Print ISSN 0253-8040
Online ISSN 0974-8164

Indian Journal of Weed Science

Volume - 47 | Number - 3
July - September 2015

Available Online @ www.indianjournals.com

Indian Society of Weed Science

Directorate of Weed Science Research
Jabalpur - 482 004
Website: www.isws.org.in

Indian Journal of
Weed Science

Volume 47 | Number 3 | July-September, 2015

*This special issue has been brought out on the occasion of 25th Asian-Pacific Weed Science Society Conference held at Professor Jayshankar Telangana State Agricultural University (PJTSAU), Hyderabad, India during 13-16 October 2015.

INDIAN SOCIETY OF WEED SCIENCE

(Founded in 1968)

Regd. S. No. SOR/BLU/DR/518/08-09

IJWS REGD. NO. MAG (5) PRB 249/82-83

Indian Journal of Weed Science **47**(3): 216–223, 2015

Weedy rice invasion and its management

C.T. Abraham* and Nimmy Jose
Kerala Agricultural University, Thrissur, Kerala 680 656

Received: 4 August 2015; Revised: 12 September 2015

ABSTRACT

Weedy rice (*Oryza sativa* f. *spontanea*) is the complex of morphotypes of *Oryza* species, evolved largely by natural hybridization between wild and cultivated rice. With diverse biotypes, weedy rice has already infested large rice growing areas across the globe. It has also become a threat in major rice tracts of eastern and southern India. The weed has distributed in the commercial rice fields especially in areas where farmers have switched to direct-seeding due to labour shortage and high cost. Weedy rice has competitive advantage over cultivated rice as it grows taller and faster, tillers profusely and competes with cultivated rice for nutrients, light and space. It flowers much earlier than cultivated rice and produces grain that shatter easily thus enhancing the weed seed bank. Survey conducted has revealed the presence of weedy rice variants with respect to morphological characters like number of tillers per plant, height of plant, length of ligule, panicle characters, colour of grains, and length and colour of awns. Management of weedy rice infestation is complex mainly because of its morphological similarities to cultivated rice and lack of herbicides for selective control of weedy rice in cropped fields. Management options found effective for the control of weedy rice in direct seeded puddled rice include pre sowing surface application of oxyfluorfen 0.3 kg/ha, three DBS in thin film of water and selective drying of weedy rice panicles by direct contact application of glufosinate-ammonium or glyphosate or paraquat 15- 20% concentration at 60-65 DAS using specially designed wick applicator. Stale seedbed technique with dry and wet ploughing followed by the application of a broad spectrum herbicide and flooding proved to be effective in exhausting soil seed bank. Integrated management strategies are to be adopted for effective control of weedy rice.

Key words: Dormancy, Oxyfluorfen, Pre-sowing application, Stale seedbed, Weedy rice, Wick applicator

Rice, being a short statured crop grown during the warm climate in moist and flooded soil condition, experience very severe competition from weeds. Losses due to weeds range from 30-100% under very severe competition. Of late, weedy rice infestation has become a serious threat in the traditional rice belts of the country. Weedy rice (*Oryza sativa* f. *spontanea*) evolved largely by natural hybridization between wild and cultivated rice, is an emerging threat to rice cultivation as it affects crop production, harvest, quality and income. As the conspecific weed, weedy rice is morphologically and biochemically similar to cultivated and wild counterpart species. Control of weedy rice by hand weeding or herbicides is almost incomplete and impractical. Heavy infestation of weedy rice and subsequent reduction in crop yield in rice fields of India during recent years have forced farmers to abandon rice cultivation mostly in the traditional rice belts.

Origin and spread of weedy rice

Cultivated rice is included in the genus O*ryza* of the grass family (Poaceae). This genus includes two cultivated species (Asian rice - *Oryza sativa*, and African rice - *O. glaberrima*) and more than 20 wild species with ten different genome types, *i.e.* AA, BB, CC, BBCC, CCDD, EE, FF, GG, JJHH, and JJKK. The wild relatives of rice with different genome types usually have significant reproductive isolation, making them unlikely to hybridize under natural conditions. The AA genome weedy and wild relatives are highly compatible sexually with cultivated rice. Their interspecific F_1 hybrids could form complete chromosome pairing in meiosis and have relatively high pollen and seed fertility to produce viable offspring (Lu and Snow 2005). It is widely hypothesized that weedy rice has a variety of origins.

With diverse biotypes, weedy rice has already infested more than 50 countries of Asia, Africa and Latin America. In India, weedy rice infestations are seen in West Bengal, Andhra Pradesh, Assam, Bihar, Karnataka, Madhya Pradesh, Orissa, Tamil Nadu and Uttar Pradesh. Wild and weedy forms are problematic in Eastern India (Eastern U.P., Bihar, Odisha, Manipur and West Bengal) and Southern India (Kerala). Weedy rice plants are adapted to a wide range of environmental conditions. The spread of weedy rice

***Corresponding author:** ctabraham@yahoo.co.in

as contaminants with seed material, its distribution through irrigation water, machinery and animals, and efficient replenishment to the soil seed bank also add to the severity of infestation and invasion to newer areas (Chauhan 2013a).

Characters of weedy rice

Weedy rice plants showed wide variability of anatomical, biological and physiological features (Vaughan *et al.* 2001). At seedling stage, it is difficult to distinguish weedy rice as they mimic the crop, while it is possible after tillering, due to many morphological differences with the rice varieties *i.e.*, more numerous, longer and more slender tillers, leaves are often hispid on both surfaces, tall plants, pigmentation of several plant parts, grains with awns and red pericarp and shattering of seeds (Kwon *et al.* 1992, Suh *et al.* 1997). The grains of weedy rice ripen earlier and less regularly than those of cultivated rice and are extremely prone to shattering. The stem of weedy rice is comparatively more brittle and round in cross section than that of cultivated rice; the surface of the leaf sheath of weedy rice is softer and spongier than that of cultivated rice. Certain weedy morphotypes have anthocyanin pigmentation in the apiculous, first internode, ligule, margins of the first leaf and auricles (Espinoza *et al.* 2005, Chauhan 2013a).

Undesirable traits of weedy rice

Like the rice crop, weedy rice seeds are unable to germinate in saturated soil. Unlike cultivated varieties, weedy rice seeds showed variable degree of dormancy and tendency for the seeds to shatter as soon as they mature (Perreto *et al.* 1993). Seeds mature within a short period and shatter immediately facilitating the buildup of weed seed bank before the farmer gets a chance to remove the seeds. Early seed shattering is a specific characteristic of weedy rice, controlled by the gene Sh which shows the shattering character in conditions of dominant homozygosys (Sh Sh) or heterozygosys (sh Sh) (Sastry and Seetharaman 1973). Ferrero and Vidotto (1998) found that seed shattering in weedy rice started nine days after flowering and increased gradually for 30 days (65% of the total grains). Ferrero (2010) reported that shattered and non-shattered seeds became viable at about nine days from the beginning of flowering, with a germinability of about 20 percent, reaching about 85% at 12 days after flowering. Many researchers emphasized the influence of environmental factors during seed development, storage, and germination on the trait (Nair *et al.* 1965, Rao 1994, Gu *et al.* 2006).

The breaking of weedy rice dormancy, obtained with substances such as sodium nitrite, propionic acid, propionate-methyl, cytokinin, n-propanol, resulted to be usually accompanied by a pH reduction of the embryo tissues (Footitt and Cohn 1992). In a study conducted in Italy, the viability of weedy rice seeds taken at a depth by ploughing in loamy soil decreased to six per cent after one year and five per cent after two years of burial (Ferrero and Vidotto 1998). The non-viable seeds appeared empty, without embryos, and reserve matter. Despite years of research on seed dormancy, mechanisms for the regulation of germinability are basically unknown (Foley 2001, Koornneef *et al.* 2002). It was observed by Veasey *et al.* (2004) that the seeds of the dry region developed longer periods of seed dormancy, waiting for the wet period when environmental conditions again became favourable for germination and seedling survival. Seed longevity in the soil was found to be ecotype dependent and also affected by burial depth, soil type and moisture, cultivation practices, the magnitude of seed production and dormancy intensity (Noldin 1995). Emergence of weedy rice is greatly influenced by the soil texture, presence of water in the field and the depth of seed burial, which in turn is strictly related to the tillage adopted for seedbed preparation (Ferrero and Finassi 1995). The minimum temperature for weedy rice germination is considered to be 10°C, same as that of cultivated rice. Seeds which remain on the surface over a depth of 4 cm have the maximum germination. Seeds buried by ploughing will germinate only when they are brought to the surface in subsequent ploughing operations.

Competitive ability and yield in crop

Yield losses largely depend on season, weed species, weed density, rice cultivar, growth rate and density of weeds and rice. Weedy rice at 35% infestation caused about a 60% yield loss and, under serious infestation, yield loss of 74% was recorded in direct seeded rice (Watanabe *et al.* 1996). Yield of weedy rice infested plots at the rate of 10, 100, and 1,000 weedy seeds/m^2 were 4.05, 2.75, and 0.43 t/ha, respectively, compared to check yield (Chin *et al.* 2000). Short varieties were usually more susceptible to weedy rice competition than tall ones and interference duration was also a yield deciding factor (Kwon *et al.* 1991). Weedy rice usually coexists with cultivated rice and is highly competitive in rice fields of China (Xia *et al.* 2011). In the context of climate change, the problem is bound to aggravate as rising CO_2 concentration may enhance the competition in rice production systems.

Control of weedy rice

Controlling weedy rice is difficult as it mimics cultivated rice. Several methods are available for the control of wild and weedy rice, but none are highly effective on their own. Therefore, effective control of weedy rice populations becomes very important for the sustainable production of rice crop in all growing regions worldwide.

Prevention

Prevention is the basic means of reducing weedy rice infestation and can be achieved mainly by sowing clean rice seeds. Another preventative measure found effective is cleaning the equipments used for rice harvesting to avoid spread of weedy rice to uninfested fields (Chauhan 2013b).

Cultural methods

Non-chemical means of weed control in rice should be centered on land preparation, varietal selection, water management and fertilizer management. In the absence of effective selective post-emergence chemical control, techniques to minimize weedy rice infestations should focus on (1) lowering the chance of emergence of weedy rice seedlings at crop establishment and (2) preventing subsequent seed return to the soil from surviving plants at maturity. The former include repeated (wet and dry) tillage to provide clean seedbeds, rotation of crop establishment methods (transplanting, water seeding, wet-direct seeding), and cultivar selection to enable water management during crop establishment. All of these practices reduce the chance of plant survival (as seed or seedling). Minimum tillage systems were used in many areas with severe red rice problems (Menezes *et al.* 1994, Azmi and Johnson 2001, Choudhary and Suri 2014). The practice they adopted was after seedbed preparation, the area was kept fallow to enable red rice and other weeds to grow and to form a good mulching cover. Rice could either be drilled or water seeded after spraying the area with non-selective herbicides (glyphosate or paraquat). The crop should be flooded soon after rice emergence; otherwise, the degree of weed control will decrease. Studies conducted at Srilanka have revealed the reduction in weedy rice seed production in transplanting (96-98%) followed by seedling broadcasting (71-87%) compared to direct-seeding method (farmers practice) of crop establishment (Chauhan 2014). Cultural strategy of weedy rice control also includes the use of weed suppressing varieties and submergence tolerant varieties. Tall and long cycle varieties usually showed a greater competitiveness than modern early and semi dwarf varieties. A new approach to chemical control of wild and red rice is the use of herbicide tolerant crop cultivars, which can be safely treated with non-selective herbicides such as glufosinate (Sankula *et al.* 1997). The best control of weedy rice could be obtained with crop rotation and in temperate climate, crops like soybean, maize, wheat, sunflower, sorghum etc. can be taken up. Introduction of mungbean cropping in Vietnam resulted in a huge decrease of the weedy rice plants and other species (Watanabe *et al.* 1998).

Stale seedbed technique: Stale seedbed, also named as false seeding technique, is a cultural method commonly applied in rice monoculture for weed management. Chen (2001) observed stale seedbed technique as an efficient means to manage weedy rice. After seedbed preparation the area is left idle, to allow weedy rice and other weeds to germinate. Rice can then either be drilled or water seeded after the weeds are destroyed by either mechanical (harrows) or chemical (non-selective herbicides) means. This technique is aimed at reducing the weed infestation in the same season in which it is applied and gradually decreasing its seed bank. Sindhu *et al.* (2011) reported the effectiveness of stale seedbed technique in reducing the weed population and decreasing soil weed seed reserves in rice fields of Kerala. According to Azmi and Johnson (2001) the success of the stale seedbed method depended on the way the soil is prepared, the water management and its duration. Wet tillage after weed germination destroyed weedy rice seedlings and promoted new emergence. Puckridge *et al.* (1988) pointed out that soil flooding during the application of the stale seedbed reduced emergence from the soil in comparison to dry or moist soil, but favoured the evenness of the germination that in turn made the control easier. The duration of this technique in temperate climate conditions should be about 25-30 days.

Enhanced seed rate: Enhanced crop seeding rates of 80–100 kg/ha, above the optimum rate of 60 kg/ha in infested fields, suppress weedy rice infestations (Bakar *et al.* 2000). Azmi and Johnson (2001) reported that seed rate of more than 150 kg/ha could suppress weedy rice in infested areas.

Row seeding: Row seeding was also reported as a better and easy method to differentiate cultivated rice plants in rows and weedy rice between rows (Luat 1997). Weeds emerging in between the rows can be controlled by mechanical weeders, and those in the intra rows by manual weeding.

Soil solarization

Soil solarization was reported as an advanced non-chemical field technology for weed management (Yaduraju 1993, Kumar *et al*. 1993). The process significantly increased the soil temperature to 10-15ºC above the normal temperature. This technique was practiced in the warmest months for duration of 4- 6 weeks using thin transparent polyethylene films of 19-25 micro meter. High initial investment and practical difficulties restrict the adoption of this technology to seed production fields and nurseries.

Water management

Water management can play an important role in weedy rice control. Early flooding 20-30 days before land preparation would help to control red rice (Noldin *et al*. 1997). After seeding of pre-germinated seeds, water management is critical to successfully suppress weedy rice. There are two management strategies for irrigation after seeding: (1) water can be maintained at a depth of 5–10 cm until drainage at harvest (continuous flooding); or (2) drain the field and keep the field saturated for 3–5 days, followed by gradual flooding. Excessive drainage will expose the soil to air and increased oxygen concentration in the soil, thus stimulating weedy rice germination. Azmi and Abdullah (1997) reported that farmers resorting to transplanting rice culture in weedy rice infested areas had minimal or no recurrent problems with weeds. Puddling combined with the presence of a thin layer of water over the well levelled soil maintained the anaerobic conditions in the top soil and prevented weedy plants from becoming established (Fisher 1999). Vidotto and Ferrero (2000) have also found that flooding in well levelled soils limited weedy rice germination.

Manual and mechanical management

The control of weedy rice is sometimes carried out manually, but this practice is. Hand weeding is costly, time consuming and quite impractical up to 30-40 days after crop emergence as it is very difficult to distinguish the cultivated varieties from the weedy rice in the early stages. Hand weeding of weedy rice plants can be carried out for light infestations and frequently it is used together with other means of control (chemical) when the latter has given poor results, so as to avoid grain dispersal and also in seed production plots.

Weedy rice can also be controlled mechanically in line planted rice using tools. This practice is aimed at preventing the spread of the weed and is mainly carried out by cutting tall weed panicles before they set seeds (Ferrero and Vidotto 1999). The European experience showed that at least 94% of the panicles could be cut down using this practice in two phases, the first at the beginning of the flowering and the second 15 days later.

Chemical control

Herbicide based weed management is generally the most popular method for weed control in the direct seeded rice fields (Kaur *et al*. 2015). However, it is very difficult to control weedy rice by the use of selective herbicides because of the close anatomical and physiological similarity of weedy rice to the crop (Chen *et al*. 2004). However, with modification in the time and method of herbicide application, chemical control can be successful in managing weedy rice.

Use of herbicides before sowing: According to Noldin *et al*. (1998), use of anti-germinative herbicides, such as metolachlor 3.5 kg/ha, alachlor 3.5 kg/ ha, applied in soybean as pre-emergence resulted in weedy rice control of about 90%. Ferrero *et al*. (1999) could obtain good control of weedy rice (often higher than 75%) in European rice conditions with pretilachlor and dimethenamid used alone or in combination 1.5 and 0.48 kg/ha, respectively. To avoid any phytotoxicity risks, both herbicides need to be applied at least 25 days before rice planting. Pre-plant incorporation of thiocarbamate herbicides like molinate and butylate also controlled weedy plants (Fisher 1999, Garcia and Rivero 1999). Kuk *et al.* (1997) found that weedy rice was completely controlled by thiobencarb 2.1 kg/ha and oxadiazon 0.24 kg/ha. Molinate (6.5 kg/ha), however, gave 26–67% control when applied six days before rice seeding.Thiobencarb application as a preplant surface treatment 4.4 kg/ha in combination with reflooding within 3 to 5 d after drainage is recommended to control red rice in the United States (Sadohara *et al*. 2000).

Use of seed protectants: The experiments carried out in Central and South America revealed that the best weedy rice control could be achieved by applying molinate 7.2 kg/ha and butylate 4.2 kg/ha with seed protectants such as oxabetrinil 1.5 g/kg and flurazole 2.5 g/kg (Smith 1992).

Use of herbicides during the crop season: Chemical control in crop post planting should only be considered as a salvage operation and it mainly relies on difference in size or growth stage between weedy rice and commercial rice. Weedy rice that had grown taller than rice could be treated with foliar systemic herbicides such as glyphosate or cycloxydim, at 20 and 5% concentrations, respectively, by using wick/ wiper applicators (Stroud and Kempen 1989). The equipment can be mounted on self-moving machines or in front of a tractor. Hand held applicators for direct contact application of the herbicide (DCA) may also be useful.

The plant growth regulator, maleic hydrazide sprayed at the rice milk stage and prior to or during red rice heading stage reduces the production of red rice seed (Dunand 1996, Andres and Menezes 1997). Rice cultivars must be earlier and head at least 10–15 days before red rice. It was noticed that maleic hydrazide reduced seed viability and so it should not be used on rice seed production fields.

Genetic and biotechnological approach

The problem of weedy rice could be tackled by the introduction of herbicide tolerant varieties which allows the selective post emergence control (Linscombe *et al.* 1996, Wheeler *et al.* 1997). Glufosinate applied at the 3-4 leaf stage of the weedy rice (red rice) resulted in a better control (91%) than at panicle initiation (74%) or boot stage (77%). Imazethapyr could be selectively applied to imidazolinone resistant varieties (IMI rice) for effective control of weedy rice and other rice weeds (Olofsdotter *et al.* 1999). A non-transgenic rice variety '*Clearfield*' tolerant to herbicide imazethapyr had been in use in red rice infested fields of United States of America from 2002 onwards (Shivrain *et al.* 2009). However, possibility of out crossing of resistant variety with wild rice is suspected to taint the advantage of this technology.

The transfer of resistance genes to weedy species is likely to occur as the incidence of natural hybridization ranges between 1-52% in early and late flowering varieties (Langevin *et al.* 1990). Such problems have already occurred in Arkansas and Malaysia. Liu *et al.* (2012) made a major finding to prevent the spread of transgenes form GM rice to weedy rice which in due course would taint the advantage of GM herbicide resistant crop. They developed an insect-resistant and glyphosate-herbicide tolerant GM rice line that is sensitive to bentazon, a commonly used herbicide. He reported that weedy rice plants containing transgenes from GM rice through gene flow can be selectively killed by the spray of bentazon when a non GM rice variety is cultivated alternately in a few year intervals. The built in control mechanism in combination of cropping management is likely to mitigate the spread of transgenes into weedy rice populations.

Integrated weedy rice management

The trend towards increased herbicide use and the likely environmental concerns and health consequences always call for integrated weedy rice management. According to Abraham (2012), the only way to avoid the problem associated with weedy rice control is the implementation of improved weed control within the context of integrated weed management, with emphasis on the eco-biology of the species.

Research on the biology and management of weedy rice in Kerala

Heavy infestation of weedy rice in rice fields of Kerala during recent years had forced the farmers to abandon the crop due to huge reduction in crop yield (around 30-60%) depending on the severity of infestation (3-10 mature weedy plants per square meter). Acute labour shortage and high wages added to the severity of the problem. Infestation became serious from 2005 when farmers started relying more on chemical weeding and mechanized harvesting. Survey undertaken in the major rice growing tracts of Kerala during 2009-12 identified the infestation of weedy rice to the tune of 1-15 plants/m^2 in infested areas. Infested polders were categorized as those with mild, moderate and severe occurrence. Variations in plant height, tiller production, pigmentation, length of awn and grain were noticed in the weedy rice types of Kerala. The weedy plants have more brittle culm and are round in cross section than that of cultivated rice. The plants generally have a spreading habit and flower earlier than cultivated rice plants. Weedy morphotypes with and without auricles, either straw or red colour, are noticed in Kerala (Jose 2015).

It was observed that the variable dormancy and staggered germination in weedy rice favoured the survival and spread in cultivated fields. Lab studies have confirmed the hull induced dormancy in weedy rice of Kerala. Among the various treatments evaluated for breaking hull induced seed dormancy of weedy rice, treatments in the descending order of efficiency were:(i) subjecting seeds to low temperature of 22ºC for 48 hours, (ii) scraping of seed hull, (iii) salt water treatment for six hours (EC– 5 dS/m and 15 dS/m) and (iv) 0.6% nitric acid soaking for six hours. These treatments can be effectively opted alone or in combination during different seasons in stale seedbed preparation for weedy rice management under different field situations (Jose *et al.* 2013). Scanning electron microscope studies of weedy rice seeds (Jose *et al.*

2013) revealed the presence of indentations on the exterior surface with silica in the mid region. The seed surface had parallel rows of trichomes which help in dispersal of seeds, give better grip for seeds in soil facilitating germination and prevent wash out during heavy rains. Observations confirmed the delayed germinability of matured weedy rice seeds compared to immature ones. The weedy rice leaves had more micro hairs and epicuticular wax which can reduce transpiration and enhance water use efficiency.

Studies in severely infested rice fields of Kerala (Jose *et al.* 2012a) revealed that stale seedbed preparation by ploughing the field in between two germinations at 25-30 days interval prior to sowing provided conditions for germination of majority of weed seeds in the soil seed bank. Ploughing (wet ploughing was more effective than dry ploughing) in between two stale seedbed operations took the buried seeds to the top soil for promoting germination, as weedy rice seeds do not germinate under continuous submergence and emerged only from top 4 cm of soil. In double cropped fields, where farmers do not get ample time for doing the staling operations twice, burning of straw before first stale broke seed dormancy and ensured uniform germination of weeds from the soil surface. Participatory technology demonstration also revealed that in severely infested double cropped areas, it is better to skip one crop season and repeat staling operations twice to prepare a weed free field, giving maximum time for exhausting soil seed bank (Table 1).

Studies at KAU revealed the effectiveness of soil solarization by using 100 micron transparent polyethylene sheets for 30 to 45 days during the summer months for getting more than 90% control of weedy rice. This technique will be useful for the rice nurseries to produce seedlings free of weedy rice seedlings. Surface application of oxyfluorfen 0.2 to 0.3 kg/ha in 2 cm standing water three days before sowing effectively controlled weeds (84% reduction in weedy rice dry weight) during (Fig.1) the initial critical period (Jose *et al.* 2012b).

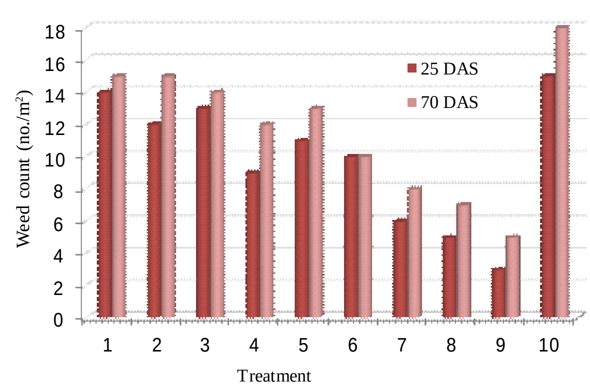
The research activities undertaken at KAU have standardized a new prototype of 'KAU Weed Wiper' for selective drying of weedy rice earheads for which patent is awaited. It was proved that better WCE can be obtained by selective killing of weedy panicles by DCA (Table 2) using a specially designed wiper device at 60-65 DAS, with broad spectrum herbicides *viz.*, glufosinate ammonium, paraquat or glyphosate 15-20% concentration of the formulated product, taking advantage of 15-20 cm height difference between rice and weedy rice plants (Jose 2015).

Integrated management strategies like stale seedbed technique to exhaust soil seed bank, pre-emergence application of herbicides to prevent the early emergence, and use of wiper device to selectively dry the panicles of weedy rice in standing crop to prevent buildup of soil seed bank are viable technologies for managing this difficult to control weed in rice. Effective management of weedy rice is possible by following other management options like higher seed rate, use of pigmented rice varieties, straw burning, appropriate tillage practices, adoption of mechanized transplanting or dibbling, scientific water management, and hand weeding in an integrated approach (Abraham *et al.* 2012). Participatory technology demonstration have confirmed that weedy rice infestation in farmers' fields required a management program aimed at local eradication at the field level followed by integrated management strategies.

Table 1. Effect of stale seedbed technique in managing weedy rice

Treatment	Plant density at 45 DAS (no./m^2)		Grain yield (t/ha)	WCE (%)
	Weedy rice	Rice		
One SSB	6	75	5.69	49.8
Two SSB	3	75	6.56	75.2
SSB with skip crop	1	74	7.50	89.6
Control	12	73	2.42	0
LSD (P=0.05)	2	NS	0.59	-

SSB - Stale seedbed



1	Butachlor 2.0 kg/ha	6	Oxyfluorfen 0.2 kg/ha
2	Butachlor 2.5 kg/ha	7	Oxyfluorfen 0.3 kg/ha
3	Pretilachlor 1.5 kg/ha	8	Oxyfluorfen 0.4 kg/ha
4	Pretilachlor 2.0 kg/ha	9	H.W. 20 & 40 DAS
5	Oxyfluorfen 0.1 kg/ha	10	Un weeded control

Fig. 1. Effect of pre-sowing application of herbicides on weedy rice infestation

Table 2. Effect of direct contact application (DCA) of herbicides on control of weedy rice panicles

Herbicide	Formulation (%)	Panicles (no./m^2)		Panicles dried (%)
		Before sweeping	Not dried	
Paraquat dichloride 24 SC	10	41	15	63
Paraquat dichloride 24 SC	15	44	7	78
Glyphosate 41 SL	10	44	13	71
Glyphosate 41 SL	15	45	12	73
Glufosinate ammonium 15 SL	5	39	19	52
Glufosinate ammonium 15 SL	10	43	15	67
Glufosinate ammonium 15 SL	15	44	9	80
Control		42	42	0

REFERENCES

Abraham CT, Jose N and Rathore M. 2012. Current status of weedy rice in India and strategies for its management. p.8. In: *Biennial Conference of ISWS on Weed Threat to Agriculture, Biodiversity and Environment*, Kerala Agricultural University, Thrissur. April 19–20.

Abraham CT. 2012. Weedy rice–threat to rice ecosystems, pp. 280-285. In: *Sustainable Weed Management Options-Approaches and Applications*. CAFTA, TNAU, Coimbatore,.

Andres A and Menezes VG. 1997. Using maleic hydrazide to drive the red irrigated rice. *Annals of Irrigated Rice* **22**: 375-378.

Azmi BM and Johnson D. 2001. *Beware of Weedy Rice in Asia*. IRRI, Manila, Philippines.

Azmi M and Abdullah MZ. 1997. *A Manual for the Identification and Control of Weedy Rices in Malaysia*. Serdang, Malaysia, 30 p.

Bakar BB, Bakar MA and Man AB. 2000. Weedy rice (*Oryza sativa* L.) in Peninsular Malaysia,pp. 51-57. In: *Wild and Weedy Rice in Rice Ecosystems in Asia- A review* (Eds. Baki BB, Chin DV and Mortimer M). IRRI, Manila.

Chauhan BS. 2013a. *Management Strategies for Weedy Rice in Asia*. IRRI, Los Banos, Philippines, 16 p.

Chauhan BS. 2013b. Management strategies for weedy rice in Asia. *Crop Protection* **48**: 51-56.

Chauhan BS. 2014. Effect of rice establishment methods on weedy rice infestation and rice grain yield in Sri Lanka. *Crop Protection* **55**: 42-49.

Chen L, Lee D, Song Z, Suh HS and Lu B. 2004. Gene flow from cultivated rice (*Oryza sativa*) to its weedy and wild relatives. *Annals of Botany* **93**: 67–73.

Chen WM. 2001. Wild rice- biological characteristics and integrated control. In: *Proceedings of the Eighteenth Asian Pacific Weed Science Society Conference*, 28 May-2 June 2001, Beijing, China.

Chin DV, Hien TV and Thiet LV. 2000. Weedy rice in Vietnam. In: *Wild and Weedy Rice in Rice Ecosystems in Asia- A review* (Eds. Baki BB, Chin DV and Mortimer M). IRRI, Manila

Choudhary AK and Suri VK. 2014. Integrated nutrient management technology for direct-seeded upland rice (*Oryza sativa*) in North-Western Himalayas. *Communications in Soil Science and Plant Analysis* **45** (6): 777-784.

Dunand RT. 1996. Maleic hydrazide for red rice suppression - direct effects on rice. *Proceedings of the Rice Technologists Working Group* **26**:193-194.

Espinoza GA, Sanchez E, Vargas S, Lobo J, Queseda T and Espinoza AM. 2005. The weedy rice complex in Costa Rica. *Genetic. Resources and Crop Evolution* **52**: 575-587.

Ferrero A and Finassi A. 1995. Viability and soil distribution of red rice (*Oryza sativa* L. var. *sylvatica*) seeds, pp. 205-211. In: *Med. Fac. Landbouw Rijksunv. Gentics*.

Ferrero A and Vidotto F. 1998. Germinability after flowering, shattering ability and longevity of red rice seeds, pp. 205-211.In*: Proceedings of the Sixth EWRS Mediterranean Symposium 1998,* Montpellier.

Ferrero A and Vidotto F. 1999. Red rice control in rice pre- and post-planting, pp.95-107. In: *FAO Report of the Global Workshop on Red Rice Control*. Varadero, Cuba, 30 August-3 September.

Ferrero A, Vidotto F, Balsari P and Airoldi G. 1999. Mechanical and chemical control of red rice (*Oryza sativa* L. var. *sylvatica*) in rice (*Oryza sativa*) pre-planting. *Crop Protection* **18**: 245-251.

Fisher AJ. 1999. Problems and opportunities for managing red rice in Latin America, pp. 77-85. *Report of the Global Workshop on Red Rice Control*. 30 August-3 September, Varadero, Cuba.

Foley ME. 2001. Seed dormancy: An update on terminology, physiological genetics, and quantitative trait loci regulating germinability. *Weed Science* **49**: 305–317.

Footitt S and Cohn MA. 1992. Seed dormancy in red rice - embryo acidification during dormancy breaking and subsequent germination. *Plant Physiology* **100**: 1196-1202.

Garcia De La, OJ and Rivero LE. 1999. Red rice - studies and perspectives of its management in rice production in Cuba, pp. 25-31. *Report of the Global Workshop on Red Rice Control*, 30 August-3 September, Varadero, Cuba.

Gu XY, Kianian SF and Foely ME. 2006. Dormancy genes from weedy rice respond divergently to seed development environments. *Genetics* **172**: 1199-1211.

Jose N, Abraham CT and Leenkumary S. 2012a. Alternates strategies for management of weedy rice complex in direct seeded rice, pp. 783-784. In: *Extended Summaries Vol.3: Third International Agronomy Congress*, November 26-30, New Delhi, India.

Jose N, Abraham CT and Leenkumary S. 2012b. Alternate strategies for management of weedy rice complex in rice fields of Kerala, p.71. In: *Abstracts of the Biennial Conference of Indian Society of Weed Science on Weed Threat to Agriculture, Biodiversity and Environment,* 19-20 April, 2012, Kerala Agricultural University, Thrissur, Kerala.

Jose N, Abraham CT, Mathew R and Leenkumary S. 2013. Biology and management of weedy rice in direct-seeded puddled rice, 454-461. In: *Procedings 24th Asian-Pacific Weed Science Society Conference.* October 22-25, 2013, Bandung, Indonesia .

Jose N. 2015. *Biology and Management Of Weedy Rice*. Ph.D. Thesis, Kerala Agricultural University, Thrissur. 230 p.

Kaur R, Singh K, Deol JS, Dass A and Choudhary AK. 2015. Possibilities of improving performance of direct-seeded rice using plant growth regulators: A review. *Proceedings of the National Academy of Sciences, India Section B: Biological Sciences.* Published online DOI 10.1007/s40011-015-0551-8.

Koornneef ML, Bentsink and Hilhorst H. 2002. Seed dormancy and germination. *Current Opinionon Plant Biology* **5**:33–36.

Kuk YI, Guh JO and Chon SU. 1997. Difference of classification, growth and herbicidal tolerance in collected weedy rice. *Korean Journal of Weed Science* **17**: 31-43.

Kumar B, Yaduraju NT, Ahuja KN and Prasad D. 1993. The role of soil solarization in weed management. *Weed Research* **33:** 423-429.

Kwon SL, Smith RJ and Talbert RE. 1991. Interference of red rice (*Oryza sativa* L.) densities in rice (*Oryza sativa* L.). *Weed Science* **39**: 197-174.

Kwon SL, Smith RJ and Talbert RE. 1992. Comparative growth and development of red rice (*Oryza sativa*) and rice (*O. sativa*). *Weed Science* **40**: 57-62.

Langevin AS, Clay K and Grace BJ. 1990. The incidence and effect of hybridization between cultivated rice and its related weed, red rice (*Oryza sativa* L.). *Evolution* **44**: 1000-1008.

Linscombe SD, Jodary F, Christou P, Braverman MP, Oard JH. and Sanders DE. 1996. Potential for the use of transgenic rice for the control of *Oryza sativa* and other rice weeds, pp. 435-439 .In: *Proceedings of the Second International Weed Control Congress*, Copenhagen.

Lu BR and Snow AA. 2005. Gene flow from genetically modified rice and its environmental consequences. *BioScience* **55**: 669-678.

Luat NV. 1997. Effect of broadcasting and row seeding with different seed rate on rice yield. *Paper Presented at a Workshop on Increasing efficiency of Fertilizer Application*, 29-30 July 1997, CLRRI-Mega Project, Cuu Long Delta Rice Research Institute, Can Tho, Vietnam.

Menezes VG, Andres A, DeSouza PR and Carrao VH. 1994. Native Serradela: uma alternative winter for as varzeas do sul do Brasil. *Preco Agricultura, Piracicaba*, SP. 4 p.

Noldin JA, Knoblauch R, Dal Piva CA and Alfonso-Morel D. 1997. Quality in irrigated rice Semente em Santa Catarina. *Anais da Cultura do Irrigated Rice* **22**: 487- 490.

Noldin JA. 1995. *Characterization, Seed Longevity, and Herbicide Sensitivity of Red Rice (Oryza Sativa L.) Ecotypes and Red Rice Control in Soybeans [Glycine max (L.) Merr.]*. Ph.D. Texas A&M University, College Station, Texas. 218 p.

Puckridge DW, Chankasom L, Vonsaroj P, Thongbai P and Chinawong S. 1988. Effect of tillage and sowing methods on control of wild rice, pp. 593-598. In: *Proceedings of the 1987 International Deepwater Rice Workshop*. International Rice Research Institute, Manila, Philippines.

Rao SP. 1994. Studies on seed dormancy in traditional rice varieties as affected by seasons. *Indian Journal of Physiology* **37**: 113–115.

Sadohara H, Watanabe O and Rich G. 2000. Control of red rice, pp. 83-86. In: *Wild and Weedy Rice in Rice Ecosystems in Asia- A review* (Eds. Baki BB, Chin DV and Mortimer, M). IRRI, Manila

Sankula S, Braverman MP, Linscombe SD. 1997. Glufosinate-resistant, BAR-transformed rice *(Oryza sativa*) and red rice (*Oryza sativa*) response to glufosinate alone and in mixtures. *Weed Technology* **11**: 662-666.

Sastry MVS and Seetharaman R. 1973. Inheritance of grain shattering and lazy habit and their interrelationship in rice. *Indian Journal of Genetics and Plant Breeding* **38**: 318-321.

Shivrain VK, Burgos NR, Gealy DR, Mauroumoustakos A and Black H. 2009. Red rice (*O. sativa)* emergence characteristics and influence on rice yield at different planting dates. *Weed Science* **57**: 94-102.

Sindhu PV, Thomas CG and Abraham CT. 2011. Stale seedbed and green manuring as an effective weed management strategy in dry-seeded rice (Oryza sativa*). Indian Journal of Agronomy* **56**: 109-115.

Smith RJ. 1992. Integrated red rice management, pp.143-158. In: *Rice in Latin America: Improvement, Management and Marketing*. (Ed. Cuevas-Pérez F.). CIAT and IRRI.

Stroud D and Kempen HM. 1989. Wick/Wiper, pp. 148-150. In: *Principles of Weed Control in California*. California Weed Conference. Thomson Publication, Fresno.

Suh HS, Sato YI and Morishima H. 1997. Genetic characterization of weedy rice (O*ryza sativa* L.) based on morpho-physiology, isozymes and RAPD markers. *Theoretical and Applied Genetics* **94**: 316-321.

Vaughan LK, Ottis BV, Prazak-Havey AM, Bormas CA, Sneller C and Chandler JM. 2001. Is all red rice found in commercial rice really *Oryza sativa*? *Weed Science* **49**: 468-476.

Veasey EA, Karasawa MG, Santos PP, Rosa MS, Mamani E and Oliveira GCX. 2004. Variation in the loss of seed dormancy after ripening of wild and cultivated rice species. *Annals of Botany* **94**: 875-882.

Vidotto F and Ferrero A. 2000. Germination behaviour of red rice (*Oryza sativa* L.) seeds in field and laboratory conditions. *Agronomie* **20**: 375-382.

Watanabe H, Vaughan DA and Tomooka N. 1998. Weedy rice complexes: Case studies from Malaysia, Vietnam and Suriname. In: *International Symposium on Wild and Weedy Rices in Agro-ecosystems*, 10-11 August, Ho Chi Minh City.

Wheeler CC, Baldwin FL, Gealy D. and Gravois K. 1997. *Weed control in Liberty-tolerant rice*, pp. 64-66. In: Research Series, Arkansas Agricultural Experiment Station.

Xia H-B, Wang W, Xia H, Zhao W and Lu BR. 2011. Conspecific crop-weed introgression influences evolution of weedy rice *(Oryza sativa* f. *spontanea)* across a geographical range. *On line PLoS ONE 6: e16189.*

Yaduraju NT 1993. Soil solarization in weed management, pp. 18-20. In: *Proceedings of the International Symposium of Indian Society of Weed Science*, Hisar, November, Vol. 1

Indian Journal of Weed Science **47**(3): 224–232, 2015

Weed management in lowland rice

B. Duary*, M.M. Mishra[1], R. Dash[1] and K.C. Teja
Institute of Agriculture, Visva-Bharati, Sriniketan, Birbhum, West Bengal 731 236

Received: 18 August 2015; Revised: 2 September 2015

ABSTRACT

Lowland rice ecosystem in India is infested with complex weed flora including semi-aquatic and aquatic weeds. Recently weeds having mimics with rice, perennial and other weeds which propagate by vegetative means are emerging as major threat. Weeds cause yield losses from 15 to 76% in rice crop. Besides, weeds remove about 21-42 kg N, 10-13.5 kg P and 17-27 kg K/ha in transplanted rice. Research on weed management in lowland rice in India has been reviewed in this paper with respect to weed flora and their impact, biology and ecology of weeds, weed management methods and future thrust areas of research and management. The weed flora in lowland rice is very much diverse and dynamic over times and places. Very limited information is available on biology and ecology of major weeds. Studies have been carried out on cultural, manual, mechanical, chemical means of weed management. Shortage of labours, lack of suitable weed control implements and problem of specific weeds have compelled the farmers to think for alternative strategies and herbicides have been the obvious choice to the farmers. Many herbicides either alone or in combinations as ready or tank mixed have been recommended in India. Studies on integrated weed management have also been undertaken. But majority of researches focused on herbicide based IWM. Future research and weed management in lowland rice should be focused on ecophysiology and biology of major weeds, HR genetically modified rice, integrated weed management, exploring biocontrol agents and screening and use of allelopathic and weed competitive rice cultivars.

Key words: Lowland rice, Weed ecology, Weed flora, Weed management

Rice is a staple for more than 60% of the world's seven billion people and more than 90% of this rice is consumed in Asia (Mohanty 2013, Chauhan *et al.* 2014). Based on the hydrology and topography of land, the rice area is divided into various ecologies *viz.*, rainfed upland (16%), irrigated medium land (45%) and rainfed low land (shallow, intermediate, semi deep and deep) (39%), with a productivity of 0.87, 2.24 and 1.55 t/ha, respectively. Out of 61.3% of total rice area in eastern India 20% (5.2 Mha) are rainfed upland, 28.5% (7.8 Mha) medium land and 51.5% (14.0 mha) are rainfed low land (Mahapatra *et al.* 2012). Lowland rice is grown generally under rainfed situations in which soil is puddled for transplanting or wet seeding. The rainfed ecology is characterized by frequent drought and/or submergence and flood depending on rainfall distribution and nature of monsoon. Depending upon topography and rainfall pattern, lowland rice experiences drought, flooding and intermittent submergence at different stages of crop growth.

In India, low land rice area is mostly locate in the eastern region comprising of Assam, Bihar, Madhya Pradesh, Eastern Uttar Pradesh, Odisha and West Bengal. Area under rainfed lowland has been classified into three major ecosystems based primarily on surface hydrology during cropping period. These are shallow lowland (30-50 cm water), semi-deep lowland (50-75 cm water) and deep-water lowland (>75 cm water). India needs to produce 120 million tons of rice by 2030 to feed its one and a half billion plus population (Adhya 2011). However, to meet this demand the crop should perform to its full potential.

Many weeds which propagate by vegetative means are becoming dominant due to increased use of tractor and power tiller. Weeds like *Echinochloa crusgalli, E. colona* and *Sacciolepis* sp. having mimics with rice crop are appearing as major weeds in many rice growing areas of Eastern India. Moreover, shortage of labours, increased wages and lack of suitable weed control implements have compelled farmers to think for alternative strategies of weed management. Herbicides have been the obvious choice to the farmers, which has resulted incresed use of herbicides in India. But most of them are specific and work against narrow range of weed species (Mukherjee and Singh 2005) besides leading several problems in long run. Therefore, appropriate and economic weed management technology has to be developed for sustainable rice cultivation under

***Corresponding author:** bduary@yahoo.co.in
[1]All India Coordinated Research Project on Weed Management, OUAT, Bhubaneswar, Odisha

low land ecosystem. In the present paper, an attempt has been made to review the weed flora and their impact, biology and ecology of weeds, weed management methods, future thrust areas of research for the lowland rice ecosystem in India.

Weeds and their impact on lowland rice

Weed flora

Weed composition is dynamic over times and places and its competition depends on soil, climate and management practices. The weed flora in lowland rice is very much diverse and consists of grasses, sedges, broad-leaved and algae. In India, rice is grown under a wide variety of cultural practices in different agro-ecological systems. In irrigated and shallow depth of water *Echinochloa* spp., *Paspalum* spp., *Cyperus iria* and *Fimbristylis miliacea* predominates while with more than 2.5 cm of water *Sphenoclea zeylanica, Monochoria vaginalis, Ammania baccifera, Hydrolea zeylanica* are the most predominant. In coastal belt of West Bengal and Odisha,where rice–rice cropping system is followed under lowland, the problem of algae weeds like, *Nittella hyaline, Hydrodictyon reticulatum, Chara zeylanica, Spirogyra condensate etc.* are reported. The predominant weed flora associated with lowland rice in Eastern India were *Ammania baccifera, Fimbristylis miliacea, Cyperus microiria, Ludwigia parviflora, Monochoria vaginalis, Echinochloa crus-galli, Echinochloa colona, Lindernia ciliata, Marsilea quadrifolia, Spilanthes acmella, Cyperus difformis* and *C. iria* (Anonymous 2003, Kundu *et al.* 2003, Mondal *et al.* 2005, Mahapatra *et al.* 2012). *Ludwigia parviflora* was observed with highest frequency (Duary and Mukherjee 2013). The wet-seeded rice was infested with composite weed flora comprising of grasses, sedges and broad-leaved weeds majority of which was under grasses (Singh *et al.* 2007a, Ravisankar *et al.* 2008). *Echinochloa crusgalli, E. colona, Panicum repens, Sacciolepis interrupta* and *Paspalum distichum* among the grasses, *Cyperus difformis, C. iria, C. microiria, F. dichotoma, F. miliacea,* S*cirpus acutus* and *Scripus grossus* among sedges and *Alternanthera philoxeroides, Ipomoea aquatica, Nymphaea odorata, Monocharia vaginalis, Sphenoclea zeylanica, Eclipta alba, Aeschenomene indica* L., *Ludwigia parviflora, L. octovulvis, Cyanotis axillaris, Ammania baccifera, Marsilia quadrifolia, Lemna minor, Aeschenomene aspera, Potamogeton distinctus* and *Eichhornia crassipes* among broad-leved were the predominant weeds under puddled medium lowland conditions during rainy season (Mondal *et al.* 2005, Mondal and Duary 2009, Pal *et al.* 2009a, Ghosh 2010, Mishra *et al.* 2012, Teja *et al.* 2015a, 2015b). Much of the rainfed rice in lowland plains was dominated by *Echinochloa crussgalli* and *Paspalum scorbiculatum* among annual grasses, *Cyperus iria*, *C. difformis* and *F. miliacea* among sedges and *Sphenoclea zeylanica* and *Monochoria vaginalis* among broad-leaved weeds (Malik *et al.* 2014).

Weed competition

Weeds are recognized as major biological constraints that hinder the attainment of optimal rice productivity (Kumar and Ladha 2011, Rao and Nagamani 2013) and quality. It is estimated that every year, weeds cause yield losses from 15 to 76% in rice crop (Singh *et al.* 2004, Mondal *et al.* 2005, Rao and Nagamani 2010, Mishra *et al.* 2012, Mandal *et al.* 2013). Direct yield loss has been estimated to the range from 16-86% depending on type of rice culture, cultivars, weed species and density, cropping season, plant spacing, fertilizer rate, duration and time of weed infestation and climatic and environmental conditions (Duary *et al.* 2004, Kolay 2007). It is well established that weeds remove considerable quantities of nutrient from rice crop field. Estimate showed that weeds can deprive the crops by 47% N, 42% P, 50% K, 39% Ca and 24% Mg of their nutrient uptake thereby reduce the yield potential of rice (Balasubramaniyan and Palaniappan 2001). Hence, timely and effective weed control was essential for obtaining higher yield of rice (Sathyamoorthy *et al.* 2004, Kumar *et al.* 2007). Nutrient removal by weeds has been reported to be about 21-42 kg N, 10-13.5 kg P and 17-27 kg K/ha in transplanted rice depending upon the soil, condition of cropping and location of growing rice (Sudhalakshmi *et al.* 2005, Puniya *et al.* 2007b, Gowda *et al.* 2009). In rain fed lowland rice, a period of 30-60 days after sowing was considered as critical period for crop weed competition to avoid grain yield losses (Moorthy and Saha 2005). The critical period of crop-weed competition in lowland transplanted and direct-seeded rice were 30-60 DAT and 40-60 DAS respectively (Das *et al.* 2012).

Biology and ecology of major weeds

Ecological and biological studies of major weed species in lowland system help identifying the susceptible stage in life cycle to make better strategy for effective weed management. *Ludwigia parviflora* is one of the most dominant species in different rice ecosystems throughout rice growing areas in Eastern India. The probable reason for its wide ecological amplitude might be the adaptation by special structure like periderm and pneumatophores as reported by Mukhopadhyay and Duary (1999) and Duary and Mukherjee (2013). Recently, the increased use of tillage implements (power tiller and tractor-drawn) has aggravated the problem of weeds by cutting into pieces which further grow and multiply as separate individuals (Duary and Mukhopadhyay 2004, Duary 2014b). In nursery bed, *Echinochloa crusgalli* emerges simultaneously with rice and owing to mimicry, it is transplanted simultaneously with rice seedlings in main field.

Most of the weeds are angiospermic plant except *Marsilea* which is a pteridophyte. It creeps through rhizomatous stems just below the surface of the soil and reproduce through the structure "Sporocarp" which is capable of retaining viability for several years. Current information about weed biology and ecology is very limited. More research efforts are needed on the biology and ecology of major weeds in order to prepare better strategy for their management in low land rice in India.

