t/ha at 60 DAP of sugarcane provided effective weed control (Singh *et al*., 2001). Pre-emergence application of atrazine at 1 kg/ha, atrazine 0.75 kg/ha+straw mulch in maize (Kumar and Walia, 2003) and pendimethalin at 1.0 kg/ha+farm wastes as mulch (7.5 t/ha)+one hand weeding at 45 days after sowing (DAS) of direct-seeded rice (Singh *et al*., 2001a) also resulted in effective weed control and higher crop yield.

The high cost of mulching makes it economic only for high value horticultural crops. In ber, use of black or white polyethylene sheets as a mulch after one hand weeding at 70 DAS of ber nursery was found to provide more than 98% control of *Cyperus rotundus* and there was no regeneration of this weed. Spray of glyphosate at 0.75, 1.0 and 1.5% solution in ber orchard, the control of *C. rotundus* was to the extent of 77, 85 and 95%, respectively (Yadav *et al*., 1996). In okra, the most economical treatment was stale seed bed with glyphosate application integrated with eucalyptus mulching, which recorded the highest net return and B : C ratio (Ameena *et al*., 2006).

(e) Integration of Zero Tillage with Herbicides

The use of zero tillage would also reduce the costs of seeding. In addition, early sowing results in increased crop yield (Vincent and Quirke, 2002).

In rice-wheat system, under zero tillage, the time taken between rice harvest and wheat sowing is considerably shortened. In wheat, nutrient uptake by *P. minor* as well as broadleaf weeds were significantly reduced with zero till sowing in standing stubbles, zero till sowing after partial burning and bed planting techniques (Brar and Walia, 2007a). They also observed that post-emergence application of clodinafop 60 g/ha fb 2, 4-D 0.5 kg/ha, sulfosulfuron 25 g/ha and mesosulfuron+iodosulfuron 12.0 g/ha significantly reduced the dry matter accumulation by all weeds.

Sulfosulfuron+metsulfuron 15+4 g/ha, sulfosulfuron+triasulfuron 15+30 and 15+40 g/ha and metsulfuron+triasulfuron 3+30 g/ha proved better against all weeds under zero tillage (Malik *et al*., 2007). The residual effects of only sulfosulfuron+chlorsulfuron 15+20 g/ha, sulfosulfuron+metsulfuron 15+4 g/ha, sulfosulfuron+triasulfuron 15+40 g/ha and metsulfuron+ triasulfuron 3+30 g/ha on succeeding crop of forage sorghum were noticed in terms of reduced plant height, fresh weight (kg/m^2) at 45 DAS and fodder yield of sorghum (75 DAS) only under the situation where field was prepared by giving one harrowing fb one pass of one cultivator and planking before sowing of sorghum (i. e. after wheat harvest). But such residual toxicity on sorghum was not observed due to any herbicidal treatment when sorghum was sown under unprepared (no-tillage) condition after wheat harvest (Malik *et al*., 2007).

If weed seed production was minimized during the growing season, weed seedling emergence in no-till would decline more across years compared with tilled systems as the surface weed seed pool in no-till is depleted more rapidly by emergence and mortality. Burial of weed seeds in soil by tillage favours persistence across time, thus leading to more weed seedlings in later years. Farmers can get additional benefits from this pattern of weed seedling emergence in no-till systems when combined with crop diversity in their rotations.

(f) Integration of Hand Weeding with Herbicides

Hand weeding is being practised by farmers in India since they initiated agriculture. It is effective on annual weeds. Hand weeding is ineffective against perennial weeds due to their regenerative capability. Raising cost of labour and their non-availability lead to the search for alternative methods such as herbicide use either alone or in combination with hand weeding. Several research publications (Singh *et al*., 1999; Singh *et al*., 2001a; Rameshwar *et al*., 2002; Dungarwal *et al*., 2003a,b; Sardana *et al*., 2006; Rao and Nagamani, 2007; Nagar *et al*., 2009) have proved that integration of herbicides with hand weeding is the most effective and economical method of weed management (Table 3).

7. ECONOMICS OF IWM

Economic analyses are needed for arriving at management decisions by farmers, policy making by administrators and setting research priorities by researchers. The fundamental economical principle for weed management is simple : act only if benefits exceed the cost (King *et al*., 1998). Every researcher may not agree but farmers' decision-making mostly depends on the economic benefits of the available weed management options. Researchers' economic analysis of IWM options for different crops (Table 3) indicated that for majority of the crops, herbicide application followed by hand weeding was most economical.

8. FUTURE RESEARCH

The review revealed that research carried out on IWM in India was mostly herbicide-based. However, majority of the farmers have not been benefitted by herbicides in India. Herbicides must be made economically and ecologically affordable to farmers by innovatively integrating with other components of IWM. There is significant scope of growth in herbicides, as a component of IWM, specifically as exports and domestic consumption of food grows. Need to step up coordinated extension efforts to educate farmers on judicious use of herbicides in India, in integration with other weed management methods.