Weed management methods

Cultural methods

Cultural practices greatly alter the competitive relationship between rice and weeds. Proper agronomic management practices like suitable crop establishment method, efficient fertilizer use, proper crop stand, selection of competitive crop cultivars play important role providing competitive advantages to low land rice against weeds. The risks of crop yield loss due to competition from weeds in direct-seeded rice is greater than in transplanted rice because the weeds emerge concurrently with rice and farmers are not usually able to use standing water to suppress weeds at the early growth stages (Chauhan and Johnson 2010a). Transplanting of rice experiences lowest weed competition thereby records the lower weed population and dry weight (Prasad *et al.* 2001, Singh *et al.* 2007a, Mishra *et al.* 2009) as compared to sowing of sprouted seeds in puddled condition and dry drilling of seeds and SRI. Intensive puddling with continuous submergence was very effective in reducing the weed dry weight (Subramanyam *et al.* 2007). *Azolla* intercropping (dual cropping) significantly reduced the weed density (Singh 2000, Biswas *et al.* 2005). Flooding is one of the most important weed management options in lowland rice as many weeds will not germinate in anaerobic conditions. It is the timing, duration and depth of flooding that determines the extent of weed suppression by flooding (Mortimer *et al.* 2005). But its effect on weeds is species specific (Chauhan and Johnson 2010b, Singh 2010). However, it is hardly possible to maintain water depth in rainy season. Two cultural practices which are often not given adequate attention in most of the farmer's field are through land preparation and proper land leveling. Land leveling should be an integral part of tillage operations because it is extremely important for good drainage in lowland rice ecosystems. An uneven field results in poor rice emergence in low spots and enhanced weed growth in high spots. In many areas, farmers do not take much care in leveling the land. Weed competitive rice cultivars are one of the integral parts of integrated weed management in transplanted rice. But little information is available in this aspect in India. Rice cultivar '*Prabhat*' and '*PR 108'* exhibited greater smothering effect on weeds grown under puddled transplanted conditions (Singh *et al.* 2004, Ghuman *et al.* 2008). Stale seedbed technique, a cultural-cum-preventive measure has been found very effective against weeds during *Kharif* season in lowland rice (Sindhu *et al.* 2010, Duary and Mukherjee 2013).

Manual weeding

The traditional method of weed control practice in India is manual weeding by hoe and hand pulling. Usually, hand weeding is practiced two or three times for growing a rice crop depending upon the nature of weeds, their intensity and the method of rice establishment. Hand weeding twice at 20 and 45 DAS/DAT for broadcast or transplanted crop has been found superior to the chemical weed control for all the growth and yield attributes (Chander and Pandey 2001, Prasad *et al.* 2001, Dutta *et al.* 2005, Pal *et al.* 2009b). Manual weeding is ineffective for weeds having mimicry with rice in early stage of crop. The presence of perennial weeds and other weeds propagated vegetatively that fragment over hand pulling also renders hand weeding ineffective and uneconomic. At the time of the peak period of the labor crisis and unfavorable weather condition, weeding sometimes becomes late. But delay in weeding beyond 15-25 days sharply reduces the yield to the tune of 43 kg/ha/day between 25 to 45 days (Mahapatra *et al.* 2012). With the use of rotovator and power tiller, the weeds like *Jussiaea, Marsilea, Cardenthera*, *Paspalum* are fragmented and floated after land preparation. Before transplanting, these fragmented parts should be collected using proper screen.

Mechanical weeding

In view of the increasing labour scarcity, negative impact of indiscriminate herbicide use, weed management strategy needs to be reoriented towards mechanical means for satisfactory monetary benefits. Rotary weeder was effective in controlling the weeds present in inter row space, but failed to control the weeds in intra row space or those in the vicinity of the crop (Choubey *et al.* 1998). The use of cono weeder resulted in 10-17% increase in grain yield during wet season (Thiyagarajan *et al.* 2002, Mandal *et al.* 2013). Cono weeder reduced man-days required for weeding from 30 to 10 (Mrunalini and Ganesh 2008) thus helped saving labour and time. The cost of weeding for labours could be reduced by 6.6 and 7.6 times by using rotary weeder and cono weeder, respectively, compared to hand weeding (Remesan *et al*. 2007). However, the problem of incorporation of perennial weeds and vegetatively propagated weeds may result in faster regeneration of those under mechanical weeding (Sudhalakshmi *et al*. 2005, Duary and Mukherjee 2013).

Chemical method

Herbicide usage is one of the most labour saving innovations (Moody 1993). Herbicide application has increased significantly over the last decade due to labor shortages, low herbicide prices, increased herbicide effectiveness and other advantages. A number of herbicides has been tested since last two and half decades for the management of weeds in transplanted rice with different times of application like pre-emergence, early post-emergence or post-emergence in India. Wide range of herbicides are available for the management of grassy weeds (pretilachlor, butachlor, anilofos, fenoxaprop and oxadiargyl)as well as broad-leaved weeds (metsulfuron, chlorimuron, ethoxysulfuron and 2, 4-D). Pre-emergence herbicides in rice have very narrow application window and need continuous stagnation of water for their efficacy. Many times due to various constraints at farm level, the application of herbicides in the early growth stages is not possible and continuous use of same herbicide might cause resistance in weeds. Under such situation, the post-emergence herbicides are another option (Puniya *et al*. 2007a). Sulfonylurea group is one of the most important classes of herbicide that has become popular all over the world which represent high level of activity, application flexibility, excellent selectivity and low mammalian toxicity even at very low dose with broad spectrum of weed control (Mukherjee and Singh 2005, Saha 2006, Saha and Rao, 2009, Duary, 2014a). Application of metsulfuron-methyl (10%) + chlorimuron-ethyl (10%) as early post-emergence showed better weed control efficiency against broad-leaved and sedges as compared to grasses (Singh *et al*. 2007b, Saha and Rao 2009, Pal *et al.* 2009b, Mandal *et al*. 2013). In lowland transplanted wet season rice, glyphosate as pre-planting, followed by pyrazosulfuron-ethyl, pretilachlor, butachlor as pre-emergence or metsulfuron-methyl + chlorimuron-ethyl (Almix), sodium bispyribac, ethoxysulfuron to a limited extent as early post-emergence are applied in rice fields in eastern India (Duary and Mukherjee 2013). But *Leptochloa chinensis*, *Dactyloctenium aegyptium* and *Eragrostis* spp. are not controlled by bispyribac–sodium (Malik *et al*. 2014). Bispyribac-sodium has been found effective in rice nursery as well as main field where *E. crusgalli, E. glabrescens* are major problem (Duary and Mukherjee 2013). Application of oxadiazon as pre-emergence on puddle soil in lowland conditions where direct-seeding has been done is quite effective against annual grasses particularly on *Commelina benghalensis* (Das 2008). The lowland rice condition is very often encountered with algal infestation in a luxuriant way, which cause suffocation and prevent root growth and tillering of rice. The application of copper sulphate effectively controlled the algae (Mishra and Mishra 2008, Das 2008, Mishra *et al.* 2012). Butachlor, pretilachlor, oxadiazon, bentazon, oxadiargyl, pyrazosulfuron-ethyl, bispyribac-Na, metsulfuron-methyl, metsulfuron-methyl+chlorimuron-ethyl, imazosulfuron, anilofos, 2,4-D, azimsulfuron, bensulfuron-methyl, ethoxysulfuron, cyhalofop-butyl are the herbicides, which have been found quite effective in transplanted rice in India (Saini and Angiras 2002, Saini 2003, Mondal *et al.* 2005, Yadav *et al*. 2008a, 2009, Saha 2009, Duary *et al.* 2009, Pal *et al.* 2009a, Kiran *et al.* 2010, Saha and Rao 2010a, 2010b, 2012, Das *et al*. 2012, Soren 2011, Mandal *et al*. 2013, Duary, 2014a). Penoxsulam either as pre- or early post-emergence controlled all categories of weeds in transplanted rice (Singh *et al*., 2007c, Mishra *et al*. 2007, Yadav, *et al*. 2008b, Malik *et al*. 2011, Prakash *et. al*. 2013).

Repeated and injudicious use of same herbicide or herbicides having similar mechanism of action may lead to shift of weed flora, development of herbicide resistance and buildup of herbicide load in the environment (Duary and Yaduraju 1999, Das and Duary 1999, Duary 2008). Continuous use of butachlor and anilofos in rice, particularly in North-West India, has led weed flora shifting to sedges, such as *Cyperus* sp., *Scirpus* sp., *Fimbristylis* sp. and *Eleocaris* sp. and broad-leaved weeds, such as *Caesulia auxillaris* (Chauhan *et al*. 2014). Herbicide rotation and mixture herbicide use are two major strategies to prevent shift of weed flora and development of herbicide resistance in weeds. More recently use of mixture herbicides is increasing due to the benefits of managing complex weed flora with mixture- either tank or ready mix. In addition to metsulfuron-methyl + chlorimuron-ethyl (Almix) ready mix product of bensulfuron + pretilachlor at 60 + 600 g /ha and tank mixed application of azimsulfuron with metsulfuron + chlorimuron or metsulfuron-methyl,bispyribac +Almix, fenoxaprop + ethoxysulfuron has also been found quite effective against complex weed flora (Jayadeva 2010, Sunil *et al.* 2010, Chauhan and Abugho 2012, Anonymous 2012, Parthipan *et al.* 2013, Teja *et al.* 2015a, 2015b). To improve herbicide use efficiency and avoid the problem associated with herbicide use, emphasis should be given on use of herbicide mixture and rotation and to impart training and awareness to stakeholders.

Integrated weed management

The aim of integrated weed management (IWM) is not to eliminate the use of herbicides but to improve their efficiency through their rational usage by combining with better crop management options and other methods which give an advantage to the crop. Combination of SRI method of crop establishment with alternate wetting and drying method of irrigation and cono weeding recorded lower weeds and higher growth attributes of rice (Vijayakumar *et al.* 2006). Pretilachlor with safener as pre-emergence and chlorimuron + metsulfuron at 21 DAS/DAT followed by hand-weeding or cono weeding or two way rotary weeder weeding could effectively control most of the weeds (Singh *et al.* 2008, Babar and Velayutham 2012, Sridevi *et al.* 2013). Combination of stale seedbed technique with pre-emergence spray of herbicides or with hand weeding or concurrent growing of green manure crops gave better control of weeds and higher grain yields (Sindhu *et al.* 2010). Several research publications have proved that integration of herbicides with hand weeding is the most effective and economical method of weed management (Rao 2011). Integrated use of herbicide azimsulfaron or pyrazosulfuron-ethyl with hand weeding at 40 DAT or butachlor and anilofos along with closer planting was effective for reducing weed population and dry weight (Gogoi *et al.* 2001, Mondal *et al.* 2005, Mondal and Duary 2009). Effective weed control in terms of reduced weed density and dry weight was achieved by pretilachlor with safener combined with *Sesbania* intercropping and *Azolla* dual cropping in wet-seeded rice (Subramanian and Martin 2006). In India, the information like effect of changes in plant geometry (transplanting in a triangular or paired row manner), performance of rice genotypes under different plant geometry is not available (Chauhan *et al.* 2014). However, this aspect may be exploited as a component of IWM in lowland rice. The strategies for integrated weed management should be developed and evaluated considering all the available options in the region.

Future thrust areas and strategies of weed management

Herbicide–resistant genetically modified rice

Herbicide resistant (HR) rice technologies have the potential to control a wide range of weeds including grasses, broad-leaved and sedges which cause serious problems in lowland rice, including problematic weeds like *Echinochloa* spp. and weedy rice (Rodenburg and Demont 2009). The ability to control problem weed species efficiently makes HR rice an attractive technology and farmers may rapidly adopt it in many cases. Three HR systems have been developed in rice: imidazolinone, glufosinate and glyphosate -resistant varieties (Gealy *et al.* 2003). Glyphosate and glufosinate are considered as relatively environmentally benign and, as post-emergence herbicides, the application rates can be adjusted to the weed population, and the technology has wider herbicide application time window compared to conventional technologies. Despite the possible advantages of HR options, there are concerns regarding the likelihood of gene flow from HR rice to wild and weedy rice species. In India, *O. sativa f. spontanea* is considered as weedy species in cultivated rice. In Eastern India (*e.g.* Eastern Uttar Pradesh, Bihar, Odisha, Manipur, and West Bengal) and Southern India, wild and weedy relatives are common and gene flow may occur from HR rice to these species (Kumar *et al.* 2008). The reliance on HR technology for effective weed control in rice will depend thus on careful introduction and management.

Eco-physiology and economic threshold

Simulation of competitive relationship between major weeds and rice in terms of economic yield loss and development of economic threshold (ET) may be useful in taking decision for initiation of weed management -specially use of herbicides. Very limited information is available for threshold levels of predominant weeds species in India. Threshold levels for a few weed species like *Cyperus iria* (30/m^2), *Echinochloa crus-galli* (20/m^2) has been worked out (Singh and Angiras 2003, 2008). Grass weed seedlings of rice nursery are unintentionally transplanted with rice seedlings and average rice yield reductions from transplanted *E. glabrescens* ranged from 6 at the 5% infestation level to 73% at the 40%

infestation level (Rao and Moody 1992). *Ludwigia parviflora* density of only 5/m[2] reduced the grain yield of rice about 10.2%. Single season economic threshold density varied from 1.4 *Ludwigia* /m[2] for 2, 4-D to 6.74 /m[2] for hand weeding under low land transplanted rice (Kolay 2007). More emphasis should be given on ecophysiological aspects of rice and major weeds.

Exploration of potential bioagents

In some developed countries several biocontrol agents have been used successfully in specific situations. In India also few attempts have been made for application of some fungal pathogen and insect biocontrol agents over rice weeds. However, very low abundance of these biocontrol agents at specific situation has resulted in failure of wider application and commercial success. In lowland rice *Ludwigia parviflora* was reported to be completely defoliated in lowland transplanted rice by Halticid beetle (Mukhopadhyay and Duary 1999) indicating its potentiality as a biocontrol agent against the weed. The possibilities of such biocontrol agents should be explored by identifying natural enemies through autecological studies of major weeds in lowland rice.

Developing allelopathic rice and C_4 rice

Some rice lines or wild rice species have been found to be allelopathic and can inhibit the growth of some weeds like barnyard grass and broad-leaf weeds (Fujii 1992, Olofsdotter *et al*. 1995). A number of compounds such as phenolic acids, fatty acids, phenylalkanoic acids, hydroxamic acids, terpenes and indoles have been identified as potential rice allelochemicals. The momilactone B secreted from rice seedlings appears to be the major contributor to the allelopathic activity of rice crops at least against barnyard grass (Kato-Noguchi 2013). Similar attempts may be made in India and rice cultivars are to be screened for their allelopathic potentials. Rice scientists are aiming for a second Green Revolution by developing a C_4 rice through traditional breeding or transgenic methods (Gunawardana 2008). At present rice being a C_3 plant is less competitive than C_4 weeds like *E. crusgalli* and *C. rotundus*. A C_4 rice will be more competitive against weeds, more efficient in photosynthesis and will yield high even with less water, since water requirement of C_4 plants is much lower than that of C_3 plants (Baltazar and Johnson 2013).

REFERENCES

Adhya TK. 2011. Vision 2030: *Central Rice Research Institute Technical Bulletin,* Cuttack, Odisha, 22 p.

Anonymous 2003. *Eighteenth Annual Progress Report of All India Coordinated Research Programme on Weed Control.* Visva Bharati, Sriniketan Centre.

Anonymous 2012. *Twenty seventh Annual Progress Report of All India Coordinated Research Programme on Weed Control*. Visva Bharati, Sriniketan Centre.

Babar SR and Velayutham A. 2012.Weed management practices on nutrient uptake, yield attributes and yield of rice under system of rice intensification. *Madras Agricultural Journal* **99**(1-3): 51-54.

Balasubramanian P and Palaniappan SP. 2001. *Principles and Practices of Agronomy*. Agrobios Publishing co. Pvt. Ltd, New Delhi.

Baltazar AM and Johnson DE. 2013. Challenges and problems in managing weeds in rice: present and future solutions, pp.116-125. In: *Proeedings of 24th Asian-Pacific Weed Science Society Conference,* October 22-25, 2013, Bandung, Indonesia.

Biswas M, Parveen S, Shimozawa H and Nakagoshi N. 2005. Effects of *Azolla* species on weed emergence in a rice paddy ecosystem. *Weed Biology and Management* **5** (4): 176-183.

Chander S and Pandey J. 2001. Effect of rice (*Oryza sativa*) culture, nitrogen and weed control on nitrogen competition between scented rice and weeds. *Indian Journal of Agronomy* **46**(1): 68-74.

Chauhan BS and Abugho SB. 2012. Effect of growth stage on the efficacy of post-emergence herbicides on four weed species of direct-seeded rice. *The Scientific World Journal* 2012: 1-7.

Chauhan BS and Johnson DE. 2010a. Relative importance of shoot and root competition in dry seeded rice growing with jungle rice and *Ludwigia*. *Weed Science* **58**: 295-299.

Chauhan BS and Johnson DE. 2010b. The role of seed ecology in improving weed management strategies in the tropics. *Advances in Agronomy* **105**: 221-262.

Chauhan BS, Kumar Vivek and Mahajan G. 2014. Research needs for improving weed management in rice. *Indian Journal of Weed Science* **46** (1): 1-13.

Choubey NK, Tripathi RS, Ghosh BC and Kolhe SS. 1998. Effect of water and weed management practices on weed growth and performance of transplanted rice. *Oryza* **35**(3): 252-255.

Das TK and Duary B. 1999. Herbicide resistance in weeds: current scenario, mechanisms and management strategies for now and future. *Annals of Agricultural Research* **20:** 393–398.

Das TK, Tuti MD, Sharma R, Paul T and Mirjha PR. 2012. Weed management research in India: An overview. *Indian Journal of Agronomy* **57**(3rd IAC Special issue): 148-156.

Das TK. 2008.*Weed Science: Basics and Applications.* Jain Brothers, New Delhi Publishers, 901 p.

Duary B and Mukherjee A. 2013. Distribution pattern of predominant weeds of wet season and their management in West Bengal, India, pp.191-199. In: *Proceedings 24th Asian-Pacific Weed Science Society Conference,* October 22-25, 2013, Bandung, Indonesia.

Duary B and Mukhopadhyay SK. 2004. Biotechnology and herbicides – the new tools to combat the weeds – the major cause of biotic stress in Agriculture, pp. 24-28. In: *Extended Abstract of Seminar on Biotic Stress on Agro-ecosystems.* West Bengal Academy of Science and Technology Section of Agricultural and Forestry Sciences. Visva-Bharati, Santiniketan, Feb. 22, 2004.

Duary B and Yaduraju NT. 1999. Herbicide resistance in weeds – a potential threat to world Agriculture *Pestology Annual* pp.16-27. Volume No?.

Duary B, Mondal DC and Hossain A. 2004. Integrated weed management in direct seeded dry sown rice in the lateritic belt of West Bengal. *Indian Journal of Weed Science* **37:** (1&2): 101-102.

Duary B, Roychowdhury S and Mukherjee A. 2009. Effect of sole and sequential application of herbicides on weed growth and productivity of transplanted *Kharif* rice in the lateritic belt of West Bengal, p.28. In: *Abstracts of National Symposium on Weed Threat to Environment, Biodiversity and Agricultural Productivity*, 2-3 August, 2009 at TNAU, ISWS, Jabalpur..

Duary B. 2008. Recent advances in herbicide resistance in weeds and its management. *Indian Journal of Weed Science* **40** (3&4):124-135.

Duary B. 2014a. Efficacy of imazosulfuron on weed flora and productivity of wet season transplanted rice in West Bengal. *International Journal of Bioresource Science* **1**(1):1-6.

Duary B. 2014b Weed prevention for quality seed production of crops. *SATSA Mukhopatra-Annual Technical Issue* **18**:48-57.

Dutta A, Patra BC, Jana P and Mandal N. 2005. Effect of fertility levels and weed management practices on growth, yield attributes and yield of direct seeded rice in the rainfed and lateritic belt of West Bengal, p. 69. In: *First International Weed Science Seminar on Innovative Approaches for Ecosafety Weed Management*, Kolkata, India.

Fujii Y. 1992. The potential biological control of paddy weeds with allelopathy: Allelopathic effect of some rice varieties, *Allelopathy in Control of Paddy Weeds. Tech Bull. No. 134,* ASPAC Food and Fertilizer Technology Center, Taiwan.

Gealy DR, Mitten DH and Rutger JN. 2003. Gene flow between red rice (*Oryza sativa*) and herbicide-resistant rice (*O. sativa*): implications for weed management. *Weed Technology* **17:**627-645.

Ghosh RK. 2010. Weed management in transplanted and direct seeded rice in India, pp. 19-20. In: *Extended Summaries/ Abstracts of Biennial Conference of Indian Society of Weed Science on Recent Advances in Weed Science Research-2010,* February, 25-26, 2010. IGKV, Raipur, Chhatishgarh, India.

Ghuman RS, Brar LS and Walia US. 2008. Role of variety and plant geometry on weed management in transplanted rice (*Oryza sativa* L.). *Indian Journal of Weed Science* **40** (3&4): 137-141**.**

Gogoi AK, Rajkhowa DJ and Kandali R. 2001. Integrated weed control in rainy season rice under medium land situation. *Indian Journal of Weed Science* **33**:18-21.

Gowda PT, Govindappa M, Murthy KNK, Shankaraiah C and Jnanesha AC. 2009. Effect of herbicides and cultural treatments on uptake of major nutrients by crop and weeds under aerobic rice cultivation. *Journal of Crop and Weed* **5**(1): 326-329.

Gunawardana D. 2008. Supercharging the rice engine. *Rice Today* **7**(3): 20-21.

Jayadeva HM. 2010. Bioefficacy of post emergent herbicides in weed management of transplanted rice (*Oryza sativa* L.). *Journal of Crop and Weed* **6**(2): 63-66.

Kato-Noguchi H. 2013. Momilactone plays a crucial role in rice allelopathy, pp. 60-67. In: *Proceedings 24th Asian-Pacific Weed Science Society Conference,* October 22-25, 2013, Bandung, Indonesia

Kiran YD, Subramanyam D and Sumathi V. 2010. Growth and yield of transplanted rice (*Oryza sativa*) as influenced by sequential application of herbicides. *Indian Journal of Weed Science* **42** (3 & 4): 226-228.

Kolay S. 2007. *Weed management in transplanted Kharif rice and ecophysiological studies on competition between rice and Ludwigia parviflora (Roxb.).* Ph.D. thesis. Department of ASEPAN, Institute of Agriculture, Visva-Bharati, Sriniketan.

Kumar A, Shivay YS and Pandey J. 2007. Effect of crop establishment methods and weed control practices on weed dynamics, productivity, nutrient removal by weeds vis-a-vis crop and quality of aromatic rice (*Oryza sativa* L.). *Indian Journal of Agricultural Science* **77** (3): 179-183.

Kumar V and Ladha JK. 2011. Direct-seeded rice: recent developments and future research needs. *Advances in Agronomy* **111:**297-413.

Kumar V, Bellinder RR, Brainard DC, Malik RK and Gupta RK. 2008. Risks of herbicide-resistant rice in India: A review. *Crop protection* **27**: 320-329.

Kundu S, Mukhopadhyay SK, Duary B and Mondal DC. 2003. *Spilanthes acmella* –a new weed in West Bengal, p.80. In: *Abstracts of Papers of National Seminar on Alien Invasive Weeds in India,* Assam Agriculture University, Jorhat, April 27-29, 2003.

Mahapatra IC, Rao KS, Panda BB and Shivay YS. 2012. Agronomic research on rice (*Oryza sativa* L.) in India. *Indian Journal of Agronomy* **57** (3rd IAC Special issue): 9-31.

Malik RK, Kumar V, Yadav A and McDonald, A. 2014. Conservation agriculture and weed management in south Asia: perspective and development. *Indian Journal of Weed Science* **46** (1): 31-35.

Malik S, Singh VP, Singh SP, Dhyani VC, Singh MK, Tripathi N and Kumar A. 2011. Efficacy of penoxsulam against weed complex weed flora, crop growth and yield in transplanted rice, *Pantnagar Journal of Research* **9**(1): 141-144.

Mandal MK, Duary B and De GC. 2013. Effect of crop establishment and weed management practices on weed growth and productivity of Basmati rice. *Indian Journal of Weed Science* **45**(3): 166–170.

Mishra JS, Dixit A and Varshney JG. 2007. Efficacy of penoxsulam on weeds and yield of transplanted rice (*Oryza sativa*). *Indian Journal of Weed Science* **39**(1&2): 24-27.

Mishra MM and Mishra SS. 2008. Control of algae in deep water and low land rice. pp.3-4 In: *Weed news*, AICRP on Weed Control.

Mishra SS, Mishra MM and Mishra KN. 2012. Low land weed management .*Weed news*, AICRP on Weed Control. OUAT, Bbubaneswar, Odisha, India. pp. 1-4.

Mishra SS, Mishra MM and Mishra KN.2009.Integrated weed management in upland rice under Eastern and South-Eeastern Coastal plain zone of Orissa. *Indian Journal of Weed Science* **41**(1&2): 106-108.

Mohanty S. 2013. Trends in global rice consumption. *Rice Today*: 44-45.

Mondal DC, Hossain A and Duary B. 2005. Effect of pyrazosulfuron–ethyl on weeds and yield of transplanted rice under Lateritic Belt of West Bengal. *Indian Journal of Weed Science* **37**(3&4): 263-64.

Mondal S and Duary B. 2009. Effect of tillage and weed management practices on growth and productivity of rice-wheat cropping system in the lateritic belt of West Bengal, p. 44. In: *Souvenir of National Symposium on Agriculture in the Paradigm of Intergeneration Equity,* May, 22-23, 2009, BCKV, Kalyani.

Moody K. 1993. Weed control in wet seeded rice. *Experimental Agriculture* **29**: 393-403.

Moorthy BTS and Saha S. 2005. Studies on crop weed competition in rainfed direct seeded lowland rice (*Oryza sativa* L.). *Indian Journal of Weed Science* **40**(3-4): 112-116.

Mortimer AM, Namuco O, Johnson DE. 2005. Seedling recruitment in direct-seeded rice: weed biology and water management, pp. 202-205. In: *Rice is Life: Scientific Perspectives for the 21st Century.* (Eds. Toriyama K, Heong, KL and Hardy B.). IRRI, Tokyo and Tsukuba, Japan.

Mrunalini A and Ganesh M. 2008. Work load on woman using cono weeder in SRI method of paddy cultivation. *Oryza* **45**(1): 58-61.

Mukherjee D and Singh RP. 2005. Effect of micro-herbicides on weed dynamics, yield and economics of transplanted rice (*Oryza sativa*). *Indian Journal of Agronomy* **50**(4): 292-295.

Mukhopadhyay SK and Duary B. 1999. Autecology of *Ludwigia parviflora* Roxb. – a predominant weed of *Kharif* rice in West Bengal, p.75. In: *Proceedings of the Seventeenth Asian Pacific Weed Science Society Conference,* Nov. 22-27, 1999, Bangkok.

Olofsdotter M, Navarez DC and Moody K. 1995. Allelopathic potential in rice (*Oryza sativa* L.). *Annals of Applied Biology* **127**: 543-560.

Pal D, Ghosh RK, Sounda G, Dolai AK, Pramanick M and Mallick S. 2009a. Bio efficacy of some promising herbicides in transplanted *Kharif* rice and their influence on soil microflora. *Indian Agriculturist* **53**(3&4): 193-198.

Pal S, Banerjee H and Mandal NN. 2009b. Efficacy of low dose herbicides against weeds in transplanted *Kharif* rice (*Oryza sativa* L.). *The Journal of Plant Protection Sciences* **1**(1): 31-33.

Parthipan T, Ravi V, Subramanian E and Ramesh T. 2013. Integrated weed management on growth and yield of transplanted rice and its residual effect on succeeding blackgram. *Journal of Agronomy* **12**(2): 99-103.

Prakash C, Shivran RK and Koli NR. 2013. Bioefficacy of penoxsulum against broad spectrum weed control in transplanted rice. *Advance Research Journal of Crop Improvement* **4**(1): 51-53.

Prasad SS, Mishra S and Singh SJ. 2001. Effect of establishment methods, fertility levels and weed management practices on rice (*Oryza sativa*). *Indian Journal of Agronomy* **46**(2): 216-221.

Puniya R, Pandey PC and Bisht PS. 2007a. Performance of trisulfuron, trisulfuron + pretilachlor and bensulfuron-methyl in transplanted rice (*Oryza sativa* L.). *Indian Journal of Weed Science* **39** (1&2): 120-122.

Puniya R, Pandey PC, Bisht PS and Singh DK. 2007b. Nutrient uptake by crop and weeds as influenced by trisulfuron, trisulfuron + pretilachlor and bensulfuron-methyl in transplanted rice (*Oryza sativa* L.). *Indian Journal of Weed Science* **39**(3&4): 239-240.

Rao AN and Moody K. 1992. Competition between *Echinochloa glabrescens* and rice (*Oryza sativa*). *Tropical Pest Management* **38**: 25-29.

Rao AN and Nagamani A. 2013. Eco-efficient weed management approaches for rice in tropical Asia, pp.78-87. In: *Proeedings 4th Tropical Weed Science Conference* 2013. January 23-25, 2013, Chiang Mai, Thailand.

Rao AN. 2011. Integrated weed management in rice in India, pp 1-35. In: *Rice Knowledge Management Portal (RKMP,* Directorate of Rice Research, Rajendranagr, Hyderabad.

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

Ravisankar N, Chandrsekaran B, Raja R, Din M, and Chaudhuri SG. 2008. Influence of integrated weed management practices on productivity and profitability of wet seeded rice (*Oryza sativa*). *Indian Journal of Agronomy* **53**(1): 57-61.

Remesan R, Roopesh MS, Remya N and Preman PS. 2007. Wet land paddy weeding - a comprehensive comparative study from south India. *Agricultural Engineering International* **9***: Manuscript MES 07 006,* 21 p.

Rodenburg J, Demont M. 2009. Potential of herbicide resistant rice technologies for sub-Saharan Africa. *AgBioForum* **12**: 313-325.

Saha S and Rao KS. 2009. Efficacy of sulfonyl urea herbicides for broad spectrum weed control in wet direct sown summer rice. *Oryza* **46** (2): 116-119.

Saha S and Rao KS. 2010a. Efficacy of metsulfuron-methyl for controlling broadleaf weeds in transplanted rice (*Oryza sativa*) under rainfed shallow low land. *Indian Journal of Agricultural sciences* **80** (6): 522-526.

Saha S and Rao KS. 2010b. Evaluation of bensulfuron-methyl for weed control in wet direct sown summer rice. *Oryza* **47** (1): 38-41.

Saha S and Rao KS. 2012. Efficacy of azimsulfuron against complex weed flora in transplanted summer rice. *Oryza* **49** (3): 183-188.

Saha S. 2006. Comparative study on efficacy of sulfonylurea herbicides and traditional recommended herbicides in transplanted rice. *Indian Journal of Agronomy* **51**(4): 304-306.

Saha S. 2009. Efficacy of bensulfuron-methyl for controlling sedges and non-grassy weeds in transplanted rice (*Oryza sativa*). *Indian Journal of Agricultural Sciences* **79**(4): 313-316.

Saini JP. 2003. Efficacy of pyrazosulfuron-ethyl against mixed weed flora in transplanted rice. *Pesticide Research Journal* **15**(2): 157-159.

Saini JP and Angiras NN. 2002. Evaluation of ethoxysulfuron against broad-leaved weeds and sedges in direct-seeded puddled rice. *Indian Journal of Weed Science* **34** (1&2): 36-38.

Satyamoorthy NK, Mahendran S, Babu R and Ragavan T. 2004. Effect of integrated weed management practices on total dry weight, nutrient removal of weeds in rice-rice wet-seeded system. *Journal of Agronomy* **3**(4): 263-267.

Sindhu PV, Thomas CG and Abraham CT. 2010. Seedbed manipulations for weed management in wet-seeded rice. *Indian Journal of Weed Science* **42** (3&4): 173-179.

Singh I, Ram M and Nandal DP. 2007. Efficacy of new herbicides for weed control in transplanted rice under rice-wheat system. *Indian Journal of Weed Science* **38**: 28-31.

Singh KP and Angiras NN. 2003. Ecophysiological studies of *Cyperus iria* L. in transplanted rice under mid-hill conditions of Himachal Pradesh, India. *Physiology and Molecular Biology of Plants* **9**: 283-285.

Singh KP and Angiras NN. 2008. Studies on the threshold level of *Echinochloa crusgalli* L. in transplanted rice under mid hill conditions of Himachal Pradesh. *Advances in Plant Sciences* **21**: 505-508.

Singh P, Singh P and Singh SS. 2007. Response of aromatic rice (*Pusa Basmati 1*) to establishment methods, fertility levels and weed management practices. *Indian Journal of Weed Science* **39**(1&2): 32-35.

Singh P, Singh P, Singh R and Singh KN. 2007. Efficacy of new herbicides in transplanted rice (*Oryza sativa*) under temperate conditions of Kashmir. *Indian Journal of Weed Science* **39**(3& 4): 167-171

Singh P, Singh P and Singh SS. 2008. Production potential and economic analysis of direct-wet seeded aromatic Rice (*Pusa Basmati 1*) as influenced by fertility levels and weed management practices. *Oryza* **45**(1): 23-26.

Singh PK. 2000. Biology of *Azolla* and blue green algae, pp.1-23. In: *Biofertilizer-Blue Green Algae and Azolla*. (Eds. Singh PK, Dhar DW, Pabby S, Prasanna R, Arora A). Venus Printers and Publishers, New Delhi

Singh S. 2010. Effect of seeding depth and flooding duration on the emergence of some rainy season weeds. *Indian Journal of Weed Science* **42**: 35-43.

Singh VP, Singh G and Singh M. 2004. Effect of fenoxaprop-p-ethyl on transplanted rice and associated weeds. *Indian Journal of Weed Science* **36**(3&4): 190-192.

Soren U. 2011. *Bioefficacy of Azimsulfuron and other Herbicides in Transplanted Wet Season Rice (Oryza sativa L.) under Lateritic Soil of West Bengal*. M. Sc. (Ag.) Thesis. Department of ASEPAN, Palli Siksha Bhavana (Institute of Agriculture), Visva-Bharati, Sriniketan, West Bengal.

Sridevi V, Jeyaraman S, Chinnusamy C and Chellamuthu V. 2013. Weed management in lowland rice (*Oryza sativa* L.) ecosystem- a review. *International Journal of Agricultural Science and Research* **3** (3): 13-22.

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

Subramanyam D, Reddy CR and Reddy DS. 2007. Influence of peddling density and water management practices on weed dynamics and yield of transplanted rice (*Oryza sativa* L.). *Indian Journal of Agronomy* **52**(3): 225-230.

Sudhalakshmi C, Velu V and Thiyagarajan TM. 2005. Weed management options on the dynamics of nitrogen fractions in the rhizosphere soil of rice hybrids. *Madras Agricultural Journal* **92**(7-9): 444-448.

Sunil CM, Shekara BG, Kalyanamurthy KN and Shankaralingappa BC. 2010. Growth and yield of aerobic rice as influenced by integrated weed management practices. *Indian Journal of Weed Science* **42**(3&4): 180-183.

Teja KC, Duary B and Bhowmik MK. 2015a. Efficacy of herbicides on weed management in wet season transplanted rice. *Journal of Crop and Weed,* **11**(Special Issue): 224-227.

Teja KC, Duary B, Kumar M and Bhowmick MK. 2015b. Effect of bensulfuron-methyl + pretilachlor and other herbicides on mixed weed flora of wet season transplanted rice. *International Journal of Agriculture, Environment and Biotechnology* **8**(2): 323-329.

Thiyagarajan TM, Senthilkumar K, Bindraban PS, Hengsdijk H, Ramasamy S, Velu V, Durgadevi D, Govindarajan K, Priyadarshini R, Sudhalakshmi C, Nisha PT and Gayathry C. 2002. Crop management options for increasing water productivity in rice. *Journal of Agricultural Resource Management* **1**(4): 169-181.

Vijayakumar M, Ramesh S, Prabhaharan NK, Subbian P and Chandrasekaran B. 2006. Influence of System of Rice Intensification (SRI) practices on growth characters, days to flowering, growth analysis and labour productivity of rice. *Asian Journal of Plant Sciences* **5**(6): 984-989.

Yadav DB, Singh S and Yadav A. 2008a. Evaluation of azimsulfuron and metsulfuron-methyl alone and in combination for weed control in transplanted rice. *Indian Journal of Weed Science* **40**(1&2): 16-20

Yadav DB, Yadav A and Punia SS. 2008b. Efficacy of penoxsulam against weeds in transplanted rice. *Indian Journal of Weed Science* **40** (3&4): 142-146.

Yadav DB, Yadav A and Punia SS. 2009. Evaluation of bispyribac-sodium for weed control in transplanted rice. *Indian Journal of Weed Science* **41**(1&2): 23-27.

Indian Journal of Weed Science **47**(3): 233–239, 2015

Weed management in zero-till wheat

A.P. Singh*, Makhan S. Bhullar[1], Ramawatar Yadav[1] and T. Chowdhury
Department of Agronomy, Indira Gandhi Krishi Vishwavidyalaya, Raipur, Chhattisgarh 492 012

Received: 8 July 2015; Revised: 12 August 2015

ABSTRACT

In India, wheat covers an area of 30 Mha with 3.1 t/ha productivity. Rice–wheat system has started showing the signs of fatigue. Certain reports say that the wheat yield reduces by 8% when sown after puddled transplanted rice compared to wheat sown after direct-seeded rice. The conventional method of wheat sowing by repeated tillage delays the sowing by 10 to 15 days, which adversely affect yield. To curtail problems faced by intensive tillage in rice and delayed sowing of wheat, adoption of no or reduced tillage is a viable option. The high input requirement and less competitive nature of high yielding dwarf wheat varieties have provided conducive environment for weed infestation. The average yield losses caused by weeds in different wheat growing zones ranged from 20 to 32%. Uncontrolled weeds in wheat caused 60.5% reduction in wheat grain yield under CT and 70% in ZT conditions. Potential solutions include a shift from intensive tillage to no or reduced tillage and/or from transplanting to direct-seeding. Zero tillage ameliorates the problem of delayed sowing as well as reduces weeds like *Phalaris minor* in wheat. A shift from an intensive tillage to reduced/no tillage system cause major changes in weed dynamics, herbicide efficacy and weed seed recruitment. Therefore, an attempt has been made in this article to review works done on several aspects of weed management in zero-till wheat.

Key words: Conventional tillage, Weed management, Wheat, Zero tillage

Wheat is the king of the cereals and provides more nourishment (rich in carbohydrates). In India, wheat production has increased from 11.0 million Mt during 1960-61 to 93.9 million Mt during 2011-12. It covers an area of 30 Mha with an average yield of 3117 kg/ha (Anonymous 2012-13). This more than eight-fold increase in wheat production was mainly due to the adoption of short stature high yielding varieties, increased fertilizers, irrigation and herbicides use. The high nutrient and water requirements along with less competitive nature of these high yielding dwarf varieties have provided the conducive environment for increased weed infestation which poses challenge for successful wheat cultivation in India. The area under wheat has stabilized, and further expansion seems to be unlikely.

Growth in cereals yield has reached to a plateaue in many high-potential agricultural areas, owing to soil nutrient mining, declining organic matter, increasing salinity, falling water tables and the build-up of weed, pathogen and pest populations. The share of wheat output from high-income countries has fallen from about 45% in the early 1950s to about 35% in recent years. The challenge, therefore, is to further increase productivity while making agriculture more efficient, ecologically sound and sustainable. The farmers could produce more and help conserve their natural resource base by adopting conservation tillage practices (FAO 2001). Conventional tillage with tractors and ploughs is a major cause of severe soil loss in many developing countries. Infact soils in tropical countries are not required to be tilled. The most desirable form of tillage is to leave a protective blanket of surface residues.

Rice–wheat system is the dominant cropping system occupying about 18 Mha in Asia, of which 13.5 Mha area in Indo-Gangetic Plains (IGP) of India (10 Mha), Pakistan (2.2 Mha), Bangladesh (0.8 Mha) and Nepal (0.5 Mha) and feeds about 1.3 billion people (20% of the world population) (Farooq *et al.* 2007, Saharawat *et al.* 2010). Exhaustive nature of both the crops belonging to the same family and extreme tillage requirements particularly of rice has made the system unviable due to the development of hard pan, multi-nutritional deficiencies and destruction of soil structure. It has been reported that on average wheat yield is reduced by 8% when sown after puddled transplanted rice compared to wheat sown after direct-seeded rice in unpuddled conditions (Kumar *et al.* 2008). Now the system has started showing the signs of fatigue. Due to the long duration

***Corresponding author:** *apsinghagron@gmail.com*
[1]Department of Agronomy, Punjab Agricultural University, Ludhiana

rice varieties that decreases the turn-around period and poor rice-stubble management, unavailability of appropriate farm tools and machinery, the sowing of wheat gets delayed. The reduction in grain yield due to delay in wheat sowing has been recorded as 35–60 kg/day/ha in the IGP (Pathak *et al.* 2003). In no-till systems, seeds of weeds and volunteer crops are frequently deposited on the topsoil. Therefore, in no-till and reduced tillage systems, pre-sowing herbicides are a requisite.

Zero tillage in wheat

Reduced and zero tillage systems can overcome low wheat yields by timely sowing. The late harvesting of the preceding rice/cotton crop, often delays the planting of wheat which is the first fortnight of November. "With animal-drawn ploughs, farmers make 6-10 passes over the land to prepare a seedbed for wheat," says a recent report of the rice-wheat consortium for the Indo-Gangetic Plains, a joint program involving Bangladesh, India, Nepal, and Pakistan, and International Agricultural Research Centers. "the tractors prepare land more rapidly for wheat after rice, yet, 6-8 passes of the ploughing implement are common. Substituting mouldboard plough by other tillage equipments can, under some conditions, avoid an increase in weed pressure, as observed by Bàrberi and Cascio (2001), with regard to rotary harrow (reduced tillage). Soil tillage for preparation of autumn-winter cereal seedbed can improve the conditions for germination of weeds (Mirsky *et al.* 2010, Morris *et al.* 2010), which will increase the population density of the weeds in the crop (Bräutigam and Tebrügge 1997). With regard to no-till systems, which are characterized by depositing seeds on topsoil (Morris *et al.* 2010), it is necessary to follow an appropriate procedure, to avoid high weed densities and prevent unacceptable problems (Brainard *et al.* 2013). For the adoption of conservation agriculture systems and their wide spread uptake, weed flora and its dynamics must be understood (Brainard *et al.* 2013).

Sowing of wheat in North India is generally delayed due to cultivation of long and medium duration rice varieties and time required in field preparation of wheat. Tripathi *et al.* (2005) estimated that each one day delay of wheat planting past the optimal date results in a yield loss of 26.8 kg/ha/day. Zero tillage technique not only ameliorates the problem of delayed sowing but also reduces the incidence of most problematic weeds like *Phalaris minor* in wheat. Potential solutions include a shift from intensive tillage to no or reduced tillage and/or from transplanting to direct-seeding. Due to combine harvest of rice, large quantities of crop residues are left on soil surface and poses problem in tillage operations resulting delayed sowing of succeeding wheat crop. Recent estimates indicated that average area under zero-till wheat in India is 7.60 Mha and maximum area under zero-till is recorded in Punjab state (46.6%).

Weed flora and density

Weed flora of wheat differ from field to field, depending on environmental conditions, irrigation, fertilizer use, soil type, weed control practices and cropping sequences. The predominant weeds associated with conventional till wheat are *Phalaris minor*, *Poa annua, Polypogon monspeliensis, Avena ludoviciana, Rumex dentatus, R. spinosus, Anagallis arvensis, Convolvulus arvensis, Malva parviflora, Medicago denticulata, Chenopodium album, Vicia sativa, Lathyrus aphaca, Circium arvense, Melilotus alba, Coronopus didymus, Polygonum plebejum* and *Spergula arvensis*. Among grassy weeds, *P. minor* and among broad-leaved weeds, *Rumex dentatus* and *Medicago denticulata* are of major concern in irrigated wheat under rice-wheat system in India (Balyan and Malik 2000, Chhokar *et al.* 2006). *Phalaris minor* is major problem in heavy soils, whereas, wild oat is more prevalent in light textured soil under non rice-wheat rotation. Both *P. minor* and *R. dentatus* are highly competitive weeds and can cause drastic yield reduction under heavy infestation. Evolution of resistance in *P. minor* (Malik and Singh 1993, Chhokar and Malik 2002, Chhokar and Sharma 2008) against isoproturon has made it a single weed species limiting wheat productivity in the North-Western plains of India.

With the shift from CT to ZT, soil disturbance is reduced drastically and soil surface is often covered with previous crop residues. Tillage can influence the vertical weed seed distribution in the soil profile, soil moisture, diurnal temperature fluctuations, light availability, and activities of seed predators and microbes. All these factors can affect weed recruitment in the field by influencing seed dormancy, emergence, and seed mortality. Reduced tillage favoured the growth of *Cirsium arvense* and *Convolvulus arvensis* (Catizone *et al.* 1990). ZT wheat lowers the *P. minor* infestation, which is the main threat to the sustainability of wheat production under rice-wheat system (Franke *et al.* 2007). The less *P. minor* problem under ZT system was due to less soil disturbance as a result *P. minor* seeds present in lower soil layer fail to germinate due to mechanical impedance. Yadav and Singh (2005) observed that maximum *P. minor* population emerged from 0-3 cm soil depth. In both CT and ZT wheat, after direct-seeded unpuddled and puddled rice, there was no emergence of *P. minor* from 6-9 cm depth but still 5% population could emerge from this layer after transplanted rice. Under CT wheat, there was 16% increase in *P. minor* density during 15 to 20 days after sowing in the field before irrigation, but after first irrigation the density of this weed increased by 175% during 20 to 40 days after sowing. In ZT wheat, the density of this weeds increased by 61% before irrigation and after irrigation this increase was only 102%.

Radhey Shyam *et al.* (2009) reported that wheat sown with CT led to significantly higher density of *P. minor, M. indica, M. denticulata* and *C. album* as compared to ZT sown crop. Contrary to this, weed seeds remained in sub-surface under zero till sown crop due to puddling carried out during paddy transplanting and failed to germinate because of unfavorable conditions (Sinha and Singh 2005). ZT wheat helps to control weeds like *P. minor* (Franke *et al.* 2007), *C. album* (Mishra *et al.* 2010), *A. ludoviciana* (Yaduraju and Mishra 2002), *R. dentatus* (Chhokar *et al.* 2007). Singh *et al.* (2004), also reported that the minimum weed population was recorded in ZT sown crop which was significantly less than CT sown wheat. Rahman and Mukherjee (2006), while studying the effect of different tillage practices and herbicides observed that CT+ pendimethalin have more weed control efficiency and higher grain yield than zero tillage with application of different herbicides.

The shift from CT to ZT in wheat has resulted in a shift in weed flora. Main reason for change of weed flora seems to be the use of herbicides for control of grassy weeds and non adoption of any measure to control broad-leaved weeds in wheat over the time. This increases population of perennial and broad-leaved weeds in the zero-tillage system. Also control of *P. minor* reduces competition for other weeds. Singh *et al.* (2002) found in a long term experiment at Karnal (Haryana) that the intensity of *P. minor* decreased by 30-40% in ZT when compared to CT wheat, while the intensity of broad-leaved weeds increased. Laxmi *et al.* (2003), reported that 51% of farmers in Haryana and 85% of farmers in Bihar perceived that weed infestation had decreased due to adoption of ZT in wheat. Unchecked weed growth during crop season caused maximum yield loss in conventional tillage. In Pantnagar, average of 10 year data revealed that there was less intensity of weeds specially *P. minor, Melilotus* spp. and *Polygonum* spp. in ZT wheat as compared to wheat sown by conventional practice at 30 DAS, resulting less infestation of weeds and less competition with crop. The grain yield obtained was also higher in zero tillage wheat over the conventional practice. Mishra and Singh (2012) in Jabalpur found that wild oats showed a strong propensity to increase under all the tillage systems (ZT and CT in rice and wheat continuous and alternated) indicating its ability to persist under modern cropping systems. But in subsequent years, continuous zero tillage lowered its population. *Chenopodium album* seedling emergence declined significantly due to ZT wheat sowing during first year; in subsequent years, population of *C. album* was completely eliminated due the increased density of *A. ludoviciana* and *M. hispida* in all the tillage systems. Brar and Walia (2009) conducted a field survey in the three districts of Punjab *i.e.* Patiala, Sangurur and Moga and found slightly higher population of broad-leaved weeds in zero tillage as compared to the conventional methods while adverse trend was seen in case of grass weeds.

Wheat yield losses

Spectrum of weed flora in wheat has changed from dominance of broad-leaved weeds in the 1960s to mixed flora of broad-leaved and grassy weeds in early 1970s; and then the dominance of grass weeds, especially, *Phalaris minor* in late 1970s. The chemical weed control, therefore, became a necessity in late 1970s. Weeds have enjoyed dominance over crop basically because of poor agronomic management. To introduce good agronomic practices and the ecology, it is important to understand the competition between weeds and the wheat crop. Weed-crop competition begins when crop plants and weeds grow in close proximity and their root or shoot system overlaps. In rice-wheat system, due to enough soil moisture after harvesting of rice, weeds emerge earlier than wheat or along with wheat crop. Losses in wheat yield are primarily due to reduction in tillering. The average yield losses caused by weeds in different wheat growing zones ranges from 20 to 32%. The wheat yield losses due to weeds in North Western Plains Zone (NWPZ) Northern Hills Zone (NHZ) and North Eastern Plains Zone (NEPZ), are higher compared to Peninsular Zone (PZ) and Central Zone (CZ) (Mongia *et al.* 2005). The losses depend on weed species and density, time of emergence, wheat cultivar, planting density, soil and environmental factors (Chhokar and Malik 2002, Malik and Singh 1993, Malik and Singh 1995). Yield reductions due to weeds in wheat vary from 15-50%, depending upon the weed density and type of weed flora (Jat *et al.* 2003). Uncontrolled weeds in wheat caused 60.5% reduction in wheat grain yield under conventional tillage (CT) and 70% in zero-till (ZT) conditions. In extreme cases the losses caused by weeds can be up to complete crop failure (Malik and Singh 1995). The cases of complete crop failure were quite common during late seventies in the absence of effective herbicides and mid nineties due to heavy population of *P. minor,* after the evolution of resistance against isoproturon. Under both the situations, some of the farmers were forced to harvest their immature wheat crops as fodder (Malik and Singh 1993, Chhokar and Malik 2002). The critical period of weed control in wheat is 30-45 days after sowing and crop should be kept weed free during this period. Zero tillage or surface seeding technology is gaining popularity in wheat cultivation, as it not only reduces the incidence of weeds like *Phalaris minor* and *Chenopodium album,* but also improves the input-use efficiency (Mishra *et al.* 2005), improves soil condition due to in-situ decomposition of crop residues, increase in infiltration rate, reduced cost of seed bed preparation and timely sowing of wheat in rice-wheat system. No-till cropping system leaves most of weed seeds in top 1.0 cm of the soil profile (Chahal *et al.* 2003).

Herbicide management

Herbicide use has increased in both CT and ZT systems because it provides effective and economical weed control and saves labor, which has become more scarce and expensive (Rao *et al.* 2007). Hence, it is of paramount importance to work out weed management technology in zero tilled wheat. Mukhopadhyay and Rooj (1971) were the first to conduct the work on zero tillage in West Bengal (India) by using the non selective herbicide paraquat and reported that in zero tillage 3.75 l/ha of paraquat application produced more rice yield as compared to conventional tillage supplemented with one hand weeding (HW). Wheat crop grown as succeeding crop in same field also obtained more grain yield in zero tillage as compared to conventional tillage. Walia *et al.* (2005) reported that wheat sown with zero till after spray of paraquat exhibited significantly less dry matter of *P. minor* as compared to zero till sown wheat without paraquat application as well as conventional tillage sown crop. Hence, it was realized that chemical weeding with application of non selective herbicide would be a key factor for management of weeds and success of zero tillage in wheat.

The studies conducted in Punjab indicated that in areas where *P. minor* has not evolved resistance to isoporturon, its application at 600-1000 g/ha, depending on soil type, before or after first irrigation provided effective control of *P. minor, A. ludoviciana* and *Poa annua*, and many broad-leaved weeds in ZT wheat. In areas, where *P. minor* has evolved resistance to isoproturon, application of pinoxaden 50 g, sulfosulfuron 25 g, clodinafop 60 g, fenoxaprop 100 g/ha at 30-35 DAS of wheat provided effective control of *P. minor* and *A. ludoviciana* in ZT wheat. In case of broad-leaved weeds like *C. album, Anagallis arvensis, Medicago denticulata, Coronopus didymus, R. dentatus etc*., 2,4-D sodium salt or 2,4-D ethyl ester at 400-500 g/ha at 35-45 DAS when wheat is sown at normal time and at 45-55 DAS in late sown crop (December) are effective.

Metsulfuron 5 g/ha at 30-35 DAS provides effective control of *R. spinosus* along with other broad-leaved weeds, as 2,4-D do not control this weed. Carfentrazone-ethyl at 20 g/ha at 20-25 DAS provides effective control of all other broad-leaved weeds including *Malva parviflora* and *R. spinosus*. In fields where both grass and broad-leaved weeds are present, one post-emergence application of sulfosulfuron + metsulfuron at 30 g, mesosulfuron + iodosulfuron at 15 g, fenoxaprop + metribuzin at 500 g or tank-mixture of clodinafop 60 g + 2,4-D 400 g/ha, metsulfuron 5 g/ha at 30- 35 DAS is effective. In fields, where rapeseed and mustard crop is sown with wheat, use of only clodinafop and fenoxaprop is advisable. Do not use sulfosulfuron, sulfosulfuron + metsuflruon, mesosulfuron + iodosulfuron herbicides in wheat fields in which sorghum (jowar), maize or bajra is to be sown after wheat. Do not use the same herbicide year after year as it leads to the evolution of resistance in weeds. Herbicide rotation should be followed every year to prevent the evolution of resistance and for getting the best efficacy from the herbicides.

Crop residue management

The majority of farmers in rice-wheat systems, especially in North-Western IGP, burn residues of previous rice crop for its rapid disposal before wheat sowing because it can interfere with drilling. Such burning of rice straw increases the germination of *P. minor* and reduces the efficacy of soil-active herbicides like isoproturon and pendimethalin (Chhokar *et al.* 2009). Recent advances in planting technology have made it possible to sow wheat successfully into heavy residues and facilitated the use of residues as mulches for weed suppression. In particular, the rotary disc drill and turbo/happy seeder can sow/place the wheat seed in heavy residue mulch of up to 8 to 10 t/ha without any adverse effect on crop establishment (Kumar and Ladha 2011, Sharma *et al*. 2008). In addition to the suppressive effects on emergence of weeds, residues can contribute to weed seed bank depletion through seed predation. When rice residues are kept on soil surface as mulch, emergence of *P. minor, Chenopodium album*, and *R. dentatus* was inhibited by 45,83 and 88%, respectively at 6 t/ha rice residue load compared to without residue mulch (Kumar *et al*. 2013). With 8-10 t/ha of rice residue mulch, *P. minor* emergence was inhibited by 65% and that of *C. album* and *R. dentatus* by >90%. ZT also facilitates timely wheat planting which further create ecological conditions in favour of crop than *P. minor*. When ZT in wheat is combined with residue mulch (6-8 t/ha) and early planting (25 October), the emergence of *P. minor* was reduced by 83-98% compared with normal (mid November) or delayed (25 November) planting without residue. Chhokar *et al*. (2009) observed that 2.5 t/ha rice residue mulch was not effective in suppressing weeds, but 5.0 and 7.5 t/ha residue mulch reduced weed biomass by 26-46%, 17-55%, 22-43%, and 26-40% of *P. minor, Rumex dentatus, Meliloyus indica* and *Polypogon monspeliensis*, respectively compared with ZT without residue.

Herbicide resistance management

Herbicide resistance in *P. minor* against isoproturon was the most serious problem in wheat in rice-wheat cropping system (RWCS) during early 1990s. Efforts on herbicide resistance management before 1996-97 were concentrated around alternate crops (Malik *et al*. 2002). The problem of resistance was so serious that farmers in Haryana started sowing sunflower and in Punjab the farmers started growing mustard, sugarcane, egyptian clover (fodder) to exhaust the seed bank of *P. minor*. Crop rotation was possible only in small area and farmers needed a viable technology for herbicide resistance management. Zero-tillage made it possible to achieve three major objectives leading to create competition in favour of crop. These are optimum plant population, seeding at a time which is not conducive to *P. minor* emergence and accurate fertilizer placement. In a study conducted by Franke *et al*. (2007) at farmer's field in Haryana, correlating the number of germinable *P. minor* seeds in soil with the number of *P. minor* seedling emerged, it was found that ZT reduced the emergence rate of first flush of *P. minor* by 50%. Rate of emergence of second and third flush was also lower in ZT plots compared to CT plots. The first flush of *P. minor* is more damaging to the crops compared to later flushes and ZT is found relatively more effective in reducing first flush than other flushes.

The continuous use of alternate herbicides having similar mode of action, for many years, have resulted in reduced efficacy of a particular group of herbicides at farmers fields in Punjab and Haryana. This has happened with respect to the control of *P. minor* with the use of clodinafop and fenoxaprop and in some areas also with suflosulfuron group of herbicides. Recently, *Rumex dentatus* have evolved resistance to metsulfuron-methyl (Chhokar *et al*. 2013) and the problem of *Rumex dentatus* and *Malva parviflora* in wheat is increasing under no-till situations. In future, the menace of these weeds may increase due to increase in area under no till conditions and resistance evolution. This indicates that the farmers need to rotate herbicide mode of action every year.

The adoption of non-chemical approaches like early sowing of wheat from last week of November to first week of November reduces/minimizes the infestation of *P. Minor*. Its infestation can also be reduced by rotating wheat with other crops like berseem, potato, raya, gobhi sarson and winter maize. Sowing wheat in narrow rows (15 cm spacing) and selection of quick growing wheat varieties like '*WH 502*' , '*WH 542*' and '*HD 2967*' and '*PBW 621*' and '*HR 1105*' suppresses the growth and development of *P. minor*. The adoption of these non-chemical approaches and herbicides will delay the evolution of resistance in weeds.

This paper concludes that conventional tillage system can be replaced by more economical reduced tillage options with proper recommended weed management strategies, however, some long term research is needed to determine medium-term positive or negative effects of reduced tillage on sustaining wheat yields.

REFERENCES

Anonymous. 2013. *Agricultural Statistics at a Glance*. Directorate of Economics and Statistics, Department of Agriculture and Coperation.

Balyan RS and Malik RK. 2000. New herbicides for jungali palak (*Rumex retroflexus* L.). *Indian Journal of Weed Science* **32**: 86-88.

Bàrberi P, and Lo Cascio B. 2001. Long-term tillage and crop rotation effects on weed seed bank size and composition. *Weed Research* **41**: 325-340.

Brainard DC, Haramoto E, Williams II and MM Mirsky S. 2013. Towards a no-till no-spray future? Introduction to a symposium on non-chemical weed management for reduced tillage cropping systems. *Weed Technology* **27**(1): 190-192.

Brar AS and Walia US. 2009. Weed dynamics and wheat (*Triticum aestivum* L.) productivity as influenced by planting techniques and weed control practices. *Indian Journal of Weed Science* **41**: 161-166.

Bräutigam V and Tebrügge F. 1997. Influence of long-termed no-tillage on soil borne pathogens and weeds, pp 17-29. In: *Experience with the Applicability of No-tillage Crop Production in the West-European Countries* (Eds. Tebrügge F and Böhrnsen A). Proceedings of the EC-Workshoop - III -Évora.

Catizone P, Tedeschi M. and Baldoni G. 1990. Influence of crop management on weed population and wheat yield. *Proceeding of EWRS Symposium*, Helsinki, Finland, 4-6 June 1990.

Chahal PS, Brar HS and Walia US. 2003. Management of *Phalaris minor* in wheat through integrated approach. *Indian Journal of Weed Science* **35**(1&2): 1-5.

Chhokar RS and Malik RK. 2002. Isoproturon resistant *Phalaris minor* and its response to alternate herbicides. *Weed Technology* **16**: 116-123.

Chhokar RS and Sharma RK. 2008. Multiple herbicide resistance in littleseed canarygrass (*Phalaris minor*): A threat to wheat production in India. *Weed Biology and Management* **8**: 112-123.

Chhokar RS, Sharma RK, Chauhan DS and Mongia AD. 2006. Evaluation of herbicides against *Phalaris minor* in wheat in North-Western Indian plains. *Weed Research* **46**: 40-49.

Chhokar RS, Sharma RK, Garg R and Sharma Indu. 2013. Metsulfuron resistance in *Rumex dentatus*. *Wheat Barley Newsletter* **7**(2): 11.

Chhokar RS, Sharma RK, Jat GR, Pundir AK, Gathala MK. 2007. Effect of tillage and herbicides on weeds and productivity of wheat under rice–wheat growing system. *Crop Protection* **26**: 1689–1696.

Chhokar RS, Singh S, Sharma RK and Singh M. 2009. Influence of straw management on *Phalaris minor* control. *Indian Journal of Weed Science* **41**: 150–156.

FAO. 2001. *Spotlight Magazine.* FAO.

Farooq U, Sharif M and Erenstein O. 2007. *Adoption and Impacts of Zero Tillage in the Rice–Wheat Zone of Irrigated Punjab, Pakistan.* Research Report. CIMMYT India & RWC, New Delhi, India.

Franke AC, Singh S, Mcroberts N, Nehra AS, Godara S, Malik RK and Marshall G. 2007. *Phalaris minor* seed bank studies: Longevity, seedling emergence and seed production as affected by tillage regime. *Weed Research* **47**: 73-83.

Jat RS, Nepalia V and Chaudhary PD. 2003. Influence of herbicide and methods of sowing on weed dynamics in wheat (*Triticum aestivum*). *Indian Journal of Weed Science* **35**(1&2): 18–20.

Kumar V and Ladha JK. 2011. Direct-seeding of rice: Recent developments and future research needs. *Advances in Agronomy* **111**: 297–413.

Kumar V, Bellinder RR, Gupta RK, Malik RK and Brainard DC. 2008. Role of herbicide-resistant rice in promoting resource conservation technologies in rice–wheat cropping systems of India: A review. *Crop Prot*ection **27:** 290–301.

Kumar V, Singh S, Chhokar RS, Malik RK, Brainard DC and Ladha JK. 2013. Weed management strategies to reduce herbicide use in zero-till rice-wheat cropping systems of the Indo-Gangetic Plains. *Weed Technology* **27**: 241-254.

Laxmi V, Gupta RK, Swarnalatha A and Perwaz S. 2003. Environmental impact of improved technology - farm level survey and farmers' perception on zero tillage (case study). *Proceedings of Roles of Agriculture Workshop*, 20–22 October, 2003 - Rome, Italy. Indira Gandhi Institute of Development Research, Mumbai.

Malik RK and Singh S. 1993. Evolving strategies for herbicide use in wheat. Resistance and integrated weed management, pp. 225-238. In: *Integrated Weed Mmanagement for Sustainable Agriculture.* Proceedings of Indian Society of Weed Science International Symposium, 18-20 November, 1993, Hisar. India Vol. **1.**

Malik RK and Singh S. 1995. Littleseed canarygrass (*Phalaris minor* Retz.) resistance to isoproturon in India. *Weed Technology* **9**: 419-425.

Malik RK, Yadav A, Singh S, Malik RS, Balyan RS, Banga RS, Sardana PK, Jaipal S, Hobbs PR, Gill G, Singh S, Gupta RK and Bellinder R. 2002. *Herbicide Resistance Management and Evolution of Zero-tillage - A Success Story.* Research Bulletin, CCS Haryana Agricultural University, Hisar, India, 43 p.

Mirsky, SB, Gallandt ER, Mortensen DA, Curran WS and Shumway, DL.2010. Reducing the germinable weed seedbank with soil disturbance and cover crops. *Weed Research* **50**(4): 341–352.

Mishra JS, Singh VP and Yaduraju NT. 2005. Effect of tillage practices and herbicides on weed dynamics and yield of wheat under transplanted rice-wheat system in Vertisol, *Indian Journal of Agronomy* **50**(2): 106-109.

Mishra JS and Singh VP. 2012. Tillage and weed control effects on productivity of a dry-seeded rice–wheat system on a Vertisol in Central India. *Soil and Tillage Research* **123**: 11–20.

Mishra JS, Singh VP and Jain Namrata. 2010. Long-term effect of tillage and weed control on weed dynamics, soil properties and yield of wheat in rice–wheat system. *Indian Journal of Weed Science* **42**: 9-13.

Mongia AD, Sharma RK, Kharub AS, Tripathi SC, Chhokar RS and Jag Shoran. 2005. Coordinated research on wheat production technology in India. Karnal, India: *Research Bulletin No. 20,* Directorate of Wheat Research, 40 p.

Morris NL, Miller PCH, Orson JH and Froud-Williams RJ. 2010. The adoption of non-inversion tillage systems in the United Kingdom and the agronomic impact on soil, crops and the environment: A review. *Soil and Tillage Research* **110**(1-2): 1-15.

Mukhopadhyay SK and Rooj SK. 1971. Minimal cultivation of rice by use of gramoxone. *Indian Journal of Agronomy* **16**(3): 79-81.

Pathak H, Ladha JK, Aggarwal PK, Peng S, Das S, Singh Y, Singh B, Kamra SK, Mishra B, Sastri ASRAS, Aggarwal HP, Das DK and Gupta RK. 2003. Trends of climatic potential and on-farm yields of rice and wheat in the Indo-Gangetic Plains. *Field Crops Res*earch **80**: 223–234.

Radheyshyam, Singh R, Singh VK and Guru SK. 2009. Effect of wheat establishment methods and weed management practices on weed dynamics and productivity of wheat grown in succession to rice. *Indian Journal of Weed Science* **41**(1&2): 70-72.

Rahman S and Mukherjee PK. 2006. Effect of zero tillage, conventional tillage and their interaction with herbicides on weed control in wheat under tarai agro ecological region of West Bengal. *Proceeding of the National Symposium on Conservation Agriculture and Environment*, October 26-28, 2006.

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

Saharawat YS, Singh B, Malik RK, Ladha JK, Gathala M, Jat ML Kumar V. 2010. Evaluation of alternative tillage and crop establishment methods in a rice–wheat rotation in North-Western IGP. *Field Crops Research* **116:** 260–267.

Sharma RK, Chhokar RS, Jat ML, Singh Samar, Mishra B and Gupta RK. 2008. Direct-drilling of wheat into rice residues: Experiences in Haryana and Western Uttar Pradesh, pp. 147–158.In: *Permanent Beds and Rice-Residue Management for Rice–Wheat Systems in the Indo-Gangetic Plain*.(Eds. Humphreys E and Roth CH). Canbera, Australia: Australian Centre for International Agricultural Research (ACIAR) Proceedings No. 127. www. aciar.gov.au/publication/PR127.

Singh S, Yadav A, Malik RK and Singh H. 2002. Long-term effect of zero tillage sowing technique on weed flora and productivity of wheat in rice-wheat cropping zones of Indo-Gangetic plains, pp.155-157. In: *Herbicide Resistance Management and Zero Tillage in Rice -Wheat Cropping System.* (Eds. Malik RK, Balyan RS, Y adav Aand Pahwa SK) CCSHAU, Haryana, India.

Singh S, Singh G and Singh VP. 2004. Weed dynamics in wheat as affected by rice and wheat establishment methods. *Indian Journal of Weed Science* **36**(3&4): 193-198.

Sinha AK and Singh RP. 2005. Influence of cultivars under different tillage and weed management in wheat. *Indian Journal of Weed Science* **37**(3&4): 175-179.

Tripathi SC, Mongia AD, Sharma RK, Kharub AS, and Chhokar RS. 2005. Wheat productivity at different sowing time in various agro-climatic zones of India. *SAARC Journal of Agriculture* **3**:191–201.

Walia US, Singh Manpreet and Brar LS. 2005. Weed control efficacy of herbicides in zero-till wheat. *Indian Journal of Weed Science* **37**(3&4): 167-170.

Yadav SK and Singh G. 2005. Studies on the depth and periodicity of *Phalaris minor* emergence in wheat under different crop establishment methods. *Indian Journal of Weed Science* **37**(1&2): 29-32.

Yaduraju NT and Mishra JS. 2002. Zero-Tillage in rice–wheat cropping system on vertisols in Madhya Pradesh: Prospects and problems, pp.117–119. In: *Herbicide Resistance Management and Zero Tillage in Rice-Wheat Cropping System.* (Eds. Malik RK, Balyan RS, Yadav A and Pahwa SK). CCSHAUH, Haryana, India.

Indian Journal of Weed Science **47**(3): 240–245, 2015

Weed management in zero till-maize

M. Yakadri, P. Leela Rani*, T. Ram Prakash, M. Madhavi and N. Mahesh
College of Agriculture, Rajendra Nagar, Hyderabad, Telangana 500 030

Received: 14 August 2015; Revised: 2 September 2015

ABSTRACT

Rainy season maize contributes 85% of the total maize area in India. Among major *Rabi* maize growing States, earlier Andhra Pradesh contributed maximum with 45.5% share. The present review reveals that *Echinochloa colona* L. is the most dominant weed species with importance value index (IVI) of 37.64 followed by *Panicum repens* L. (32.29), *Trianthema portulacastrum* L. (16.33) and *Digera arvensis* L Forsk (13.37). Wider spacing and initial slow growth of maize during the first 3-4 weeks provides enough opportunity for weeds to invade and offer severe competition, resulting in 30-93% yield losses. Among weed management practices, hand weeding twice at 15-21 DAS and 30-42 DAS, and integrated weed management like pre-emergence application of atrazine 1.5 kg/ha, pendimethalin 1.50 kg/ha, atrazine + alachlor 0.75 + 1.25 kg/ha, or alachlor 1.5 kg/ha followed by hand weeding at 30 DAS was found effective. Among sequential applications, atrazine as pre-emergence 1.25 kg/ha, or pendimethalin as pre-emergence 1.5 kg/ha followed by paraquat 0.6 kg/ha at 3 weeks after sowing or atrazine 1.0 kg/ha as pre-emergence followed by topramazone 0.030 kg/ha at 30 DAS were found economical with higher gross returns, net returns and B:C.

Key words: Maize, Weed management, Zero tillage

Maize (*Zea mays* L.) is the third most important cereal after rice and wheat, which is widely grown in the world and used as primary staple food in many developing countries. The world area under maize cultivation was 177 Mha with 967 Mt production in 2013-14. It contributes almost 9% to India's food basket and 5% to world's dietary energy supply. Because of its wider adaptability and high yield potential, it suits best in many cropping systems. Maize is predominantly a rainy season (*Kharif*) crop that constitutes 85% of total maize area in the country. The area under maize cultivation is 9.43 Mha in 2013-14 with productivity, 2.58 t/ha (Director's Review 2015). Maize production in India has grown annually by 5.5% over the last 10 years from 14 mt in 2004-05 to 24.35 MT in 2013-14. In India, the current consumption pattern of maize as poultry-pig-fish feed, human diet, cattle feed, and seed and brewery industry is 52, 24, 11 and 1%, respectively. The renowned Nobel Laureate, Dr. Norman E. Borlaug believed that "The last two decades saw the revolution in rice and wheat, the next few decades will be known for maize era". The demand for maize in Asia is expected to grow in the next 20 years, due to the growth of the livestock and poultry feed industry and Asian consumers shifting towards animal-based diets. The rapid expansion of the biofuel industry in recent years and high fossils energy costs also influence global maize demand and supply. The increasing demand for maize is rapidly transforming cropping systems in certain parts of Asia. Significant shifts from rice monoculture to more profitable rice-maize systems have either occurred or are emerging (IRRI and CIMMYT 2006).

***Corresponding author:** leelagro@gmail.com

History of zero tillage

Zero tillage technology was first reported in USA in 1930s and from there spread to many countries of Europe, Australia, Canada, Asia and Africa. In India, research on zero tillage (ZT) for wheat started almost three decades ago (Ekboir 2002). Several State Agricultural Universities tried ZT in the 1970s but their efforts failed due to technical difficulties such as the lack of adequate planting equipment and the difficulty in controlling the weeds chemically. In 1990, Centro Internacional de Mejoramiento de Maiz y Trigo [International Maize and Wheat Improvement Center] (CIMMYT) introduced inverted-T openers and in 1991, a first prototype of the Indian ZT seed drill was developed at GB Pant University of Agriculture and Technology, Pantnagar. After considerable investment of resources and several design changes, the first ZT seed drill was made available for field testing within 12 months. Rice-

Wheat Consortium (RWC) for the Indo-Gangetic Plains and CIMMYT contributed significantly for the widespread adoption of zero tillage at the turn of this century. Zero tillage technology has turned into a great success story and seems to be one of the best technologies after Green Revolution (Singh *et al*. 2010)

Heralding *Rabi* (winter) maize revolution in India

In India, maize is grown during *Kharif* season (June to October) when both drought and water logging occurs, which results in lower production. In order to enhance the production of this crop a collaborative project to introduce maize hybrids in India was taken up with Dr. L.M Humphrey, Agriculture Advisor to the Technical Cooperation Mission of USA. Double cross hybrids, *'Texas 26'*, '*Texas 32*' and '*Dixie 11*' introduced under this project from USA in year 1959, were grown on experimental basis in Bihar state during *Kharif* season. These hybrids could not yield up to the expectation due to heavy rainfall during the crop period which is a usual phenomenon of *Kharif* season. In order to protect the crop from heavy rainfall, maize inbred, single cross hybrids and double cross hybrids were grown in *Rabi* season first time on farmers fields in Bihar in the year 1961.

The results were quite encouraging as the crop was free from incidence of insects, pests and diseases in addition to higher yield as compared to *Kharif* maize. This opened up new vista of *Rabi* maize in the country. Keeping in view the opportunities in *Rabi* season, multi-pronged strategies were adopted such as hybrid seed production along with farmer's field demonstrations resulted in heralding maize revolution in Bihar.

The *Rabi* maize in Bihar state occupied 0.49 Mha area out of a total area of 0.75 Mha during 2013-14. This indicates the acceptance of *Rabi* maize technology by farmers of this state. Later it caught the attention of other states like Andhra Pradesh, West Bengal, Uttar Pradesh, Madhya Pradesh, Tamil Nadu, Karnataka, Punjab, *etc*., where it is now being grown successfully (Singh *et al* . 2012).

In India *Rabi* maize is grown on an area of 1.7 Mha with the grain production of 6.67 Mt, and average productivity of 3.93 t/ha (Director's Review 2015). The predominant *Rabi* maize growing states are Andhra Pradesh (45.5%), Bihar (20.1%), Tamil Nadu (9.3%), Karnataka (8.5%), Maharastra (7.7%) and West Bengal (5.3%).

In Andhra Pradesh, *Rabi* maize is grown on an area of 0.44 Mha with production of 2.79 MT, having an average productivity of 6.35 t/ha (Director's Review 2015). The trends in area, production and productivity of maize in *Rabi* season in Andhra Pradesh has shown a remarkable increase with the passing years. Maize occupies more acreage under non-traditional season as well as non-traditional areas of the State, indicating that it is emerging as one of the potential driver for crop diversification. The major cropping systems in Andhra Pradesh are rice-based rotations followed by sorghum, groundnut, cotton, sugarcane and maize systems. Maize systems are dominant in Telangana State during monsoon season, whereas during winter season, maize systems are mainly practised in Krishna and Godavari zones in rice fallows. This shift has become possible due to no-till maize in rice-maize system and cultivation of single cross hybrids.

Zero till-maize in Andhra Pradesh and Telangana

Rice-relay pulse crop is an important crop sequence covering 0.3 Mha in Andhra Pradesh. For the past half decade, the greengram and blackgram were subjected to yellow vein mosaic and *Cuscuta* problem. In addition to this, since 2003 onwards in Krishna delta of Andhra Pradesh, due to late release of water, transplanting of rice is delayed and ultimately timely sowing of blackgram as relay crop is not possible. Therefore, farmers are switching over to non-traditional crop like maize in rice fallows as an alternative to blackgram. Under the emerging and potential crop sequence (rice-maize) in coastal region of Andhra Pradesh, the conventional tillage for planting maize under heavy textured soil of rice needs 25-30% higher energy for field preparation which limits the farm profitability and delays maize sowing leading to lower productivity. Generally rice is harvested during second fortnight of November. In case of zero tillage under rice-maize rotation, the farmers can sow maize in time. Further no till maize in rice fallow demonstrated a potential benefit of saving on cost of production ranging from Rs. 3800-5500/ha.

In the conventional rice-maize cropping system, due to efficient land preparation after rice, the problem of rejuvenation of rice stubble was not encountered and initial weed problem is solved with pre-emergence application of atrazine. In rice-zero till maize due to sowing of maize crop after rice harvest, wide spacing, erect and slow early growth problems of weed has become acute. But, in zero till system residues, when retained on the soil surface, serve as physical barrier for emergence of weeds, moderate the soil temperature, conserve soil moisture, add organic matter and improve the nutrient-water interactions.

Weed flora

In clay loam soils of Guntur (Andhra Pradesh), Rao *et al.* (2009) reported the dominant weed flora as *Echinochloa colona* (L.) Link (41%), *Dinebra retroflexa* (Vahl) Panzer (4%), *Panicum repens* L. (3%) and *Cynodon dactylon* (L.) Pers. (2%), *Leptochloa chinensis* (L.) Nees (5%) (grasses), *Cyperus rotundus* L. (5%) (sedges), *Chrozophora rottleri* (Geisel) A. Juss. Ex Spreng. (15%), *Trianthema portulacastrum* L. (13%), *Digera arvensis* (4%), *Merremia emerginata* (Burm. f.) Hall. F. (3*%), Phyllanthus niruri* (3%) and *Euphorbia hirta* L. (2%) (broad-leaved weeds). Mukundam *et al.* (2011) from clay loam soils of Bapatla reported that *C. rotundus* and dicots *T. portulacastrum*, *D. arvensis*, *P. niruri* and *C. dactylon* among grasses were most dominant. In clay loam soils of Warangal, *E. colona* (13%), *D. retroflexa* (11%), *P. repens* (8%) and *L. chinensis* (7%) among the grasses, *C.rotundus* L. (8%) among sedges and *C. rottleri*. (11%), *T. portulacastrum* (9 %), *D. arvensis* (9%), *M. emerginata* (12%), *P. niruri* (3%) and *E. hirta* (9%) among the broad-leaved weeds (Reddy *et al.* 2012). In another study, *E. colona* among the grasses, *C. rotundus* among the sedges, *Ageratum conizoides* and *T. portulacastrum* were the predominant broad-leaved weeds observed in sandy loam soils of Hyderabad (Parameshwari 2013). Weed survey for three years in Krishna zone of Andhra Pradesh revealed that zero till sown maize crop was infested with a total of 21 weed species, of which 7 were grasses, 3 sedges and 11 broad-leaved weeds. Among the weeds, *E. colona* was the most dominant species with IVI of 37.64 followed by *P. repens* (32.29), *T. portulacastrum* (16.33), *D. arvensis* (13.37) (Kiran and Rao 2014). In sandy loam soils of Rajendra Nagar during *rabi* 2014, the predominant weed flora observed in zero tillage maize during crop growing season at 30 DAS were *C. rotundus, E. crusgulli, Paspalum distichum, T. portulacastrum, Parthenium hysterophorus, Sonchus oleraceus, Acalypha indica and Eclipta alba* (Annual Report 2014).

Critical period of weed competition and yield loss

The critical period is useful in defining the crop growth stage which is most vulnerable to weed competition. In practice, the critical period is defined as a number of days after crop emergence during which crop must be weed free in order to prevent yield losses more than 5%. Based on this approach critical period for maize ranges from 1 to 8 weeks after the crop sowing (Thomas and Allison 1975). Wider spacing and slow growing nature of the crop during the first 3-4 weeks provide enough opportunity for weeds to invade and offer severe competition resulting in 30-100% yield reduction (Sandhu *et al.* 1999). Yield losses of 77.4%, 44.2% and 38.4% were observed in maize due to grasses, non-grassy weeds and sedges, respectively (Pandey *et al*. 2002). Losses due to weeds under zero till sown condition in Telangana state and Andhra Pradesh varied from 30 to 93%. In clay loam soil of Guntur, unchecked weed growth caused a yield loss of 43% due to severe weed competition (Rao *et al.* 2009). But, Mukundam *et al.* (2011) reported a yield reduction of 30% with unweeded check treatment in clay loam soils of Bapatla. In another study from clay loam soil of Warangal, Reddy *et al.* (2012) reported a yield loss of 76% due to season-long crop-weed competition. Yield reduction of as high as 93% was observed due to uncontrolled weed growth during entire crop growth season from sandy clay loam soils of Kampasagar (Telangana) (Pasha *et al.* 2012). In sandy loam soils of Hyderabad (Telangana State) under zero till conditions, a significant reduction in grain yield by 69.7 and 70.34% was noticed during 2011 and 2012, respectively (Parameswari 2013). A yield reduction of 50% was observed due to competitive stress of weeds from zero till sown maize during *Rabi* 2014 under Rajendra nagar conditions of Hyderabad (Annual Report 2014).

Rice stubble rejuvenation and weed growth

In rice-zero till maize, the removal of apical dominance due to rice harvest stimulated the lower buds. The wider spacing and initial slow (3-4 weeks) growth of maize maintain high soil moisture, which promotes both rice stubble rejuvenation and first flush of weeds. These problems were not seen in the traditional rice-fallow pulse sequence due to high seed rate, emergence and development of pulse seedlings prior to removal of apical dominance by rice harvest. Consequent to lower moisture regimes (as the pulse crop raised on receding soil moisture) and ephemeral crop growth nature, the rejuvenation of rice stubbles and first flush of weeds did not have any impact on pulse crops. Short duration rice variety promoted more rejuvenation of rice stubbles than medium and long duration varieties (Table 1). On the other hand, higher weed growth and dry matter was recorded in long duration varieties when compared to medium and short duration varieties.

Among herbicides, paraquat spray on rice stubbles controlled rice stubble rejuvenation but was less effective in controlling first flush of weeds in zero-till sequential maize. Immediately after rice harvest, consequent to removal of apical dominance, the lower buds were stimulated and spray of paraquat

Table 1. Sprouted rice stubble (%) and weed dry matter (g/m²) in zero-till maize as affected by treatments (mean of two years)

Treatment	Sprouted rice stubble (%)	Weed dry matter (g/m²)
Kharif rice variety		
Tellahamsa	21.14	16.88
Early Samba	17.54	21.45
Samba Mahsuri	14.99	26.70
LSD (P=0.05)	2.33	2.12
Rabi cropping system		
Maize without herbicide	32.47	35.97
Maize with atrazine	13.12	12.66
Maize with paraquat	8.08	16.40
LSD (P=0.05)	3.17	3.31

Source : Mukundam *et al.* (2011)

instantly killed the emerging cells in the bud and inhibited their growth and rejuvenation. As paraquat was adsorbed by soil particles, there was no control of first flush of weeds.

Weed growth and dynamics

Reddy *et al.* (2012) reported the lowest density (no./m²) and dry weight (g/m²) of grasses (1.0 and 1.0, respectively), sedges (9.0 and 2.0, respectively) and broad-leaved weeds (1.0 and 0.5 respectively) at 30 DAS with tank mix application of atrazine + glyphosate (0.75 + 0.8 kg/ha). Glyphosate (1.6 kg/ ha) was found superior to atrazine (1.5 kg/ha) and paraquat (1.5 kg/ha) for density, dry weight of weeds and weed-control efficiency. In Guntur, pre-emergence application of atrazine 1.5 kg/ha followed by (*fb*) hand weeding at 30 DAS recorded the lowest weed dry weight and highest weed control efficiency (WCE) at 60 DAS and harvest. In clay loam soils of Bapatla, two hand weedings at 3 and 6 WAS and intercultivation with power weeder at 4 WAS recorded significantly lowest weed density and dry-matter. Likewise, pre-emergence application of atrazine 1.25 kg/ha in combination with paraquat 0.6 kg/ha at 3 WAS recorded lower weed density (13.67 m²) and dry-matter. Pendimethalin 1. 5 kg/ha + paraquat 0.6 kg/ha was found similar with weed free check and intercultivation with power weeder (Mukundam *et al.* 2011). From sandy clay loam soils of Kampasagar (Telangana State), Pasha *et al.* (2012) reported that pre-emergence application of atrazine 1.25 kg/ha + paraquat 0.75 kg/ha were found effective in reducing weed density (3/m²) and weed dry-matter (7 g/m²). Similarly effective treatments were pre-emergence application of atrazine 1.25 kg/ ha + glyphosate 0.5 kg/ha (97.6%), atrazine as post-emergence 1.0 kg/ha (92.4%) and atrazine as pre-emergence 1.25 kg/ha (92.0%), pre emergence application of atrazine 1.0 kg/ha *fb* topramazone 0.030 kg/ha at 30 DAS due to higher WCE, increased growth and yield of zero till maize (Parameswari 2013). At Hyderabad, (Telangana), hand weeding twice at 20 and 40 DAS and pre-emergence application of oxyfluorfen 0.15 kg/ha + paraquat 0.60 kg/ha treatment at 30 DAS, 60 DAS and 120 DAS was found effective (Annual Report 2014).

Growth and yield of zero-till maize

In clay loam soils of Guntur Rao *et al* (2009) were the first to conduct the work on zero tillage maize in Andhra Pradesh (India) without using non selective herbicides. Among all the weed control treatments hand weeding twice at 15 and 30 DAS recorded significantly higher plant height (245 cm) and crop dry matter (398 g). Among herbicides, pre-emergence application of atrazine 1.5 kg/ha *fb* hand weeding (HW) at 30 DAS or pre-emergence application of atrazine 1.5 kg/ha alone recorded higher plant height and dry matter over unweeded check at all stages of crop growth. Experimental results of Mukundam *et al.* (2011) under clay loam soil revealed that, the maximum plant height of maize was noticed with conventional tillage than that under zero tillage. According to studies of Parameswari (2013), among different crop establishment methods significantly higher plant height, dry matter production of maize was obtained when maize was grown after transplanted rice under zero till condition. Higher plant height and crop dry matter was observed with HW twice at 20 and 40 DAS and it was *fb* pre-emergence application of atrazine 1.0 kg/ ha *fb* topramezone 0.030 kg/ha. In clay loam soil of Hyderabad under Rajendranagar conditions (Telangana) the highest crop dry matter was noticed with HW twice at 20 and 40 DAS and was on a par with pre-emergence application of atrazine 1.0 kg/ha + paraquat 0.60 kg/ha and pre-emergence application of oxyfluorfen 0.150 kg/ha + paraquat 0.60 kg/ha (Annual Report 2014). In clay loam soils of Guntur Rao *et al.* (2009), recorded the highest maize yield (10.53 t/ha) with HW twice at 15 and 30 DAS. The increased yield in these treatments was owing to higher WCE and increased crop growth and number of seeds/ cob. In another study, either two HW at 3 and 6 WAS or intercultivation with power weeder at 4 WAS recorded significantly higher grain yield under conventional and zero tillage methods. Among the herbicides sequential application of either atrazine as pre-emergence 1.25 kg/ha *fb* paraquat 0.6 kg/ha at 3 WAS or pendimethalin as pre-emergence 1. 5 kg /ha *fb* paraquat 0.6 kg /ha at 3 WAS (Srividya *et al.* 2011). Reddy *et al.* (2012), who conducted experiment with herbicides alone and tank mix application of selective and non selective herbicides showed that, the grain yield obtained with tank mix application of atrazine + glyphosate (5.25 t/ha) was 170 and 70% more than weedy check and sole atrazine, respectively. In sandy clay loam soils of Kampasagar (Telangana), Pasha *et al.* (2012) reported, tank mix application of atrazine 1.25 kg/ha + paraquat 0.75 kg/ha as pre-emergence produced significantly higher grains/cob, cob diameter and 100 grain weight than other herbicides. Comparable grain yields were recorded with atrazine alone as pre-emergence 1.25 kg/ha (6.7 t/ha) and atrazine 1.25 kg/ha + glyphosate 0.5 kg/ha (7.0 t/ha) as pre emergence application. Under sandy loam soil of Hyderabad, two HW at 20 and 40 DAS resulted in highest yield attributes and yield , followed by pre-emergence application of atrazine 1.0 kg/ha *fb* topramezone 30 g/ha at 30 DAS and atrazine 1.0 kg/ha as pre-emergence alone (Parameswari 2013). Under sandy clay loam soils of Rajendranagar, significantly higher grain yield (5.63 t/ha) and stover yield (6.11 t/ha) was obtained with HW twice at 20 and 40 DAS and was at par with either tank mix pre-emergence application of atrazine 1.0 kg/ha + paraquat 0.60 kg/ha or oxyfluorfen 0.15 kg/ha + paraquat 0.60 kg/ha (Annual Report 2014).

Nutrient uptake

Under irrigated conditions of clay loam soils of Bapatla, Srividya *et al.* (2011) reported that, pre-emergence application of atrazine 1.5 kg/ha or pendimethalin 1.5 kg/ha *fb* paraquat 0.6 kg/ha at 3 WAS recorded significantly lower N, P and K uptake by weeds over application of atrazine or pendimathalin alone. Parameswari (2013) observed that the nutrients depletion by weeds was reduced and crop uptake was enhanced when maize was grown after transplanted rice under zero till condition. The application of atrazine 1.0 kg/ha pre-emergence *fb* topramazone 0.030 kg/ha at 30 DAS was found effective in reducing nutrient uptake by weeds.

Economics

Rao *et al*. (2009) recorded highest gross and net monetary returns and benefit: cost ratio with two HW at 15 and 30 DAS and with pre-emergence application of atrazine 1.5 kg/ha *fb* HW at 30 DAS. In clay loam soils of Warangal, tank mix application of atrazine + glyphosate (0.75+ 0.8 kg/ha) gave the maximum net returns (₹ 29,350/ha) and benefit: cost ratio (1.71) followed by atrazine + paraquat (0.75+0.75 kg/ha) due to the broad-spectrum control of weeds. Amongst weed management practices evaluated, the highest B:C ratio was registered with application of atrazine 1.0 kg/ha *fb* topramezone 0.030 kg/ha at 30 DAS in zero till maize (Parameswari 2013). Higher gross returns, net returns and B.C ratio (88,570, 50820 and 2.35) was obtained with HW twice at 20 and 40 DAS. This was closely followed by pre-emergence application of atrazine 1.0 kg/ha + paraquat 0.60 kg/ha (77915, Rs 45905 and 2.43), pre-emergence application of oxyfluorfen 0.150 kg/ha + paraquat 0.60 kg/ha (77747, Rs 45135 and 2.38) and early post-emergence application of atrazine 1.0 kg/ha (74733, 43763 and 2.41).

Conclusion

Among IWM practices, pre-emergence application of atrazine 1.5 kg/ha *fb* HW at 30 DAS, pendimethalin 1.50 kg/ha *fb* hand weeding at 30 DAS, atazine + alachlor (0.75 + 1.25 kg/ha) *fb* hand weeding at 30 DAS, or alachlor 1.5 kg/ha *fb* hand weeding was more effective against weeds and more economical in maize. Among the sequential herbicide applications, atrazine pre-emergence 1.25 kg/ha *fb* paraquat 0.6 kg/ha at 3 WAS, pendimethalin pre-emergence 1.5 kg/ha *fb* paraquat 0.6 kg/ha at 3 WAS, or atrazine 1.0 kg/ha pre-emergence *fb* topramazone 0.030 kg/ha at 30 DAS was proved location-wise effective. The tank-mix pre-emergence applications of atrazine + glyphosate (0.75+0.8 kg/ha or 1.25+0.5 kg/ha) and atrazine + paraquat (0.75+0.75 kg/ha or 1.25+0.75 kg/ha) pre-emergence was more economical in clay loam soils and sandy clay loam soils, respectively, when compared with selective herbicides alone.

Future thrusts

Successful adoption of zero till sown maize calls for development of suitable machinery for crop establishment. Understanding of the dynamics of soil physical, chemical and biological properties, which in turn, affect root growth and crop yield is essential. Understanding of the dynamics of weed shift and herbicide residues in soil also is of paramount importance.

REFERENCES

Annual Report. 2014. All India Coordinated Research Project on Weed Management.

Director's Review. 2015. Annual Workshop on *All India Coordinated Research Project on Maize,* 4-6 April, 2015, PAU, Ludhiana.

Ekboir, J.M. 2002. No-till netwoks in developing countires, pp.70-74. In: *Agricultural Innovations Systems: An Investement Source Book. World Bank, Washington DC*

IRRI and CIMMYT. 2006. *Rice-Maize Systems for Improving the Quality of Life of Asia's Poor.* CIMMYT.

Kiran GGR and Rao AS. 2014. Survey of weed flora in zero till sown maize in Krishna zone of Andhra Pradesh. *The Andhra Agricultural Journal* **61**(3): 494–496.

Mukundam B, Srividya S and Raja V. 2011. Productivity and economics of rice-zero till maize as influenced by weed management practices in Southern Telangana region of Andhra Pradesh. *Indian Journal of Weed Science* **43** (3&4): 163–168.

Pandey AK, Prakash V, Singh RD and Mani VP. 2002. Studies on crop-weed competition and weed dynamics in maize under mid-hill conditions of north-west Himalayas. *Indian Journal of Weed Science* **34**: 63–67.

Parameshwari YS. 2013. *Influence of Rice Crop Establishemnt Methods and Weed Management Practices on Succeeding Zero-till Maize*. Ph.D Thesis. Professor Jayashankar Telangana State Agricultural University. Hyderabad.

Pasha Md. L, Bhadru D, Krishna L and Naik RBM. 2012. Evaluation of different herbicides in zero tillage. *Madras Agricultural Journal* **99**(7-9): 471-472.

Rao AS, Ratnam M and Reddy TY. 2009. Weed management in zero-till down maize. *Indian Journal of Weed Science* **41**(1 & 2): 46-49.

Reddy MM, Padmaja B, Veeranna G and Reddy DVV. 2012. Bio-efficacy and economics of herbicide mixtures in zero-till maize (*Zea mays*) grown after rice (*Oryza sativa*). *Indian Journal of Agronomy* **57**(3): 255–258.

Sandhu KS, Singh T and Singh S. 1999. Weed competition of maize (*Zea mays*) fields in Punjab. *Indian Journal of Weed Science* **31**: 18–24.

Singh N, Rajendran RA, Shekhar M, Jat SL, Kumar R and Kumar RS. 2012. *Rabi* maize opportunities and challenges. Directorate of Maize Research, Pusa Campus, New Delhi -110 012, *Technical Bulletin* **9,** 32 p.

Singh VP, Abnish Kumar and Banga A. 2010. Current status of zero tillage in weed management. *Indian Journal of Weed Science* **42**(1&2): 1–9.

Srividya S, Chandrasekhar K and Veeraraghavaiah R. 2011. Effect of tillage and herbicide use on weed management in maize (*Zea mays*. L). *The Andhra Agricultural Journal* **58**(2): 123–126.

Thomas PEL and Allison JCS. 1975. Competition between maize and *Rottboellia exaltata*. *Journal of Agricultural Sciences* **84**: 305–312.

Indian Journal of Weed Science **47**(3): 246–253, 2015

Weed management in millets: Retrospect and prospects

J.S. Mishra*
ICAR-Research Complex for Eastern Region, Patna, Bihar 800 014

Received: 8 August 2015; Revised: 2 September 2015

ABSTRACT

Millets are important staple foods in semi-arid tropics of Asia and Africa. Low productivity and susceptibility to biotic and abiotic factors are the major reasons for declining area and productivity of millets in India. As the millets are grown predominantly in the hot and humid rainy season, weeds deprive these crops of vital nutrients and moisture and reduce the yield considerably. Because of wider row spacing and slow initial growth in millets, weeds are more problematic during initial crop growth period, and hence, early control is needed to optimize the yield. The objective of this paper is to review the research that has been conducted pertaining to various aspects of weed management in different millets while also identifying key knowledge gaps that should be addressed in future research. Literature suggests that satisfactory weed control can be achieved with integration of pre-emergence herbicides with one manual/mechanical weeding. Additionally, future research is needed to evaluate the post-emergence herbicides that are the best suited for different millets and millet-based intercropping systems to improve weed control and reduce environmental impacts, including herbicide residues.

Key words: Crop-weed competition, Herbicides, Losses, Millets, *Striga*, Weeds

Millets as a group of crops are represented by sorghum (*Sorghum bicolor*), pearl millet (*Pennisetum glaucum*), finger millet (*Eleusine coracana*), foxtail millet (*Setaria italica*), barnyard millet (*Echinochloa frumentacea*), proso millet (*Panicum miliaceum*), kodo millet (*Paspalum scorbiculatum*) and little millet (*Panicum sumatrense*). They are the major crops of the semi-arid regions of the country, and have the potential to contribute substantially for food, fodder and nutritional security. Because of their drought tolerance, millets can be cultivated in areas that are often too hot and dry for other crops to be grown. Weeds are a major obstacle in increasing the productivity of millet crops especially during rainy season. Burnside and Wicks (1969) reported that weed competition had a greater effect on sorghum yield than crop row spacing or crop population. Millets grow slowly at first and are relatively poor competitor with weeds during the first few weeks of growth. Planting in wider rows to facilitate inter-row cultivation and/or ditch furrow irrigation worsen the problems. Because the crop canopy forms slowly and provides little shading of weeds between rows until mid season; by then, most weeds are well established. Weeds compete with millets for light, soil moisture and nutrients and reduce crop yields and quality. Therefore, appropriate weed management would help improve productivity and input use-efficiency of these crops. When improved agricultural technologies are adopted, efficient weed management becomes even more important, otherwise the weeds rather than the crops benefit from the costly inputs.

***Corresponding author:** jsmishra31@gmail.com

Weed distribution

A mixed population of broad-leaved, grasses and cyperaceous weeds grows with millet crops under different agro-climatic conditions (Table 1).

Losses due to weeds

Weeds compete with crops for nutrients, soil moisture, sunlight and space when they are limiting, resulting in reduced yields, lower grain quality and increased production costs. The magnitude of losses depends on crop cultivars, nature and intensity of weeds, spacing, duration of weeds infestation, environmental conditions and management practices. Yield loss due to weeds in maize, sorghum and pearl millet are given (Table 2). In grain sorghum, uncontrolled weeds removed 29.94-51.05, 5.03-11.58 and 48.74-74.34 kg/ha NPK, respectively from soil (Satao and Nalamwar 1993).

Weeds also harbor insect-pests and diseases (Table 3). Weeds are an important plant resource for insects, although feeding by insects on weeds can have both positive and negative effects on crop productivity (Capinera 2005).