Although herbicide-based systems have benefitted the agricultural community in many ways, the heavy reliance on herbicides creates an environment

Table 3. Most economical IWM methods for managing weeds in certain crops of India

Crop	IWM	Reference
Asgandh (*Withania somnifera* Dunal)	PE of isoproturon at 0.50 kg/ha and glyphosate at 1.0 kg/ha fb HW 45 DAS	Kulmi and Tiwari (2005)
Blackgram	(i) Pendimethalin at 0.75 kg/ha fb HW 45 DAS (ii) Pendimethalin at 0.50 kg/ha fb HW 60 DAS (iii) Trifluralin (PE) at 0.50 kg/ha fb HW	(i) Kumar *et al*. (2006) (ii) Rathi *et al*. (2004) (iii) Sardana *et al*. (2006)
Coriander	Pendimethalin (PE) at 1.0 kg/ha fb HW 45 DAS	Nagar *et al*. (2009)
Cowpea	Pendimethalin 0.75 kg/ha fb HW 35 DAS	Mathew *et al*. (1995)
Garlic	PE of oxyfluorfen (0.15 kg/ha) or pendimethalin (1.0 kg/ha) fb HW 40 DAS	Porwal (1995)
Groundnut	Pendimethalin or alachlor 1 kg/ha fb HW 30 DAS	Itnal *et al*. (1993)
Indian mustard	(i) Pendimethalin (PE) at 0.50 kg/ha or fluchloralin at 0.50 kg/ha each fb HW 30 DAS (ii) Fluchloralin at 0.75 kg/ha fb HW 25 DAS	(i) Singh *et al*. (1999) (ii) Singh (2006)
Onion	(i) Pendimethalin at 1.5 kg/ha fb HW 60 DAT (ii) Oxyfluorfen applied at 0.25 kg/ha fb HW 40 DAT (iii) Oxyfluorfen at 0.15 kg/ha fb HW 35 DAT (iv) Fluchloralin or pendimethalin at 0.9 kg/ha fb HW 40 DAT	(i) Rameshwar *et al*. (2002) (ii) Nandal and Singh (2002) (iii) Kolhe (2001) (iv) Sukhadia *et al*. (2002)
Okra	Stale seed bed with glyphosate application integrated with eucalyptus mulching	Ameena *et al*. (2006)
Opium poppy (*Papaver somniferum* L.)	Isoproturon at 375 g/ha or 500 g/ha PE fb HW 30 DAS	Kulmi and Tiwari (2004)
Dwarf pea	Sowing at 20 cm apart with two HW fb pendimethalin at 1 kg/ha	Tewari *et al*. (2003)
Pigeonpea/Groungnut intercrop	Pendimethalin (1.0 kg/ha) or fluchloralin (1.0 kg/ha) each fb two HW 30 and 42 DAS	Vijaykumar *et al*. (1995)
Pigeonpea/pearl millet intercrop	Pendimethalin at 1.50 kg/ha+HW 40 DAS	Shinde *et al*. (2003)
Rice-transplanted rice	(i) Application of butachlor 1.0 kg/ha, anilofos 0.4 kg/ha alongwith closer planting (ii) Anilophos 0.6 kg/ha 7 DAT+HW 27 DAT	(i) Gogoi *et al*. (2001) (ii) Singh and Kumar (1999)
Rice-dry-seeded rice	Butachlor at 1.0 kg/ha fb one hand weeding at 30 DAS by local tool 'Kutla'	Singh and Singh (2001)
Sesame	60 kg N/ha+fluchloralin at pre-planting@ 1.0 kg/ha fb HW 21 DAS	Singh *et al*. (2001c)
Soybean	(i) Butachlor (Pre-em) 1.5 kg/ha fb HW 30 DAS (ii) Rows spacing of 22.5 cm with alachlor at 1 kg/ha	(i) Chandrakar and Urkurkar (1993) (ii) Shekara and Nanjappa (1993)
Sugarcane	Metribuzin or atrazine at 1 kg/ha+trash mulching (3.5 t/ha) in between cane rows at 60 DAP	Singh *et al*. (2001b)
Wheat	Pendimethalin at 0.75 kg/ha+HW 30 DAS	Singh and Singh (2004)

DAS–Days after seeding, DAT–Days after transplanting, DAP–Days after planting, HW–Hand weeding, fb–followed by, PE–Pre-emergence.

favourable for weed resistance to herbicides, weed population shifts, and off-site movement of herbicides. The current challenge for producers is to manage herbicides and other inputs in a manner that prevents adapted species from reaching troublesome proportions. Other major areas of future IWM research include :

(a) Assessment of On-farm Losses Caused by Weeds

The yield losses caused by weeds in different crops and cropping systems in the farmers' fields at different agro-ecological regions need to be assessed.

(b) Weed Ecology

For farmers to completely benefit from integrated weed management technologies, mechanistic research must be conducted in weed ecology, genetics and physiology to increase basic understanding of the processes that regulate weed-crop interactions, weed population dynamics, adaptation and persistence under various management practices. IWM should have a primary focus on practices that affect propagule production, survival and the propagule-seedling transition within the agro-ecosystem.

(c) Interdisciplinary Effort

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, environmental issues and potential benefits of weeds.

(d) 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. Despite decades of research and extension efforts in popularizing the integrated weed management (IWM) practices, its importance and effectiveness are not completely understood and hence less adopted by the farmers (Yaduraju, Personal communication). Closer linkage between research and extension is needed in evolving IWM strategies and popularising effective and economical options to farming community.

(e) Need for 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 as integrated weed management tool for growers and extension staff, as well as for predicting further areas where research is required.

The challenge for weed scientists is to develop innovative, effective, economical and environmentally safe IWM systems that can be integrated into current and future cropping systems to bring a more diverse and integrated approach to weed management.

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