Table 1. Major weeds of millets in different states of India

States	Grasses	Broad-leaved	Sedges
Andhra Pradesh	*Cynodon dactylon, Echinochloa colona*	*Commelina benghalensis, Celosia argentea, Euphorbia geniculata, E. hirta, Digera arvensis, Corchorus olitorius*	*Cyperus rotundus*
Bihar	*Cynodon dactylon, Echinochloa colona, Dactyloctenium aegyptium*	*Canabis sativa, Ageratum conyzoides, Fumaria parviflora, Leucas aspera, Amaranthus viridis, Trianthema portulacastrum*	*Cyperus rotundus, Fimbristylis diphylla*
Gujarat	*Cynodon dactylon, Echinochloa colona, E. crus-galli*	*Chrozophora rottleri, Convolvulus arvensis, Digera arvensis, Corchorus aestuans*	*Cyperus rotundus, C. esculentus Eragrostis major*
Haryana	*Echinochloa colona, Dactyloctenium aegyptium, Paspalum paspaloides*	*Celosia argentea, Trianthema portulacastrum, Alhagi camelorum*	*Cyperus rotundus*
Himachal Pradesh	*Digitaria sanguinalis, Echinochloa colona, Panicum dichotomiflorum, Brachiaria ramosa*	*Ageratum conyzoides, Commelina benghalensis, Oxalis latiifolia, Ipomoea purpurea*	*Cyperus iria*
Karnataka	*Cynodon dactylon, Echinochloa colona, Digitaria marginata,*	*Amaranthus viridis, A. spinosus, Borreria articularis, Celosia argentea*	*Cyperus rotundus, C. esculentus*
Madhya Pradesh	*Cynodon dactylon, Echinochloa colona, E. crusgalli, Saccharum spontaneum*	*Amaranthus viridis, A. spinosus, Commelina benghalensis, Eclipta alba, Phyllanthus niruri, Leucas aspera*	*Cyperus rotundus*
Maharashtra	*Cynodon dactylon, Echinochloa colona, Brachiaria eruciformis*	*Celosia argentea, Striga asiatica, Commelina benghalensis, Sonchus arvensis, Striga asiatica.*	*Cyperus rotundus*
Odisha	*Echinochloa colona, Digitaria ciliaris, Paspalum scorbiculatum, Ischene despaire*	*Ageratum conyzoides, Cyanotis* spp., *Celosia argentea*	*Cyperus iria*
Punjab	*Digitaria ciliaris, Eleusine aegypticum, Sorghum halepense*	*Phyllanthus niruri, Celosia argentea, Cleome viscosa*	*Cyperus rotundus*
Rajasthan	*Echinochloa colona, Eleusine indica*	*Amaranthus viridis, A. spinosus, Commelina benghalensis, Digera arvensis,*	*Cyperus rotundus*
Tamil Nadu	*Echinochloa colona, Cynodon dactylon, Panicum repens*	*Amaranthus viridis, Tridax procumbens, Digera arvensis, Trianthema portulacastrum, Euphorbia hirta, Celosia argentea*	*Cyperus rotundus*
Uttar Pradesh	*Cynodon dactylon, Echinochloa colona, Brachiaria ramosa*	*Trianthema portulacastrum, Ageratum conyzoides, Phyllanthus niruri, Commelina benghalensis,*	*Cyperus rotundus*
West Bengal	*Digitaria sanguinalis, Cynodon dactylon*	*Commelina benghalensis, Celosia argentea, Croton bonplandianum*	*Cyperus rotundus*

Table 2. Losses due to weeds in millets

Crop	Reduction in grain yield (%)	Reference
Sorghum	15-83	Mishra (1997), Stahlman and Wicks (2000)
Pearlmillet	55	Banga *et al*. (2000)
	35-90	Umarani *et al*. (1980)
	31-46	Gautam and Kaushik (1984)
	16-94	Balyan *et al*. (1993)
	40	Sharma and Jain (2003)
Finger millet	55-61	Ramachandra Prasad *et al*. (1991)

Critical period of crop-weed competition

In rainy season, weeds emerge in succession almost throughout the crop season. Removing weed competition any time during the growing season is not desired. Time of weed removal is as important as removal *per se*. 'Critical period' defines the maximum period weeds can be tolerated without affecting final crop yields (Zimdahl 1980). This provides information on the active duration when the presence of weeds make their deleterious effect on crops (Table 4). Millets are very susceptible to competition

Table 3. Weeds as alternate host for insect-pests and diseases

Weed species	Organism	Disease/insect-pests	Reference
Cynodon dactylon	*Sporisorium sorghi*	Sorghum covered smut	Marley (1995)
Sorghum halepense	*Colletotrichum graminicola*	Sorghum anthracnose	Frederiksen (1984)
	Stenodiplosis sorghicola	Sorghum midge	Monaghan (1978), Bilbro (2008)
	Claviceps africana	Sorghum ergot	Reed *et al*. (2000)
Brachiaria distachya, Panicum repens, Setaria intermedia, Cyperus rotundus		Sorghum shoot fly	Nwilene *et al.* (1998)

from weeds early in the life of the crop. Therefore efficient weed control at the pre- and early post-emergence stages is essential. Once the crop reaches approximately 0.5 m in height, weed control no longer affects yield. Millet-weed competition is largely influenced by moisture availability. Wiese *et al.* (1964) obtained a higher yield for irrigated sorghum in narrow rows without cultivation than in wide rows with cultivation, where as in dry-land, plants in wide rows were more able to compete for limited soil moisture.

Table 4. Critical period of crop-weed competiton in maize, sorghum and pearl millet

Crop	Critical periods (days after sowing)	Reference
Sorghum	28-42	Sundari and Kumar (2002)
Pearlmillet	28-42	Singh *et al.* (1986)
Fingermillet	25-42	Sundraesh *et al.* (1975)

Climate change and weed competition

Changes in temperature and carbon dioxide are likely to have significant influence on weed biology and vis-à-vis crop-weed interaction. Ziska (2003) studied the effect of elevated CO_2 on the interaction of dwarf sorghum (C_4) with and without presence of a C_3 weed (velvetleaf; *Abutilon theophrasti*) and a C_4 weed (redroot pigweed; *Amaranthus retroflexux*) and reported that in a weed-free environment, increased CO_2 significantly increased the leaf weight and leaf area of sorghum but no significant effect on seed yield or total above-ground biomass relative to the ambient CO_2 condition. Increase in velvet leaf biomass in response to increasing CO_2 reduced the yield and biomass of sorghum. Similarly, as CO_2 increased, significant losses in both seed yield and total biomass were observed for sorghum-redroot pigweed competition. Increased CO_2 was not associated with a significant increase in redroot pigweed biomass. These results indicate potentially greater loss in a widely grown C_4 crop from weedy competition as atmospheric CO_2 increases. In another experiment, Ziska (2001) observed that the vegetative growth, competition and potential yield of sorghum (C_4) could be reduced by co-occurring of common cocklebur (*Xanthium strumarium*: C_3) as the atmospheric CO_2 increases. Watling and Press (1997) investigated the effects of CO_2 concentrations (350 and 700 µmol/ml) in sorghum with and without *Striga* infestation. They observed that a high CO_2 concentration resulted in taller sorghum plants, and greater biomass, photosynthetic rates, water-use efficiencies and leaf areas. A high CO_2 concentration resulted in lower *Striga* biomass/host plant and a greater rate of photosynthesis. Parasite stomatal conductance was not responsive to CO_2 concentration. *Striga* emerged above ground and flowered earlier under the lower CO_2 concentration.

Control strategies

Mechanical and cultural options: Manual and mechanical weeding is by far the most widely followed method of weed control in millets. Hand weeding or inter-row cultivation provides reasonable weed control. But during rainy season, there are not many clear days and as a result, inter-culture operations have to be delayed and this help weeds to overtake the crops and cause severe reduction in yield. Also with rising labour wages and non-availability of adequate labour at times required, it is becoming a serious problem to control weeds manually on larger area at the proper time.

Growing of mungbean, groundnut, cowpea, soybean etc. as intercrops in sorghum/pearl millet could exert suppressing effect on weeds. Similarly narrow row spacing, use of higher seed rate, early application of nitrogen and its placement near to plants can help in increasing vigour of the crop and exert smothering effect on weeds. Narrow rows (<30 cm) are beneficial in reducing weed competition and increasing yield of foxtail and proso millets (Nelson 1977, Agdag 1995).

Herbicides: Use of herbicide saves labour and thus helps in diverting them to more important and productive activities. Depending upon the chemicals they may be applied either before planting of the crop (pre-planting e.g., fluchloralin), after planting but before emergence of the crop (pre-emergence e.g., atrazine, metolachlor, pendimethalin) or after emergence of the crop (post-emergence *e.g.* 2,4-D). In no-till conditions, herbicides are becoming a major component of weed management in maize and grain sorghum as they improve weed control and production efficiency (Brown *et al.* 2004). Foxtail millet lacks tolerance to saflufenacil, However, lower doses of saflufenacil (50 g/ha) may be safely applied as near as 7 days before planting proso or pearl millets. If situation demands, saflufenacil at 36 g/ha can also be applied as pre-emergence to either crop with risk of some crop injury (Reddy *et al.* 2014). Several herbicides have been evaluated for weed control efficacy and crop safety in sorghum (Table 5), however in other millets, the herbicide recommendations are limited (Table 6). At present atrazine is the only herbicide most commonly used as pre-emergence for weed control in millets at various doses.

Table 5. Herbicides recommended for sorghum

Herbicide	Dose (kg/ha)	Time of application	Weeds controlled	Remarks
Atrazine	0.75-1.0	Pre-emergence/ early post-emergence	Broad-spectrum weed control. Some grasses are tolerant	For sole crop only. Did not control *Acrachne racemosa*, *Brachiaria reptans* and *Commelina benghalensis* (Walia *et al.* 2007)
Pendimethalin	0.75-1.0	Pre-emergence	Effective control of grasses	Suitable for intercropping, higher doses may cause phytotoxicity
Alachlor	1.5-2.0	Pre-emergence	Effective control of grasses	Suitable for intercropping
Metolachlor	1.0-1.5	Pre-emergence	Effective control of grasses	Suitable for intercropping
2,4-D	0.50-0.75	Post-emergence	Effective against broad-leaved weeds	For sole crop only. Apply at 4-6 weeks after planting. Good as sequential application to pre-emergence herbicides
Atrazine + pendimethalin	0.75+0.75	Pre-emergence	Broad-spectrum weed control	For sole crop only
Atrazine + alachlor	0.75+0.75	Pre-emergence	Broad-spectrum weed control	For sole crop only
Atrazine + metolachlor	0.75+0.50	Pre-emergence	Broad-spectrum weed control	For sole crop only

Table 6. Herbicides recommended for other millets

Millets	Herbicide	Dose (kg/ha)	Time of application	Weeds controlled	Remarks
Pearlmillet	Atrazine +	0.50	PE/early POE (10 DAS) 30 DAS	*Trianthema portulacastrum* and *E. colona*	For sole crop only (Banga *et al.* 2000).
	HW	1			Ramakrishna (1994)
	2,4-D	0.50-0.75	POE	Effective against broad-leaved weeds	For sole crop only. Apply between 4-6 WAS. Good as sequential application to pre-emergence herbicides
	Pendimethalin	1.0	PE	Broad-spectrum	Each supplemented with one hand
	Oxadiazone	1.0	PE	weed control	weeding at 45 DAS (Ram *et al.* 2005)
Finger millet	Oxadiazone	1.0	PE	Broad-spectrum weed control	
	Isoproturon	0.50-0.75	PE		Ashok *et al.* (2003)
	Butachlor	0.75	PE		Prasad *et al.* (2010)
Kodomillet	Isoproturon + intercultivation + HW	0.50 1 1	PE 20 DAS 40 DAS	Broad-spectrum weed control	Prajapati *et al.* (2007)
Prosomillet	Atrazine	0.28-0.56	PE	Broad-spectrum weed control	Anderson and Greb (1987)
	Propazine	0.28-0.56	PE	Broad-spectrum weed control	

One supplementary weeding at 30 days after sowing following pre-emergence herbicides is required for broad-spectrum weed control and higher yields.

Herbicide mixtures: Most of the presently available herbicides provide only a narrow spectrum weed control. Herbicide mixtures may allow control of wider spectrum of weeds with less total active in gradient. In grain sorghum, Ramakrishna *et al.* (1991) reported that pre-emergence application of metolachlor at 1.0-1.25 kg/ha or combination of atrazine + metolachlor or sequential application of metolachlor and bentazon, atrazine at 0.75 kg/ha yielded as good as repeated weedings. Jadhav *et al.* (1988) found oxyfluorfen at 0.15 kg/ha and atrazine 0.75 kg/ha as pre-emergence as safe herbicides for post-rainy sorghum. Kalyansundaram and Kuppuswamy (1999) reported that tank mix application of butachlor at 0.75 kg/ha + atrazine 0.75 kg/ha followed by 1 HW at 45 DAS controlled the weeds effectively and produced the highest grain yield. Wu *et al.* (2004) reported that soil incorporation of atrazine mixed with metolachlor at sorghum planting provided effective seasonal control of barnyard grass (*E. colona*). Atrazine + pendimethalin or trifluralin applied late-post emergence (when weeds and sorghum were 10-15 cm tall) resulted in 99% control of tumble pigweed (*Amaranthus albus*) with less than 3% sorghum stunting (Grichar *et al.* 2005). Ishaya *et al.* (2007) observed that pretilachlor + dimethametryne at 2.5 kg/ha or cinosulfuron 0.05

kg/ha or piperophos + cinosulfuron 1.5 kg/ha effectively controlled weeds, increased crop vigour, plant height, reduced plant injury and produced higher grain yield of sorghum.

Intercropping

Growing of intercrops in widely spaced row not only reduces intensity of weeds but also gives additional yield. Although intercropping may reduce weed infestation and growth, there is still a need for some degree of weed management in most cases. While second weeding may be needed in sole crop, this is often not required in intercropping since the canopy coverage is almost complete and weed growth after first weeding is minimal.

Manual or mechanical weed control is the main method in intercropping systems. Most of the herbicides are crop specific and thus, can't be applied in inter cropping systems. Use of pendimethalin (0.75-1.0 kg/ha), metolachlor (1.0 kg/ha), butachlor (0.75-1.0 kg/ha) has been found safe and effective in intercropping systems. Metolachlor was however, not effective against *Celosia argentea*. Pendimethalin 1.0 kg/ha was toxic for sorghum germination (Ponnuswami *et al.* 2003).

Sequence cropping/ double cropping systems

Weed management in sequential cropping is a little different from those in intercropping systems. Continuous presence of crop cover, residual toxicity of herbicides applied to the previous crops on succeeding crops and changing weed flora with the season all need a different approach in weed management practices. Selective herbicides are available for sole crops but the residual effect of these herbicides have to be carefully evaluated before using them in crop sequence. Very little attempt has been made in this direction. In a three year study with a fixed three crop rotation, cotton-sorghum-*ragi*, raised under zero tillage conditions with chemical weed control, *Cynodon dactylon* became a major problem after the second year and was difficult to control (Palaniappan, 1988). In sorghum-cotton cropping sequence, pre-emergence application of atrazine 0.25 kg/ha in sorghum and pendimethalin 1.0 kg/ha in cotton was effective for control of broad-leaved weeds. Atrazine applied as pre-emergence at 0.50 kg/ha gave effective weed control in sorghum but the establishment of legumes such as greengram and groundnut which followed sorghum was poor. The following cotton was not affected (Palaniappan and Ramaswamy 1976). In sorghum-safflower sequence, Giri and Bhosle (1997) observed that pre-emergence application of atrazine at 0.75 kg/ha alone or atrazine at 0.50 kg/ha combined with weeding and hoeing 6 weeks after sowing were as effective as 2 weeding and hoeing at 3 and 6 weeks after sowing in controlling weeds without any phytotoxic effect on succeeding safflower.

Management of *Striga*

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

There are no reliable global figures, based on rigorous sampling, for the total area affected by *Striga*, but an estimated 44 million ha were considered to be 'at risk' of *Striga* attack in the Africa, and the total loss of revenue from maize, pearl millet and sorghum 'could total' $US 2.9 billion. More recent figures suggest that 50 million ha and 300 million farmers are affected by *Striga* species in Africa, with losses of $US 7 billion (Ejeta 2007). In India, incidence of *Striga* alone caused 75% reduction in grain yield of sorghum (Nagur *et al.* 1962, Rao 1978). In sub-Saharan Africa, *S. hermonthica* caused 70-100% crop loss in sorghum and pearl millet (Emechebe *et al.* 2004).

Hand pulling is the most common control measure used by the small-scale farmers, but only effective when the *Striga* population is low. However, hand-pulling is no solution to a dense infestation but it should be encouraged to prevent new or light infestations getting worse, and as a part of integrated methods for control of moderate infestations. Plants which are pulled, within 2-3 weeks of the start of flowering, should be taken out of the field and burned so that seeds are not produced and shed from the drying plants. Cattle should not be fed the witch weed plants as the seeds pass through the cattle and are distributed in the manure.

Cultural practices such as stubble cleaning in sorghum fields after harvest, crop rotation with non hosts and with catch crops, mixed cropping without host crops, fertilizer management with high doses of nitrogen as top dressing, and use of resistant or tolerant varieties help in reducing *Striga* infestation. Whatever the methods, the ideal objective must be to prevent all *Striga* seed production - continuing control through and beyond harvest if necessary. Trap crops stimulate *Striga* germination but are not themselves attacked. Without supply of food from the plant root, the germinated *Striga* seeds die. It is therefore possible to rotate these crops with sorghum to induce suicidal germination. Crop rotation with trap/catch crops like soybean and cotton, intercropping with groundnut, soybean and cowpea and green manuring crops like sunhemp help in reducing the problem of parasitic weed *Striga*. Fertilizer, especially nitrogen, tends to reduce, or at least delay, *Striga* emergence and can be used to further reduce the numbers of parasite that need to be hand-pulled to prevent seeding.

In general, it has proved difficult to find good selective herbicide to control *Striga* in field crops. Since *Striga* is a broad-leaved plant, use of pre-plant/pre-emergence herbicides such as atrazine, oxyfluorfen show some effect, though not efficient. Post-emergence application of 2,4-D is effective when sprayed on the *Striga* leaves. However, sorghum is vulnerable to stalk twisting and lodging if 2,4-D is sprayed into the leaf whorl, hence, proper precautions should be taken while spraying.

Herbicide resistance in grain sorghum

Acetolactate synthase (ALS)-inhibitor herbicides, *viz.* nicosulfuron and rimsulfuron are widely used to control broad-leaved and grassy weeds in corn (*Zea mays*), but the sorghum is susceptible to these herbicides. However, by transferring a major resistance gene from wild sorghum relative, researchers at Kansas State University (KSU), USA developed a grain sorghum that is resistant to several ALS-inhibiting herbicides as Steadfast (nicosul-furon), Accent (nicosulfuron), Resolve (rimsulfuron) and Ally (metsulfuron) (Tuinstra and Al-Khatib 2007, Tuinstra *et al.* 2009).

Sorghum roots exude a potent bio-herbicide known as ‘sorgoleone’, which is produced in living root hairs and is phytotoxic to broadleaved and grassy weeds at concentrations as low as 10 micro M (Yang *et al.* 2004). Herbicide tolerance through transgenic technology is not addressed worldwide because of the opinion of development of “Super Weed”. It is understood that crops and related wild or weedy plants can and will exchange genes through pollen transfer, if provided with the opportunity, and have been doing so ever since there have been crops and weeds (Harlan 1982). Transfer of herbicide tolerant gene to johnsongrass from cultivated sorghum is considered a threat if hybrid develops due to their cross compatibility.

Future research needs

Millets have now been emphasized as nutri-cereals, and will play a major role in crop diversification, and food and nutritional security under changing climate scenario. As these crops are grown as subsistence crops mainly during rainy season by resource poor farmers on marginal lands with low inputs, efficient weed management is a major challenge. Most of the minor millets are the improved species of most troublesome grassy weeds. Hence, it is very difficult to identify weeds in early stages and control them. In general, weeds in millets are removed manually using hand tools and implements at the stage when they attain good amount of biomass and used as source of animal fodder. But the crop yield reduces drastically due to severe competition for nutrients and moisture. Therefore, the critical period of crop-weed competition, especially for the minor millets needs to be identified and weeds should be managed during that period. There is need to develop energy efficient small weeding tools for different agro-ecological regions. Herbicides though very effective for weed control in millets, are rarely used in millets except in sorghum and pearl millets. As these crops are also used as major fodder source for animals, farmers fear that use of herbicides may deteriorate the fodder quality and animal health. Hence, they should be educated and trained about the use of herbicides in millets. As the millets are grown in moisture stress conditions, the efficacy of pre-emergence herbicides like atrazine is reduced. Hence, there is a need for exploring potential post-emergence herbicides for safe and effective weed control. Millets are mainly grown as intercrop with pulses and oilseeds. Under such conditions, safe and effective broad-spectrum herbicides need to be developed and evaluated. Herbicide residues in soil and plant (grain and stover) need to be studied in different situations. More investigations are needed on integrated weed management, especially in minor millets.

REFERENCES

Agdag MI. 1995. *Row Spacing in Proso Millet*. Univ. Nebraska, Lincoln. M.S. Thesis.

Anderson RL and Greb BW. 1987. Residual herbicides for weed control in prosomillet (*Panicum miliaceum* L.). *Crop Protection* **6**(1): 61-63.

Ashok EG, Chandrappa M, Kadalli GG, Kirankumar MV and Krishnegowda KT. 2003. Integrated weed control in drill-sown rainfed fingermillet. *Indian Journal of Agronomy* 48(4): 290-293.

Balyan RS, Kumar S, Malik RK and Panwar RS. 1993. Post-emergence efficacy of atrazine in controlling weeds in pearl millet. *Indian Journal of Weed Science* **25**: 7-11.

Banga RS, Yadav A, Malik RK, Pahwa SK and Malik RS. 2000. Evaluation of tank mixture of acetachlor and atrazine or 2,4-D Na against weeds in pearl millet. *Indian Journal of Weed Science* **32**: 194-198.

Bilbro JD. 2008. Grain sorghum producers contends with many insect pests. Southwest farm Press, Sept 4, 2008, Available at *www.southwestfarmpress.com*.

Brown DW, Al-Khatib K, Regehr DL, Stahlman PW, Loughin TM. 2004. Safening grain sorghum injury from metsulfuron with growth regulator herbicides. *Weed Science* **52**: 319-325.

Burnside OC, Wicks GA. 1969. Influence of weed competition on sorghum growth. *Weed Science* **17:** 332-334.

Capinera JL. 2005. Relationship between insect pests and weeds: an evolutionary perspective. *Weed Science* **53**(6): 892-901.

Ejeta G. 2007. The *Striga* scourge in Africa: a growing problem, pp.3–16. In: *Integrating New Technologies for Striga Control: Toward Ending the itchhunt* . (Eds. Ejeta G and Gressel J). World Scientific Publishing Co., Hackensack, NJ,

Emechebe AM, Ellis Jones, J Schulz S, Chikoye D, Douthwaite B, Kureh I, Tarawali G, Hussaini MA, Kormawa P and Sanni A. 2004. Farmers perception of the *Striga* problem and its control in Northern Nigeria. *Experimental Agriculture* **40**: 215-232.

Frederiksen RA. 1984. Anthracnose stalk rot. Sorghum root and stalk rots: A critical review, pp. 37-42. In: *International Crop Research Institute for the Semi-Arid Tropics*, (Ed. LK Mughogho), Patencheru, A.P., India.

Giri AN and Bhosle RH. 1997. Weed management in sorghum (*Sorghum bicolor*)-safflower (*Carthamus tinctorius*) sequence. *Indian Journal of Agronomy* **42**: 214-219.

Grichar WJ, Besler BA and Brewer KD. 2005. Weed control and grain sorghum response to post-emergence application of atrazine/pendimethalin and trifluralin. *Weed Technology* **19**: 999-1003.

Harlan JR. 1982. Relationship between crops and weeds. Madison, WI: *American Society of Agronomy* 295 p.

Ishaya DB, Dadari SA, Shebayan JAY. 2007. Evaluation of herbicides for weed control in sorghum (*Sorghum bicolor*) in Nigeria. *Crop Protection* **26:** 1697-1701.

Jadhav NS, Shelke DK and Bhosle RH. 1988. Screening of herbicides for *Rabi* sorghum. *Indian Journal of Weed Science* **20**: 88-89.

Kalyansundaram D and Kuppuswamy G. 1999. Effect of different weed control methods on the performance of sorghum and soil health, p. 37. In*: 8th Biennial Conference, Indian Society of Weed Science*, 5-7 February, Varanasi, India.

Kaushik SK and Gautam RC. 1984. Weed control studies in pearl millet under rainfed condition. *Indian Journal of Agronomy* **29:** 31-36.

Marley PS. 1995. *Cynodon dactylon*: An alternate host for *Sporisorium sorghi*, the causal organism of sorghum covered smut. *Crop Protection* **14**: 491-493.

Mishra JS. 1997. Critical period of weed competition and losses due to weeds in major field crops. *Farmers and Parliament* **33** (6):19-20.

Monaghan N. 1978. Problems caused by *Sorghum halepense* in Australia. *Proceedings of the National Academy of Sciences* **24**: 172-176.

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

Nelson LA. 1977. Influence of various row widths on yields and agronomic characteristics of proso millet. *Agronomy Journal* **69**: 351-353.

Nwilene FE, Nwanze KF and Reddy YVR. 1998. Effect of sorghum ecosystem diversification and sowing date on shoot fly, stem borer and associated parasitoids. *Crop Research* **16**: 239-245.

Palaniappan SP. 1988. *Cropping Systems in the Tropics: Principles and Management*. Wiley Eastern Limited, New Delhi.

Palaniappan SP and Ramaswamy R. 1976. Residual effect of atrazine applied to sorghum on the succeeding crops. *Madras Agricultural Journal* **65**: 230-232.

Ponnuswami K, Santhi P and Sankaran N. 2003. Effect of intercrops and herbicides on weeds and productivity of rainfed sorghum, p. 43. In*: Biennial Conference, Indian Society of Weed Science,* 12-14 March 2003, GBPUAT, Pantnagar, India.

Prajapati BL, Upadhyay VB and Singh RP. 2007. Integrated weed management in rainfed kodomillet (*Paspalum scorbiculatum*). *Indian Journal of Agronomy* **52**(1): 687-69.

Prasad TV, Ramachandra Kiran, Kumar VK, Denesh GR and Sanjay MT. 2010. Long-term herbicide usage on weed shift and productivity in transplanted fingermillet - groundnut cropping system in southern Karnataka. *Journal of Crops and Weeds* **6**(1): 44-48.

Umrani MK, Bhoi PG and Patil NB. 1980. Effect of weed competition on growth and yield of pearlmillet. *Journal of Maharashtra Agricultural University* **5**: 56-57.

Ram B, Chaudhary GR, Jat AS and Jat ML. 2005. Effect of integrated weed management and intercropping systems on growth and yield of pearlmeillet. *Indian Journal of Agronomy* **50**(3): 254-258.

Ramachandra, Prasad RV, Narasimha N, Dwarkanath N, Munigowda MK and Krishnamurthy K. 1991. Integrated weed management in drilled fingermillet. *Mysore Journal of Agricultural Sciences* **25**: 13-17.

Ramakrishna A. 1994. Efficacy of herbicides for weed control in pearlmillet. *Indian Journal of Plant Protection* **22**(2): 202-206.

Ramakrishna A, Ong CK and Reddy SLN. 1991. Studies on integrated weed management in sorghum. *Tropical Pest Management* **37**: 159-161.

Rao AN. 1978. Ecophysiological responses of crops and weeds against herbicides and their residues. *Ph. D. Thesis*, Vikram University, Ujjain, Madhya Pradesh, India.

Reed JD, Ramundo BA, Claflin LE and Tuinstra MR. 2000. Analysis of resistance to ergot in sorghum and potential alternate hosts. *Crop Science* **42**: 1135-1138.

Reddy SS, Stahlman PW, Geier PW, Charvat LD, Wilson RG and Moechnig MJ. 2014. Tolerance of foxtail, proso and pearl millets to saflufenacil. *Crop Protection* **57**: 57-62

Satao RN and Nalamwar RV. 1993. Studies on uptake of nitrogen, phosphorus and potassium by weeds and sorghum as influenced by integrated weed control. Integrated weed management for sustainable agriculture, pp. 103-107. In*: Proceedings of an Indian Society of Weed Science International Symposium*, 18-20 November, Hisar, India.

Sharma OL and Jain NK. 2003. Integrared weed management in pearl millet (*Pennisetum glaucum*). *Indian Journal of Weed Science* **35**: 34-35.

Singh RP, Zaidi PH, Singh Raju and Yaduraju NT. 2005. Weed management in tropical maize, pp 445-461. In. *Stresses on maize in Tropics* (Eds. Zaidi PH and Singh PH), Directorate of Maize Research, New Delhi, India.

Sundari and Kumar SMS. 2002. Crop-weed competition in sorghum. *Indian Journal of Weed Science* **34**: 311-312.

Sundraseh HN, Rajappa MG, Lingegowda BK and Krishnashastry KS. 1975. Critical stages of crop-weed competition in ragi (*Eleusine coracana*) under rainfed conditions. *Mysore Journal of Agricultural Sciences* **9**(4): 582-585

Tuinstra MR and Al-Khatib K. 2007. New herbicide tolerance traits in grain sorghum. In: *Proceedings of the 2007 Corn Sorghum and Soybean Seed Research Conf. and Seed Expo*. Chicago, IL: Am. Seed Trade Assoc.

Tuinstra MR, Soumana S, Al-Khatib K, Kapran I, Toure A, Ast AV, Bastiaans L, Ochanda NW, Salami I, Kayentao M and Dembele S. 2009. Efficacy of herbicide seed treatments for controlling *Striga* infestation of sorghum. *Crop Science* **49**: 923-929.

Umrani MK, Bhoi PG and Patil NB. 1980. Effect of weed competition on growth and yield of pearl millet. Journal of Maharashtra Agricultural University 5: 56-57.

Walia US, Singh S and Singh B. 2007. Integrated control of hardy weeds in maize. *Indian Journal of Weed Science* **39**: 17-20.

Watling JR and Press MC. 1997. How is the relationship between the C_4 cereal Sorghum bicolor and the C_3 root hemi-parasites *Striga hermonthica* and *Striga asiatica* affected by elevated CO_2? *Plant Cell and Environment* **20**: 1292-1300.

Wiese AF, Collier JW, Clark LE and Havelka UD. 1964. Effect of weeds and cultural practices on sorghum yields. *Weeds* **12**: 209-211.

Wu Han Wen, Walker S, Osten V, Taylor I and Sindel B. 2004. Emergence and persistence of barnyard grass (*Echinichloa colona* (L.) Link) and its management options in sorghum. Weed Management: Balancing people, planet, profit, pp. 538-541. In: *Proceedings of 14th Australian Weeds Conference,* 6-9 September, Wagga, New South Wales, Australia.

Yang XH, Scheffler BE and Weston LA. 2004. SOR1 a gene associated with herbicide production in sorghum root hairs. *Journal of Experimental Botany* **55:** 2251-2259.

Zimdahl RL. 1980. *Crop-weed competition: A review*. International Plant Protection Centre, Oregon State University, Corvallis, Oregon 97331, USA.

Ziska LH. 2001. Changes in competitive ability between a C_4 and a C_3 weed with elevated carbon dioxide. *Weed Science* **49**: 622-627.

Ziska LH. 2003. Evaluation of yield loss in field sorghum from a C_3 and C_4 weed with increasing CO_2. *Weed Science* **51**: 914-918.

Indian Journal of Weed Science **47**(3): 254–266, 2015

Weed management in maize-based cropping system

Anil Kumar*, Jai Kumar[1], R. Puniya, Amit Mahajan, Neetu Sharma and Lobzang Stanzen
Division of Agronomy, FOA, Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu, Main campus, Chatha, Jammu, J&K 180 009

Received: 15 July 2015; Revised: 18 August 2015

ABSTRACT

Maize (*Zea mays* L), being a C_4 plant, is one of the most vibrant food grain crops under diverse edaphological conditions. In India, maize-wheat is by and large a predominant cropping system that is followed on a large scale, particularly in central and northern part of the country. The low productivity of maize in India, as compared to major maize growing countries of the world, can be attributed to several limiting factors, of which poor weed management poses a major threat to crop productivity. The most important weeds that can be associated with maize/maize-based cropping systems in the country are *Echinochloa colonum*, *Brachiaria ramosa*, *Digitaria sanguinalis*, *Dactyloctenium aegyptium*, *Eleusine indica, Setaria glauca*, *Sorghum halepense*, *Panicum* spp. *Cynodon dactylon*, *Digitaria setigera*, *Digitaria ciliaris*, and *Leptochloa chinensis* among grasses; *Ageratum conyzoides*, *Galinsoga parvif]ora, CommeIina benghalensis, Undernia cilata, Polygonum hydropiper, Euphorbia geniculata, Oxalis latifolia, Celosia argentea*, *Cleome viscose, Sida acuta, Aschynomene indica, Acanthospermum hispidum, Portulaca oleracea, Phyllanthus niruri, Amaranthus viridis, Acalypha indica, Tridax procumbens*, *Ipomoea pestigridis*, *Parthenium hysterophorus* and *Euphorbia hirta* among non-grassy weeds and *Cyperus rotundus* and *Cyperus iria* among sedges. In the rainy season, it was reported thet the emergence of maize and weeds was simultaneous and the first 20-60 days was the most critical period of competition for the crop. However, in winter maize the period beyond 30 days and up to 45 days after sowing was detrimental to maize growth. In India, presence of weeds reduce the maize yields by 27-60%, depending upon the growth and persistence of weed population. The agronomic manipulations, *viz*. tillage and inter-cultivation, intercropping, mulching, cover crops, crop rotation, higher seed rate or plant populations, planting at closer spacing, nutrient management, planting methods, and other agro-techniques are used for weed management in maize/maize-based cropping systems. However, herbicides play a key role providing an option of economical weed management.

Key words: Cropping system, Herbicides, Maize, Weed management

Maize (*Zea mays* L) is one of the most versatile cereal crops having wider adaptability under diverse soil and climatic conditions. Globally, maize is known as the queen of cereals because it has the highest genetic yield potential amongst the cereals owing to its better dry matter accumulation efficiency in a unit area and time particularly up to 30^0 North and South latitude. Maize was first used as a source of food by ancient American and Indian civilizations and it also played an important role in their cultural heritage. These civilizations were responsible for its early domestication and utilization which helped to spread its acreage in various parts of the world. Today, maize has become one of the leading food grain crops in many parts of the world, not only in tropical and subtropical areas but also in temperate and high hill ecologies. It is cultivated in an area of about 150 M ha in 160 countries in diverse soil types, climate, and management practices with wider plant biodiversity that contributes about 36% towards the global food grain production (Anonymous 2013). It is the third most important crop of India after rice and wheat that occupies an area of about 8.67 M ha with an average productivity of about 2.57 t/ha compared to the world average productivity of about 4.94 t/ha (Anonymous 2014). As maize has wide adaptability and compatibility under diverse soil and climatic conditions, hence it is considered as one of the potential drivers of crop diversification under different situations and is cultivated in sequence with different crops under various agro-ecologies of the country. Among different maize-based cropping systems in India (Table1), maize-wheat is a dominant cropping system cultivated in an area of about 1.8 M ha mainly in rainfed ecologies. Maize-wheat is the third most important cropping system after rice-wheat and rice-rice that contributes about 3% in the national food basket (Anonymous 2013). The other

***Corresponding author:** anillau@gmail.com
[1]Dryland Research Sub-Station, Dhiansar, J&K

Table 1. Maize-based sequential cropping systems in different ago-climatic zones of India

Agro-climatic region	Cropping system	
	Irrigated	Rainfed
Western Himalayan region	Maize-wheat, maize-potato-wheat, maize-wheat-greengram, maize-mustard, maize-sugarcane	Maize-mustard maize-legumes
Eastern Himalayan region	Summer rice-maize-mustard, maize-maize, maize-maize-legumes	Sesame-rice + maize
Lower Gangetic plain region	Autumn rice-maize, jute-rice-maize	Rice-maize
Middle Gangetic plain region	Maize-early potato-wheat-mungbean, maize-wheat, maize-wheat-mungbean, maize-wheat-urdbean, maize-sugarcane-mungbean	Maize-wheat
Upper Gangetic Plain region	Maize-wheat, maize-wheat-mungbean, maize-potato-wheat, maize-potato-sunflower, maize-potato, onion,maize-potato-sugarcane-ratoon, rice-potato-maize	Maize-wheat maize-barley maize-safflower
Trans Gangetic plain region	Maize-wheat, maize-wheat-mungbean, maize-potato-wheat, maize-potato-sunflower, maize-potato-onion, mungbean-maize-toria-wheat, maize-potato-mungbean	Maize-wheat
Eastern plateau and hills region	Maize-groundnut-vegetables, maize-wheat-vegetables	Rice-potato-maize jute-maize-cowpea
Central plateau and hills region	Maize-wheat	Maize-groundnut
Western plateau and hills region	Sugarcane + maize	
Southern plateau and hills region	Rice-maize Maize-rice	Sorghum-maize, maize-sorghum-pulses, maize-potato-groundnut
East coast plain and hills region	Rice-maize-pearlmillet, maize-rice, rice-maize, rice-rice-maize	Maize-maize-pearlmillet rice-maize + cowpea
West coast plain and hills region	Maize-pulses, rice-maize	Rice-maize, groundnut-maize
Gujarat plains and hills region	Maize-wheat	Rice-maize
Western dry region	maize-mustard, maize-chickpea	Maize + legumes
Island region	Rice-maize	Maize-rice, rice-maize + cowpea, rice-maize-urdbean, rice-rice-maize

Source: Yadav and Prasad (1998)

major maize-based systems in India are maize-mustard, maize-chickpea, maize-maize, cotton-maize etc. Recently, due to the changing scenario of the natural resource base, rice-maize has emerged as potential maize-based cropping system in peninsular and eastern India besides the winter maize cultivation in traditional north-west and central Indian cropping systems.

As mentioned elsewhere the low productivity of maize in India as compared to world productivity can be attributed to several limiting factors and all but the most important amongst these has been the poor weed management which poses a major threat to crop productivity. Weeds, being hardier in nature compete with maize plants for nutrients, water, sunlight and space during entire vegetative and early reproductive stages of maize, they transpire a lot of valuable conserved moisture and absorbs large quantities of nutrients from the soil and their relative density plays a significant role in reducing the yield of crop. Also, wider spacing and slow initial growth of maize favours the growth of weeds even before crop emergence. The presence of weeds reduces the photosynthetic efficiency, dry matter production and distribution to economical parts and thereby reduces sink capacity of crop resulting in poor grain yield. In

Table 2. Maize-based intercropping systems in India

Intercropping system	Suitable area/situation
Maize + pigeonpea	All maize growing areas
Maize + cowpea	
Maize + mungbean	
Maize + urdbean	
Maize + sugarcane	
Rice + maize	
Maize + soybean	
Maize + high value vegetables	Peri-urban interface
Maize + flowers	
Baby corn + vegetables	
Sweet corn + vegetables	

Source: Yadav and Prasad (1998)

agro ecosystems, ideal environmental conditions provided for optimal crop productivity are being exploited by the associated weeds. In India, the presence of weeds, in general reduces the maize yield by 27-60%, depending upon the growth and persistence of weed population in maize crop (Tripathi *et al*. 2005, Sharma and Gautam 2006, Sunitha *et al.* 2010, Jat *et al.* 2012, Singh *et al.* 2015, Kumar *et al.* 2012). Thus, proper weed management strategies would continue to play a key role to meet the food, feed and fiber demands of an increasing population of India. Hence, it is required to redesign the strategies from time to time for the successful management of weeds. Therefore, it is essential to review the progress so far made on maize based cropping systems vis-à-vis weed management strategies in India to redesign the future methodologies for the successful management of ever increasing problems of weeds.

Weed spectrum in maize-based cropping systems

Cyperus rotundus and *Trianthema portulacastrum* were the dominant weed species in spring maize at Hissar (Singh *et al.* 1998). Whereas in Orissa, *Cynodon dactylon, Digitaria setigera, Digitaria ciliaris, Leptochloa chinensis, Daetyloctenium aegyptium, E1eusine indica, Cyperus rotundus, Cyperus iria, Celosia* argentea, *Commelina benghalensis, Sida acuta, Aschynomene indica* and *Acanthospermum hispidum* were found dominant weeds in rainfed maize (Rout and Stapathy 1996). *Commelina benghalensls, Cyperus rotundus, Cynodon dactylon, Portulaca oleracea, Phyllanthus niruri, Amaranthus viridis, Acalypha indica* and *Tridax procumbens* were the prevalent weed species in maize at Dharwad (Lamani *et al.* 2000). On the other hand, Sharma and Thakur (1998) reported that *Digitaria sanguinalis, E1eusine indica, Setaria glauca, Panicum* spp., *Cynodon dactylon, Sorghum halepense* among grasses, *Cyperus* spp. among sedges and *Commelina benghalensis, Galinsoga parviflora, Ipomoea pestigridis* and *Euphorbia hirta* among broad-leaved weeds were dominant in maize under mid hill conditions of North-Western Himalayan regions. Whereas, Jat *et al.* (2012) reported *Cyperus rotundus, Digera arvensis, Commelina bengalensis, Euphorbia hirta, Parthenium hysterophorus* and *Cleome viscosa* in maize crop of maize-wheat cropping system in Bihar. Similarly, Singh *et al*. (2015) observed *Celosia argentea, Commelina benghalensis, Dactyloctenium aegyptium, Digera arvensis, Eluesine indica, Echinochloa colona, Corchorus trilocularis, Leptochloa chinensis* and *Rumax acetosella* as dominant weed flora in maize in maize-wheat cropping system at IARI, New Delhi. *Commelina benghalensis, Ageratum conyzoides, Echinochloa colona, Panicum dichotomiflorum, Cyperus iria, Digitaria sanguinalis, Polygonum alatum* and *Aeschynomene indica* were dominant weeds observed under Palampur conditions of Himachal Pradesh (Kumar *et al.* 2012). While Sunitha *et al*. (2010) from Thrupati reported that *Panicum repens, Digitaria sanguinalis, Celosia argentea, Acanthospermum hispidum, Cleome viscosa* were dominant weeds in sweet corn. Whereas at Pantnagar, *Cynodon dactylon, Cyperus rotundus, Echinochloa crusgalli, Echinochloa colona, Agropyron repens, Parthenium hysterophorus, Digitaria sanguinalis, Eclipta alba, Euphorbia hirta, Commelina benghalensis* weeds were observed in maize (Sharma and Gautam, 2006). The differences in weed flora with respect to soil type were also noticed by many workers. In loamy clay soils, *Echinochloa colona, Brachiaria ramosa, Digitaria sanguinalis, Dactyloctenium aegyptium, Eleusine indica, Setaria glauca, Sorghum halepense* and *Panicum* spp. among grasses, *Ageratum conyzoides, Galinsoga parviflora, Commelina benghalensis, Undernia cilata, Polygonum hydropiper, Euphorbia geniculata* and *Oxalis latifolia* among non-grassy weeds and *Cyperus rotundus* among sedges were the major weed flora observed in maize fields at Pantnagar, Uttaranchal (Pandey *et al.* 2001). During *Kharif* season, *Echinochloa colona, Trianthema portulacastrum, Cyperus rotundus* and *Eleusine indica* were the dominant weeds in maize fields at Pantnagar conditions of Uttaranchal. On the other hand during winter season maize *Chenopodium album, Chenopodium murale, AnagalIis arvensis, Melilotus indica, Euphorbia hirta, Convolvulus arvensis* among broad leaved weeds, *Cyperus rotundus* among sedges and *Cynodon dactylon* among grasses were the dominant weed flora in maize at Banswara, Rajasthan (Porwal 2000). During rainy season, *Cyperus rotundus, Cynodon dactylon, Digitaria sanguinalis, Dactyloctenium aegyptium, Parthenium hysterophorus, Commelina benghalensis, Amaranthus viridis, Digera muricata, Euphorbia geniculata* and *Trichodesma indicum* were more prevalent weed flora in maize fields at Hyderabad (Sreenivas and Satyanarayana 1994). On the contrary, *Panicum repens, Dactyloctenium aegyptium* and *Cynodon dactylon, Cyperus rotundus, Trianthema portulacastrum, Parthenium hysterophorus, Flavaria australasica* and *Amaranthus viridis* were dominant weed flora in *Rabi* maize at Coimbatore (Kandasamy and Chandrasekhar 1998). In maize + soybean intercropping system, *Echinochloa colonum, Commelina benghalensis, Physallis minima, Celosia argentea, Setaria glauca, Cyperus rotundus, Ageratum conyzoides* were found dominant (Prasad and Rafey 1995). Similarly, Kumar and Singh (1992) also observed *Cyperus rotundus, Echinochloa colonum, Brachiaria ramosa* and *Commelina benghalensis, Cynodon dactylon, Sorghum halepense* as the dominant weed flora in maize + legume intercropping system. But in· maize-mustard cropping system, primarily a dicot weed *i.e. Trianthema portulacastrum* dominated the monocot weeds in first year, while in the second year monocot weeds dominated the dicot weeds during rainy season (Saikia and Pandey 2001a).

Critical period of crop-weed competition

Maize, being a widely spaced crop with slow early growth, allows the weeds to compete easily as compared to other cereal crops. Porwal (2000) observed that in the rainy season, emergence of maize and weeds were simultaneous and found that the first 20-30 days was the most critical period of competition for maize crop. Whereas, Nayital *et al.* (1989) reported that in maize during the rainy season, critical stage of crop weed competition was between 20-60 days after sowing. However, in irrigated winter maize beyond 30 days and up to 45 days after sowing was detrimental to maize growth and caused yield loss in command area of southern Rajasthan (Porwal 1998).

Agronomic manipulations for weed management

Herbicide is a key component in almost all weed management strategies, but the indiscriminate use of herbicides has resulted in serious ecological and environmental problems. Thus, a dire need was felt to discover the agronomic manipulations for weed management which are environmentally safe. Further, since environmental protection is a global concern, the age-old agronomic manipulations, *viz.* tillage and inter-cultivation, intercropping, mulching, cover crops, crop rotation, higher seed rate or plant populations, planting at closer spacing, nutrient management, planting methods, and other agro-techniques are used for weed management. The investigations on the agronomic manipulations for weed management in maize and maize-based cropping systems are reviewed below.

Tillage, inter-cultivation and sowing method: Tillage, inter-cultivation and sowing method greatly influence weed dynamics in maize. Tillage operations in maize resulted in significant reduction in weed density and weed dry weight at all the stages of crop growth over no-tillage, which resulted in a significantly higher number of cobs per hectare, grain yield and net returns as compared to no-tilled treatment. This might have happened probably due to the fact that favourable soil conditions resulted in better crop growth and development as well as lesser crop-weed competition (Sharma and Gautam 2006). The intercultural operations like mechanical weeding or two hand weedings at 20-30 and 35-45 days after sowing effectively minimized the weed population and increased maize yield (Kandasamy and Chandrasekhar 1998, Saikia and Pandey 2001b, Tripathi *et al.* 2005, Ramachandran *et al.* 2012, Saini *et al.* 2013). To substitute manual weeding, more efficiently, less energy intensive manual and machine-operated tools/ implements have been introduced for weed control in crops (Tajuddin *et al.,* 1991). Sharma *et al.* (2000) reported that hoeing at 15 DAS effectively controlled the weed population at 30 DAS which was less than half (23-32 weeds/m^2) as compared with no intercultural operation (67-70 weeds/m^2). Further, they put forth that earthing up at 30 DAS effectively controlled diverse weed flora throughout the crop growth period of rainfed maize. Pandey *et al.* (2000) reported that pine needle mulch and earthing up after removing the mulch was most effective to control major weeds in maize. Field preparation with two ploughings followed by two harrowings in baby corn-groundnut cropping sequence resulted in lower weed density and dry weight of weeds and higher economic yields of baby corn and groundnut as compared to one ploughing followed by one harrowing and unploughed Bangalore conditions (Thimmegowda *et al.* 2007). Chopra and Angiras (2008) reported that raised seed bed recorded significantly lowest weed density and dry matter of weeds at 60 days after sowing and at harvest followed by conventional tillage over zero tillage in maize crop.

Raised seed bed and conventional tillage increased grain yield by 13.74 and 16.90% over zero tillage. Likewise, Lal *et al.* (1988) also proved superiority of conventional tillage and ridge tillage over zero tillage in maize. However, Shekar *et al.* (2014) revealed that adoption of continuous zero tillage in wheat-maize cropping system proved statistically at par with zero tillage-conventional tillage in wheat-maize cropping and both of these practices enhanced sedges population significantly over continuous conventional tillage, conventional tillage-zero tillage and furrow irrigated raised bed in wheat-maize system. The stale seed bed in zero tillage and permanent beds with tank mixture of glyphosate + 2,4-D effectively controlled the mixed weed flora in maize (Jat *et al.* 2012). Sowing of maize in maize-wheat cropping system with manual seed drill recorded significantly lower count of *Ageratuim conyzoides,* which was found to be at par with multi-crop planter as compared to zero tillage sowing and conventional seeding at Palampur conditions (Ramesh *et al.* 2014).

Soil solarization: Soil solarization by covering of 0.05 mm thick transparent polyethylene during April-May after irrigation was found effective in suppressing weeds and increasing the yield of baby corn as compared to non-soil solarization. One hand weeding at 30 days after sowing in soil solarized treatment was effective in suppressing the weed dynamics and enhanced the productivity of succeeding groundnut crop (Thimmegowda *et al.* 2007). Further they revealed that land preparation and irrigation upto field capacity are essential before solarization which will enhance the solarization effect with respect to controlling of weeds that increased yield of baby corn followed by groundnut.

Planting pattern and plant population: A planting pattern of 60 x 20 cm with 83,333 plants/ha recorded significantly lowest density of grasses, sedges and broad-leaved weeds and highest weed control efficiency which was statistically at par with a planting pattern of 75 x 16 cm. These two planting patterns were found to be significantly superior to 60 x 25 and 75 x 20 cm with 66,666 plants/ha. However, planting pattern of 60 x 25 cm recorded highest cob length and green cob weight of sweet corn and planting pattern of 60 x 20 cm recorded significantly higher green fodder yield which resulted in higher net returns (Sunitha *et al.* 2010).

Weed density and biomass was significantly lower with sweet corn (*Zea mays* L. *saccharata*) population of 1,11,111 plants/ha as compared to 83,333 plants/ha and 74,074 plants/ha. The higher and medium crop population of 1,11,111 plants/ha and 83,333 plants/ha increased the cob yield by 10.7 and 6.8%, respectively, while green fodder yield by 13.6 and 10.6%, respectively as compared to the crop population of 74,074 plants/ha (Arvadiya *et al.* 2012). Similarly, Sharma and Gautam (2006) reported that seed rate of 24 kg/ha recorded significantly lower weed density, dry weight of weeds, higher number of cobs per unit area and higher grain yield in maize as compared to 16 and 20 kg seed/ha. The significant reduction in weed density and weed dry weight at higher seed rate might have happened owing to the fact that maximum competitive efficiency of crop was obtained at higher seed rate (Kumar and Walia 2003).

Nutrient management: Deshmukh *et al.* (2008) revealed that 100% recommended doses of fertilizers recorded higher weed control efficiency at 30 days after sowing which was at par with 75% recommended doses of fertilizers + 25% nitrogen through FYM as compared to 50% recommended doses of fertilizers + 50% nitrogen through FYM. Similarly, Dubey (2008) reported that application of 100 kg N/ha recorded lower density of *Echinochloa colona*, and *Commelina communis* as compared to 50 kg N/ha in the maize-cowpea intercropping system.

Application of organic manures: Organic manuring could exercise either negative or positive influence on weed seed bank and weed competition. Some might enrich soil weed seed reserves through carryover of weed seeds endowed with them by virtue of endozoochory. Some others could deplete the soil seed bank owing to allelopathic principles and their metabolites. Accordingly, a possible component of integrated weed management in a small farm could be the right choice or organic manuring. The application of different organic manures, *viz.* farm yard manure 12.5 t/ha, goat manure 12.5 t/ ha, neem cake 6 t/ha, pungam green leaf manure 6 t/ha and glyricidia green leaf manure 6 t/ha influenced the weed seed bank in the soil as well as the weed growth and crop yield of maize (Jebarathnam and Kathiresan 2006). These manures were applied and incorporated at the time of last ploughing and left undisturbed for 15 days prior to sowing of crop.

Application of farmyard manure increased the seed bank of *Cyperus rotundus* by 23.1%, *Echinochloa* sp. by 14.2% and *Trianthema portulac-astrum* by 28% as compared to control. This might have happened due to the fact that these was on enrichment of soil weed seed bank by the voiding of farm cattle passing on the seeds after feeding on the weed in a viable state due to the process of endozoochory. Whereas all the organic manures of plant origin, *viz.* glyricidia and pungam green leaf manures, pressmud and neem cake reduced the weed density and weed dry matter in maize leading to better crop yields. Reduction in weed seed germination due to these manures was of the highest magnitude of 32.5, 27.4 and + 57.1% in the case of *Cyperus rotundus*, *Echinochloa colona* and *Phyllantus niruri*, respectively. The reduction in weed seed germination and weed seed bank could be attributed to the acidic and allelopathic nature of metabolites released during the decomposition of organic manures of plant origin. Farm yard manure increased the weed density and weed dry matter significantly over the unweeded control (Saraswat *et al.* 2003).

Intercropping with cover crops/ smother crops: Saini *et al.* (2013) from Palampur revealed that soybean intercropping + one mechanical weeding (20 DAS) recorded significantly lowest weed dry weight, higher yield attributes and maize equivalent yield which was at par with 2 mechanical weedings (20 and 40 DAS) + mash intercropping in maize among all other treatments (mechanical weeding at 20 DAS, mechanical weedings at 20 DAS and 40 DAS, hand weeding at 20 DAS, hand weedings at 20 DAS and 40 DAS, soybean intercropping, soybean intercropping + hand weeding at 20 DAS and unweeded check). One mechanical weeding at 20 DAS recorded highest benefit-cost ratio of 4.3 followed by 2 mechanical weeding at 20 and 40 DAS and soybean intercropping + one mechanical weeding (20 DAS). Similarly, Deshmukh *et al*. (2008) found that the intercropping of maize + soybean (1:1) + pre-emergence application of pendimethalin 0.75 kg/ha, recorded significantly superior WCE over rest of the treatments. However, Kumar and Thakur (2005) reported that maize intercropped with soybean and blackgram had no significant variations on weed density and weed dry matter accumulation but caused 18.4 and 13.2% reduction in weed density. While Singh *et al*. (2005) from Udaipur, Rajasthan concluded that maize + soybean (1:1 or 1:2) was found effective for controlling weeds in maize.

Blackgram intercropped with maize as smother crop suppressed the weed growth to the extent of 28.3% (Tripathi *et al*. 2005). Maize + soybean (1:1) suppressed the weed species by canopy cover which resulted in highest weed smothering efficiency as compared to maize + greengram (Shah *et al*. 2011). Maize + blackgram (1:1) was effective in controlling weeds and resulted in higher grain yield as compared to maize + blackgram (2:1) and maize + blackgram (2:2) at Raipur, Chhattisgarh (Sanjay *et al.* 2012). Mishra (2014) reported that the maize + potato (1:1), maize + mustard (1:1), maize + toria (1:2), maize + pea (1:2), maize + linseed (1:2) and maize + wheat (1:2) significantly reduced the weed count in winter maize over sole maize. Amongst intercropping treatments, maize + potato (1:1) recorded highest weed control efficiency followed by maize + pea (1:2) at Kanpur, Uttar Pradesh. Hugar and Palled (2008) found that vegetable crops (cowpea, frenchbean, coriander) intercropped with maize reduced the weed density and dry weight accumulation by weeds which resulted in higher maize equivalent yield at Dharwad, Karnataka. Also, maize + cowpea recorded higher weed control efficiency followed by maize + blackgram (Selvakumar and Sundari 2006).

Brown manuring: Weeds are controlled by various ways in maize. However, in the current scenario of agriculture, evolving ecofreindly approach of weed control is more advisable to protect the natural resources such as soil flora and fauna including human beings and animals in a holistic manner. In this context, an advanced weed management strategy which has emerged in India is brown manuring. It aims at suppressing the weeds without affecting the soil physico-chemical properties and its associated microbes. It can be achieved through raising green manure crops such as *Sesbania* (dhaincha), sunhemp *etc*. as inter crop and killing the same by application of post-emergence herbicides. *Sesbania* and maize were grown together for 35 days and thereafter, *Sesbania* was knocked down with the application of 2,4-D at 0.5 kg/ha. The killed manure is allowed to remain in the field along with main crop without incorporation/ *in-situ* ploughing until its residue decomposes itself in the soil aiming to add organic manure beside weed suppression by its shade effect. Given the post-emergence spray on green manure leaves resulting in loss of chlorophyll in leaves showing brown in colour is referred to as brown manuring (Tanwar *et al*. 2010).

Brown manuring also helps in suppressing the weeds up to 50% of total weed population on the account of the shade effect of killed green manure till 45 DAS up to which the critical period of crop weed competition continues in maize. Ramachandran *et al.* (2012) revealed that pre-emergence application of alachlor 1.0 kg/ha + brown manuring reduced the density of grasses, sedges, broad-leaf weeds and total weeds, which resulted in higher weed control efficiency of 89.65% among all other herbicidal treatments. This might have happened probably due to an effective control of weeds during the early stage and suppressed the weed growth by the shade effect of *Sesbania* crop residue and rapidly growing canopy of maize at later stages up to harvest.

Herbicidal methods of weed management

The critical period of crop weed competition is 3 to 6 weeks after sowing in the case of maize. Clean and weed free cultivation is one of the principles of modern day farming of maize crop. Hence, managing weeds during this period is most critical for higher yields. The manual eradication of weeds has proved its superiority over all the measures in managing weeds. However, the adoption of this technique has not gained popularity amongst the farmers as it is time consuming, labour intensive, expensive and many a times becomes impractical because of scarcity of labour during peak season. Timely weeding is most important to minimize the yield losses and therefore, under such circumstances the only effective tool is left to control the weeds through the use of chemicals. Management of weeds through the use of chemicals has also been found as effective as realized under manual eradication in various crops, including maize with over and above benefits in saving extra costs involved in the use of labour on manual eradication of weeds. Herbicides are one of the crucial factors in a worldwide increase in cereal production. Herbicides contribute effectively and profitably to weed control, environmental protection, and at the same time, saving labour necessary for weed control practices, reduced soil erosion, save energy, increased maize production and reduced the cost of cereal farming. Therefore, herbicides benefit society as a whole. The importance of herbicides in modern weed management in maize production is underscored by the estimates that losses in the agricultural sector would increase to about 500% without the use of herbicides (Bridges 1992, 1994). Nowadays, maize production is facing a difficult situation. The world population is rapidly increasing (over 6 billion inhabitants on Earth's surface now and estimated 9 billion in 2050) (Berca 2004), every day decreasing the arable surface (nearly 2 billion hectares worldwide have been degraded since mid of the previous century) (Scherr and Yadav 1996). However, there is delusion, controversy and lack of knowledge in the world about herbicide use and its potential benefits for the world food production. Clearly the farmer using herbicides in maize production is saving money or effort on mechanical weed control. There is an environmental benefit too in reduced use of fossil fuels and reduced soil disturbance in no-till systems – representing a common benefit to us all. Beneficiaries may be individual farmers, farming communities, business houses, regulatory authorities, researchers, national populations or the whole living world.

There are different categories of herbicides used in maize/maize-based cropping systems to manage weeds based on the time of application of herbicides, *viz.* pre-emergence herbicides, early post-emergence and post-emergence herbicides. Usage of pre-emergence herbicides assumes greater importance in the view of their effectiveness from initial stages. Atrazine, pendimethalin, alachlor, and oxadiargyl are some of the mostly used pre-emergence herbicides applied in maize/maize-based systems.

For controlling the weeds in maize crop, pre-emergence applications or early post-emergence application of atrazine ranging from 0.25 kg/ha to 1.5 kg/ha with weed control efficiency (WCE) of 36-76% depending upon the soil type, pH and seasons has been tested and recommended by different researchers from different locations (Table 3). Likewise, pendimethalin application ranged from 0.5 to 1.5 kg/ha with the weed control efficiency of 52-86% (WCE) has been recommended by different workers depending upon the soil type (Table 4).

However, the infestation of some hardy weeds like *Acrachne racemosa*, *Bracchiaria reptans* and *Commelina benghalensis* etc. is increasing day by day in the maize growing belt, especially where the

Table 3. Use of atrazine in maize- based cropping systems in different agro-ecologies

Dose	Soil parameters		WCE	Location	References
	Soil	pH	(%)		
Atrazine 1.5 kg/ha	Clay loam	5.6	60.5	Palampur (mid hills), (HP)	Kumar *et al.* (2012)
	Silty clay loam	5.6	67.8	CSKHPKV, Palampur	Chopra and Angrias (2008)
Atrazine 1.0 kg/ha	Sandy loam	7.8	86.3	Middle Gujarat	Patel *et al.*(2006)
	Loamy sand	-	73.4	Ludhiana	Walia *et al.* (2007)
	Clay	7.4	83.5	Navsari (Gujarat)	Arvadiya *et al.*(2012)
	Sandy loam	7.6	52.6	New Delhi	Singh *et al*. (2015)
	Sandy loam	7.6	52.6	New Delhi	Singh *et al*. (2015)
Atrazine 0.25 kg/ha (*Rabi*)	Sandy loam	8.0	60.9	Kanpur	Verma *et al.* (2009), Singh *et al.* (2003)
Atrazine 0.50 kg/ha (*Rabi*)	Sandy loam	8.0	73.5	Kanpur	Verma *et al.* (2009), Singh *et al.* (2003)
Atrazine 0.5 kg/ha + 2,4-D (sodium salt) 0.5 kg/ha at 30 DAS (*Rabi*)	Clay	-	53.2	Junagarh (Gujarat)	Dobariya *et al.* (2014)
Atrazine + pendimethalin 0.50 + 0.25 1.0 kg/ha	Clay	7.4	86.3	Navsari (Gujarat)	Arvadiya *et al*,(2012)
Atrazine *fb* atrazine 1.50 *fb* 0.75 kg/ha	Clay loam	5.6	80.3	Palampur (mid hills), (HP)	Kumar *et al.* (2012)
Atrazine + pendimethalin 0.75 + 0.75 kg/ha	Loamy sand	-	76.9	Ludhiana	Walia *et al.(*2007)
Atrazine + alachlor 0.75 + 1.25 kg/ha	Loamy sand	-	78.1	Ludhiana	Walia *et al.* (2007)
Atrazine + pendimethalin *fb* metasulfuron-methyl 0.75+ 0.75 *fb* 0.004 kg/ha	Clay loam	5.6	69.7	Palampur (mid hills), (HP)	Kumar *et al.* (2012)
Atrazine + pendimethalin *fb* 2,4 D 1.0+ 0.50 *fb* 0.75 kg/ha	Clay loam	5.6	67.0	Palampur (mid hills), (HP)	Kumar *et al.* (2012)
Atrazine + alachlor 0.5 + 0.5 kg/ha	Sandy loam	7.8	94.9	Middle Gujarat	Patel *et al.* (2006b)
Atrazine + pendimethalin 0.5 + 0.25 kg/ha	Sandy loam	7.8	97.9	Middle Gujarat	Patel *et al.* (2006b)
Atrazine + metolachlor 0.5 + 0.5 kg/ha	Sandy loam	7.8	94.9	Middle Gujarat	Patel *et al.* (2006b)
Atrazine + metribuzin 0.5 + 0.15 kg/ha	Sandy loam	7.8	89.3	Middle Gujarat	Patel et al. (2006b)

farmers are using atrazine year after year. Thus, it is desirable to employ tank mix combinations of two herbicides having different modes of action in order to widen the weed control spectrum. A number of tank mix combinations of atrazine with pendimethalin, alachlor, metolachlor, metribuzin, 2,4-D *etc*. were tried in different research experiments under different agro-climatic conditions with weed control efficiency of 80, 67-97, 90-94, 89, and 53-67%, respectively (Table 3). Likewise, alachlor also tank mixed with a number of herbicides like pendimethalin, metolachor, metribuzin etc. proved to be successful in controlling the hardy weeds with weed control efficiency of more than 80% (Table 5).

Atrazine, recommended as a pre-emergence herbicide, is not effective against some of the weeds, both grassy and non-grassy as well as the sedge *Cyperus rotundus*. Also, sometimes farmers skip the application of pre-emergent herbicides and also due to the scarcity of labour at that time, there is left no other alternative to control the weeds emerging during later stages. However, recently a pigment synthesis inhibitor tembotrione (42% SC), which is a post-emergent broad spectrum systemic herbicide of triketone group has been tested and proved to be successful in managing all the categories of weeds infesting the maize fields during later stages. Singh *et al*. (2012) from Pantnagar reported that post-emergence application of tembotrione 120 g/ha along with surfactant (1000 ml/ha) was found most effective to control the grassy as well as non-grassy weeds as compared to other herbicidal treatments either applied as pre- or post-emergence with maximum weed control efficiency (90%). Efficacy of tembotrione 42% SC formulation increases when used with surfactant against mixed weed flora compared to when used alone (Table 7). Similar results were reported by Akhtar (2014) in spring maize at SKUAST-Jammu. Kannan and Chinnagounder (2013) from TNAU, reported that post- emergence application of potassium salt of glyphosate at 1800 g/ha in transgenic and conventional maize hybrid of 30V92 enhanced the complete control of broad spectrum weeds and hence significantly lowered weed density, weed dry weight and higher weed control efficiency ranging from 96-99% (Table 8).

Continuous use of herbicides at high doses reduces efficiency, develops resistance in weeds and leaves residues in the environment to toxic levels. However, The application of low dose herbicides reduced the quantity of herbicides, required for weed control along with hand weeding is the key practice for environmental stewardship and herbicide mixtures may serve the need for broad spectrum weed control besides long term and economic management for farmers. Rani *et al.* (2011) reported that application of sulfosulfuron 15 g/ha + imazethapyr 25 g/ha as pre-emergence with hand weeding at 40 DAS was found to be effective and economic weed management practice for irrigated sweet corn during *Rabi* season in sandy loam soils of southern agroclimatic zone of Andhra Pradesh. However, in areas where timely labour availability is

Table 4. Use of pendimethalin in maize-based cropping systems in different agro-ecologies

Herbicide/dose	Soil parameters		WCE (%)	Location	References
	Soil	pH			
Pendimethallin 1.50 kg/ha	Clay loam	5.6	60.5	Palampur (mid-hiils), HP	Kumar *et al.* (2012)
Pendimethallin 0.50 kg/ha	Sandy loam	7.8	76.5	Middle Gujarat	Patel *et al.* (2006a)
Pendimethalin 1.0 kg/ha	Loamy sand		71.5	Ludhiana, Punjab	Walia *et al.(* 2007)
	Clay	7.4	76.7	Navsari, Gujarat	Arvadiya *et al.* (2012)
	Medium to deep black	6.5-7.5	36.5	Bijapur (rainfed), Karnataka	Singh *et al.* (2009)
Pendimethalin *fb* atrazine 1.50 *fb* 0.75 kg/ha	Clay loam	5.6	75.2	Palampur (mid-hiils), HP	Kumar *et al.* (2012)
Pendimethalin 0.9 kg/ha + 2,4-D (sodium salt) 0.5 kg/ha at 30 DAS (*Rabi*)	Clay	-	50.3	Junagarh, Gujarat	Dobariya *et al.* (2014)

Table 5. Use of alachlor in maize/maize-based cropping systems in different agro-ecologies

Dose	Soil parameters		WCE (%)	Location	References
	Soil	pH			
Alachlor 1.0 kg/ha	Sandy loam	7.8	70.3	Middle Gujarat	Patel *et al.* (2006b)
Alachlor 2. 0 kg/ha	Medium to deep black	6.5-7.5	45.6	Bijapur (rainfed), Karnataka	Singh *et al*. (2009)
Alachlor 2.5 kg/ha	Loamy sand	-	74.4	Ludhiana, Punjab	Walia *et al.(*2007)
Alachlor + metolachlor 0.5 + 0.5 kg/ha	Sandy loam	7.8	81.0	Middle Gujarat	Patel *et al.* (2006b)
Alachlor + pendimethalin 0.5 + 0.25 kg/ha	Sandy loam	7.8	81.0	Middle Gujarat	Patel *et al.* (2006b)
Alachlor + metribuzin 0.5 + 0.15 kg/ha	Sandy loam	7.8	80.4	Middle Gujarat	Patel *et al.* (2006b)

Table 6. Integrated weed management in maize/maize-based cropping systems in different agro-ecologies

Dose	Soil parameter		WCE (%)	Location	References
	Soil type	pH			
Alachlor 2.0 kg/ha + 1 HW at 30DAS	Medium to deep black	6.5-7.5	55.6	Bijapur rainfed, (Karnataka)	Singh *et al. (*2009)
Atrazine + pendimethalin *fb* 1 HW 0.50 + 0.50 kg/ha	Loamy sand	-	86.7	Ludhiana, Punjab	Walia *et al.*(2007)
Atrazine + alachlor *fb* 1 HW 0.50 + 0.75 kg/ha	Loamy sand	-	89.4	Ludhiana, Punjab	Walia *et al.(*2007)
Atrazine + trifluralin *fb* 1 HW 0.50 +0.60 kg/ha	Loamy sand	-	84.9	Ludhiana, Punjab	Walia *et al. (*2007)
Atrazine 0.5 kg/ha + 1 HW and IC at 30 DAS (*Rabi*)	Clay	-	63.4	Junagarh, Gujarat	Dobariya *et al.* (2014)
Pendimethalin 0.9 kg/ha + 1 HW and IC at 30 DAS *(Rabi*)	Clay	-	51.1	Junagarh, Gujarat	Dobariya *et al.* (2014)
Sulfosulfuron 30 g/ha as pre-emergence + HW at 40 DAS(*Rabi*)	Sandy loam	7.4	73.4	Tirupati, AP	Rani *et al.* (2011)
Imazethypyr 50 g/ha as pre-emergence + HW at 40 DAS(*Rabi*)	Sandy loam	7.4	71.5	Tirupati, AP	Rani *et al.* (2011)
Sulfosulfuron 15 g/ha + imazethaypyr 25 g/ha as pre-emergence with HW at 40 DAS (*Rabi)*	Sandy loam	7.4	88.8	TirupatiAP	Rani *et al.* (2011)

assured, hand weeding twice at 20 and 40 DAS may be followed. Tank mixtures of atrazine with pendimethalin, alachlor or metribuzin along with hand weeding were tried in different research experiments under different agro-climatic conditions with weed control efficiency of 50-89% (Table 6). Walia *et al.* (2007) reported that the application of atrazine + alachlor 0.50 + 0.75 kg/ha *fb* 1 HW proved to be significantly superior with highest weed control efficiency of 89.4% followed by atrazine + pendimethalin 0.50 + 0.50 kg/ha *fb* 1 HW and atrazine + trifluralin 0.50 + 0.60 kg/ha *fb* 1 HWwith the corresponding values of weed control efficiency of 86.8 and 84.9%, respectively.

Residual effect of herbicides: Chemical weed control is the best supplement to conventional methods and forms an integral part of the modern crop production. Most of the available herbicides provide only a narrow spectrum weed control. Moreover, mixtures of herbicides allow a wider spectrum of weed control with total active ingredient. Mixture of herbicides is recommended for each crop and in the cropping system, sequential application of herbicides for each crop leads to residue accumulation in the soil and crop, thus causing adverse effects on succeeding crops. Most of the herbicides are selective and specific to the crop and persist in the soil for a few months to a few years depending upon the chemical and concentration used. Knowledge of the persistence and residual effect of herbicides in the soil is essential to use them safely and effectively. Bioassay remains a major tool for qualitative and quantitative determination of herbicides in soil. The new weed management technology based on environmental principles uses "environment-friendly" herbicides, mainly glyphosate and glufosinate. These herbicides have little residual activity, are low in mammalian toxicity, and have an average half-life in soil of about 40-60 days. This means little restriction for crop rotation and low environmental degradation (Pacanoski 2006). Verma *et al.* (2009) from Kanpur conducted an experiment to assess the direct and residual effects of atrazine with regard to weed growth and crop growth of maize-green gram cropping system and reported that atrazine applied in maize had no residual effect on weed emergence and crop stand of succeeding greengram. Likewise, Patel *et al.* (2006) from Gujarat reported that pre-emergence application of pendimethalin 0.25 kg/ha either with atrazine or alachlor or metolachlor each 0.5 kg/ha or metribuzin 0.15 kg/ha recorded significantly lower density of monocot and dicot weeds at all the intervals and also recorded higher grain yield of maize as compared to all other treatments.

None of the herbicides applied alone or as mixture at tested rates had an adverse effect on succeeding *Rabi* oat and mustard crops. However, the use of some new herbicides belonging to the sulfonylurea group like sulfosulfuron, mesosulfuron + iodosulfuron *etc*. are reported to have some residual activity. The sulfonylurea herbicides though applied at very low rates but are known for their residue under varied type of environmental conditions because of less dissipation rates (Pandey and Singh 1994). Sulfonylurea herbicides are highly active in the soil and some crops in rotation can be sensitive to even low soil residues (Walker and Brown 1982), additionally, excessive mobility and persistence of herbicides in soils may cause groundwater

Table 7. Bio-efficacy of new molecules against mixed weed flora in maize in different agro-ecologies in India

Dose	Soil parameters		WCE (%)	Location	Reference
	Soiltype	pH			
Tembotrione + surfactant 120 g/ha + surfactant (1000 ml/ha) at 15-20 DAS	-	-	90.3	Pantnagar	Singh *et al.* (2012)
Tembotrione 120 at 15-20 DAS	-	-	74.1	Pantnagar	Singh *et al.* (2012)
Sulfosulfuron 30 g/ha as pre-emergence (*Rabi*)	Sandy loam	7.4	13.0	Tirupati (AP)	Rani *et al.* (2011)
Imazethaypyr 50 g/ha as pre-emergence (*Rabi*)	Sandy loam	7.4	14.0	Tirupati (AP)	Rani *et al.* (2011)

Table 8. Effect of glyphosate application on total weed density and weed control efficiency in conventional maize transgenic hybrids

Transgenic hybrid	Herbicide application	Soil parameters		WCE (%) at 40 DAS	Location	Reference
		Soiltype	pH			
30V92	POE glyphosate 900 g/ha			96.15		
30V92	POE glyphosate 1350 g/ha			97.66		
30V92	POE glyphosate 1800 g/ha	Sandy		99.14		
30B11	POE glyphosate 900 g/ha	clay loam	8.11	95.86	Coimbatore	Kannan and
30B11	POE glyphosate 1350 g/ha		8.31	97.17		Chinnagounder (2013)
30B11	POE glyphosate 1800 g/ha			98.87		
30V92	PE atrazine 0.5 kg/ha			68.96		

contamination and phytotoxic effects to sensitive crops grown in the following season. Balyan (1998) also reported that with the exception of 0.4 mg glufosinate on mung bean and soyabean, the three herbicides, 0.4 or 0.6 mg/litre of sulfosulfuron, chlorosulfuron or glufosinate were phytotoxic and decreased weed dry matter in all the crops i.e. mung bean, soyabean, pearl millet, maize and sorghum. Also, Yadav *et al.* (2004) reported that the sulfosulfuron 25 g/ha and pendimethalin 1500 g/ha applied in wheat caused toxicity to maize but not to mung bean and cotton. However, Kaur and Brar (2014) from PAU, Ludhiana conducted a study to assess the residual effects of sulfosulfuron (25, 37.5 and 50 g/ha) and mesosulfuron + iodosulfuron (12, 18 and 24 g/ha) herbicides applied to wheat on maize (*Zea mays* L.) grown in sequence and reported that none of the sulfonylurea herbicides applied to wheat at different doses affected the emergence of maize crop during both the years. But the effect was evident on the growth characters and yields of maize during 2005, whereas in 2004, plant height and dry matter at all the stages of maize was not affected significantly. This might be due to the difference in rainfall received at different stages of the crop growth in both the years. Hence, it is not safe to grow maize in rotation after application of these sulfonylurea herbicides on wheat, as significant effect on the growth and yield of maize was recorded during the years of less rainfall.

Future thurst areas

The review revealed that there is significant scope of application of herbicides though the current challenge is to manage herbicides and other inputs in such a manner that prevents adapted species from reaching troublesome proportions. Other major areas of future thrusts include:

Assessment of on-farm losses caused by weeds: The yield losses caused by weeds in different maize-based cropping systems in the farmer's field at different agro-ecological regions needs to be assessed.

Weed ecology: To achieve maximum possible benefit from weed management technologies, sophisticated technical research must be conducted in weed ecology, genetics and physiology to enhance the basic understanding of the processes that regulate weed-crop interactions, weed population dynamics, adaptation and persistence under various weed management practices. Weed management should have a primary focus on practices that affect propagule production and survival mechanism within the diverse agro-ecosystems.

Interdisciplinary effort: To tackle the complex weed problem, research must involve system analysis, weed community analysis, molecular biology, assessment of pre and post shifts in weed community, herbicide resistance issues, issues related to transgenic plants, environmental issues and potential benefit of weeds.

On-farm assessment of weed management options: The weed management options identified by researchers must be tested in the farmer's field to assess their effectiveness and economic viability. Despite decades of research and extension in popularizing the weed management practices, its effectiveness and importance are not completely understood and hence are less adopted by the farmers. Thus, a closer linkage between researchers and extension functionaries is needed for evolving weed management strategies and popularizing effective and economical options with the farming community.

Need for knowledge-based decision-making tools: There is a need to develop a larger database of weed ecology and biology characteristics, and also to develope improve and refine weed management system simulation models for extension work and for predicting further areas where research is required. An area of current concern is the carry over residual studies of herbicides in different maize-based cropping systems. We still don't have broad spectrum post-emergent herbicides as by and large the pre-emergence application of atrazine has remained a sole destination for the past many years towards herbicidal weed management in maize. Some new molecules like tembotrione and halosulfuron have shown some promise in post-emergence control, but still have limitations with respect to complete vegetation control. There is a need to develope single window herbicide: remote sensor based remotely sensed *in situ* instant weed management technology. Also the uses of allelochemical-based herbicides is still a far-fetched hypothesis for weed management practices.

The challenge for weed scientists is to develope effective, innovative, and environmentally safe weed management system that can be integrated into current and future maize-based cropping systems to bring a more diverse approach to weed management.

REFERENCES

Akhtar P. 2014. *Bio-Efficacy of Early Post and Post-emergent Application of Tembotrione in Spring Maize (Zea mays L.) under Irrigated Sub-Tropical Shivalik Foothill Conditions.* M.Sc. Thesis (Skuast-J).

Anonymous. 2013. *Agricultural Statistics at a Glance*. Department of Agriculture and Cooperation, Ministry of Agriculture, Government of India, New Delhi. Available at *www.dacnet.nic.in.*

Anonymous. 2014. htpp:// *www.faostat.com* accessed on 2nd May, 2015.

Arvadiya LK, Raj VC, Patel TU, Arvadia MK and Patel AM. 2012. Effect of plant population and weed management practices on productivity of sweet corn. *Indian Journal of Weed Science* **44**(3): 167–171**.**

Balyan RS. 1998. Effect of sulfosulfuron, chlorosulfuron and glufosinate–treated water on mungbean,soyabean, pearlmillet, maize and sorghum. *Annals of Applied Biology* **132**: 36-37.

Berca M. 2004. *Perspectives regarding Weeds Control*, University Foundation CERA for Agriculture and Rural Development.

Bridges DC. 1992. *Crop losses due to weeds in the United States.* Weed Science Society of America Champaign, II. 403 p.

Bridges DC. 1994. Impact of weeds on human endeavour. *Weed Tecnology* **8**: 392-395.

Chopra P and Angiras NN. 2008. Influence of tillage and weed control methods on weeds, yield and yield attributes of maize (*Zea mays* L.). *Indian Journal of Weed Science* **40**(1&2): 47-50.

Deshmukh LS, Jathure RS and. Raskar SK. 2008. Studies on nutrient and weed management in *kharif* maize under rainfed conditions. *Indian Journal of Weed Science* **40**(1&2): 87-89.

Dobariya VK, Mathukia RK, Gohil BS and Chhodavadia SK. 2014. Integrated weed management in sweet corn. *Indian Journal of Weed Science* **46**(2): 195–196.

Dubey RP. 2008. Effect of weed control and nitrogen application rates on weed infestation and productivity in maize-cowpea intercropping system. *Indian Journal of Weed Science* **40** (3&4): 155-158.

Hugar HY and Palled YB. 2008. Effect of intercropped vegetables on maize and associated weeds in maize-vegtable intercropping systems. *Karnataka Journal of Agricultural Science* **21**(2): 159-161.

Jat RK, Gopar R and Gupta R. 2012. Conservation agricultural in maize-wheat cropping systems of eastern India:Weed dynamics and system productivity. In: E*xtended summaries Vol. 3*, 3rd International Agronomy Congress, November 26-30, 2012, New Delhi, India.

Jebarathnam T, Geetha and Kathiresan RM. 2006. Influence of organic manures on the weed seed bank in maize. *Indian Journal of Weed Science* **38**(3&4): 247-249.

Kandasamy OS and Chandrasekhar CN. 1998. Comparative efficacy of chemical and non-chemical methods of weed management in rainfed maize (*Zea mays* L.). *Indian Journal of Weed Science* **30**: 201–203.

Kannan S and Chinnagounder C. 2013. Evaluation of Bio-efficacy, weed control efficiency in herbicide resistant transgenic stacked and conventional corn hybrids (NK603 x TC 1507) for crop productivity. *International Journal of Scientific and Research Publications* **3**: 1-8.

Kaur T and Brar LS. 2014. Residual effect of sulfonylurea herbicides applied to wheat on succeeding maize. *Indian Journal of Weed Science* **46**(2): 129–131**.**

Kumar A and Thakur KS. 2005. Influence of intercropping and weed control measures on weeds and productivity of rainfed maize *(Zea mays). Indian Journal of Weed Science* **37**(1&2): 65-67.

Kumar B and Walia US. 2003. Effect of nitrogen and plant population levels on competition of maize (*Zea mays* L.) with weeds. *Indian Journal of Weed Science* **35**(1&2): 53-56**.**

Kumar S, Rana SS, Chander N and Angiras NN. 2012. Management of hardy weeds in maize under mid-hill conditions of Himachal Pradesh. *Indian Journal of Weed Science* **44**(1): 11–17.

Kumar S and Singh RP 1992. Management studies in maize legume intercropping system. *Annals of Agricultural Research* **13**: 71-74.

Lal BN, Chandra and Yadav MS 1988. Response of waterlogged maize to planting methods and time of nitrogen application. *Indian Journal of Agronomy* **33**: 191-193.

Lamani CS, Palled VB and Shenoy H. 2000. Weed dynamics as influenced by integrated nutrient management in hybrid maize. *Current Research* **29(**1-2): 21-22.

Mishra A 2014. Effect of winter maize-based intercropping systems on maize yield. associated weeds and economy. *Comunicata Scientae* **5**(2): 110-117**.**

Nayital SC, Sharma J and Singh CM. 1989. Weed-crop competition studies in maize under Kulu valley conditions. *Indian Journal of Weed Sciences* **21**(1-2): 47-50.

Pacanoski Z. 2006.Herbicide-resistant crops- advantages and risks. *Herbologia* **7**(1): 47-59.

Pandey AK, Prakash V, Singh RD and Mani VP. 2001. Integrated weed management in maize. *Indian Journal of Agron*omy **46** : 260-265.

Pandey AK, Singh G and Mishra OP. 2000. Growth and development of *Oxalis latifolia* in maize. *Indian Journal of Weed Science* **32**: 1-6.

Pandey J and Singh RP. 1994. Effect of sulfonylurea herbicides on weed control in wheat (*Triticum aestivum*). *Indian Journal of Agronomy* **39**: 556-565.

Pandey S and Gardner CO. 1992. Recurrent selection for population, variety and hybrid improvement in tropical maize. *Advances in Agronomy* **48**: 1-87.

Patel VJ, Upadhyay PN, Patel JB and Meisuriya MI. 2006. Effect of herbicide mixtures on weeds in *Kharif* maize *(Zea mays* L.) under idle Gujarat Conditions. *Indian Journal of Weed Science* **38**(1&2): 54-57.

Patel VJ, Upadhyay PN, Zala SU and Patel BD. 2006. Residual effect of herbicide applied as alone and mixture to *kharif* maize on succeeding *rabi* oat and mustard. *Indian Journal of Weed Science* **38**(3&4): 258-262.

Porwal MK. 1998. Effect of gradual level of nitrogen on weeds in winter maize. *Indian Journal of Weed Science* **30**: 69-71.

Porwal MK. 2000. Economics of weed-control measures in winter maize (*Zea mays*). *Indian Journal of Agronomy* **45**(2): 433-347.

Prasad K and Rafey A. 1995. Weed control in maize (*Zea mays* L.) intercropped with soybean (*Glycine max* L.). *Indian Journal of Weed Science* **27**(3&4): 167-169**.**

Rani BS, Sagar GK and Reddy PM. 2011. Effect of integrated weed management with low volume herbicides in sweet corn (*Zea mays*). *Indian Journal of Weed Science* **43**(1&2): 110-112.

Ramachandran A, Veeramani A and Prema P. 2012. Effect of brown manuring on weed growth, yield and economics of irrigated maize. *Indian Journal of Weed Science* **44**(3): 204–206.

Ramesh, Rana SS and Kumar S. 2014 Weed dynamics and productivity of maize based cropping system as influenced by tillage/planting techniques. *International Journal of Science and Technology* **3**(3): 1059-1070.

Rout D and Satapathy. 1996**.** Chemical weed control in rainfed maize (*Zea mays* L.*). Indian. Journal of Agronomy* **41**(1): 51-53**.**

Saika TP, Pandey J and Kulshreshtha G. 2000. Investigation on residue of atrazine and fluchloralin in maize-chickpea and maize-Indian mustard cropping sequences. *Indian Journal of Agronomy* **45**: 653-657.

Saikia TP and Pandey J. 2001a. *Annals of Agricultural Research* **22**: 169-170**.**

Saikia TP and Pandey J. 2001b. *Annals of Agricultural Research New Series* **22**(2): 262-266**.**

Saini JP, Punam R, Chadha S, Sharma S, Bhardwaj N and Rana N. 2013.Non-chemical methods of weed management in maize under organic production system. *Indian Journal of Weed Science* **45**(3): 198–200.

Sanjay KD, Shrivastava GK, Singh AP and Lakpale R. 2012. Weeds and crop productivity of maize + blackgram intercropping system in chhattisgarh plains. *Indian Journal of Weed Science* **44**(1): 26–29.

Saraswat, VN, Bhan VM and Yaduraju NT. 2003. *Biology and Ecology of Weeds.* Weed Management, ICAR. pp. 23.

Scherr SJ and Yadav S. 1996. *Land Degradation in the Developing World – Implication for Food, Agriculture, and the Environment to 2020.* Agriculture and the Environment Discussion paper, No. 14 Washington.

Selvakumar T and Sundari A. 2006. Effect ofintercropping and Weed Management Practices on Weeds in Maize. *Indian Journal of Weed Science* **38**(1& 2): 133-134**.**

Shah SN, Shroff JC, Patel RH and Usadadiya VP. 2011. Influence of intercropping and weed management practices on weed and maize. *International Journal of Science and Nature* **2**(1): 47-50**.**

Sharma AR, Toor AS and Sur HS. 2000. Effect of interculture operations and scheduling of atrazine application on weed control and productivity of maize (*Zea mays*) in Shiwalik foothills of Punjab. *Indian Journal of Agricultural Sciences* **70**: 757-761.

Sharma CK and Gautam RC. 2006. Effect of tillage; seed rate and weed control methods on weeds and maize *(Zea mays* L.). *Indian Journal of Weed Science* **38**(1&2): 58-61.

Sharma V and Thakur DR.1998. Integrated weed management in maize (*Zea mays* L.) under mid hill condition of north-western Himalayas**.** *Indian Journal of Weed Science* **30** (3&4): 158-162**.**

Shekar C, Singh D,Singh AK,Nepalia B and Choudhary J. 2014. Weed dynamics,productivity and soil health under different tillage and weed control practices in wheat-maize sequence. *Indian Journal of Agronomy* **59** (4): 561-567.

Singh AK, Parihar CM, Jat SL, Singh B and Sharma S. 2015. Weed management strategies in maize (*Zea mays*): Effect on weed dynamics, productivity and economics of maize-wheat (*Triticum aestivum*) cropping system in Indogangetic plains. *Indian Journal of Agricultural Sciences* **85**(1): 87-92.

Singh *et al. 1998. HAU, Journal of Research* **28:** 58-64. (Original not seen).

Singh M, Prabhukumar S, Sairam CV and Kumar A. 2009. Evaluation of different weed management in rainfed maize on farmers field. *Pakistan Journal of Research* **15 (**2-3): 183-189.

Singh M, Singh P and Nepalia. 2005. Integrated weed management studies in maize based intercropping system. *Indian Journal of Weed Science* **37**(3&4): 205-208**.**

Singh PK, Vargeese and Dawson J. 2003. Efficacy of alachlor and atrazine independently and in combination for control of weeds in winter maize (*Zea mays* L.) var. *'Ganga Safed'*-2, p. 18. In: *Proceedings of Biennial Conference of ISWS*, March 12-14, 2003.

Singh VP, Guru SK, Kumar A, Banga A and Tripathi N. 2012. Bioefficacy of tembotrione against mixed weed complex in maize. *Indian Journal of Weed Science* **44**(1): 1–5.

Sreenivas G and Satyanarayana V. 1994. Integrated weed management in rainy-season maize (*Zea mays*). *Indian Journal of Agronomy* **39:** 166-167.

Sunitha N, Reddy MP and Malleswari S. 2010. Effect of cultural manipulation and weed management practices on weed dynamics and performance of sweet corn (*Zea mays* L.). *Indian Journal of Weed Science* **42**(3&4): 184–188.

Tajuddin A, Karunanithi R and Swaminathan KR. 1991. Desing development and testing of an engine operated blade harrow for weeding. *Indian Journal of Agricultural Engineering* **1**(2): 137-140.

Tanwar SPS, Singh AK and Joshi N. 2010. Changing environment and sustained crop production: A challenge for Agronomy**.** *Journal of Arid Legumes* **7**(2): 91–100.

Thimmegowda MN, Nanjappa HV and Ramachandrappa BK. 2007. Influence of tillage and moisture regimes with soil solarization on weed dynamics and yield of baby corn groundnut crop sequence. *Indian Journal of Weed Science* **39**(1&2): 13-16**.**

Tripathi AK, Tewari AN and Prasad A. 2005. Integrated weed management in rainy season maize *(Zea mays* L.) in Central Uttar Pradesh. *Indian Journal of Weed Science* **37**(3&4): 269-270.

Verma VK, Tewari AN and Dhemri S. 2009. Effect of atrazine on weed management in winter maize-greengram cropping system in central plain zone of Uttar Pradesh. *Indian Journal of Weed Science* **41**(1&2): 41-45.

Walia US, Singh S and Singh B. 2007. Integrated control of hardy weeds in maize (*Zea mays* L.). *Indian Journal of Weed Science* **39**(1&2): 17-20.

Walker A and Brown PA. 1982. Crop response to low dose of pendimethalin, napropamide, metazachlor and chlorosulfuron in soil, pp. 141-147. In: *Proceedings of British Crop Protection Conference on Weed*.

Yadav A, Malik RK, Punia SS, Mehta R, Dharambir, Amarjeet and Bellinder R. 2004. Study on carry-over effects of herbicides applied in wheat on succeeding crops in rotation. *Indian Journal of Weed Science* **36:** 15-18.

Yadav, RL and Prasad K 1998. *Annual Report.* ICAR-PDFSR, Modipuram,U.P.

Indian Journal of Weed Science **47**(3): 267–276, 2015

Weed management in pigeonpea-based cropping systems

Ramanjit Kaur, Rishi Raj, T.K. Das, Kapila Shekhawat, Raj Singh and Anil K. Choudhary
Division of Agronomy, ICAR-Indian Agricultural Research Institute, New Delhi 110 012

Received: 28 July 2015; Revised: 27 August 2015

ABSTRACT

Pigeonpea (*Cajanus cajan* (L.) Millsp., syn. *Cajanus indicus* Spreng), also known as *arhar*, *tur*, redgram, congopea, no eye pea, is one of the most important pulse crop of India in terms of acreage and production. Worldwide, it is grown on an area of 4.75 million hectares with 3.68 million tonnes of production (FAO 2012). Its grains are highly nutritious and rich in protein (21.7%), carbohydrates, fibre and minerals that constitute the main source of dietary protein to all vegetarian people, especially in developing countries. Weed infestation in pigeonpea is severe at the initial period during first 6-8 weeks, when the crop requires to be kept free from weeds. Chemical weed control is most promising, although there are cultural options like intercropping, crop rotation, closer spacing, tillage, etc. which could reduce the weed infestation in pigeonpea and pigeonpea-based cropping systems. Intercropping of pigeonpea with soybean (2:4) had smothering effect on weeds and resulted in 32% more grain yield than in sole crop. In pigeonpea, pre-emergence applications of pendimethalin 1.25 kg/ha was found most effective with 21.4% higher grain yield. Integration of the components of production technologies enhanced the productivity of pigeonpea by 29.8% with 27.2% higher net returns. Therefore, an attempt has been made in this article to review works done on several aspects of weed management in pigeonpea-based systems.

Key words: Crop rotation, Herbicides, Pigeonpea, Weed flora, Weed management

In terms of both area and production of all important pulses grown during rainy season, India ranks first and contributes about 25% to the total pulse basket. During 1991-2007, area under pulses ranged between 20.35 and 24.66 million hectare while production and productivity ranged from 11.15 to 15.11 million tonnes and 533 to 635 kg/ha, respectively. On account of their importance as nutritious food, feed and forage, pulses remained an integral component of subsistence cropping system since time immemorial. In India, over a dozen of pulse crops are grown, the important ones being chickpea (45.6%), pigeonpea (16%), mungbean (10%), urdbean (9.7%) and lentil (5.7%). The productivity of pulses, however, continues to be low, as they are generally grown in rainfed areas under poor management condition and face various kinds of biotic and abiotic stresses. Less fertile and nutrient deficient soils, unfavourable weather, low availability of quality seeds, socio-economic factors, weed infestation, poor postharvest handling and inadequate market support are some major constraints in realizing the potential of available technologies. They can be grown as a sole crop, intercrop, catch crop, relay crop, cover crop and green manure crop, *etc*., under sequential/mono-cropping in different agro-ecological regions. In the cropping systems of dry regions, pulses are predominant due to their low input requirements and ability to tolerate drought and consequently perform relatively better than other crops in the fragile and harsh climate prevailing in the regions. Intercropping is commonly practised to obtain sustainable production even under adverse weather conditions. In North India, the development of short duration varieties of pigeonpea (*Cajanus cajan* (*L.)* Millsp., syn. *Cajanus indicus* Spreng), mungbean (*Vigna radiata* L) and urdbean (*Vigna mungo* L.) has paved way for crop diversification and intensification. On slopes of hilly regions, urdbean, mungbean, cowpea (*Vigna unguiculata*), ricebean (*Vigna umbellata*) and frenchbean (*Phaseolus vulgaris*) not only provide nutritious food and fodder but also act as an excellent cover crop. In these regions, pigeonpea, urdbean, mungbean, soybean (*Glycine max* L), *etc*. are also grown on rice bunds. In response to market opportunities and concern for systems sustainability, many new cropping systems involving pulses have replaced/ modified the traditional crop rotations. Some glaring examples are pigeonpea–wheat (*Triticum aestivum*), rice-urdbean/mungbean, soybean + pigeonpea, groundnut + pigeonpea, potato + rajmash, *etc*. In humid regions of North-East India and drier regions of central and coastal regions of South India, some of

***Corresponding author:** ramaan180103@yahoo.com

the pulses like urdbean, mungbean, lentil and lathyrus are grown as para crop (relay) which facilitates double cropping and sustainable production of the systems.

Pigeonpea (2n=22) is one of the important grain legume crop of tropical and sub-tropical regions of the world and globaly , it is grown on area of 4.75 mha with 3.68 mt of total production (FAO 2012). It is considered to be a crop of Indian origin and diversity (Van der Maesen 1980). About 1000 years ago, it was introduced in the African continent. Pigeonpea occurs throughout tropical and subtropical regions and in the warmer temperate regions from 30°N to 30°S. India, Malawi, Kenya, Myanmar Uganda and Tanzania are the major pigeonpea producing countries. During last 4 decades, pigeonpea has recorded a 72% increase in area (2.76 6 4.33 m ha) and 72% increase in production (2.14 to 3.8 million tonnes). To break the yield barrier in pigeonpea, ICRISAT and partners have developed a cytoplasmic male-sterility (CMS) based hybrid breeding technology in pigeonpea. CMS-based medium maturity hybrids, ICPH 2671 and ICPH 2740, produced 30-40% greater grain yields than the popular varieties across farmers' fields in India. This technology is also being transferred to China, Myanmar and to the ESA region.

Among the major countries growing pigeonpea, India ranks first with about 75% of the world area and 67% of production, covering about 3.53 mha, with average production and productivity of 2.89 mt and 741 kg/ha, respectively, accounts 91% of the global pigeonpea production (FAO 2012). The major pulse producing states in the country are Madhya Pradesh, Uttar Pradesh, Maharashtra, Rajasthan, Karnataka and Andhra Pradesh, which together contribute for 75% of the total pulses production in the country.

Benefits of growing pigeonpea in systems

Pigeonpea crop being deep rooted and drought tolerant grain legume and add significant amount of organic matter/nitrogen to the soil becomes an integral part of the dry land subsistence cropping system of the semi-arid tropics. It can be grown as a sole crop, mixed crop, intercrop or ratoon crop. With the development of short duration pigeonpea cultivars in recent years, its cultivation has now been introduced in irrigated areas under multiple cropping systems. The beneficial effect of pulse crops in improving soil health and sustaining productivity has long been realized. On account of biological nitrogen fixation, addition of considerable amount of organic matter through root biomass and leaf-fall, deep root systems, mobilization of nutrients, protection of soil against erosion and improving microbial biomass, they keep soil productive and alive by bringing qualitative changes in physical, chemical and biological properties (Dass and Sudhishri 2010). As a result of this, the productivity of cereals following a preceding grain legume often increases and corresponds to 40-60 kg N equivalent. Besides this, the cost of cultivation significantly decreases and returns per rupee investment increases. In the present scenario of degradation of natural resources, the value of pulses is far more important. It is, therefore, imperative that grain legumes are given a preference in cropping systems of both irrigated and dryland areas.

Three-year experiment on sandy loam soil of Kanpur, (IIPR 1984-87) reported significant improvement in productivity and N economy in wheat preceded by *Kharif* legumes. Cowpea was most beneficial followed by pigeonpea and pigeonpea + mungbean. Soybean–wheat system was most productive followed by pigeonpea – mungbean – wheat among *Kharif* pulse based cropping systems. The nitrogen economy due to preceding pigeonpea over sorghum was 51 kg N equivalent/ha. An overview of N economy of cereals and cropping systems in different agroclimatic zones under pulse based cropping system showed that N economy in different zones varied from 30-67 kg/ha.

Pigeonpea-based cropping systems

The major cropping systems involving pigeonpea are mixed cropping or intercropping and double-cropping. A large number of crops are grown together with pigeonpea in different proportion by mixing and broadcasting seeds of the component crops to cover the risk of crop failure. The intercropping system developed in vacant years aims at efficient use of production resources, enhanced productivity and providing greater stability in production system. In the pre-green revolution period, pulses found significant place in inter/mixed cropping with major and minor cereals.

Wheat was used to be generally grown with chickpea, lentil, mustard and other oilseed crops. Similarly, the coarse cereals were grown with short duration pulses like urdbean and mungbean in intercropping/mixed cropping systems. Cropping systems based approach of agricultural research, received little attention, except some considerations for utilizing the beneficial effects of growing crops of dissimilar nature in mixed/intercropping (Aiyer 1949) or sequential cropping and role of legumes in green manuring (Singh 1972). After introduction of high yielding varieties of wheat and rice in sixties, the entire agricultural systems of country witnessed a change. The low productive, risk prone legumes and oil seed crops were shifted towards marginal and fragile land of dry areas, whereas the cereal based multiple cropping systems covered irrigated areas in North. In Andhra Pradesh, Rajasthan, Gujarat, Karnataka, Maharashtra, Madhya Pradesh and Tamil Nadu states, area under pulses increased from 13.92 Mha in 1971-75 to 16.22 Mha in 2005-06, whereas Bihar, Haryana, Punjab, Uttar Pradesh, West Bengal and Orissa witnessed reverse trend, the area declining from 8.0 Mha to 4.6 Mha during the same period.

The adverse effect of continued cereal based cropping system in Northern India- the Green Revolution belt could be visualized only in the late nineties when compound production growth rate declined from 2.74% during 1981-90 to 1.66% during 1991-2000. Gradual decline in total factor productivity, deterioration in soil health and various other negative effects necessitated crop diversification and inclusion of pulses in the cereal-based system; in which pigeonpea based system plays an important role.

Availability of short duration varieties coupled with matching agro-technologies in eighties led to development of several remunerative and more productive cropping systems, which have either already shown their promise or have tremendous potential for expansion in new niches and diversification in the existing cropping systems (Ali 1994). Considerable increase in area under mungbean, urdbean, pigeonpea and lentil was observed in mid nineties and many new cropping systems emerged. In the irrigated areas of the northern and central India, pigeonpea-wheat has emerged as a promising system. Availability of short duration varieties such as *'UPAS 120'*, *'Manak'*, *'ICPL 151'*, *'Pusa 992'*, which takes about 120-160 days to mature has enabled their introduction in rice wheat systems in irrigated area of western U.P., Punjab and Haryana, Delhi and North-East Rajasthan. This has provided desired stability and sustainability to productivity of cereal based cropping system.

New niches for pigeonpea

An ideal cropping system should use natural resources efficiently and judiciously, provide sustainable, stable and high returns and do not damage the ecological balance. More than 250 double cropping systems of primary, secondary and tertiary importance in terms of their spread in the country have been listed. Out of which 30 are of primary importance (Yadav and Prasad 1997). Among top ten popular cropping systems in the country, only two, *viz*., rice-chickpea and maize-chickpea contain a pulse crop with less than 6% of the total pulse area (Yadav 1996). The following are the important pigeonpea based cropping system in different agro-climatic zones and possible new niches for pigeonpea (Singh *et al.* 2009) (Table 1 and 2).

Table 1. Important pigeonpea-based cropping systems in different agro-climatic zones

Cropping system	Possible niches	Expected area (M ha)	Suitable varieties of pigeonpea
Pigeonpea-wheat	Haryana, Punjab, North-West U.P. and North Rajasthan	1.00	*UPAS 120, Manak, Pusa 33, AL 15, AL201*
Maize-*Rabi* pigeonpea	Central and Eastern U.P., North Bihar, West Bengal, Assam	0.30	*Pusa 9, Sharad*

Table 2. Possible new niches for pigeonpea

Agroclimatic zone	States represented	Annual rainfall (mm)	Cropping system
Western Himalayan region	Jammu & Kashmir, Himachal Pradesh,Uttar Pradesh	1650-2000	Pigeonpea-wheat
Eastern Himalayan region	Assam, West Bengal, Manipur, Meghalaya, Nagaland, Arunachal Pradesh	1840-3530	Maize-pigeonpea/ horse gram,
Central Plateau and hill region	Madhya Pradesh, Rajasthan,Uttar Pradesh	490-1570	Pearlmillet+pigeonpea-fallow, rice/maizechickpea/lentil/fieldpea,
Southern plateau and hill region	Andhra Pradesh, Tamil Nadu, Karnataka	680-1000	Maize-sorghum+pigeonpea mungbean-pigeonpea
East coast plains and hills Region	Orissa, Andhra, Pradesh, Tamil Nadu, Pondicherry	780-1290	Maize-horse gram/pigeonpea/chickpea
Gujarat, plains and hills region	Gujarat	340-1790	Pearlmillet/sorghum+ pigeonpea-chickpea

Weed flora

Because it is grown during rainy/*Kharif* season and slow initial growth and sowing at wider spacing, weed infestation in pigeonpea is as severe as in other pulses at the initial period of growth and the crop requires due care/attention towards weed control at that period, otherwise, the weed growth is very fast and weeds smother the crop and it causes reduction in yield to the tune of 55-60% (Kandasamy 1999). In some other instances, the yield losses have been reported to be 21-97% in pigeonpea. Weeds caused 79.93% reduction in pigeonpea grain yield if weeds were allowed to grow till harvest, however, grain yield losses were only 38.19% in pigeonpea + soybean intercropping system (Talnikar *et al.* 2008).

In rainy season, weeds come in 2-3 flushes and growth is very fast, therefore, they compete for light, nutrient and space ane are responsible for considerable reduction in yield. Some weed species commonly occurring in the *Kharif*/wet season pigeonpea are enlisted below. They all may neither be associated to a particular pulse/legume crop nor do all pulses and legumes have all these weeds distributed with them across states/regions of the country. However, this is an overall distribution of composite culture of weeds in the pigeonpea during *Kharif* season.

Annual grass weeds: *Acrachne racemosa, Commelina benghalensis/communis/subulata/ nudiflora, Eleusine africana/indica, Setaria viridis/ glauca/verticillata, Echinocloa colona/crusgalli, Rottboellia cochinchinensis (exaltata), Brachiaria* sp, *Panicum* sp, *Dactyloctenium aegyptium, Digitaria sanguinalis/adscendens.* Annual broad-leaved weeds: *Amaranthus graecizans/hybridus/ viridis/retroflexus, Ageratum conzoides, Bidens pilosa/biternata, Celosia argentea, Chorchorus* sp, *Capsella bursa-pastoris, Datura stramonium, Digera arvensis, Euphorbia hirta, Flaveria trinervia, Galinsoga parviflora, Galium aparine, Guizotia scabra, Heliotropium indicum, Leucas aspera, Malva prusila/parviflora, Nicandra physalodes, Physalis minima, Phyllanthus niruri, Parthenium hyster-ophorus, Scoparia dulcis, Solanum nigrum, Sonchus asper/aleraceous, Tagetes minuta, Trinthema portulacasttrum/monogyna, Tribulus terrestris, Xanthium strumarium.*

Perennial weeds: Grasses**:** *Cynodon dactylon, Plantago lanceolata* (simple perennial); Sedges: *Cyperus* sp (mainly *C. rotundus* and *C. esculentus*), Broad–leaved weeds: *Convolvulus arvensis, Launaea cornuta, Pluchea lanceolata* and *Oxalis latifolia* (simple perennial).

Critical period of crop-weed competition

The initial weed infestation depends mainly upon the extent of primary tillage, availability of soil moisture and the tilth of the seed bed. Weeds compete with the crop for resources such as moisture, nutrient, and light. Some major weeds: *Cyperus rotundus* and *Digera alternifalia,* for instance are known to have an allelopathic effect on pigeonpea. At present, weeds are controlled manually, mechanically or chemically. In India, where 90% of the world's pigeonpea is grown, manual and/or mechanical methods, weeds are more common. Weeds control methods vary greatly with the status of agriculture and the nature of the cropping system These practices have certain limitation like non-availability of labor at right time and economics. Pre emergence applications alone are not sufficient to curtail repeated flushes of weeds during rainy season, which highly necessitates a post-emergence application following pre-emergence one. Weeds do not cause harm to crops equally all through the growing period. There are certain stages in crop growth cycle when weeds are more damaging to crop growth and yield. Usually early season weed competition is most detrimental to crop and, therefore, early season weed control is indispensable, The critical period of weed competition may be defined as "the short time span in the life-cycle of a crop, when weed causes maximum reduction in its yield or in other words, when weed control measure if adopted may fetch near maximal or maximum acceptable crop yield (Das 2008)." It is the specific duration of weed-free situation of a crop resulting into near maximal yield, which is sufficiently close or equal to that obtained by the season-long weed-free situation. A "thumb rule" is that the first one-fourth ($1/4^{th}$) to one-third ($1/3^{rd}$) period of the total growing duration of a crop, irrespective of growth stages, weed species and environmental (climatic and soil) conditions may be assumed as "the critical period for weed competition." In pigeonpea, initial 6-8 weeks period is the critical period of the crop-weed competition.

Weed management strategies

Preventive and physical options

Clean cultivation, use of clean seeds, keeping the seed bed free from weeds, using well decomposed organic manures, keeping the bunds and irrigation channels free from weeds, keeping tools and farm machinery clean and control of weeds before they attain reproductive stage are some of the basic and free of cost practices to be followed for successful cultivation of any crop. In addition to these practices, destruction of weeds by cutting and removal through hand hoeing, hand pulling, tillage and flooding or desiccation and exhaustion of weeds through burning, soil sterilization and mulching can also be done. Hand hoeing is considered useful because it improves soil physical conditions in addition to the removal of weeds. Hand weeding loosens the soil surrounding the rhizosphere of crop plants and thereby enhances crop growth and yield. Hand pulling should be carried out in time and early in the crop growth. Weeds in pigeonpea can be controlled effectively with hand weeding to be done at 3 and 6 weeks after sowing (Anonymous 2014). However due to frequent rains it becomes difficult to do hand weeding at proper time, furthermore, non-availability of labour for hand weeding is another problem. So there is a need to find effective weed control techniques to keep the weed flora below economic threshold level (ETL). Further the practice of zero tillage along with residue has enough bearing towards weed suppression in cropped and non-cropped situations in addition to conserving the soil moisture by reducing evaporation. Mulching is very effective against most annual weeds and some perennial weeds such as *Cynodon dactylon* and *Sorghum halepense*.

In soil solarization, a good land preparation ensuring fine tilth and smooth and even surface of soil reduces air spaces between the polythene film and soil. Surface soil temperature may increase up to 55-60° C due to solarization during hot months, which kills weed seeds and vegetative propagules, insects, nematodes and disease pathogens and cause them to die. Solarization for a minimum period of two weeks during May and June is sufficient to control weeds. Summer ploughing significantly reduced the density and biomass of purple nutsedge (*Chenopodium album*) and increased rice yield to the tune of 58.2% as compared to control in rice – chickpea system. Under zero tillage, the density of purple nutsedge was found significantly higher in comparison to normal tillage in rice–lentil system.

Cultural options

Some cultural practices such as choice of crop species, crop cultivars, planting density, crop geometry, inter cropping, crop rotation, time of sowing, crop rotation, fertilizers and irrigation practices have profound effect on weed suppression. Normally weeds compete with crop plants more severely in early growth stages, therefore, crop planning should be done in such a way that it may boost the early growth and vigor of crop plants, which results into a better crop competition with weeds. To reduce the adverse effect of weeds in field crops, select long duration varieties as these varieties grow quickly and produce canopy early, resulting in shading and thus suppress the growth of weeds. If initial big flush of weeds germinating at one point of time is bypassed through manipulation of time of sowing of a crop, a little earlier or later than its normal time of sowing, the crop may germinate and have initial growth under almost weed-free or less weedy environment.Closer spacing (row to row) suppresses the germination and growth of weeds results in keeping the crops free from weeds as weeds get less space, light and nutrients for growth.

Crop rotation

Generally in pulses and particularly in pigeonpea and pigeonpea based cropping systems, crop rotation and intercropping plays a vital role in suppressing the weeds. The possibilities of certain weed species or a group of species occurring is greater if the same crop is grown year after year. In many instances, crop rotation can eliminate or at least reduce weed problems by changing microclimate in each field. The success of rotation systems for weed suppression appears to be based on the use of crop sequences that create varying patterns of resource competition, allelopathic interference, soil disturbance, and mechanical damage to provide an unstable and frequently inhospitable environment that prevents the proliferation of a particular weed species. Crop growth pattern, cultural practices, weed control techniques, type and intensity of tillage for different crops vary in crop rotation and this variation creates a barrier for further proliferation of crop-associated weeds. Crop rotation is highly effective against parasitic weeds such as *Striga hermonthica/asiatica, Orobanche ramosa, Cuscuta* spp. and crop associated weeds like *Echinochloa colona* in rice, *Phalaris minor* and *Avena* spp in wheat. Alfalfa/lucerne if replaced by cereal crops for 2-3 years, may control *Cuscuta* to some extent.

Results of a literature survey indicate that weed population density and biomass production may be markedly reduced using crop rotation (temporal diversification) and intercropping (spatial diversification) strategies. Crop rotation resulted in emerged weed densities in test crops that were lower in 21 cases, higher in 1 case, and equivalent in 5 cases in comparison to monoculture systems. In 12 cases where weed seed density was reported, seed density in crop rotation was lower in 9 cases and equivalent in 3 cases when compared to monocultures of the component crops. Significant advances in the design and improvement of weed-suppressive crop rotation and intercropping systems are most likely to occur if three important areas of research are addressed. First, there must be continued attention to the study of weed population dynamics and crop-weed interference in crop rotation and intercropping systems.

More information is needed concerning the effects of diversification of cropping systems on weed seed longevity, weed seedling emergence, weed seed production and dormancy, agents of weed mortality, differential resource consumption by crops and weeds, and allelopathic interactions. Second, there needs to be systematic manipulation of specific components of rotation and intercropping systems to isolate and improve those elements (*e.g.,* interrow cultivation, choice of crop genotype) or combinations of elements that may be especially important for weed control. Finally, the weed-related impacts of combining crop rotation and intercropping strategies should be assessed through careful study of extant, complex farming systems and the design and testing of new integrated approaches. Many aspects of crop rotation and intercropping are compatible with current farming practices and could become more accessible to farmers if government policies are restructured to reflect the true environmental costs of agricultural production (Liebman and Dyck 1993).

Intercropping

Intercrops may demonstrate weed control advantages over sole crops in two ways. First, greater crop yield and less weed growth may be achieved if intercrops are more effective than sole crops in usurping resources from weeds or suppressing weed growth through allelopathy. Alternatively, intercrops may provide yield advantages without suppressing weed growth below levels observed in component sole crops if intercrops use resources that are not exploitable by weeds or convert resources to harvestable material more efficiently than sole crops. The nature and magnitude of crop-weed competition differs considerably between sole and intercropping systems. Growing of crops in intercropping systems is found more productive particularly under rainfed conditions. More than 70% area of pulses in India is covered under intercropping systems. Pulses are intercropped with oilseeds, cereals, coarse grains and commercial crops. Pigeonpea is also inter/mixed cropped with short growing grain legumes. The crop species, population density, sowing geometry, duration, and growth rhythm of the component crops, the moisture and fertility status of soil, and tillage practices influence weed flora in intercropping systems. Ali (1988) reported that in pigeonpea-based intercropping, legumes (cowpea, urdbean and mungbean) suppress weed flora by 30 to 40% compared with 22% by sorghum. Studies on crop-weed competition revealed that the critical period for weed control in intercropping systems is slightly longer than that for sole crops.

Sole sorghum needs weed free conditions for the initial 4-5 weeks, whereas in sorghum/pigeonpea intercrops, this period has to be extended upto 7 weeks. Multilocational studies under AICPIP during 1984-87 revealed that in a short duration pigeonpea/ mungbean or urdbean intercropping, the initial 30 days is most critical for weed control. The uncontrolled weeds upto15, 30, 45, and 60 days of sowing caused yield loss of 13, 23, 31 and 35% respectively, over weed-free control. In a long duration pigeonpea/sorghum system, the critical period of crop-weed competition extended up to 8-9 weeks (Ali 1991).

In central and peninsular India, sorghum + pigeonpea has been found to be the most productive system on Vertisols whereas on Alfisols and Entisols, pearl millet + pigeonpea proved to be the ideal system (Ali and Singh 1997). Sowing of one row of sorghum followed by one row of pigeonpea gave additional yield of sorghum besides giving normal yield of pigeonpea. This system also reduced the wilt incidence in pigeonpea crop. The compact type varieties of pigeonpea are more suitable for intercropping systems than spreading varieties. For success of this system, choice of varieties having different plant growth habit, growth rhythm, maturity period and response to plant density are very important.

Pigeonpea + cereal intercropping systems are very common in central and western part of India. The short and early maturing cereals such as sorghum, maize and millets accumulated dry matter and utilized resources during the initial slow growth period of pigeonpea. As the reproductive growth of these intercrops does not coincide with pigeonpea, the yield of cereals is not affected adversely. After harvest of cereals, pigeonpea growth is compensated and additional pigeonpea yield is obtained. Experiment conducted at IIPR, Kanpur showed that in sorghum +

pigeonpea intercropping system, the highest pigeonpea grain yield (2.7 t/ha), pigeonpea equivalent yield (3.15t/ha), net returns (Rs. 43,303 kg/ha) and B: C ratio (3.6) was recorded with 2:1 row ratio on ridge and furrow planting system. Appropriate spatial arrangement not only helps in maintaining the required plant density but also minimizes competitions among the component crops in intercropping systems resulting in higher total productivity. In pigeonpea + sorghum intercropping system spatial arrangement of 2:1 row ratio on ridge planting system recorded higher pigeonpea equivalent yield and B:C ratio as compared to 1:1 and mixed planting system. For higher profitability, selection of high yielding pulses varieties having drought resistance and shade tolerant characteristics should be chosen (Reddy *et al.* 1990).

Intercropping enhances crop canopy and thus suppresses weeds. Short duration legumes, *viz.* urdbean, mungbean, soybean and cowpea when grown with pigeonpea under intercropping system suppressed weed flora considerably. Highest suppression ability was recorded with cowpea (45.8%) followed by urdbean (41.5%) and mungbean (38.2%). Talnikar (2008) found that weeds caused 79.93% reduction in pigeonpea grain yield if weeds were allowed to grow till harvest, however, grain yield losses were only 38.19% in pigeonpea + soybean intercropping system. Certain inter-croppings, *e.g.* pigeonpea + groundnut, sorghum + pigeonpea, perlmillet + pigeonpea *etc.* may be practised under rainfed condition in the subsistence type of farming, where there are low input investment and chance/risk of crop failure due to want of rains. This normally reduces weed competition wheather pigeonpea grown as main crop or intercrop. In intercropping systems where a main crop was sown with a 'smother' crop species, weed biomass in the intercrop was lower in 47 cases and higher in 4 cases than in the main crop grown alone (as a sole crop), a variable response was observed in 3 cases. When intercrops were composed of two or more main crops, weed biomass in the intercrop was lower than in all of the component sole crops in 12 cases, intermediate between component sole crops in 10 cases, and higher than all sole crops in 2 cases.

Manual weeding is the most common method of weed management in pigeonpea based intercrops. In broadcast sowing, weeding is also done by running a country plough at 40-50 cm spacing 4-6 weeks after sowing. However, this offers only partial control of weeds and also causes some damage to crops.

Chemical options

In any cropping system, chemical weed control should be done very carefully. While choosing a herbicide, care should be taken that a herbicide has less persistence or it remain active in the soil at least up to the critical period of weed competition in crop. A herbicide used in preceding crop should not have negative residual effect on the succeeding crop. Relatively little work has been done on herbicides for pigeonpea-based systems.Some of the recommended herbicides to be used in pigeonpea-based cropping systems are given (Table 4). In Inceptisols at Kanpur, pre-emergence application of pendimethalin (1.5 kg/ ha) proved quite effective in controlling weeds in a pigeonpea/sorghum intercropping system. In pigeonpea/short duration legumes, fluchloralin (0.5 to 0.75 kg/ha) and alachlor (2 kg/ha) have been reported to effectively control seasonal weeds (Venkateswarlu and Ahlawat 1986) and enhance productivity.

Among herbicides, pre-sowing incorporation of fluchloralin 0.5-1.0 kg/ha and oxadiazon 0.75 kg/ha were found most effective in controlling weeds in chickpea, lentil, mungbean, pigeonpea and urdbean. Pre-emergence application of pendimethalin 1.25-1.5 kg/ha was most effective in controlling broad leaved weeds in all the pulses and in pigeonpea+urdbean and chickpea + mustard intercropping systems. In French bean, pendimethalin 0.75–1.50 kg/ha or metachlor 0.50–1.0 kg/ha was found very effective.

Averaged across years, the most effective weed control among the chemical treatments was achieved with post-emergence imazapic 246 g/ha even though imazapic treatment caused temporary chlorosis and stunting (Bidlack *et al.* 2006). In terms of weed control, both of the pre-emergence, sulfentrazone + chlorimuron and metribuzin herbicides were effective in reducing the density of weeds, but those that escaped control grew large resulting in a total weed dry matter often similar to the untreated and sethoxydim grass herbicide treatments. Averaged across years there was a linear decrease in pigeon pea dry matter (g/m^2) as weed dry matter increased. Among treatments with similar total weed dry matter, pigeon pea dry matter accumulation was more adversely affected when there were many weeds (untreated and sethoxydim plots) as opposed to the metribuzin treatments resulting in fewer large weeds.

Dhonde *et al.* (2009) reported that weed intensity and weed dry matter of pigeonpea at harvest was significantly lower in weed free treatment followed by fluchloralin as pre-planting incorporation (PPl) 1.0 kg/ha plus glyphosate at 45 days after sowing (DAS). Weed control efficiency was higher (75.64%) and weed index was lower (14.06%) in pendimethalin PE 1.0 kg/ha plus glyphosate 1.0 kg/ha at 45 DAS as compared to other treatments except weed free treatment.

Integrated weed management

Dhonde *et al.* (2009) concluded that seed yield of pigeonpea (2.30 t/ha) and stick yield (6.50 t/ha) was maximum in weed free treatment followed by IWM treatment, *viz.* pendimethalin 1.0 kg/ha plus hand weeding at 45 DAS. Talnikar *et al.* (2008) reported that pre emergence application of alachlor 2 kg/ha with HW and hoeing at 6 weeks after sowing proved most effective and economical in controlling weeds and enhancing the grain yield in pigeonpea + soybean intercropping system.

Field experiments conducted from 1998 to 2004 on a loamy sand soil to study the effect of weed management on weeds, growth and grain yield of pigeonpea. In some years, weed dry matter was higher than in others, due to variation in rainfall received. Two hand weedings, pendimethalin in integration with hand weeding or ridging or both and paraquat in integration with hand weeding resulted in high weed control efficiency. Uncontrolled weeds caused 31.0 to 52.8% reduction in pigeonpea grain yield in different years. The sole application of pendimethalin as pre-emergence at 45 or 75 kg/ha was less effective in controlling weeds and improving grain yield than the above mentioned treatments as pigeonpea is a long duration (about 140 days) crop and weeds emerge in different flushes due to rainy season. Integration of pendimethalin 0.45 kg/ha + hand weeding 30 DAS + ridging 50 DAS provided the high weed control efficiency and produced the highest grain yields of pigeonpea in all the years of study (Singh and Sekhon 2013). Apart from two hand

Table 3. Herbicide recommendation for pigeonpea-based cropping systems

Pigeonpea-based cropping systems	Herbicide recommendation
Pigeonpea-wheat	
Pigeonpea	*Wheat*
Fluchloralin 1.0 kg/ha PPI*	Sulfosulfuron 0.025 kg/ha at 25-35DAS
Pendimethalin 1.0 kg/ha PE**	Clodinafop + carfentrazone 0.060 kg/ha +0.020 kg/ha at 25-35 DAS
Alachlor 1.0-2.0 kg/ha PE	Clodinafop + metsufuron 0.060 kg/ha +0.005 kg/ha at 25-35 DAS
Linuron 1.0-1.5 kg/ha PE	Sulfosulfuron + metsufuron 0.020 kg/ha + 0.004 kg/ha, 28-30 DAS
Clodinafop-propargyl 50-60 g/ha POE***	Metsufuron-methyl 0.004-0.008 kg/ha at 30-35 DAS
Quizalofop 125 g/ha POE	Carfentrazone 0.020 kg/ha at 25-35 DAS
Imazethapyr 100 g/ha POE	-
Pendimethalin 1.0 kg/ha PE *fb* imazethapyr 100 g/ha	-
Pendimethalin 1.0 kg/ha PE *fb* quizalofop 50 g/ha	-
Pigeonpea-onion	
Pigeonpea	*Onion*
As mentioned above	Oxadiazon 0.75-1.0 kg/ha within 2-3 days after transplanting Quizolofop-ethyl 0.037 kg /ha + oxyfluorfen 0.18 kg/ha at 21 DAT (POE) *fb* 1 HW at 45 DAT (Patel *et al.* 2011). Pendimethalin 1.0 kg/ha or 0.75 kg/ha *fb* one hoeing. Herbicide should be applied within a week after transplanting or after first irrigation. Pendimethalin 1.0 kg/ha PE *fb* quizalofop-ethyl 0.05 kg/ha Pendimethalin 1.0 kg/ha PE *fb* oxyfluorfen 0.2 kg/ha POE
Pigeonpea-winter maize	
Pigeonpea	*Winter maize*
As mentioned above	Atrazine 1.0 kg/ha PE Atrazine 0.75 kg/ha POE (30-35 DAS) Tankmix of atrazine 0.75kg/ha + pendimethalin 0.75 kg/ha PE

PPI-Pre-plant incorporation, **PE-Pre- emergence,***POE-Post-emergence

Table 4. Some IWM options for controlling weeds in pigeonpea

Treatment	Seed yield (t/ha)	References
Pendimethalin 1.0 kg/ha PE + HW (45 DAS)	2.23	Dhonde *et al.* (2009)
Pendimethalin 0.75 kg/ha (PE) + paraquat 0.48 kg/ha (POE) 42 DAS	1.82	Padmaja *et al.* (2013)
Paraquat 0.48 kg/ha (25 DAS) + HW (50 DAS)	1.79	Singh and Sekhon (2013)
Pendimethalin 0.45 kg/ha (PE) + HW (30 DAS)	1.84	
Imazethapyr 246 g/ha POE	2.56	Bidlack *et al.* (2006)

weedings 30 + 50 DAS, weeds can also be effectively controlled with integrated use of pendimethalin 0.45 kg/ha with hand weeding 30 DAS or ridging 50 DAS or both and integrated use of paraquat 0.48 kg/ha, 25 DAS with hand weeding 50 DAS, which ultimately provide high grain yields of pigeonpea. Tomar *et al.* (2004) and Rao *et al.* (2003) concluded that in pigeonpea, effective weed control has been achieved with integrated use of pendimethalin and hand weeding.

Integration of pendimethalin with hand weeding 40 DAS is known to provide high WCE in pigeonpea. One hand weeding 30 DAS had low WCE, as after the hand weeding weeds appeared again. Similarly, sole application of pendimethalin had low WCE, as this herbicide was effective for initial 30-days only and later on as the effect of herbicide diminished weeds appeared again. Paraquat 0.48 kg/ha 25 DAS also had recorded low WCE as after initial killing of weeds, they started to grow again (Shinde *et al.* 2003). Post-emergence application of imazethapyr 75 g/ha at 15-20 DAS + paraquat 0.40 kg/ha at 8 WAS resulting in more effective control over all types of weed flora, remained at par with that of weed free treatment for various growth and yield parameters and recorded significantly higher net returns (Rs. 26,881/ha) and B:C ratio (1.8) (Sharma *et al.* 2014).

Therefore, good crop husbandry + recommended pre-planting or pre-emergence herbicides + one hand weeding to control late emerging annuals as well as perennial weeds, namely *Cynodon dactylon, Cyperus rotundus/esculentus* can be practised. Among the crop husbandary practices, time and date of sowing, tillage, variety, fertilization, crop rotation, intercropping, pests and diseases control measures may be taken care of.

Herbicide tolerant genotypes in pigeonpea

Total 1,561 germplasm lines of pigeonpea comprising of germplasm (1119), released varieties (69), Minicore (129), wild relatives (92) and derivatives of Indo-African derivatives (152) were screened against post-emergence herbicides. Foliar application of herbicides (Imazethapyr 4 ml/liter, followed by Glyphosate 5 ml/liter of water) was done with a gap of 45 days to identify herbicide tolerant lines. Only 20 genotypes exhibited some degree of tolerance, which are being rescreened to confirm their tolerance against post-emergence herbicides. Glyphosate was used for herbicide screening which affected plant at cell level irregular cell division was observed.

Weed infestation in pigeonpea is as severe as in other pulses at the initial period of growth and the crop requires to be kept free from weeds particularly during first 6-8 weeks. Intercropping enhances crop canopy and thus suppresses weeds. Short duration legumes, *viz*. urdbean, mungbean, soybean and cowpea when grown with pigeonpea under intercropping system suppressed weed flora considerably. In central and peninsular India, sorghum + pigeonpea intercropping system has been found to be the most productive system on the Vertisols. An application of pre-emergence pendimethalin 1.0 kg/ha *fb* post-emergence application of imazethapyr 0.10 kg/ha at 30-35 DAS has been found effective towards weed control in pigeonpea.

REFERENCES

Aiyer AKYN. 1949. Mixed cropping in India. *Indian Journal of Agricultural Sciences* **19**: 439-543.

Ali M. 1988. Efficacy of herbicides for weed control in winter French bean (*Phaseolus vulgaris*). *Indian Journal of Agricultural Sciences* **58**(2): 440-443.

Ali M. 1991. Weed management in pigeonpea under rainfed conditions in India. *Tropical Pest Management* **37:** 345-348.

Ali M. 1994. 25 years of research on pulse in India pp 19-22. In: *International Symposium on Pulses Rsearch* (Eds. Ali M *et al.*), 2-6 April, New Delhi, India.

Ali M. and Singh KK. 1997. Management of pulse crops under intercropping systems. In: *Recent Advances in Pulses Research* (Eds. AN Asthana and M Ali): Indian Society of Pulses Research and Development, IIPR, Kanpur. pp 489-508.

Anonymous. 2014. *Package of Practices for Kharif Crops of Punjab*. Punjab Agricultural University, Ludhiana, India.

Bidlack James E, Andy Middick, Delmar Shantz, Charles T MacKown, Robert D Williams and Srinivas C Rao. 2006. Weed control in a pigeon pea–wheat cropping system. *Field Crops Research* **96**: 63-70.

Das TK. 2008. Weed Science: Basics and Applications. Jain Brothers Pub. New Delhi. pp. 901.

Dass Anchal and Sudhishri S. 2010. Intercropping in fingermillet *(Eleusine coracana)* with pulses for enhanced productivity, resource conservation and soil fertility in uplands of Southern Orissa. *Indian Journal of Agronomy* **55**(2): 89-94

Dhonde MB, Kate SR, Pandure BS and Tambe AD. 2009. Integrated weed management in pigeonpea. *Indian Journal of Weed Science* **41**(1&2): 102-105.

FAO Stat. 2012. Food and Agricultural Organization Statistics. http://faostat.fao.org.

IIPR.1984. Annual Report, 1984-87. Indian Institute of Pulses Research, Kanpur.

Kandasamy OS.1999. Effect of herbicides with and without manual weeding on weeds and yield of rainfed pigeonpea (*Cajanus cajan* L. Millsp.). *Legume Res*earch **22**(3): 172-176.

Liebman Matt and Elizabeth Dyck. 1993. Crop rotation and intercropping strategies for weed management. *Ecological Applications* **3**(1): 92-122.

Padmaja B, Reddy Malla M and Reddy DV. 2013. Weed control efficiency of pre- and post-emergence herbicides in pigeonpea (*Cajanus cajan* L.). *Journal of Food Legumes* **26**(1&2): 44-45.

Patel TU, Patel CL, Patel DD Thanki JD, Patel PS and Ram A Jat. 2011. Effect of weed and fertilizer management on weed control and productivity of onion (*Allium cepa*). *Indian. Journal of Agronomy* **56**(3): 267-272.

Rao MM, Ramalakshmi D, Khan MM, Sree SP and Reddy MV. 2003. Effect of integrated weed management in post-rainy season pigeonpea + mungbean intercropping system in vertisols. *Indian Journal of Pulses Research* **16**(2): 112-115.

Reddy KC, Vander Ploeg J and Maga I. 1990. Genotype effects in millet/cowpea intercropping in the semi-arid tropics of Viger. *Experimental Agriculture* **26**: 387-396.

Sharma JC, Chandra Prakash, Shivran RK and Narolia RS. 2014. Integrated weed management in pigeonpea (*Cajanus Cajan* (L.) Millsp.) *International Journal of Advances in Applied Sciences* **2**(1-2): 69-74.

Shinde SH, Pawar VS, Suryawanshi GB, Ahire NR and Surve US. 2003. Integrated weed management management studies in pigeonpea + pearlmillet Walp) intercropping (2:2) system. *Indian Journal of Weed Science* **35**(1&2): 90-92.

Singh A. 1972. Conceptual and experimental basis of cropping patterns, pp 271-274. In: *Proceedings of Symposium on Cropping Patterns in India.* 27-31 January 1968, ICAR, New Delhi,.

Singh Guriqbal and Sekhon HS. 2013. Integrated weed management in pigeonpea [*Cajanus cajan* (L.) Millsp.] *World Journal of Agricultural Sciences* **9**(1): 86-91.

Singh KK, Ali M and Venkatesh MS. 2009. Pulses in cropping system. *Technical Bulletin,* IIPR, Kanpur.

Talnikar AS, Kadam GL, Karande DR and Jogdand PB. 2008. Integrated weed management in pigeonpea [*Cajanus cajan* (L.) Millsp.] *International Journal of Agricultural Sciences* **4**(1): 363-370

Tomar J, Singh HB, Vivek and Tripathi SS. 2004. Integrated weed management in intercropping of mungbean (*Vigna radiata*) and cowpea fodder (*Vigna unguiculata*) with pigeonpea (*Cajanus cajan*) under western U.P. conditions. *Indian Journal of Weed Science* **36**(1&2): 133-134.

Van der Maesen LJG.1980. India is the native home of the pigeonpea. *Miscellaneous Papers* **19**. Landbouwhoge School, Wageningen.

Venkateswarlu U and Ahlawat IPS. 1986. Studies on weed management in pigeonpea based intercropping systems. *Indian Journal of Agronomy* **31**: 184-187.

Yadav RL and Prasad K. 1997. Identifications of predominant cropping systems in different districts of India, pp.30-49. In:*NAnnual Report*, Project Directorate of Cropping Systems Research, Modipuram. .

Yadav RL. 1996. Cropping systems, pp 117-128. In: *50 Years of Crop Science Research in India* (Eds. R.S.Paroda and K.L.Chadha), ICAR, New Delhi.

Indian Journal of Weed Science **47**(3): 277–287, 2015

Weed management in vegetable and flower crop-based systems

Makhan S. Bhullar*, Tarundeep Kaur, Simerjeet Kaur and Ramawatar Yadav
Department of Agronomy, Punjab Agricultural University, Ludhiana, Punjab 141 004

Received: 11 August 2015; Revised: 2 September 2015

ABSTRACT

Vegetable and floricultural crops are major components of the horticultural industry in India. Weed management is an important aspect in the successful production of these crops. Weeds reduce crop yields, lower their quality and increase costs of production. They host pests and diseases thereby raising the need to control them as well. Weed management may involve non-chemical and or chemical methods. The decision of method to be used depends on the environmental conditions, available labour, weed population, the crop, desired management practices and the cost of controlling weeds. The major aim is to manage the weed population to a level below that will cause a reduction in economic return for the farmer. An integration of different control methods, therefore, needs to be addressed in future research. Furthermore, specific researches on weed management in horticultural crops in India need to be addressed. This article attempts to highlight important weed flora of vegetables and flower crops in India and some of the management strategies that could be used to manage these weeds.

Key words: Critical period, Herbicides, Mulch, Solarisation, Weed competition

Vegetable and floricultural crops are important among horticultural crops in India. Vegetables are rich sources of vitamins, minerals and fibres which provide food and nutritional security, and together these horticultural crops generate foreign exchange, create employment and provide raw materials for processing industries (Njoroge 1999). Most of these crops are slow growing and have poor canopy development during the early stages. This habit makes them susceptible to competition from weeds, which adversely affect yield and quality of these crops. Product quality is a major aspect of horticultural industry. Generally, farmers do not understand the negative implications of weeds in term of yield losses and the cost of its control (Roberts 1976). Weed control has been observed as one of the most important practice in crop production because good weed control will ensure maximum yield and high quality of farm produce (Njoroge 1999). Since most horticultural crops are very slow in growth, especially in the early stages of their establishment, it becomes imperative to begin weed control early enough in order to ensure high yield and quality. This paper reviews the common weeds problems and their control with particular reference to India.

Weed competition

Weeds compete with crops for water, nutrients, space, light and oxygen resulting into a delay in maturity and low yield. Generally, these losses occur as a result of reduced yield, quality, harbouring of pests or diseases, allelopathic effects on crops *etc*. The extent of yield losses depends on the type of weed flora, their intensity and duration of weed competition and soil and climatic factors. Research studies demonstrated the yield losses of up to 66% in spring cabbage, 51% in cauliflower, 70% in pea, 40% in okra, 60% in tomato, 62-82% in potato, 95% in beetroot, 28-78% in carrot, 2-41% in root and 86% in radish seed yield, 42% in onion, and 60% in garlic (Leela 1987, 1993, Sandhu *et al.* 2002, Kumar *et al.* 2001, Ahuja *et al.* 1999, Singh and Bhan 1999, Kaur *et al.* 2015). Reports from Rodenburg *et al.* (2009) have shown that weeds reduce onion bulbs, heads in lettuce and cabbage. Weeds serve as many hosts for pests and diseases, causing phyto-sanitary problems. The aphid (*Aphis gossipi*), which is known to transmit a viral disease 'potato leaf roll; and 'potato mosaic' has been found to live in *Eleusine indica* as a host (Rao 2006). Removal of such a weed has been found to reduce the incidence of this pest on potatoes (Gogoi *et al.* 1997). Weeds also carry pests over season to season. Some weeds exert allelopathic effects on some crops. For an example, *Centrosema* spp. has allelopathic effect on banana and plantain (Okezie 2000). Thus, to get maximum returns from inputs applied to these horticultural crops, there is a great need of proper weed control measures in these crops. Most of these weeds are not host specific because they infest both vegetables and flowers. It is, therefore, very difficult to draw a clear cut boundary between vegetable or flower weeds (Adeyemi and Olaniyi 2008).

***Corresponding author:** bhullarms@pau.edu

Weed control is especially important early in the season when weed competition can substantially reduce vigour, uniformity and overall yield. The period from emergence to four weeks has been found to be critical in the competition of weeds in many row crops including vegetables. Only a few vegetables are good competitors with weed flora because they quickly cover the soil, topping the weed growth like potato, transplanted brinjal and cabbage. But most vegetables, such as carrots, turmeric or direct-seeded vegetable crops like cabbage grow slowly and they cover the soil very sparsely, suffering strong weed competition not only for water, nutrients and light, but even for space. Thus, if weed control is not carried out timely, there will be no production at all. There are many examples of problems in crop-yield reduction (Labrada 1996) that indicate the great sensibility of vegetables to early weed competition and the need to control weeds at early crop stages. Weed competition is more severe when a direct-seeded vegetable is grown.

Critical period of weed control

This period has been defined as an interval in the life-cycle of the crop when it must be kept weed-free to prevent yield loss. Horticultural crops are very sensitive to weed competition and need to keep them weed-free, from planting, emergence or until the end of their critical weed free period (Table 1). If the crop is kept weed-free for the critical period, generally no yield reduction would be there. Again, weeds emerging after the critical weed-free period will not affect yield, but control efforts after this time may make harvest more efficient, or reduce weed seed banks and reduce weed problems in subsequent years. The critical period of weed competition is usually longer in direct-seeded than in transplanted crops. For example, if transplanted pepper has to be weeded from the second week until the third month after transplant to prevent a 10% yield loss, direct-seeded pepper must be weeded during the first four months after emergence to prevent the same loss (Medina 1995). Some traditional techniques, *viz*. transplant, earthing-up as done in potato are thought to increase crop competitiveness. Obviously, weather conditions and weed density have a great influence on the length of critical periods.

Weed flora

Weeds in vegetable and flower fields are in different sizes, forms and behaviours. They belong to many families varying in physiology, morphology and habits of growth. The first step in weed management is to identify the weeds and understand their life-cycles. Weeds can be categorised by their life-cycles and management strategies developed accordingly (Nwafor *et al.* 2010). Annual weeds complete their life-cycles in one year and reproduce solely by seeds. Annuals are divided into summer and winter groups depending on when they grow. The perennial weeds live for more than two years and can reproduce by seed or vegetative structures such as stolons, rhizomes, tubers, bulbs and roots (Njoroge 1999). Because perennial weeds are difficult to manage in vegetables, it is better not to use a field with severe perennial weed problems. A detailed list of annual and perennial weeds infesting different vegetable and flower crops during different growing seasons are presented (Tables 2 and 3).

Table 1. Critical weed-free period for some vegetable crops

Crop	Critical weed-free Period
Beet	2-4 weeks after emergence
Cabbage, early	3 weeks after planting
Carrot	3-6 weeks after emergence
Cucumber, pickling	4 weeks after seeding
Lettuce	3 weeks after planting
Onion	The whole season
Potato	15-45 days after planting
Squash	Early plantings compete better
Tomato transplanted	6 weeks after transplanting
Tomato seeded	9 weeks after seeding
Chilli	30-45 days after transplanting
Pea	30-60 days after planting
Turmeric	60-150 days after planting

The composition of present weed flora in vegetables needs to be well determined. Based on this data, we shall then be able to prepare the best control methods to be implemented. It is well known that weeds are very well adapted to the crop that they infest, because of their morphological and phenological characteristics. An autumn crop like onion and garlic can be infested by two generations of species, first by winter annuals such as *Chenopodium album* and *Poa annua* and perennials like *Cirsium arvense*, and later by the summer annuals like *Amaranthus retroflexus, Dactyloctenium aegyptium.* Weed communities may have various species, but many of them are more adapted to a particular crop. Parasitic weeds can also be a problem in vegetable crops (*Orobanche crenata* in legumes; *Apiaceae* in lettuce; *O.ramosa* in solanaceous crops and cucurbits; *Cuscuta* spp. in legumes, tomato, carrots, onion, and asparagus) (García-Torres 1993). With a sound knowledge of weed phenology and environmental factors at the local level, it is possible to predict when and where certain weeds will raise problems. Major problems in vegetables are caused

Table 2. Commonly infested annual weeds of vegetable and flower crops in India

Weed	Grass	Broad-leaf
Summer annuals		
Setaria verticillata	X	
Dactyloctenium aegyptium	X	
Eleucine indica	X	
Digitaria sanguinalis	X	
Echinochloa colona	X	
Trianthema portulacastrum		X
Cucumis callosus		X
Amaranthus viridis		X
Digera arvensis		X
Euphorbia microphylla		X
Phyllanthus niruri		X
Portulaca oleracea		X
Commelina benghalensis	X	
Cannabis sativa		X
Setaria verticillata		X
Winter annuals		
Phalaris minor	X	
Avena ludoviciana	X	
Lolium temulentum	X	
Polypogen monspeliensis	X	
Poa annua	X	
Sonchus arvensis		X
Rumex dentatus		X
Euphorbia simplex		X
Chenopodium album		X
Melilotus alba		X
Stellaria media		X
Coronopus didymus		X
Malva parviflora		X

Table 3. Commonly infested perennial weeds of vegetables and flower crops in India

Weed	Grass	Broad-leaf	Sedge
Summer perennials			
Sorghum halepense	X		
Cynodon dactylon	X		
Cyperus rotundus			X
Parthenium hysterophorus		X	
Winter perennials			
Convolvulus arvensis		X	
Cuscuta reflexa		X	
Cuscuta chinensis		X	
Orobanche aegyptiaca		X	
Cirsium arvense		X	

by broad-leaf weeds because grass weeds are much better managed in rotation or they can be successfully eliminated with the use of selective foliar-applied herbicides. The choice of control method depends on environmental concerns, marketing opportunities, desired management intensity, labor availability, weed pressure, and the crop.

Methods of weed control

Weed control in vegetables especially important early in the season when weed competition can substantially reduce vigour, uniformity and overall yield. The period from emergence to four weeks has been found to be critical in the competition of weeds in many row crops including vegetables. The methods used for controlling weeds have been divided into two broad categories, non-chemical and chemical. Many non-chemical weed management methods are common sense farming practices. These practices are of increasing importance due to consumers' concerns about pesticide residues, potential environmental contamination from pesticides, and unavailability of many older herbicides (Masiunas 2000).

Non-chemical methods

Weed management should start with non-chemical strategies. The aim should be to manage the weed population below a level that reduces economic return. In some instances, the cost of controlling weeds may be more than the economic return obtained from any yield increase. This situation occurs when a few weeds are present or the weeds germinate late in the season. In those instances, the best strategy may be to do nothing. In other situations, weed populations and other considerations may require combining herbicides with non-chemical approaches.

Preventive methods: These methods are closely connected with crop rotations and necessary when no direct measures of weed control can be taken for economic reasons. They are based on a reduction in the soil seed and propagule bank and the early awareness of the infestations. It is necessary to avoid the invasion of new species through the use of clean planting material and to prevent seed dispersal on the irrigation water, implements and machines. A written record of the history of weed infestation in the field is very useful. Another aspect is to impede perennial weed dispersal (or parasitic weeds) through the use of treatments and tillage and the use of drainage tillage to prevent propagation of some species (*Phragmites* spp., *Equisetum* spp., *Juncus* spp.) that need high moisture levels. It is also necessary to scout the field edges to prevent invasions, acting only when necessary, and bearing in mind the usefulness of the edges and borders to control erosion and hosting useful fauna (Zaragoza 2001).

Cultural methods: One should aim to establish a vigorous crop that competes effectively with weeds. This approach starts with land selection. A general rule is not to plant vegetables on land with a history of heavy weed infestation, especially of perennial weeds.

Stale seedbed: Stale ('false') seedbeds are sometimes used for vegetables when other selective weed control practices are limited or unavailable. Success depends on controlling the first flush of emerged weeds before crop emergence, and on minimal disturbance, which reduces subsequent weed flushes. It consists of preparation of a seedbed 2-3 weeks before planting to achieve maximum weed-seed germination near the soil surface. These seedlings are killed by light cultivation or by applying non-residual herbicides glyphosate and paraquat just before or after planting, but before crop emergence. The crop is planted with minimum soil disturbance to avoid exposing new weed seed to favourable germination conditions. The pre-germination should occur as close as possible to the date of planting to ensure that changes in weather conditions do not have an opportunity to change the spectrum of weeds (cool vs. warm season) in the field.

Planting to moisture: The majority of small seeded weeds germinate in upper 1 to 2 inches of soil. This aspect of the germination ecology of weeds can be exploited for control of these weeds. After the weeds are killed by cultivation, the top 1 to 2 inches of soil are allowed to dry and form a 'dust mulch'. At planting, the dust mulch is pushed away and large-seeded vegetables such as corn or beans can be planted into the zone of soil moisture. These seeds can germinate, grow, and provide partial shading of the soil surface without supplemental irrigations that would otherwise provide for an early flush of weeds.

Crop rotation: Crop rotation is a key control method to reduce weed problems in vegetables. It was considered for a long time to be a basic practice for obtaining healthy crops and good yields. This concept was mistakenly eliminated with the use of more agrochemicals. At present, however, crop rotation is gaining interest and is of value in the context of integrated crop management. Weeds tend to thrive with crops of similar growth requirements. Cultural practices designed to contribute to the crop may also benefit the growth and development of weeds. Monoculture results in a build-up of weed species that are adapted to the growing conditions of the crop. When diverse crops are used in a rotation, weed germination and growth cycles are disrupted by variations in cultural practices associated with each crop (tillage, planting dates, crop competition, and weed control methods). Traditionally, potato was included in the rotation to reduce weed problems before a less competitive crop was grown. Introducing a fallow in the rotation is essential to reduce difficult weeds like perennials. It is best to alternate legumes with grasses, row crops with close planted crops and heavy feeders with light feeders. The broad principles and examples of ideal crop rotations are given below:

1. Alternating crops with a different type of vegetation: leaf crops (lettuce, spinach, cole), root crops (carrot, potato, radish) - bulb crops (onion, garlic) - fruit crops (squash, pepper, melon).

2. Alternating grass and dicot crops, such as maize and vegetables.

3. Alternating different crop cycles: winter cereals and summer vegetables.

4. Avoiding succeeding crops of the same family: apiaceae (celery, carrot)-solanaceae (potato, tomato).

5. Alternating poor (carrot, onion) and high weed competitors (maize, potato).

6. Avoiding problematic weeds in specific crops (*e.g.* mulvaceae in celery or carrots, parasitic and perennials in general).

Cover crops: Rapid development and dense ground covering by the crop will suppress weeds. The inclusion of cover crops such as clovers, oilseed radish, summer greengram, summer black gram, sunhemp, *Sesbania* or forages in the cropping system can suppress weed growth. Highly competitive crops may be grown as short duration 'smother' crops within the rotation. Additionally, cover crop residues on the soil surface will suppress weeds by shading and cooling the soil. When choosing a cover crop, consideration should always be given to how the cover crop will affect the succeeding crop. In addition, decomposing cover crop residues may release allelo chemicals that inhibit the germination and development of weed seeds. The cover-crop systems tend to control small seeded annual broadleaf weeds the best.

Planting patterns: Crop population, spatial arrangement, and the choice of cultivar (variety) can affect weed growth. Narrow row spacing and proper plant density assure that the crop rapidly closes the canopy. A closed canopy shades out late emerging weeds and prevents germination of weed seeds requiring light. Similarly, fast-growing cultivars can have a competitive edge over the weeds. Weeds seldom pose a problem once the canopy closure occurs.

Planting time: The crop planted at the right time showed more competitiveness towards weeds than late planted crop. Crops may be divided into warm- and cool-season plants, depending on the optimal temperature for their growth. The planting date effects the time of emergence and early seedling vigour of the crop, which are important in determining crop competitiveness. Cool-season crops germinate at cooler soil temperatures and thus compete better against early emerging weeds than do warm-season crops. The crop should be planted at a time when the temperatures are favourable for crop growth.

Mulching: Mulching or covering the soil surface can prevent weed seed germination by blocking light transmission preventing seed germination. Mulches may be classified as either natural or organic (straw, bark, compost) or synthetic (plastic). As natural mulches are difficult to apply over large areas, they are best for small, specialized areas. Natural mulches should be spread evenly at least 1.5 inches thick over the soil to prevent light penetration; weeds can easily manage to reach the surface if the layer is not thick enough. Allelopathic chemicals in natural mulch also can physically suppress seedling emergence. Some manual weeding may be required along with the practice of mulching (Nogueroles and Zaragoza 1999). Paddy straw mulch at 6 t/ha in potato and 9-10 t/ha in turmeric recorded effective control of mixed weed flora (Kaur *et al*. 2008, Anonymous 2015). Natural mulch materials must be free of weed seeds and other pest organisms and be heavy enough that they are not easily displaced by wind or water. A major advantage of natural mulches is their biodegradability adding organic matter to the soil.

The use of plastic mulching is very popular in many vegetable-growing areas. Plastic mulches have been developed that filter out photosynthetically active radiation, but let through infrared light to warm the soil. These infrared transmitting mulches have been shown to be effective at controlling weeds. Synthetic mulches control weeds within the row, conserve moisture, increase soil temperature, and are easy to apply. Black plastic mulches are the most common and are particularly effective in improving early season growth of warm-season crops such as tomatoes, muskmelons, watermelons, and peppers. Better early season growth of these crops improves their competitive ability against weeds. Plastic mulches used in combination with trickle irrigation also improve water use efficiency. The biggest disadvantage of plastic mulch is disposal, as many landfills do not accept it. Photodegradable plastic mulches have been developed, but their season long persistence is a problem. Also, photodegradable mulches just degrade into smaller pieces of plastic that still contaminate the environment. Biodegradable plastic mulches are not yet widely available.

Mulching generally prevents the germination of light sensitive weeds like *Ageratum conyzoides, Portulaca oleraceae etc*. (Adeyemi and Olaniyi 2008). Some perennial weeds are not controlled (*e.g. Cyperus* spp., *Convolvulus arvensis*) by this process and for them inter-row cultivation or herbicidal treatments are necessary.

Solarisation: In this process, moist soil is covered with a clear, thin transparent plastic sheet, to trap the soil radiation for 30-45 days. Solarization works when the heat created under the plastic film becomes intense enough to kill weed seeds. The maximal soil temperature reaches nearly 60°C under polyethylene covered plots. The factors involved in solarization are soil temperature, moisture and probably gases due to which solarization reduces the germination, establishment and biomass of heat sensitive weed species. Results are often variable, depending on weather conditions. In Northern India, high soil temperature (50-60°C) can develop in soil covered with transparent polyethylene sheets in May-June (Kumar *et al.* 1993). Cold (high latitude) or cloudy places are usually not suitable for implementing solarization. Some species can tolerate solarization (*e.g.* deep rooted perennials, *viz. Sorghum halepense, Cyperus rotundus,* and also some big weed seeds such as legumes). After solarisation, the use of deep or mouldboard tillage must be avoided and the sowing should be done with minimal soil disturbance. This system is more suitable for small areas of vegetables, but is widely used under plastic greenhouse conditions.

Mechanical method: Mechanical removal of weeds is both time consuming and labor-intensive but is one of the most effective methods. Mechanical weed management starts with seedbed preparation. Moldboard plowing is usually the first step in mechanically managing weeds. It is particularly useful in controlling emerged annual weeds. An important second step is often rotary hoeing for mechanically managing weeds in large-seeded vegetable crops (sweet corn, snap beans and peas). Rotary hoeing needs to be done after the weeds germinate but before they emerge; it controls only small-seeded weeds. Once the crops have emerged or transplants are established, a row cultivator may be used to manage emerged weeds. Adjust the cultivator sweeps or teeth to dislodge or cover as many weed seedlings as possible. Seedling weeds can be killed by cultivating 1-2 inches deep. The best weed control is obtained with a row cultivator in relatively dry soils by throwing soil into the crop row to cover small weed seedlings. Avoid crop injury from poor cultivation, which reduces crop yields. Relying entirely on mechanical practices to manage weeds is difficult on large acreages. Also, several weeds especially perennials, are extremely difficult to manage unless herbicides are combined with non-chemical approaches.

The tillage operations for seed bed preparation should be planned keeping in view with the type of weeds present in the field. When annual weeds are predominant (crucifers, solanaceous, grass weeds) the objectives are unearthing and fragmentation. This must be achieved through shallow cultivation. If weeds have no dormant seeds (*Bromus* spp.), deep ploughing to bury the seeds will be advisable. If the seeds produced are dormant, this is not a good practice, because they will be viable again when they return to the soil surface after further cultivation. When perennial weeds are present, adequate tools will dependon the types of rooting. Pivot roots (*Rumex* spp.) or bourgeon roots (*Cirsium* spp.) require fragmentation and this can be achieved by using a cultivator. Fragile rhizomes (*Sorghum halepense*) require dragging and exposure at the soil surface for their depletion, but flexible rhizomes (*Cynodon dactylon*) require dragging and removal from the field. This can be done with a cultivator or harrow. Tubers (*Cyperus rotundus)* or bulbs (*Oxalis* spp.) require cutting when rhizomes are present and need to be dugup for exposure to adverse conditions (frost or drought). This can be done with the mouldboard or disk ploughing. Chisel ploughing is useful for draining wet fields and reducing the infestation of deep-rooted hygrophilous perennials (*Phragmites, Equisetum, Juncus)*. This is why reliable weed information is always necessary.

Chemical method

Herbicides offer a great scope for minimizing the cost of weed control irrespective of the situation and offer a good weed control alternative to cultural or mechanical methods in horticultural crops. Chemical control, however, is relatively poorly developed in vegetable crops as they tend to be grown in relatively small areas, hence making use of herbicides expensive and uneconomical. With this method, less labour is required; this allows the transfer of labour to other activities. Usage of pre-emergence herbicides assumes greater importance in view of their effectiveness from the initial stages of crop growth, which is the most critical period of weed competition (Bhutani *et al.* 1978). The weeds emerging later also compete with the crop and reduce its productivity and need for post-emergence herbicides or other non-chemical approaches described above. However, the herbicides alone could not provide long term control of a wide range of weed flora present in a field. This necessitates the use of an integrated approach for long term control of weeds in vegetable crops. Several herbicides are often labeled for a crop. Scouting in your area to determine which weeds are present can allow you to select the herbicide that can give you the best control. Potential environmental hazards must be considered when selecting a herbicide. Herbicide labels contain information on these hazards. The details of herbicides commonly used for weed control in vegetable crops (Table 4) and in flower corps are listed (Table 5). If an user is not familar with the use of herbicdes, it requires preliminary tests to verify its effectiveness in local conditions and selectivity to available crop cultivars.

Good practices during the use of herbicides

- A summary of a ‘decalogue’ of good practices in the use of herbicides in extensive vegetable crops (Zaragoza 2001) is provided below:
- Periodically inspect the fields and assess the weed of importance. Identify correctly the major weeds.
- The weed and crop stage of growth must be taken into account.
- Careful selection of the product and dosage, bearing in mind points one and two.
- Read the product label and follow the recommendations.
- Avoid adverse conditions at the time off application: wind, temperatures, rainfall. Do not delay treatment.
- Quality of the spraying is obtained by the correct calculation of dosage (surface to be treated must be well measured) and by the spraying equipment, which must be calibrated and in good condition (especially nozzles).
- Band or patch application to save herbicide and reduce residues.
- Keep to the environmental norms: avoid spills, drift, respect the edges, water ways, and sensitive areas. Rinse all empty cans or containers thrice and do not re-use them.
- To avoid propagation of resistant species, the same herbicide or herbicides with the same mode of action must not be used repeatedly.

Table 4. List of herbicides for use in vegetable crops

Crop	Herbicide	Dose (kg/ha)	Time of application	Reference
Garlic	Pendimethalin	0.75-1.25	PRE	Madan*et al.* (1994), Suresh *et al.* (2013), Singh *et al.* (2002a), Anonymous (2009, 2015)
	Oxyfluorfen	0.125-0.240	PRI/Early POST	Madan*et al.* (1994), Suresh *et al.* (2013), Ramani and Khanpare (2010), Anonymous (2009, 2015)
	Metolachlor	1.500	PRE	Madan *et al.* (1994), Suresh *et al.* (2013), Kumar *et al.* (2013)
	Oxadiazon	1.5	PRE	Vermani *et al.* (2001), Singh *et al.* (2002a)
	Fluchloralin *fb* Oxadiazon/ Quizalofop-ethyl	0.95 *fb* 1.0/0.05	PPI *fb* POST	Sharma *et al.* (1983), Sampat *et al.* (2014)
	Oxadiargyl	0.090- 0.667	PRE/Early-POST/ POST	Ramani and Khanpare (2010), Anonymous (2009)
	Fenoxaprop-P-ethyl	0.075	POST	Ramani and Khanpare (2010)
Root crops (Carrot, Radish)	Trifluralin	0.9-1.5	PRE	Jadhao *et al.* (1999), Singh *et al.* (2009), Kumar *et al.* (2001)
	Pendimethalin	0.75-1.87	PPI/PRE	Sandhu *et al.* (2002), Singh *et al.* (2009), Sharma (2000), Reddy *et al.* (2002)
	Alachlor	1.25-2.5	PRE	Channappagoudar *et al.* (2007b), Singh Bakshish *et al.* (2009), Leela (1987, 1993), Reddy *et al.* (2002)
	Oxyfluorfen	0.147-1.0	PRE	Singh *et al.* (2009), Leela (1993)
	Butachlor	1.0 – 2.0	PRE	Leela 1987, (1993), Channappagoudar *et al.* (2008)
	Metolachlor	2.0	PRE	Sharma (2000)
	Sethoxydim	0.8	POST	Reddy *et al.* (2002)
	Fluazifop-butyl	0.75	POST	Leela (1987)
Potato	Isoproturon	0.94	PRE	Anonymous (2009, 2015)
	Alachlor	2.5	PRE	
	Alachlor + Atrazine	1.25+0.125	PRE	
	Paraquat	0.25 – 0.375	at 5-10% of crop emergence	
	Metribuzin	0.250 -0.750	PRE	Channappagoudar *et al.* (2007a), Anonymous (2009, 2015)
	Atrazine	0.35-1.0	PRE	Bhullar *et al.* (2015), Anonymous (2015)
	Pendimethalin	0.75-1.5	PRE	Shekhawat and Maliwal (1991), Patel *et al.* (1995), Anonymous (2015)
	Diuron	1.0	PRE	Channappagoudar *et al.* (2007b)
Brinjal	Oxyfluorfen	0.10-0.15	PRE	Singh (2014), Reddy *et al.* (2000)
	Butachlor	1.0	PRE	Reddy *et al.* (2000), Bangi *et al.* (2014)
	Pendimethalin	1.0-1.5	PRE	Reddy *et al.* (2000), Kunti *et al.* (2012), Anonymous (2009)
	Metolachlor	1.0	PRE	Reddy *et al.* (2000)
	Alachlor	1.0	PRE	
	Oxadiazon	1.25	PRE	Nandal and Pandit (1988)
	Quizalofop	0.040	POST	Meena *et al.* (2006)
Cabbage	Pendimethalin	0.75-2	PRE	Noonia *et al.*(1992), Kaur *et al.* (2015)
	Sethoxydim	1.5	POST	Singh and Tripathi (1988)
	Alachlor	1.0	PRE	Nandal *et al.* (2005), Dhiman *et al.* (2005)
	Oxadiazon	1.0	PRE	Nandal *et al.* (2005), Dhiman *et al.* (2005)
	Oxyfluorfen	0.09-0.234	PPI/PRE	Nandanwar *et al.* (2006), Kaur *et al.* (2015), Kaur (2012)
	Trifluralin	0.90	PRE	Kaur (2012)
Cauliflower	Fluchloralin	0.84-1.5	PPI	Porwal and Singh (1993), Anonymous (2015)
	Alachlor	2.0	PRE	Govindra *et al.* (1983)
	Pendimethalin	0.50-1.0	PPI/PRE	Anonymous (2009, 2015)
Broccoli	Pendimethalin	0.50-1.0	PPI/PRI	
Onion	Pendimethalin *fb* Oxyfluorfen + Quizalofop-ethyl	0.750-1.5 *fb* 0.12-0.85+0.037-0.050	PPI *fb* POST	Kalhapure *et al.* (2013, 2014), Ved Parkash *et al.* (2000), Bhat and Bhushan (2005), Sardhar and Guggari (2015), Anonymous (2009, 2015)
	Alachlor	2.0	PRE	VedParkash *et al.* (2000)
	Fluchloralin	1.12	PPI	Bhat and Bhushan (2005)
	Metolachlor	1.0	PRE	Shekar *et al.* (2002)
	Oxadiargyl	0.667	PRE	Anonymous (2009)
Transplanted onion	Oxyflourfen	0.12	PRE	Shekar *et al.* (2002)
	Metolachlor	1.0	PRE	
	Pendimethalin	1.0	PRE	
Onion nursery	Pendimethalin	0.5	PRE	Sharma *et al.* (2009)
	Oxyfluorfen	0.125	PRE	
Chilli	Pendimethalin	0.75-3.0	PPI/PRE	Mukund *et al.* (1995), Kaur (2002), Patel *et al.* (2004), Anonymous (2009, 2014), Prakash *et al.* (1999)
	Fluchloralin	1.0	PRE	Singh *et al.* (1985), Anonymous (2014)
	Oxyfluorfen	0.10-1.25	PRE	Kumar and Thakral (1993), Kumar *et al.* (1995), Shaikh *et al.* (2005)
	Alachlor	3.0	PRE	Prakash *et al.* (1999)
	Oxadiazon	1.0	PRE	Singh *et al.* (1985), Anonymous (2014)
Bell pepper	Pendimethalin + Oxyfluorfen	1.00 + 0.15	PPI	Singh *et al.* (1991, 1992)

Crop	Herbicide	Dose (kg/ha)	Time of application	References
Chilli (seeded)	Pendimethalin	1.0	PRE	Agasimani and Channappagoudar (2005)
	Oxadiargyl	0.09	PRE	
Tomato	Pendimethalin	0.56-1.0	PRE- transplant	Sandhu *et al.* (1993)
	Metribuzin	0.37- 0.525	PRE- transplant	Rana and Barevadia (1995)
	Isoproturon	0.62- 1.25	PRE- transplant	Anonymous (2009, 2014)
	Sulfosulfuron	0.75	PRE	Dinesha*et al.* (2012)
Chilli + Coriander	Pendimethalin	1.0	PRE	Muthusankaranarayanan *et al.* 1997 Parkash *et al.* (1999)
Peas	Pendimethalin	1.20-1.50	PRE	Rana 2002; Anonymous (2009)
	Imazethapyr	0.15-1.5	POST	Singh *et al.* (2014), Rana *et al.* (2013)
	Quizalofop-ethyl	0.050	POST	Singh *et al.* (2014)
	Trifluralin	0.75	PPI	Banga *et al.* (1998). Anonymous (2015)
Okra	Pendimethalin	0.50-0.75	PRE	Anonymous (2015)
	Alachlor	2.5	PRE	
	Metolachlor	0.75	PRE	Anonymous (2014)
	Oxyflourfen	0.15	PRE	
Coriander	Pendimethalin	1.0	PRE	Anonymous (2009)
Turmeric	Pendimethalin	0.975	PRE	Kaur *et al.* (2008)
	Metribuzin	0.70	PRE	Anonymous (2015)
	Atrazine	0.75	PRE	

PP- Pre-plant incorporation; PRE- Pre-emergence; POST- Post-emergence; *fb*- followed by. The above herbicides, especially at their lower doses, should be integrated with hand weeding to remove the weeds escaped/emerged after the application of herbicides.

Table 5. List of herbicides for use in flower crops

Crop	Herbicide	Dose (kg/ha)	Time of application	Reference
Gladliolus	Oxyfluorfen	0.25	PRE	Manuja *et al.* (2005)
	Alachlor	1.0	PRE	Manuja *et al.* (2005)
	Atrazine	1-2	PRE	Chahal *et al.* (1994)
	Pendimethalin	0.75-1.0	PRE	Bhat and Sheikh (2015)
	Metribuzin	0.5	PRE	Rao *et al.* (2014)
	Butachlor	1.5	PRE	Rao *et al.* (2014)
	Pendimethalin + Metribuzin	0.75+0.3	PRE	Jankiram*et al.* (2014)
	Oxyfluorfen	0.5	PPI	Yadav and Bose (1987)
	Glyphosate	1.0	POST-directed	Manuja *et al.* (2005)
Gerbera	Pendimethalin	1.0	PRE	Shalini and Patil (2006)
	Alachlor	1.5	PRE	Shalini and Patil (2006)
Rose	Diuron	2-2.5	PRE	Yaduraju *et al.* (1997), Rajamani *et al.* (1992)
	Glyphosate	0.5	POST-directed	Rajamani*et al.* (1992)
	Oxyfluorfen	1.0	PRE	Rajamani (1992)
	Atrazine	1.0-2.0	PRE	Kumar and Singh (2013)
	Metribuzin	0.75-1.50	PRE	Kumar and Singh (2013)
China aster	Oxyfluorfen	0.1	PRE	Kumar and Gowda (2010)
	Metolachlor	1.0	PRE	Kumar and Gowda (2010)
Marigold	Trifluralin	1.0	PPI	Kumar *et al.* (2010)
Tuberose	Metolachlor	2.0	PRE	Murthy and Gowda (1993)
	Pendimethalin	1.25	PRE	Murthy and Gowda 1993
Winter annuals	Pendimethalin	0.50	PRE	Badhesha (2003)
(Helichrysum-bracteatum, Coreopsis lanceolata Chrysanthemum carinatum)				

PP- Pre-plant incorporation; PRE- Pre-emergence; POST- Post-emergence

REFERENCES

Adeyemi OR and Olaniyi SM. 2008. Critical period for weed removal in garden egg (*Solanum gilo*). *Nigerian Journal of Horticultural Science* **13**: 82-90.

Agasimani CA and Channappagoudar BB. 2005. Weed management in direct seeded onion + chilli cropping system, p.38. In: *Quincunnial Review Team Report, AICRP on Weed Control*. University of Agricultural Sciences Dharwad, Karnataka.

Ahuja KN, Yaduraju NT, Singh R and Singh DK. 1999. Chemical weed control in potato (*Solanum tuberosum* L.). *Indian Journal of Weed Science* **31**: 8–12.

Anonymous. 2014. TNAU Agritech portal Horticulture-vegetable crops. *www.agritech.tnau.ac.in/horticulture*

Anonymous. 2009. Vegetable seed production, pp. 48. In: *BPD Manual No. 1*. CCS Hisar Agricultural University, Hisar. www.hau.ernet.in

Anonymous. 2015. Package of practice for cultivation of vegetables, pp.158. *Punjab Agricultural University, Ludhiana*.

Badhesha GS. 2003. *Weed Control Studies in Winter Annuals for Seed Production.* M.Sc Thesis, PAU, Ludhiana.

Banga RS, Yadav Ashok and Malik RS. 1998. Evaluation of different herbicides for weed control in pea (*Pisum sativum* (L). *Indian Journal of Weed Science* **30**(3&4): 145-148.

Bangi Shivalingappa S, Eugenia P Lal, Bangi Santosh S and Sattigeri Umesh T. 2014. Effect of herbicides on weed control efficiency (WCE) and yield attributes in brinjal (*Solanum melongena* L.). *Journal of Agriculture and Veterinary Science* **7**(6): 59-65.

Barman D, Rajni K, Pal R and Upadhyay RC. 2005. Effect of mulching on cut flower production and corm multiplication in gladiolus. *Journal of Ornamental Horticulture* **8:** 152-54.

Bhagchandani PM, Pal N, Choudhury B and Mani VS. 1973. Chemical weed control in onion. *Indian Journal of Horticulture* **30**(1&2): 421-424.

Bhat KL and Bhushan A. 2005. Efficiency of different herbicides viz. pendimethalin and fluchloalin for weed control in onion. *Journal of Research SKUAST-J* **4**: 66-70.

Bhat ZA and Sheikh MQ. 2015. Evaluation of different herbicides in Gladiolus (*Gladiolus grandiflorus* L.). *International Journal of Technology Enhancements and Emerging Engineering Research* **3**(4): 56-59.

Bhullar MS, Kaur S, Kaur T and Jhala AJ. 2015. Integrated weed management in potato (*Solanum tuberosum*) using straw mulch and atrazine. *Hort Technology* **25**(3): 1-5.

Bhutani RD, Pandita ML and Singh R. 1978. Weed control studies in cauliflower variety '*Snowball-16*'. *Haryana Journal of Horticultural Science* **7**: 187-191.

Chahal DS, Sehgal OP and Singh KK. 1994. Effect of chemical and agronomic treatments on population and growth of weeds in gladiolus field. *Annals of Biology* **10:** 245-249.

Challa P and Ravindra V. 1999. Allelopathic potential of mango leaves for weed management in rose (*Rosa hybrida*) cv. *'Happiness basins'*. *Allelopathy Journal* **6:** 75-80.

Channappagoudar BB Biradar NR, Bharmagoudar TD and Koti RV. 2007a. Crop weed competition and chemical control of weeds in potato. *Karnataka Journal of Agricultural Science* **20**(4): 715-718.

Channappagoudar BB, Koti RV, Biradar NR and Bharmagoudar TD. 2007b. Influence of herbicides on growth parameters and yield in radish. *Karnataka Journal of Agricultural Science* **20**(4): 710-714.

Channappagoudar BB, Koti RV, Biradar NR and Bharmagoudar TD. 2008. Influence of herbicides on physiological and biochemical parameters in radish. *Karnataka Journal of Agricultural Science* **21**(1): 8-11.

Dhiman NK, Nandal TR and Rajender S. 2005. Effect of herbicides and their combinations on economics of cabbage production. *Crop Research* **30**: 73-76.

Dinesha MS, Dhanapal GN, Prabhudev Dhumgond NS, Vignesh V, Madhukumar and Raghavendra K. 2012. Efficiency and economics of broomrape (*Orobanche cernua* Loefl.) control with herbicides in infested tomato (*Lycopersicon esculentum* Mill.) field. *Plant Archives* **12**(2): 833-836.

Gogoi S, Gogoi PH, Mazunder A and Saikia TP. 1997. Integrated method of weed control in a seed crop of okra (*Abelmoschus esculentus*). *Annals of Agricultural Research* **18**(4): 432-436.

Jadhao BJ, Kulwal LV, Patil BM and Joshi PS. 1999.Chemical weed control in seed crop of radish. *Vegetable Science* **26**(2): 190-191.

Jankiram T, Kishan S, Das TK. 2014. Chemical weed management effects on productivity and profitability of gladiolus (*Gladiolus hybridus*) in north-western Indo-Gangetic Plains**.** *Indian Journal of Agricultural Sciences* **84**(8): 1021-1027.

Kalhapure AH, Shete BT and Bodake PS. 2013. Integrated weed management in onion (*Allium cepa*). *Indian Journal of Agronomy* **58**(3): 122-125.

Kalhapure A, Balasaheb S and Madhukar D. 2014. Weed management in onion by pre-planting and post-emergence herbicides for seed production. *Indian Journal of Weed Science* **46**(2): 142–145.

Kaur B. 2002. *Efficiency of Different Herbicides for Weed Control in Chilli*. MSc Thesis, Punjab Agricultural University, Ludhiana, India.

Kaur K, Bhullar MS, Kaur J and Walia US. 2008. Weed management in turmeric (*Curcuma longa*) through integrated approaches. *Indian Journal of Agronomy* **53**(3): 224-229.

Kaur M. 2012. *Weed Management in Direct-seeded Cabbage (Brassica oleracea var capitata)*. M.Sc. Thesis, Punjab Agricultural University, Ludhiana.

Kaur N, Bhullar MS and Gill G. 2015. Weed management options for sugarcane-vegetable intercropping systems in North-Western India. *Crop Protection* **74**: 18-23.

Kumar A and Thakral K. 1993. Effect of herbicides and nitrogen fertilization on growth and yield of chilli (*Capsicum annuum)*, 206-208. In: *ProcInternational Symposiumon Integrated Weed Management for Sustainable Agriculture*, Hisar, India Vol. III.

Kumar A, Sharma BC, Kumar R, Sharma PK and Wazir V. 2010. Integrated weed management in marigold under irrigated sub-tropical conditions of Jammu and Kashmir. *Indian Journal of Weed Science* **42**(1&2)**:** 10-13.

Kumar A, Thakral KK and Partap PS. 1995 Studies on effect of weed management practices and nitrogen levels on weed biomass with special reference to *Trianthema portulacastrum* in Chilli. *Haryana Journal of Horticultural Science* **24**: 136-140.

Kumar B, Yaduraju NT, Ahuja KN and Prasad D. 1993. Effect of soil solarization on weeds and nematodes under tropical Indian conditions. *Weed Research* **33**: 423-429

Kumar CV and Gowda JVN. 2010. Chemical weed management in china aster (*Callistephus chinensis* L. Nees). *Asian Journal of Horticulture* **5**(2)**:** 486-490.

Kumar P, Tewatia AS, Khurana SC, Duhan DV and Lajpat. 2001. Effect of cultural practices and herbicides on the growth and development of carrot. *Haryana Journal of Horticultural Science* **30**(1&2): 97-99.

Kumar S, Rana SS, Chander N and Sharma N. 2013. Integrated weed management in garlic. *Indian Journal of Weed Science* **45**(2): 126-130.

Kumar R and Singh RD. 2013. Integrated weed management in damask rose (*Rosa damascena*) nursery. *Indian Journal of Agronomy* **58**(3): 416-420.

Kumar S, Banga RS, Yadav A and Malik RK. 1998. Effect of post-emergence herbicides on weed control in potato. *Indian Journal of Weed Sci*ence **30**(3&4): 129-132.

Kunti, Sharma G and Singh AP. 2012. Weed management practices on growth and yield of winter season brinjal under Chhattisgarh plain conditions. *Indian Journal of Weed Science* **44**(1): 18-20.

Labrada R. 1996. Manejo de malezas en hortalizas, pp. 298-308. In: *Manejo de malezas para países en desarrollo* (Eds. Labrada, R., Caseley, J.C., Parker, C. Estudio). FAO Producción y Protección Vegetal 120. FAO, Roma.

Leela D. 1987. Weed control by herbicides in knoll khol and radish. *Tropical Pest Management* **33**(3): 214-219.

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

Madan SP, Jassal S and Saimbhi MS. 1994. Herbicidal control of weeds in garlic. *Punjab Vegetable Grower* **29**: 1-2.

Mani VS, Das B, Gautam KC, Singh N and Singh YR. 1973.Chemical weed control in cabbage-onion relay cropping systems, pp. 57.In: *Proceedings of 3rd All India Weed Control Seminar*, Hisar Agricultural University, Hisar, India.

Manuja S, Ram R, Singh RD and Mukherjee D. 2005. Evaluation of different herbicides for protection of gladiolus (*Gladiolus* spp.) crop from weeds. *Crop Protection* **24:** 921-26.

Masiunas J. 2000. Weed control for commercial vegetable crops, pp. 197-225. In: *Illinois Agricultural Pest Management Handbook.*

Medina A. 1995. *Estudio de la Flora arvense y su competencia en los Cultivos de Transplante y Siembra Directa de pimiento* (*Capsicum annuum* L.).Ph.D. thesis. Escuela T.S. de Ingeniería Agraria. Univ. de Lérida, Spain.

Meena RK, Kolhe SS, Sumeriya HK and Mishra PK. 2006. Response of brinjal to various weed management practices. *Haryana Journal of Agronomy* **22**: 181.

Mukund J, Kumaraswamy AS, Rudrachya M and Murthy NK. 1995. Effect of herbicides on weed control and seedling growth in chilli nursery. *Current Research* **24**: 220-221.

Murthy GMA and Gowda JVN. 1993. Evaluation of herbicides for weed control in tuberose (*Polianthes tuberose*) cv. Double. *Crop Research* **6**(1): 176-178.

Murugan M and Gopinath G. 2001. Effect of organic and inorganic mulches on growth and flowering of crossandra *(Crossandra undulaefolia* Salisb) cv. *'Saundarya'*. *Research on Crops* **2:** 346-350.

Muthusankaranarayanan A, Mohmed Ali A and Veerbadran. 1997. Weed smoothening effect of intercrops in chilli. *Indian Journal of Weed Science* **29**(3&4): 133-137.

Nandal TR and Pandit ML. 1988.Chemical weed control in brinjal. *Indian Journal of Weed Sci*ence **20**: 55-59.

Nandal TR, Dhiman NK and Sharma R. 2005. Integrated weed management in cabbage (*Brassica oleracea* var. *capitata* L.). *Indian Journal of Weed Science* **37**: 240-243.

Nandanwar A, Gonge VS, Warade AD, Mohariya A and Jagdale YL. 2006. Influence of integrated weed management on growth and yield of cabbage**.** *International Journal of Agricultural Sciences* **2**: 93-94.

Njoroge JM. 1999. Weeds and their vontrol in horticultural crops with special reference to East Africa, pp. 65-71. In: *17th East African Biennial Weed Science Conference Proceedings.*

Nogueroles-Andreu C and Zaragoza C. 1999. Buenas prácticas para el control de malas hierbas en agricultura ecológica, pp.185-206. In: *Control Integrado de las Malas Hierbas. Phytoma-España* (Eds. Fernández-Quintanilla C. Garrido M., Zaragoza C., Jacinto C.S). Valencia, Spain.

Noonia MS, Thakral KK and Vashistha RN. 1992. Effect of weed control treatments on growth and yield of cabbage (*Brassica oleracea* var. *capitata* L.). *Haryana Journal of Horticultural Sciences* **21**: 289-295.

Nwafor OE, Adepoju SO, Mba AA, Okonkwo MC, Emefiene M and Aminu K. 2010. *Proceedings of 24 Annual National Conference of Farm Management Association of Nigeria* (FAMAN). Adamawa State University, Mubi. October 11-14, 2010.

Okezie A. 2000. Getting weed management technologies to farmers in developing world, pp. 124-128. In: *Abstract of III International Weed Science Congress*, USA.

Parkash V, Pandey AK, Singh RD and Mani VP. 1999. Integrated weed management in chilli (*capsicum annuum* L.) under mid hill condition of north western Himalayas. *Indian Journal of Weed Science* **31**: 164-66.

Patel NM, Shah PM and Patel PN. 1995. Comparative effect of different herbicides in potato Cv. Kufri Badshah. *Journal of Indian Potato Association* **22**(1-2): 74-76.

Patel RB, Barevadia TN, Patel BD and Meisuriya M. 2004. Effect of cultural and chemical methods on weed and fruit yield of green chilli. *Indian Journal of Weed Science* **36** (3&4): 300-301.

Porwal MK and Singh MM. 1993. Efficacy of herbicides for weed control in cauliflower (*Brassica oleracea L.*). *Indian Journal of Weed Science* **25**: 55-60.

Rajamani K, Thanburaj ST, Thangaraj T and Murugesan S. 1992. Studies on the effect of certain herbicides in rose cv. Happiness. *South Indian Horticulture* **40:** 121-122.

Ramani BB and Khanpare VD. 2010. Efficacy of various herbicides and determination of their persistence through bioassay technique for garlic (*Allium sativum* L.*) Indian Journal of Weed Science* **42**(3&4): 198-202.

Rana HC and Barevadia TN. 1995. Efficacy of different herbicides on nutrient uptake by weeds and yield of tomato (*Lycopersicon esculentum*). *Indian Journal of Environmental Toxicology* **5**: 75-76.

Rana SS. 2002. Integrated weed management in pea (*Pisum sativum* L.) under Sangla Valley conditions of Himachal Pradesh. *Indian Journal of Weed Science* **34**(3 &4) 204-207.

Rana MC, Nag Manu, Rana SS, Sharma GD. 2013. Influence of post-emergence herbicides on weeds and productivity of garden pea (*Pisum sativum*) under mid hill conditions of Himachal Pradesh. *Indian Journal of Agronomy* **58**(2): 226-230.

Rao VS. 2006. *Principles of Weed Science*, 2nd Edition,. Published by Mohan Primlani, New Delhi.

Rao K, Dhanumjaya, Kameswari P, Lalitha GA and Rani T. 2014. Chemical weed management in gladiolus (*Gladiolus grandiflorus*). *Agricultural Science Digest - A Research Journal* **34**(3): 194-198.

Reddy CN, Reddy MD and Devi MP. 2000. Efficiency of various herbicides on weed control and yield of brinjal. *Indian Journal of Weed Science* **32**: 150-152.

Reddy SHP, Sivakumar KC, Deepu M and Reddy MAN. 2002. Effect of weed control treatments on the fresh and dry weight of total weeds and their weed control efficiency in carrot. *Current Research University of Agricultural Sciences, Bangalore* **32**(5/6): 96-98.

Roberts HA. 1976. Weed competition in vegetable crops. *Annual Applied Biology* **83**: 321-324.

Rodenburg J and Johnson DE. 2009. Weed management in rice based cropping systems in Africa. *Advances in Agronomy* **103**: 149-216.

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

Sandhu KS, Singh D, Sandhu MS, Gill BS and Singh J. 2002. Weed management in seed crop of radish. PAU *Journal of Research* **39**(4): 504-507.

Sandhu KS, Singh D, Singh J and Saimbhi MS. 1993.Investigation in integrated and economical weed management in tomato at Ludhiana, India. *Proceedings Indian Society of Weed Science* **3**: 211-212.

Sardhar and Guggari AK. 2015. Management of *Cuscuta* spp. in transplanted onion under irrigated condition. *Karnataka Journal of Agricultural Sciences* **28**(1): 99-101.

Sarmah D, Mahanta P, Talukdar MC and Das R. 2014. Effect of mulching on growth and flowering of gerbera (*Gerbera jamesonii* Bolus) cv. *'Red Gem;* under Assam Condition. *Research on Crops* **15:** 211-214.

Shaikh AR. 2005. Integrated weed management in *Rabi* chilli. (*Capsicum annuum*).*Indian Journal of Weed Science* **37**(3&4): 285-286.

Shalini M and Patil VS. 2004. Effect of integrated weed management practices on vegetative, reproductive and yield parameters in gerbera (*Gerbera jamesonii* H. Bolus). *Journal of Ornamental Horticulture* **7:** 144-147.

Shalini M and Patil VS. 2006. Effect of integrated weed management practices on vegetative, reproductive and yield parameters in gerbera. *Karnataka Journal of Agricultural Sciences* **19**(3): 649-652.

Sharma AB, Patel RK and Tiwari JP. 1983. Chemical weed control in garlic. *Indian Journal of Weed Science* **15**: 17-22.

Sharma JJ. 2000. Weed management in radish under mid-hills of Himachal Pradesh. *Indian Journal of Weed Science* **32**(1&2): 108-109.

Sharma SP, Buttar GS, Singh S and Khurana DS. 2009. Comparative efficacy of pendimethalin and oxyfluorfen for controlling weeds in onion (*Allium cepa* L.) nursery. *Indian Journal of Weed Science* **41**(1&2): 76-79.

Shekhar BG, Ramachanraprasad TV and Kenchaiah K. 2002. Weed management in transplanted onion under protective irrigated situation. *Indian Journal of Weed Science* **34** (3&4): 327-328.

Shekhawat PS and Maliwal PL. 1991. Evaluation of herbicides for weed control in potato. *Indian Journal of Agricultural Sciences* **59**(11): 739-741.

Singh B, Bhullar MS, Walia US and Randhawa SK. 2009. Effect of herbicides on weed control yield, quality and herbicide residue in radish. *Indian Journal of Weed Science* **41**(1&2): 46-48.

Singh GP, Thakral KK and Pandita ML. 1985. Efficacy of various herbicides and hand weeding for weed control and fruit yield of chillies (*Capsicum annuum* L.). In: Abstracts of papers, Annual Conference of *Indian Society of Weed Science,* HAU, Hisar.

Singh M, Satish Kumar, Rakesh Kumar and Rajesh Kumar. 2014. Effects of post emergence herbicides on weed control and yield of field pea and their residual effect on succeeding sorghum and mungbean crop. *Legume Research* 37(4): 387-394.

Singh NP, Johri AK and Singh AK. 1992. Weed management in bell paper (*Capsicum annuum* L.). *Indian Journal of Weed Science* **24**(3&4): 56-59.

Singh NP, Johri AK and Singh KK. 1991. Economics of herbicides in bell pepper (*Capsicum annuum* L.). *Vegetable Science* **18**(2): 130-133.

Singh PP and Tripathi SS. 1988. Relative efficacy of herbicides for weed control in cauliflower (*Brassica oleracea* L.). *Indian Journal of Weed Science* **20**: 60-62.

Singh R, Nandal TR, Singh R. 2002a. Studies on weed management in garlic (*Allium sativum* L.). *Indian Journal of Weed Science* **34**: 80-81.

Singh VP and Bhan VM. 1999. Herbicidal control of weeds in potato (*Solanum tuberosum* L.) in Vertisol. *Indian Journal of Weed Science* **31**: 214-217.

Singh VP, Mishra JS and Yaduraju NT. 2002b. Impact of irrigation levels and metribuzin on weed growth and tuber yield of potato (*Solanum tuberosum*) under vertisols. *Indian Journal of Agricultural Sciences* **72**(3): 174-176.

Singh S. 2014. Integrated weed management in brinjal (*Solanum melongyna* L.). M.Sc. Thesis. Punjab Agricultural University, Ludhiana.

Suresh Kumar, Rana SS, NavellChander and Sharma Neelam. 2013. Integrated weed management in garlic. *Indian Journal of Weed Science* **45**(2): 126-130.

Ved Parkash, Pandey AK, Singh RD and Mani VP. 2000. Integrated weed management in winter onion (*Allium cepa*) under mid-hill conditions of north-western Himalayas. *Indian Journal of Agronomy* **45**(4): 816-821.

Vermani A, Nandal TR, and and Singh R. 2001. Nutrient uptake and economic weed management in garlic (*Allium sativum* L.*). Indian Journal of Weed Science* **33**(3&4): 225-226.

Yadav Ashok, Malik RK, Balyan RS and Malik RS. 1999. Evaluation of Linuron for Control of Weeds in Potato *Indian Journal of Weed Science* **31**(1&2): 13-17.

Yadav LP and Bose TK. 1987. Chemical weed control in tuberose and gladiolus. *Acta Horticulture* **205:** 177-185.

Yaduraju NT, Bhattacharji SK and Ahuja KN. 1997. Evaluation of some herbicides for weed control in roses. *Indian Journal of Weed Science* **29**: 73-74.

Zaragoza C. 2001. Uso de herbicidas en cultivos hortícolas, pp.169-182. In*: Uso de Herbicidas en la Agricultura del Siglo XXI (*Eds. De Prado R and Jarrín, J). Cap.15. Servicio de Publicaciones. Universidad de Córdoba, Spain.

Indian Journal of Weed Science **47**(3): 288–295, 2015

Climate change, crop-weed balance and the future of weed management

V.S.G.R. Naidu*
Krishi Vigyan Kendra, ICAR-CTRI. Rajahmundry, East Godavari, Andhra Pradesh 533 105

Received: 30 June 2015; Revised: 23 July 2015

ABSTRACT

Ever increasing global population, rapid industrialization, increased fossil fuel consumption, deforestation *etc*. lead to the increased concentration of greenhouse gases in the atmosphere. IPCC reports provide strong evidence that rising CO_2 and other trace gases could lead to a 3±12°C increase in global surface temperatures with subsequent effects on climate. Relationship between climate change and agriculture is of particular importance as the world population and world food production showing imbalance under pressure. As mean temperature increases, weeds expand their range into new areas. Climate change is likely to trigger differential growth in crops and weeds and may have more implications on weed management in crops and cropping systems. Growth at elevated CO_2 and elevated temperatures would result in anatomical, morphological and physiological changes that could influence herbicidal uptake rates, besides translocation and overall effectiveness. Climate change has an indirect influence on the occurrence of weeds via crop management and land use. There is a possibility that agricultural weed populations will evolve new traits in response to emerging climate and non-climate selection pressures. Reducing the impacts of weeds and preventing new weeds are essential to increasing the resilience of ecosystems and giving native species the best chance to deal with the adverse impacts of climate change.

Key words: Climate change, Elevated CO_2, Weeds, Weed invasion, Weed management

Global climate change is no doubt a severe problem that the world is facing today. Climate change means a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and, which is in addition to natural climate variability observed over comparable time period (UNFCC 1994). Climate change is the change in statistical distribution of weather pattern that lasts for an extended period of time. Since the industrial revolution began around 1750, human activities have contributed substantially to climate change by adding CO_2 and other heat-trapping gases to the atmosphere. These gas emissions have increased the greenhouse effect and caused earth's surface temperature to rise. Projections suggest 2.4–6.4^{0}C increase of global average temperature by the end of 21st century (IPCC 2007). Studies indicate that significant warming is inevitable regardless of future emission reductions. Climate change will modify rainfall, evaporation, runoff and soil moisture storage. If these forecasts come into reality, crops and cropping systems are likely to experience significant changes. A relationship between climate changes and agriculture is of a particular importance as the world population and world food production showing imbalance under pressure.

***Corresponding author:** naidudwsr@gmail.com

Increased CO_2 concentrations could have a direct effect on the growth rates of individual crop plants and weeds and also cause vegetation communities to change. Increased CO_2 concentration and temperature will alter the plant's ability to grow and compete with other individuals within a given environment. Increased CO_2 would enable many plants to tolerate environmental stresses, such as drought and temperature fluctuations (IPCC 1996, Parry 1998, Bunce 2001). Weeds affect agricultural production and biodiversity as they out-compete crops and native species and contribute to land degradation. Increased tolerance to stress is likely to modify the competitiveness of weeds and their distribution. Weeds with high reproduction and efficient seed dispersal mechanisms may better be able to take advantage of the expected calamities like cyclones and floods.

Crop-weed balance under climate change

Climate change is likely to trigger differential growth in crops and weeds and may have more implications on weed management in crops and cropping systems. The effects of climate change on crop-weed interactions are likely to vary by region and crop type. As the crop-weed interactions are balanced by various environmental factors, local changes in these factors may alter the balance towards either crop or weed. Changes in temperature and carbon dioxide are likely to have significant direct (CO_2 stimulated growth) and indirect (climatic variability) effects on weeds and that would affect crop-weed balance or lead to weed invasion.

Direct effects

Effect of elevated CO_2: The United Nations Inter-governmental Panel on Climate Change (UN-IPCC) predicts that atmospheric CO_2 concentration could exceed 700 ppm by the end of 21st century (Houghton *et al*. 1996). While the extent of temperature increases remains speculative, there is acknowledged consensus on the direct physiological impact of increasing CO_2 concentration on plant photosynthesis and metabolism (Stitt 1991, Bowes 1996). Increasing CO_2 concentration has been shown to stimulate growth and development significantly in hundreds of plant species (Kimball 1983, Kimball *et al*. 1993, Poorter 1993, Sage 1995). Plants vary in their response to CO_2 because of differential photosynthetic pathways *i.e.* C_3 and C_4.

Due to the ongoing increases in atmospheric CO_2 there would be stimulation in leaf photosynthesis in C_3 plants by increasing the CO_2 level in the leaf interior and by decreasing the loss of CO_2 by photorespiration. The C_4 plants, however, have internal biochemical pump for concentrating the CO_2 at carboxylation site that reduces the oxygenase component of the rubisco thereby eliminating the carbon loss by photorespiration. Because of this differential response of the plants to the CO_2, it has been postulated that with higher CO_2 levels in the atmosphere, there may be significant alterations in the competitive interactions and certain genotypes or species may become extinct after several generations of altered competition. This differential response by C_3 and C_4 plants to higher CO_2 is specifically relevant to crop-weed competition because, most of the crops are C_3 plants and most of the weeds are C_4 plants. Several observations on the response of growth of C_3 and C_4 species to elevated CO_2 support the general expectation that the C_3 species are more responsive than C_4 species. For a C_3 crop such as rice and wheat, elevated CO_2 may have positive effects on crop competitiveness with C_4 weeds (Yin and Struik 2008, Fuhrer 2003). But this is not always true. To date, for all crop–weed competition studies, where the photosynthetic pathway is the same, weed growth is favoured as CO_2 is increased. Therefore, C_3 weeds like *P. minor* and *A. ludoviciana* in wheat (C_3) would aggravate with the increase in CO_2 due to climate change.

Elevated CO_2 has been shown to increase growth and biomass accumulation of the C_4 weed *Amaranthus viridis* (Naidu 2007). As high temperatures would also create increased evaporative demand, with its high water use efficiency and CO_2 compensation point, C_4 photosynthesis is better adapted to high evaporative demand (Bunce 1983). Developing leaves of C_4 plants use C_3 photosynthetic pathway until 'kranz anatomy' is fully differentiated (Nelson and Langdale 1989). During this early period a large proportion of the leaf area of these plants use C_3 photosynthetic pathway and therefore, they get benefited from elevated CO_2 condition.

It is evident that an increased CO_2 concentration leads to partial closure of stomata that reduces transpiration per unit area thereby reduces the plants' water requirement while promoting photosynthesis. Reduced water requirement and enhanced photosynthesis improve water use efficiency (WUE). Kimbal and Idso (1983) reported improvement of WUE by 70-100% for both C_3 and C_4 plants. Under the condition of high CO_2 concentration, C_3 plants are likely to become more water-efficient, potentially allowing C_3 weeds to move into drier habitats (Kriticos *et al.* 2003). With high CO_2 fixation rates and with characters like shorter life cycle, vegetative reproduction or easily disseminated seeds, the weeds would become very competitive.

Effect of elevated temperature: Climate change projections suggest 2.4–6.4^{O}C increase of global average temperature by the end of 21st century (IPCC 2007). Studies indicate that significant warming is inevitable regardless of future emission reductions. If these forecasts are realized, crops and cropping systems are likely to experience significant changes and it is so for the associated weeds too. Changes in temperature generally affect the length of growing period in plants. Most significant effect of temperature increase in the regions where temperature is the main limiting factor would be an extension of plant growth period. As mean temperatures increases, weeds expand their range into new areas. As animals, including invasive species, move into new areas in response to climate change, they are likely to spread weeds or create disturbance advantageous for weeds. Under high temperature, plants with C_4 photosynthesis pathway (mostly weeds) have a competitive advantage over crop plants possessing the more common C_3 pathway (Yin and Struik 2008). Most of the weeds in rice are of C_4 type in India. For instance, incidence of *Ischaemum rugosum*, which was a common weed of rice in tropical areas, but has become a common weed with significant presence in northern states (Singh *et al.* 1991). Similarly, the incidence of *Rumex spinosus* in wheat in north-west India has increased.

Introduced in 1877 from Central America as a drought tolerant species suitable for afforestation in arid and semi arid zones of India, *Prosopis juliflora* has invaded nearly 6.0 million hectares of land contributing for 1.8% of geographical area of the country (Kathiresan 2005). The most potential invasive feature of the species is typical that a greater portion of assimilates are partitioning towards root, leading to extraordinary enlargement in the root mass with rich food reserves, aiding rapid and robust regeneration after mechanical lopping or after revival of ecological stress conditions such as drought or inundation. The annual increase in root bio-mass is greater in areas where the mean annual temperature is higher than that in areas of lesser mean annual temperature. The increase in root biomass largely contributes for the weed's ability to tolerate climatic extremes such as a peak summer associated with high temperature and water scarcity and a peak monsoon winter with water inundation and flooding. This adaptation favors the weed to predominate over other native floras that are susceptible to any one of the two extremes.

Effect of changes in rainfall: Weeds constrained by rainfall may also find new habitats under new climatic conditions. *Lantana camara*, for example, could expand if rainfall increased in some areas (McFadyen 2008). The meteorological data available at the Annamalai University showed that in the tail end of Cauvery river delta region of Tamil Nadu state, the average annual rainfall during the period of 1991 to 2000 has increased by 129 mm compared to the period during 1981 to 1990. The record also revealed that the annual evaporation has reduced by 255 mm from the period between 1981 to 1990 and 1991 to 2000. Further, wet years (years with excess average annual rainfall by more than ten per cent) are also more frequent during 1991 to 2000 than during 1980 to 1990. Phyto-sociological survey of floristic composition of weeds in this region reveals that rice fields were invaded by alien invasive weeds *Leptochloa chinensis* and *Marsilea quadrifolia*. These two weed species dominated over the native weeds such as *Echinochloa* spp. and others by virtue of their amphibious adaptation to alternating flooded and residual soil moisture conditions prevalent during this period in this region (Yaduraju and Kathiresan 2003, Kathiresan 2005).

Interaction effect of CO_2 and other factors: The interaction between increased CO_2 concentration and other environmental factors such as water, light intensity, nutrient availability and temperature may also result in differential response to increased CO_2 among weeds and crops (Bazzaz and Carlson 1984, Patterson and Flint 1982).

CO_2 and temperature: Plant response to the interaction effect of CO_2 and temperature may be complex (Bazzaz 1990). Some studies have shown that low or high temperatures reduce or eliminate the high CO_2 growth enhancement (Hofstra and Hesketh 1975, Idso 1990, Coleman and Bazzaz 1992) whereas, others have shown that CO_2 enrichment may increase the plant tolerance to temperature extremes (Sionit *et al.* 1981, Potvin 1985, Baker *et al.* 1989). Based on the differences in temperature optima for physiological processes, it is predicted that C_4 spp. will be able to tolerate high temperature than C_3 spp. Therefore, C_4 weeds may benefit more than the C_3 crops from any temperature increases that accompany elevated CO_2 levels. High CO_2 levels have been shown to ameliorate the effects of sub-optimal temperatures (Sionit *et al.* 1987) and other forms of stress (Bazzaz 1990) on plant growth. Tremmel and Patterson (1993) have shown that high CO_2 ameliorated the high temperature effects on quack grass (*Elytrigia repens*). Carter and Patterson (1983) obtained similar results. Data from the results of the experiments by Alberto *et al.* (1996) suggest that competitiveness could be enhanced in C_3 crop (rice) relative to a C_4 weed (*Echinochloa glabrescens*) with elevated CO_2 alone but simultaneous increases in CO_2 and temperature still favor C_4 spp. O'Donnell and Adkins (2001) reported that wild oat plants grown at high temperature 23/19 ^{0}C (day/night) completed their development faster than those grown at normal temperature 20/16^{0}C. If the maturation rate is faster relative to the crop, more seeds may be deposited in the soil seed bank with a consequent increase in the number of wild oat plants. The wild oat plants grown at 480 ppm CO_2 produced 44% more seed than those grown at 357 ppm.

CO_2, temperature and light intensity: It was reported that plants which are efficient in fixing CO_2 become relatively more competitive as light intensity increases. In addition, these species have high optimum temperature for photosynthesis and thus would become more competitive as temperature increases from 20^{0}C to 30^{0}C or 40^{0}C. At midday when light intensity and temperature both reach peak values weed species like redroot pigweed (*Amaranthus retroflexus*, C_4) and Johnson grass (*Sorghum halepense*, C_4) are expected to fix CO_2 at higher rate than the crops like soybean (C_3) and

Cotton (C_3). As high temperatures would also create increased evaporative demand with its high water use efficiency and CO_2 compensation point C_4 photosynthesis is better adapted to high evaporative demand (Bunce 1983).

CO_2 and moisture stress: The CO_2 enrichment tends to reduce the deleterious effects of drought (Sionit and Patterson 1985). Due to CO_2 enrichment, the wheat plant could gain biomass against *P. minor.* Under water stress conditions, however, *P. minor* had advantage over wheat with CO_2 enrichment (Naidu and Varshney 2011).

Even under water limited conditions growth enhancement by CO_2 appears to be greater in C_3 crops than C_4 weeds if the temperature increase is not as dramatic as predicted (Patterson 1986). An increase in temperature with accompanying soil moisture stress will offset the growth benefits from CO_2 fertilization; the net effect depends on the level of moisture stress. Plants with C_4 photosynthetic metabolism sometimes increase photosynthesis and growth at elevated CO_2 concentration under dry conditions (Patterson 1986, Knap *et al.* 1993), when elevated level of CO_2 slows the development of stress.

CO_2 and nutrient availability: Number of studies showed that the rise in CO_2 concentration induces growth stimulation in crops as well as in weeds. If the availability of a resource changes within the environment, the weeds with greater genetic diversity and adaptability will show a better growth and reproductive response than that of crops. Nitrogen-fixing weeds may especially benefit because growth stimulated by CO_2 will not be constrained by low nitrogen levels (Poorter and Navas 2003). Under extreme nutrient deficiencies, there may be no response to elevated CO_2 in terms of biomass increase; under moderate limitations more relevant to agricultural situations, the increase in biomass may be reduced but the relative stimulation by elevated CO_2 is often similar (Wong 1979, Rogers *et al.* 1993). As in the case of water stress, reduction in growth caused by nutrient deficiency may reduce the impact of weeds on crop production (Patterson 1995b), since smaller plants interfere less among themselves.

Indirect effects

As weeds are closely associated with the cropping system (Pysek *et al.* 2005, Andreasen and Skovgaard 2009, Cimalova and Lososova 2009, Gunton *et al.* 2011), climate change has an indirect influence on the occurrence of weeds via crop management and land use. Irrigation water in North-West India is increasingly become scarce and many resource–conservation technologies have recommended to conserve irrigation water, for instance, zero tillage in wheat, bed planting in rice and wheat, and dry-seeded rice. This will have consequences on weed abundance and composition. Alternate wetting and drying in puddled as well as dry-seeded rice may encourage weeds such as *Leptochloa chinensis*, *Eleusine indica* and *Eclipta prostrata* (Mahajan *et al.* 2012).

Due to changing climate, timing of life-cycles are expected to changes and that will affect flowering, fruiting and reproduction as the flowering is the most thermal sensitive stage of plant growth (Boote *et al.* 2005). Flowering can be faster, slower or unchanged at elevated CO_2, depending on species. Reekie *et al.* (1994) reported that elevated CO_2 delayed flowering in four short day species and hastened it in four long day species. During the studies conducted in Open Top Chambers (OTCs) at the Directorate of Weed Research, Jabalpur, India, it was observed that CO_2 enrichment hastened the seed maturity in *Avena fatua* (wild oat), a common weed in wheat. The seeds matured 13 days in advance compared to the plants grown under ambient CO_2 conditions and may probably resulted into the enrichment of soil seed bank as the wild oat seeds shatter well before the harvest of the crop. Drought and dry soil conditions prolong the weed seed bank longevity.

Higher temperatures and other factors are likely to increase pollinators' (insects') breeding cycles and provide more weed pollination thereby increase the weed population. As animals, including invasive species, move into new areas in response to climate change, they are likely to spread weeds or create disturbance advantageous for weeds. Climate change will render native species more vulnerable to weeds either directly or indirectly, for example by facilitating the spread of the serious plant diseases. Importing of fodder and grain into drought prone areas can bring new weed problems to the region.

In their responses to climate change, humans are likely to introduce more weeds and create more opportunities for invasion. Many crops proposed for biofuels, jatropha (*Jatropha curcas*) and giant reed (*Arundo donax*) for example are serious weeds (Low and Booth 2007). New hardier pasture and garden plants developed to withstand drier conditions expected under climate change are likely to have a high weed risk (Booth *et al.* 2009) Agricultural adaptations to climate change, including new products and shifts into new areas will also create more opportunities for weeds. More weeds will be one of the inevitable results of the proposed shift of more intensive agriculture.

Rise in CO_2 level increases the pollen production and thus the asthma by quadrupling in US since 1980 (AAAAI 2000). Increased CO_2 stimulated ragweed (*Ambrosia artemisifolia*) pollen production several times more than that it stimulates overall growth (Singer *et al.* 2005). Most of the weed species are associated with contact dermatitis, an immune-mediated skin inflammation. Chemical irritants can be present on all plant parts including leaves, flowers, and roots, or can appear on the plant surface when injury occurs. The amount and concentration of these chemicals vary with a range of factors, including maturity, weather, soil, and ecotype. These facts suggest plausible links among rising CO_2, plant biology, and increased contact dermatitis. Production of morphine in wild poppy (*Papaver setigerum*) showed significant increases with both recent and projected CO_2 concentrations (Ziska *et al.* 2008). Concurrent increases in temperature and CO_2 also affected the production and concentration of atropine and scopolamine in jimson weed (*Datura stromonium*) (Ziska *et al.* 2005).

Climate change and weed invasion

Climate change is expected to increase the risk of invasion by weeds from neighboring territories. With the competitive ability, weeds often find an opportunity to establish new populations when natural or desirable plant species decline. Climate change may also favour expansion of range of weeds that have already established but are currently restricted in range. The range expansion can be attributed to evolutionary adaptation (Clements and DiTommaso 2011, 2012). Weeds which have higher spread and establishment potential have the potential to invade new areas and increase their range.

Extreme weather events create conditions congenial for weeds to extend their range and invade new areas or out-compete native species in their existing range. Under drought, the competitiveness of native vegetation gets reduced and new weeds get the opportunity to invade. Flood assist in spreading weeds to weed free areas; provide opportunity for new weed invasion by washing away the vegetation and exposing the areas of disturbed soil. Warmer temperature will force some species to relocate, adapt or perish. Species that are active in summer will develop faster. Warmer climate restricts temperature sensitive species to high altitudes. In plains, this effect on distribution range is magnified because species without the ability to move to higher elevations must relocate further in the same altitude. Weeds with efficient dispersal mechanisms are better equipped to shift their range, while species with short life cycles are better equipped to evolve and increase their tolerance of warmer temperatures.

Weeds that are well-suited to adapt to the impacts of climate change may not only fill gaps left by more vulnerable native plants but, they may have an even greater effect by altering the composition of ecosystems and their integrity. In fact, climate change may favour certain native plants to such an extent that they then become weeds. Land management practices such as land clearing, habitat fragmentation and over grazing that clear native vegetation and degrade its condition adversely affect the biodiversity and favour weed invasion by providing opportunities for them to colonise new areas and by reducing the ability of native vegetation to compete with and suppress invading species.

Alien weeds are usually non-native, whose introduction results in wide-spread economic or environmental consequences (e.g. *Lantana camara*, *Parthenium hysterophorus*, *Eichhornia crassipes etc.* in India). These weeds have strong reproductive capability and are better dispersers and breeders. With these characteristics, they are benefitted from climate change. Studies indicate that these weeds may show a strong response to recent increases in atmospheric CO_2 (Ziska and George 2004). From the studies conducted at the Directorate of Weed Research, Jabalpur, India it was observed that the invasive weed *Parthenium hysterophorus* had shown tremendous growth response to elevated CO_2 (Naidu and Paroha 2008, Naidu 2013) suggesting the possibility that the recent increase in CO_2 during 20^{th} century may have been a factor in the invasiveness of this species. Responses to climate change will be specific to individual species and will depend on a range of interacting factors.

Climate change and weed management

Cultural, manual, and mechanical weed management: A standard means of controlling weed populations, and the one most widely used in developing countries is mechanical removal. Tillage, either by animal or by mechanical means is regarded as a global method of weed control in agronomic systems. Elevated CO_2 commonly stimulate the growth of roots and rhizomes more than that of shoots. Increased below ground growth in such species may make manual removal a difficult task as

CO_2 rises. Consequently, mechanical tillage may lead to additional plant propagation in a higher CO_2 environment, with increased asexual reproduction from below ground structures and will have negative effects on weed control (Rogers *et al.* 1994, Ziska and Goins 2006). Cultural practices like manual weeding and intercropping may also be affected by altered growing seasons induced by climate change. Climate extremes *i.e.* precipitation or drought could also limit the opportunity for field operations. Changes in rice cultivation from transplanting to direct seeding under limited water availability necessitates emphasis on post emergence weed management in order to keep the yields high.

Chemical weed management: Under increased temperature and unpredictable precipitation scenarios, current recommendations of herbicides may not be effective. Increased temperature and drought can reduce herbicide uptake, increase volatility, structural degradation and reduce its effectiveness. Growth at elevated CO_2 would result in anatomical, morphological and physiological changes that could influence herbicidal uptake rates, besides translocation and overall effectiveness.

Stimulation of below ground growth under elevated CO_2 may lead to abundance of perennial weeds. Manea *et al.* (2011) showed that three of four C_4 grass species displayed increased tolerance to glyphosate under elevated CO_2. Similar results were also reported by Ziska and Goins (2006). The reasons for the reduced efficacy of the herbicides might be that increasing CO_2 can increase leaf thickness and reduce stomatal number and conductance possibly limiting the uptake of foliar applied herbicides. Greater increases in biomass could result in dilution of applied herbicide and thereby reducing its efficacy (Patterson 1995a).

High concentrations of starch in leaves which commonly occurs in C_3 plants grown under CO_2 enrichment (Wong 1990) might interfere with herbicide activity (Patterson *et al.* 1999). In general, protein content per gram tissue can be reduced with increasing CO_2 (Bowes 1996), which could result in less demand for aromatic amino acids thereby reducing the efficacy of glyphosate, a non-selective herbicide which inhibits the aromatic amino acid production through shikimic acid pathway. Decreasing stomatal conductance with increasing CO_2 could also reduce the transpiration and thereby the uptake of soil applied herbicides. If the growth of the weeds is stimulated by the future levels of atmospheric CO_2, the efficacy of the post-emergence herbicides would be reduced because the time spent by the weeds in seedling stage *i.e.* the stage of greatest herbicide sensitivity would be shortened (Ziska *et al.* 1999). In this situation, further applications or additional concentrations of the herbicides may be needed to control such weeds but add to the cost of control.

Drought-stressed weeds are more difficult to control with post-emergent herbicides than plants that are actively growing. For example, systemic herbicides that are translocated within the weed need active plant growth to be effective. Pre-emergent herbicides or herbicides absorbed by plant roots need soil moisture and actively growing roots to reach their target species.

Biological weed management: Introduction of biocontrol agent for weed management is a low cost technology and permanent strategy, because an effective and successful biocontrol agent is self-sustaining. Natural and manipulated biological control of weeds and other potential pests could be affected by increasing atmospheric CO_2 and climate change. Climate changes could alter the efficacy of the biocontrol agent by changing the growth, development and reproduction of the selected weedy target. Elevated CO_2 and temperature directly alter morphology and reproduction of weeds. Change in C:N ratio may alter the feeding habits and growth rate of herbivores. Direct effects of CO_2 on increasing starch concentration in leaves and lowering nitrogen contents could also affect the biocontrol by altering the behavior and growth rate of herbivores.

Conclusion

Almost all the studies indicate that both crops and weeds respond to climate change, but the balance will tilt towards weeds since they are naturally evolved with better adaptation strategies. The physiological plasticity of weeds and their greater intraspecific genetic variation compared with most crops could provide weeds with a competitive advantage in a changing environment. Controlling weeds is likely to be more difficult and expensive under climate change. Prediction of future damage by weeds is very important for sustainable weed management. In order to get the assured yields in light of predicted future climatic conditions and extreme weather events, adoption of intensive management practices is inevitable. However, climate is not the only factor that will be changing in future. Other factors like population growth, socio-economic and technological changes will have effect no less than climate change.

REFERENCES

AAAAI. 2000. *The Allergy Report*, Milwaukee, WI: American Academy of Allergy, Asthma and immunology.

Alberto AMP, Ziska LH, Cervancia CR and Manalo PA. 1996. The influence of increasing carbon dioxide and temperature on competitive interactions between a C_3 crop rice (*Oryza sativa*) and a C_4 weed (*Echinochloa glabrescens*). *Australian Journal of Plant Physiology* **23**: 795-802.

Andreasen C and Skovgaard IM. 2009. Crop and soil factors of importance for the distribution of plant species on arable fields in Denmark. *Agriculture, Ecosystem and Environment* **133**: 61–67.

Baker JT, Allen LH Jr, Boote KJ, Jones P and Jones JW. 1989. Response of soybean to air temperature and carbon dioxide concentration. *Crop Science* **29**: 98-105.

Bazzaz FA and Carlson RW. 1984. The response of the plants to elevated CO_2. I.Competition among an assemblage of annuals at different levels of soil moisture. *Oecologia* **62**: 196-198.

Bazzaz FA. 1990. The response of natural ecosystems to the rising global CO_2 levels. *Annual Review Ecological Systems* **21**: 167-196.

Boote KJ, Allen LH Jr, Prasad PV, Baker JT, Gesch RW and Snyder AM. 2005. Elevated temperature and CO_2 impacts on pollination, reproductive growth and yield of several globally important crops. *Journal of Agricultural Meteorolgy* **60**: 469–474.

Booth C, Carr G and Low T. 2009. *Weedy Pasture Plants for Salinity Control: Sowing the Seeds of Destruction*. Invasive Species Council and the Wilderness Society. www.invasives.org.au.

Bowes G. 1996. Photosynthetic responses to changing atmospheric carbon dioxide concentrations, pp 387-407. In: *Photosynthesis and the Environment* (Ed. Baker NR), Kluwer Academic Publishers, The Netherlands..

Bunce JA. 1983. Differential sensitivity to humidity of daily photosynthesis in the field in C_3 and C_4 species. *Oecologia* **54**: 233-235.

Bunce JA. 2001. Weeds in changing climate, pp 109-118. In: BCPC symposium proceedings No.77: *The World's Worst Weeds*. British Crop Protection Council, Surrey, U.K.

Cimalova S and Lososova Z. 2009. Arable weed vegetation of the north eastern part of the Czech Republic: effects of environmental factors on species composition. *Plant Ecology* **203**: 45–57.

Clements DR and DiTommaso A. 2011. Climate change and weed adaptation: Can evolution of invasive plants lead to greater range expansion than forecasted? *Weed Research* **51**(3): 227-240.

Clements DR and DiTommaso A. 2012. Predicting weed invasion in Canada under climate change: measuring evolutionary potential. *Canadian Journal of Plant Science* **92**(6): 1013-1020.

Coleman JS and Bazzaz FA. 1992. Effects of CO_2 and temperature on growth and resource use of co-occurring C_3 and C_4 annuals. *Ecology* **73**: 1244-1259.

Fuhrer J. 2003. Agroecosystem responses to combinations of elevated CO_2, ozone, and global climate change. *Agriculture, Ecosystem and Environment* **97**(1-3): 1-20.

Gunton RM, Petit S and Gaba S. 2011. Functional traits relating arable weed communities to crop characteristics. *Journal of Vegetation Science* **22**: 541–550.

Hofstra G and Hesketh JD. 1975. The effects of temperature and CO_2 enrichment on photosynthesis in soybean, pp. 71-80. In: *Environmental and Biological control of Photosynthesis*. (Eds. Marcelle R), Dr. W. Junk Publishers, The Hague, The Netherlands.

Houghton JT, Meira-Filho LG, Callander BA, Harris N, Kattenburg A and Maskell K. 1996. *IPCC Climate Change Assessment 1995: The Science of Climate Change*. Cambridge: Cambridge University Press.

Idso SB. 1990. Interactive effects of carbon dioxide and climate variables on plant growth, pp. 61-69. In: *Impacts of Carbon dioxide, Trace Gases, and Climate Change on Global Agriculture*. (Eds. Kimball BA, Rosenberg NJ and Allen LH Jr.) ASA special publication No. 53, American Society of Agronomy, Inc., Madison, WI.

IPCC. 1996. Climate Change 1995: The Science of Climate Change. (Eds: Houghton J, Meira Filho LG, Callander BA, Harris N, Kattenberg Aand Maskell K.) Cambridge University Press, Cambridge.

IPCC. 2007. *Climate Change 2007-Synthesis Report*, . Summary for Policy makers.

Kathiresan RM. 2005. *Case study on Habitat management and rehabilitation for the control of alien invasive weed (Prosopis juliflora).* Report submitted to water Resource Organization, Public Works Department, Tamilnadu, India. (Unpublished)

Kimbal BA and Idso SB. 1983. Increasing atmospheric CO_2: Effects on crop yield, water use and climate. *Agricultural Water Management* **7**: 55-72.

Kimball BA, Mauney JR, Nakayama FS and Idso SB. 1993. Effects of increasing atmospheric CO_2 on vegetation. *Vegetatio* **104/105**: 65-75.

Kimball BA. 1983. Carbon dioxide and agricultural yield: an assemblage and analysis of 430 prior observations. *Agronomy Journal* **75**: 779-788.

Knapp AK, Hamerlyn CK and Owensby CE. 1993. Photosynthetic and water relations response to elevated CO_2 in the C_4 grass *Andropogon gerardii*. *International Journal of Plant Science* **154:** 459-466.

Kriticos DJ, Sutherst RW, Brown JR, Adkins SW and Maywald GF. 2003. Climate change and the potential distribution of an invasive alien plant: *Acacia nilotica* spp. indica in Australia. *Journal of Applied Ecology* **40**: 111-124.

Low T and Booth C. 2007. The weedy truth about biofuels. Invasive Species Council, Inc. www.invasives.org.au/home.

Mahajan G, Samunder Singh and Chauhan BS. 2012. Impact of climate change on weeds in the rice–wheat cropping system. *Current Science* **102**(9-10): 1254-1255.

Manea A, Leishman , M R and Downey P O. 2011. Exotic C_4 grasses have increased tolerance to glyphosate under elevated carbondioxide. *Weed Science* **59**: 28-36.

McFadyen R. 2008. *Invasive Plants and Climate Change. Weeds* CRC Briefing Notes. CRC for Australian Weed Management.

Naidu VSGR and Paroha S. 2008. Growth and biomass partitioning in two weed species, *Parthenium hysterophorus* (C_3) and *Amaranthus viridis* (C_4) under elevated CO_2. *Ecology Environment and Conservation* **14**(4): 9-12.

Naidu VSGR and Varshney JG. 2011. Interactive effect of elevated CO_2, drought and weed competition on carbon isotope discrimination in wheat.*Indian Journal of Agricultural Sciences* **81**: 1026–1029.

Naidu VSGR. 2013. Invasive potential of C_3-C_4 intermediate *Parthenium hysterophorus* under elevated CO_2. *Indian Journal of Agricultural sciences* **83**(2): 176-179.

Nelson T and Langdale JA. 1989. Patterns of leaf development in C_4 plants. *Plant Cell* **1**: 3-13.

O'Donnell CC and Adkins SW. 2001. Wild oat and climate change: the effect of CO_2 concentration, temperature, and water deficit on the growth and development of wild oat in monoculture. *Weed Science* **49**: 694-702.

Parry ML. 1998. The impact of Climate change on European agriculture,pp: 325-338. In: The Bawden Memorial Lectures 1973-1998T. (Ed. Lewis). Silver Jubilee Edition, . British Crop Protection Council, Surrey, U.K.

Patterson DT. 1995a. Weeds in a changing climate. *Weed Science* **43:** 685-701.

Patterson DT. 1995b. Effects of environmental stress on weed/crop interactions. *Weed Science* **43**: 483-490.

Patterson DT and Flint EP. 1982. Interacting effects of CO_2 and nutrient concentration. *Weed Science* **30**: 389-394.

Patterson DT, Westbrook JK, Joyce RJV, Lingren PD and Rogasik J. 1999. Weeds, insects and diseases. *Climate Change* **43**: 711-727.

Patterson DT. 1986. Response of soybean and three C_4 grass weeds to CO_2- enrichment during drought. *Weed Science* **34**: 203-210.

Poorter H and Navas M. 2003. Plant growth and competition at elevated CO_2: on winners, losers and functional groups. *New Phytologist* **157**: 175-198.

Poorter H. 1993. Interspecific variation in the growth response of plants to an elevated ambient CO_2 concentration. *Vegetatio* **104/105**: 77-97.

Potvin C. 1985. Amelioration of chilling effects by CO_2 enrichments. *Physiologie Vegetale* **23**: 345-352.

Pysek P, Jarosik V, Kropac Z, Chytry M, Wild J and Tichy L. *2005*. Effects of abiotic factors on species richness and cover in Central European weed communities. *Agriculture, Ecosystem and Environment* **109**:1–8.

Reekie JYC, Hicklenton PR and Reekie EG. 1994. Effects of elevated carbon dioxide on time of flowering in four short-day and four long day species. *Canadian Journal of Botany* **72**: 533–538.

Rogers GS, Payne L, Milham P and Conroy J. 1993. Nitrogen and phosphorous requirements of cotton and wheat under changing atmospheric CO_2 concentrations. *Plant and Soil* **155/156**: 231-234.

Rogers HH, Runion GB and Krupa SV. *1994*. Plant responses to atmospheric CO_2 enrichment with emphasis on roots and the rhizosphere. *Environmental pollution* **83**: 155-189.

Sage RF. 1995. Was low atmospheric CO_2 during the Pleistocene a limiting factor for the origin of agriculture? *Global Change Biology* **1**: 93-106.

Singer BD, Ziska LH, Frenz DA, Gebhard DE and Straka JG. 2005. Increasing Amb a 1 content in common ragweed (*Ambrosia artemisiifolia*) pollen as a function of rising atmospheric CO_2 concentration. *Functional Plant Biology* **32**: 667–670.

Singh T, Kolar JS and Bhatia RK. 1991. Emergence behaviours of *Ischaemum rugosum* (Wrinkle Grass) as affected by variable temperature, submergence period and depth of seed placement in the soil. *Indian Journal of Weed Science* **23**: 56–60.

Sionit N and Patterson DT. 1985. Responses of C_4 grasses to atmospheric CO_2 enrichment. II. Effect of water stress. *Weed Science* **25**: 533-537.

Sionit N, Strain BR and Beckford HA. 1981. Environmental controls on the growth and yield of okra. I. Effects of temperature and of CO_2 enrichment at cool temperature. *Crop Science* **21**: 885-888.

Sionit N, Strain BR and Flint EP. 1987. Interactions of temperature and CO_2 enrichment on soybean: Growth and dry matter partitioning. *Canadian Journal of Plant Science* **67**: 59-67.

Stitt M. 1991. Rising CO_2 levels and their potential significance for carbon flow in photosynthetic cells. *Plant, Cell and Environment* **14**: 741-762.

Tremmel DC and Patterson DT. 1993. Response of soybean and five weeds to CO_2 enrichment under two temperature regimes. *Canadian Journal of Plant Science* **73**: 1249-1260.

UNFCC. 1994. T*he United Nations Framework Convention on Climate Change.* 21 March 1994.

Wong SC. 1979. Elevated atmospheric partial pressure of CO_2 and plant growth. I. Interaction of nitrogen nutrition and photosynthetic capacity in C_3 and C_4 plants. *Oecologia* **44**: 68-74.

Wong SC. 1990. Elevated atmospheric partial pressure of CO_2 and plant growth. II. Non-structural carbohydrate content in cotton plants and its effect on growth parameters. *Photosynthesis Research* **23**: 171-180.

Yaduraju NT and Kathiresan RM. 2003. Invasive Weeds in the Tropics, p. 59-68.In: *Proceedings of 19th Asian Pacific Weed Science Society Conference.* Manila, Philippines.

Yin X and Struik PC. 2008. Applying modelling experiences from the past to shape crop. *New Phytologist* **179**: 629–642.

Ziska LH and George K. 2004. Changes in biomass and root: shoot ration of field grown Canada thistle (*Circium arvense*), a noxious, invasive weed with elevated CO_2: Implications for control with glyphosate. *Weed Science* **52**: 584-588.

Ziska LH and Goins EW. *2006*. Elevated atmospheric carbon dioxide and weed populations in. glyphosate treated soybean. *Crop Science* **46**:1354-1359.

Ziska LH, Emche SD, Johnson EL, George K, Reed DR and Sicher RC. 2005. Alterations in the production and concentration of selected alkaloids as a function of rising atmospheric carbon dioxide and air temperature: implications for ethno-pharmacology. *Global Change Biology* **11**: 1798–1807.

Ziska LH, Panicker S and Wojno HL. 2008. Recent and projected increases in atmospheric carbon dioxide and the potential impacts on growth and alkaloid production in wild poppy (*Papaver setigerum* DC.). *Climate Change* **91**: 395–403.

Ziska LH, Teasdale JR and Bunce JA. 1999. Future atmospheric carbon dioxide may increase tolerance to glyphosate. *Weed Science* **47:** 608-615.

Indian Journal of Weed Science **47**(3): 296–305, 2015

Problem weeds and their management in the North-East Himalayas

Jayanta Deka* and Iswar Chandra Barua
AICRP on Weed Management, Assam Agricultural University, Jorhat, Assam 785 013

Received: 20 June 2015; Revised: 31 July 2015

ABSTRACT

The North East Himalayan region recognized as one of the seven biodiversity hotspots of the world where Indo-Malayan, Indo-Chinese, and Indian bio-geographical realms have converged. Based on the elevation, climate and soil conditions, water availability and socio-economic aspects, different agro-ecosystems are prevalent in the north eastern India. However, the agro-ecosystems of the region can be broadly classified as i) *Jhum* agro-ecosystem, ii) Terrace land agro-ecosystem, and iii) Valley land agro-ecosystem. The major production ecosystems of the region are: rice, jute, sugarcane, tea, horticultural crops and forest and wetland. Shifting cultivation is a primitive agricultural system still practiced in some of the hill areas which is characterized by uniqueness of weed problem and its weed flora is primarily governed by altitude, slope of the land, *jhum*-cycle and fallowing, burning, rainfall, run-off, crops and cropping geometry and many other relevant issues like biotic interference coupled with climatic factors. The nature and severity of weed menace in different crop ecosystems vary according to the agro-ecosystems in which the crop is grown. Weeds are one of the main production constraints in all crop ecosystems. The common agronomic factors contributing to weed problems in different crops are inadequate land preparation, seed contamination with weed seeds, use of poor quality seeds, broadcast seeding in lowlands, use of overage rice seedlings for transplanting, inadequate water management, inadequate fertilizer management, mono-cropping, labour shortages for weeding operations, delayed herbicide applications and other interventions. In this article, the distribution of weeds and their management practices are reviewed exhaustively.

Key words: Himalayan region, Jhum cultivation, North-East, Weed

The Indian Himalayan Region spans over ten Indian states starting in Jammu & Kashmir and extending up to the North East Region (NER) of India. The Tibetan Plateau is to the north of this mountain range and the Indo-Gangetic Plain borders in the south. The north eastern part of this mountain is named as Purvanchal ranges which is parallel to Karakoram and Ladakh ranges. The NER is comprised of eight states which are characterized by diverse physiographic and climatic conditions. The region is surrounded by other countries like China, Bhutan, Bangladesh and Myanmar and a 'Chicken neck' corridor of 21 km length connects the region with the mainland India. The region in itself is a 'mini India' as a vast diversity in all aspects marks the region. The region has a unique ethnic diversity in customs, manners, value systems, attire along with the transitional diversity of the environment and biota. Apart from the valleys of Brahmaputra, Barak and Imphal, there are some flat lands in between the hills of Meghalaya and Tripura. The remaining two-thirds of the area is hilly terrain with valleys and plains in between the discreet hills. The altitude varies from near sea-level to about 7000 meters above MSL. A very high rainfall, undulating topography, a large number of rivers, tributaries and streams, high seismic activity and recent spurt in human activities like big construction works have resulted in natural problems like severe soil erosion and flood. Thus a fragile ecosystem has led to loss of biodiversity, loss of soil fertility, lower crop productivity and many other inevitable problems.

The climate of the region, in general, varies from warm humid sub-tropical climate with summer season hot and humid and winter season mild to extreme Alpine type. The region is classified under the humid-per humid agro-ecological zone with hot sub humid to humid and warm per humid eco-regions and soil type of alluvium-derived in valleys of Assam, brown and red hill in mountain ranges close to the Himalayas and red and lateritic in other north eastern hills (Sehgal *et al.* 1990). The NER has a total geographical area of 18.37 million ha of which about 55% is covered by forest. About 1.2 million ha land area is cultivated and about 2.2 million ha is not available for cultivation. The normal mean minimum and maximum temperatures vary between 18^{o}C to

***Corresponding author:** jayantadeka.2008@rediffmail.com

32°C during summer months and 0°C to 22°C during winter months. Heavy fog is a common feature all over the high mountain areas throughout the year. The temperature in the snow-covered mountains is well below freezing point. It is marked by severe monsoons with very high rainfall and the highest annual rainfall of the world is received at Cherrapunji and Mawsynram in Meghalaya.

The Indo-Malayan, Indo-Chinese, and Indian bio-geographical realms have converged in this part of India and it is recognized as one of the mega biodiversity hotspots of the world. The region supports large number of plant and animal species and it is the 'center of origin' of many economically important plant species either cultivated or wild forms. There is a record of 40 out of 54 species of gymnosperms, 500 out of 1012 species of pteridophytes, 825 out of 1145 orchid species, 80 out of 90 rhododendrons, 60 out of 110 bamboo species and 25 out of 56 cane species and all these species belong to about 200 plant families out of 315. Thus the region is an open repository of phyllogenetically important biodiversity but gradually it has degraded and the existence of many species has been seriously threatened.

Major ecosystems and associated weed problems

Based on the elevation, climate and soil conditions, water availability and socio-economic aspects, different agro-ecosystems are prevalent in the north eastern India. However, the agro-ecosystems of the region can be broadly classified as : i) *Jhum* agro-ecosystem, ii) Terrace land agro-ecosystem, and iii) Valley land agro-ecosystem.

The *Jhum* agro-ecosystem or shifting cultivation is the major land use pattern of the tribes of the mountains and hills of the region. *Jhum* pattern is decided by the preference of the particular tribe, ecological conditions and *Jhum* cycle or the intervening gap between two cropping period in the same time (Kuswaha and Ramakrishnan 1987). It involves slashing and burning of natural vegetation followed by cultivation and then abandonment for the revegetation and regeneration (Ramakrishnan 1992). In some of the medium slopes of the hills, the tribal communities have replaced *Jhum* with terrace land cultivation which help *in situ* water harvesting, use of modern inputs and permanent nature of agriculture. Valley land agro-ecosystem is common in the plain areas and the scattered valleys among the hills of the region. This ecosystem offers an ample scope for cultivation of a variety of crops throughout the year with assured water supply.

Rice forms the main component in the *Jhum* lands and a variety of other crops including maize, millets like finger millet and foxtail millet, pulses, oilseed like sesame, fibre crops like cotton, spices like ginger, turmeric, chili and vegetables like cucurbits, colocasia, brinjal, tomatoes, beans, tapioca are grown in mixture in this ecosystem. Chatterjee *et al.* (2006) reported that there are as many as 35 crops of different varieties in the *Jhum,* the primal agricultural economy. At lower elevation of Meghalaya, Toky and Ramakrishnan (1981) recorded 13 different crops in mixtures in *Jhum* cultivation. Chatterjee *et al.*(2006) mentioned about the rich biodiversity in north-east India as evidenced by a number of plant species available in this region. The common weed flora of *Jhum* fields were listed as *Ageratum conyzoides*, *A. houstoniunum*, *Arundo donax*, *Borreria articularis*, *Erigeron canadensis*, *Chromolaena odorata*, *Hyptis suaveolensis*, *Imperata cylindrica*, *Lantana camara*, *Mikania micrantha*, *Osbeckia crinia*, *Panicum maximum*, *Phragmitis karka*, *Saccharum spont-aneum*, *S. procerum*, *Solanum* spp., *Thysanolaena maxima etc*. Neogi *et al.* (1992) observed that the number of weed species varied in different seasons in *Jhum* areas in the hills of Meghalaya; maximum number was observed during May to October during the rainy season and the number gradually decreased from November to February during the winter. The growth and vigour of crop plants coupled with climatic factors of a particular season played an important role in distribution of these weeds. The frequency of weeds like *Polygonum plebeium*, *Rotala rotundifolia*, *Pseudognaphalium luteoalbum*, *Hydrolea zeylanica*, *etc*. increased from winter to early summer till spring, whereas that of *Eragrostis unioloides*, *Galinsoga parviflora*, *Ageratum* spp., *Echinochloa colona* and *Ludwigia octavalvis* increased from late summer to winter. Altitude played a critical role in distribution of *Galinsoga parviflora*, *Rotala rotundifolia*, *Setaria pumila* and *Hydrolea zeylanica*. Besides altitude, other factors like slope, *jhum*-cycle, burning, rainfall, run-off, crops and cropping geometry and many other relevant issues govern the kind of weed flora in a particular *Jhum* field. High intensity of weeds is always noticed from the second year of cropping.

A study conducted by Barua *et al.* (2002) in the fields of pointed gourd crop under traditional shifting cultivation in the greater Silonijan area of Karbi Anglong district of Assam located in the north-eastern slope showed as many as 29 weed species during the cropping period. These weeds mostly belonged to Asteraceae, Poaceae and Cyperaceae families with seven, six and three species, respectively. Further, most of the weed species were exotic and migrated from tropical climate. *Ageratum houstonianum* was the most dominant species with maximum density, frequency and IVI value and it was followed by *Crassocephalum-Gynura* complex*;* these weeds were truly problematic in the field. Lower IVI values of perennial grassy weeds might be due to temporary suppression of growth by entire cultivation practices and smothering effect of the crop (pointed gourd). The authors also reported that most of the recorded weed species were common with the upland crops of the fertile plains of NER. The biotic interference coupled with climatic factors determine the life-form spectrum of *Jhum* areas and it was cited as the reason for much variation of the weed flora of *Jhum* fields of Karbi Anglong (Barua *et al.* 2002).

Intensity of weed problem in *Jhum* cultivation primarily depends upon the *Jhum* cycle (Cutting et al. 1959, Zinke *et al.* 1978 and Kushwaha *et al.* 1981). Fujisaka (1991) cited weed as a primary factor of lower rice yields in shifting cultivation and reduced system sustainability in northern Laos. The shorter *Jhum* cycle limits the resource build up in *jhum* lands. The crop-weed competition also intensified under shorter *Jhum* cycle besides hindering further regeneration of vegetation. Barua *et al.* (2002) also mentioned that the lowering down of *Jhum* cycle caused the domain of shrubby scrab jungles, that too of a few weedy species during the *Jhum* fallow period. Thus the weed community is maintained in a permanent state of arrested succession (Kushwaha *et al*. 1981). However, Saxena and Ramakrishnan (1984) reported that a *Jhum* cycle of 10-years kept the weeds under control through natural suppression by regenerated vegetation.

Keeping in view the severity of weed menace, weed management plays an important role in deciding productivity of crops in *Jhum* areas. Burning is an inevitable practice in *Jhum* cultivation and a good burn and right time of burning are very important at least for the first crop season. The *Jhumias* (*Jhum* farmers) do timely weeding manually for optimum yield especially during the months of June and July. Depending on the soil fertility status and weed intensity, farmers cultivate crops during the second year or even continue for longer time. As soon as the labour cost of weed management exceeds the cost of new site clearance, the *Jhumias* shift to a new site. While clearing a site for cultivation, the farmers cut the trees of the forest leaving tree stumps intact in their fields for a quick regeneration of the forest. Ramakrishnan (1992) justified this process by stating that it helped in proper weed management and the soil erosion in steep slopes is also checked due to a quicker coverage of the ground. The main practice of control in shifting cultivation is hand weeding 3-4 times during crop growth incurring higher labour cost and reduced net return (Rathore *et al.* 2012). The use of modern herbicides is also negligible in *Jhum* lands and some farmers are still using common salts for control of weeds especially the broad leaf weeds and sedges; the Asteracean weeds like *Ageratum houstonianum*, *Crassocephalum crepediodes*, *Gynura* spp., along with *Cyperus rotundus* were the most common weeds though many forest enduring seedlings also appear in *Jhum* fields. The extremely acidic soil condition in *Jhum* areas was cited as the reason for the good performance of common salt.

Fallowing is an essential part of shifting cultivation and three different types of fallow are found based on the gap period of the *Jhum* cycle and predominant vegetation type regrowing and covering the ground during the fallow period. These fallow types are forest fallow (20-25 years), bush fallow (6-10 years) and grass fallow (<5 years). Increasing population pressure and decreasing land availability have compelled the *jhumias* in NER to shorten the fallow period and now most of the *Jhum* areas could afford a fallow up to about 5 years only (grass fallow). *Imperata cylindrica* and *Saccharum* spp. were the predominant grasses; *Chromolaena odorata*, *Hyptis suaveolensis* and *Lantana camara* also appeared amidst the grasses which strengthened their population stand with the increase of fallow period.

Rice agro-ecosystem

Rice is the most important crop of all the states of the NER under terrace, valley and plain area agro-ecosystems. It is cultivated primarily in a rainfed production system with very meager area with irrigation facility. Rice ecosystems can be classified as different sub-ecosystems depending upon the land situations like upland, medium land, lowland and very lowland, accordingly a particular land situation decide the rice culture that is followed. The north east India being in primary centre of origin of rice, a vast diversity is observed in the crop with respect to morphology, growing habits, adaptability to environment, productivity and quality characters. Six species of wild relatives of rice are also reported to occur in Assam; theses are *Oryza meyriana*, *Oryza meyriana* var. *granulata*, *Oryza minuta*, *Oryza rufipogon*, *Hygroryza aristata*, and *Leersia hexandra* besides the doubtful species like *Oryza collina* and

Oryza sativa var. *plena* (Barua and Talukdar 2015). These wild rice types occur as weeds in rice fields depending upon the rice cultures. The total weed population comprised of 34.1% broad-leaved, 42.2% grasses and 23.6% sedges under puddled condition of sandy clay loam soil during rainy season (Singh *et al.* 2007). Ravisankar *et al.* (2008) reported that the wet seeded rice was infested with 51.5% grass, 30.9% sedge and 17.5% broad-leaved weeds. Barua and Gogoi (2002) enumerated as many as 134 weed species of upland direct seeded rice in Assam and classified according to life forms. The predominant weed flora of different rice ecosystems recorded in regular survey and numerous trials on weed management under All India Coordinated Research Programme on Weed Control (presently renamed as All India Coordinated Research Project on Weed Management), Assam Agricultural University, Jorhat is listed in Table 1.

Weeds are one of the main production constraints in any of the rice ecosystems (Adesina *et al.* 1994, Ampong-Nyarko 1996, Becker and Johnson 1999). Rodenburg and Johnson (2009) listed the common agronomic factors which contribute to weed problems in rice as inadequate land preparation, seed contamination with weed seeds, use of poor quality seeds, broadcast seeding in lowlands, use of overage rice seedlings for transplanting, inadequate water management, inadequate fertilizer management, mono-cropping, labour shortages for weeding operations, delayed herbicide applications and other interventions. The nature and severity of weed menace in rice vary according to the ecosystem in which the crop is grown. Weeds are a critical production constraint in the rainfed upland and unbunded medium and lowlands where water submergence is not done. Similarly, the deep water rice ecosystems is also affected severely by weeds that emerge along with dry-seeded crop prior to flooding and high water level and most of the weeds that are predominant can tolerate the water level. In the plains of the north-eastern region, the irrigated rice cultures during the pre-monsoon period as early *ahu* and *boro* is gaining popularity among the farmers due to higher productivity and less risk of flood under more sunshine hours during the period. But there is always a wetting and drying condition prevailing under such situation which encourages the emergence of weeds and their severe intensity posing

Table 1. Weed flora in different rice ecosystems

Weed	Weed	Reference
Nursery (boro rice or summer rice)		
Alternanthera philoxeroides	*Eleocharis acutangula*	Ann. Rep., (1999-2000, 2006-07),
Cyperus spp.,	*Monochoria hastata*	AICRP on Weed control, AAU,
Echinochloa crussgalli	*Sagittaria sagettifolia*	Jorhat
Echinochloa stagnina	*Scirpus* spp.	
Main field (boro rice or summer rice)		
Echinochloa spp.	*Ludwigia adscendens*	Ann. Rep., (1999-2000, 2006-07),
Eichhornia crassipes	*Polygonum* spp.	AICRP on Weed control, AAU,
Eragrostis unioloides	*Marsilea minuta*	Jorhat
Commelina diffusa	*Scirpus* spp.	
Ludwigia lini folia	*Physalis minima*	
Direct seeded upland rice (ahu or autumn)		
Ageratum houstonianum	*Cyperus rotundus, C. iria*	Ann. Rep., (1999-2000, 2000-01),
Alternanthera philexeroides	*Digitaria -Paspalum* complex	AICRP on Weed control, AAU,
Borreria aricularis	*Eleusine indica*	Jorhat
Cynodon dactylon	*Fimbristylis* spp.	
Ludwigia linifolia	*Melochia corchorifolia*	
Transplanted ahu (autumn)		
Aeschynomene indica	*Cyperus iria + Fimbristylis littoralis*	Ann. Rep., (2000-2001), AICRP on
Ludwigia linifolia	*Isachne himalaica*	Weed control, AAU, Jorhat
Polygonum glabrum	*Leersia hexandra*	
Echinochloa crusgalli	*Monochoria vaginalis*	
Melochia corchorifolia	*Scirpus* spp.	
Deep water rice (bao)		
Aeschynomene indica	*Hymanachne acutigluma*	Ann. Rep., (2000-2001,2002-
Alternanthera philoxeroides	*Oryza rufipogon*	03,2004-05) AICRP on Weed
Paspalum scrobiculatum	*Sacciolepsis interrupta*	control, AAU, Jorhat
Melochia corchorifolia	*Eichhornia crassipes*	
Eleocharis acutangulus, E. dulcis	*Hygroryza aristata*	
Echinochloa crusgalli	Weedy rice	

a major limiting factor of production. Uncontrolled weed growth causes yield losses to the tune of 28-74% in transplanted lowland rice, 28-89% in direct-seeded lowland rice and 48-100% in upland ecosystems in West Africa (Rodenburg and Johnson 2009). Weed problem of rice cultures in NER is as severe as in Africa and it is mainly because of very rich soil seed bank. A study at Jorhat, Assam recorded an emergence of about 12000-15000 and 4000-6000 numbers of weeds from the soil seed bank in rice-wheat and rice-rice sequence, respectively, even after fifth year in immigration controlled atmosphere (AICRPWC, AAU, Jorhat 2013-14).

There is a linear correlation between yield loss and weed population, however, beyond certain population limits, yield reductions become nearly constant due self competition among the weeds (Sridevi 2013). Like other crops, rice also faces maximum competition by weeds in its early growth stages. When the crop growth is only 2-3% during the establishment phase, the weeds already achieve 20-30% growth (Moody 1990). Researchers from different locations have reported a critical period of competition ranging between 40-45 days in transplanted rice (Govindarasu *et al.* 1998, Sathyamoorthy and Kandasamy 1998, Chinnusamy 2000, Tewary and Singh 1991, and Thapa and Jha 2002). Moorthy and Saha (2005) reported that the losses in grain yield of rice due to competition from weeds for a period of 30, 60 and 90 days were 17.7, 11.8 and 5.0%, respectively. Umapathy and Sivakumar (2000) found that the competition from grassy weeds, sedges and broad-leaved weeds in rice was in descending order. It was reported by Chauhan and Johnson (2010) that shoot competition between weeds like *Echinochloa* spp., *Ludwigia* spp. and direct seeded rice was more severe than their root competition and reflected on yield of rice; however rice grain yield was highly correlated with both above and below ground biomass of the weeds. The crop-weed competition was most severe in upland direct seeded rice and grain yield loss to the tune 76-78% due to unchecked weed growth was recorded (AICRPWC, AAU, Jorhat 2009-10). The plant characters like tiller number and leaf angle are more important for smothering of weed than plant height in upland rice. The findings of AICRPWC, AAU, Jorhat (1999-2000) showed that the variety *"IEI-15998"* recorded the highest tiller number (152/m^2) at 40 DAS, highest primary tiller angle (7.1^0), the lowest plant height of 67.6 cm and lowest weed dry weight but it recorded highest grain yield of 3.75 t/ha among the tested varieties.

Works carried out at AAU, Jorhat revealed that application of pretilachlor 0.75 kg/ha + safener + one hand weeding 30 DAS and butachlor 1.5kg/ha + one hand weeding 30 DAS resulted better weed control and grain yield in direct seeded upland rice as compared to other treatments. Time of sowing before or after pre-monsoon showers did not affect the density and dry weight of weeds as well as grain yield of rice. Different herbicides were compared in respect of performance in upland direct seeded rice and combination of oxyfluorfen 300 g/ha pre-emergence + 2,4-D 0.5 kg/ha post-emergence was found to be effective.

A two years trial during 2009 and 2010 showed higher grain yield in lowland rice under normal transplanting than SRI method. Among the weed management treatments, pretilachlor 0.75 kg/ha + mechanical weeding (paddy weeder) 30 days after transplanting resulted highest grain yield in rice and the increase was about 56% over weedy check (AICRPWC, AAU, Jorhat Centre 2009-10). During 2011 and 2012, pyrazosulfuron 20 g/ha + manual weeding 30 days after transplanting was as good as pretilachlor 1000 g/ha + Almix 4 g/ha in respect of weed control and grain yield in transplanted rice (AICRPWC, AAU, Jorhat centre 2011-12 and 2012-13). The threshold values of a few major weeds of transplanted rice were determined (AICRPWC, Jorhat Centre 2005-06 and 2013-14). Accordingly the values were 60/m^2 for *Echinochloa crusgalli*, 120/m^2 for *Monochoria vaginalis*, 140/m^2 for *Scirpus juncoides* and *S.maritimus*, 2/m^2 for *Ludwigia decurens* and *L. linifolia* and 70/m^2 for *Cyperus iria*. Beyond these threshold levels, there was significant reduction in grain yield of rice.

Jute agro-ecosystem

The hot and humid climate of the NER coupled with high rainfall during the summer season in which jute is an important crop of the valley regions encourages weed growth resulting in severe crop-weed competition (Saraswat 1999); yield losses may be up to 75 to 80% (Sahoo and Saraswat 1988); implying the need for judicious weed management. The major weed flora in the jute growing areas comprised of *Ageratum houstonianum*, *Alternanthera sessilis*, *Amaranthus spinosus*, *Axonopus compressus*, *Commelina diffusa*, *Cynodon dactylon*, *Digiteria setigera*, *Echinochloa colona*, *Eragrostis unioloides*, *Mikania micrantha*, *Murdania* spp., *Paspalum conjugatum*, *Spilanthes paniculata*, *Fimbristylis littoralis*, *Cuphea balsamona*, *Cyperus rotundus*, *Euphorbia hirta*, *Impatiens* spp. *etc*.

The weeds of jute could be effectively controlled by application of quizalfop-P-ethyl 60 g/ha at 15 days after emergence followed by one hand weeding 7 day after herbicide application (Anonymous 2010).

Suagarcane agro-ecosystem

Sugarcane is cultivated up to 183 m altitude from MSL in NER. Barua and Gogoi (1995) recorded as many as 48 species of common weeds in sugarcane fields of Assam belonging to 22 families and also observed 11 significant positive associations and 16 negative associations of weeds in their phyto-sociological behaviour. A reduction of cane yield in the range of 12 to 72% in sugarcane due to unchecked weeds has been estimated. The severity of weed infestation in this crop is primarily due to its planting with a wider row spacing, very slow initial growth (about 30-45 days to complete germination and another 60-75 days for developing full canopy cover), abundant water and nutrient supply to the crop, very little preparatory tillage in ratoon crop allowing the already established weeds flourish well. Among the weeds, *Mikania micrantha*, *Ageratum hostonianum* and *Borreria articularis* were found to occur throughout NER as the most common and problematic weeds of sugarcane. Barua and Gogoi (1995) recorded *Setaria-Paspalum-Panicum* complex along with *Borreria articularis* in Barak valley and *Digitaria-Paspalum* complex in the hill zone as the predominant weed groups in this crop. The average weed dry weight may go up to the tune of 250 g/m^2 in summer and 190 g/m^2 in monsoon. Unlike upland rice, the prevalence of perennial weeds is several times more than annual weeds.

The problem of weed menace in sugarcane can be efficiently managed with pendimethalin 1.0 kg/ha in sugarcane + cowpea intercropping (Anonymous 2010).

Tea agro-ecosystem

The environmental condition of the NER is very ideal for production of a wide range of plantation crops, *viz.* tea, coffee, rubber, coconut and arecanut. The plantation crops altogether occupy 8.97% of the total cultivated area of the region which is about 3.33 lakh ha and among these crops, tea alone accounts for 3.18 lakh ha (95.5%). In the middle of nineteenth century, tea was introduced in Assam and Tripura and the area expanded in a short time; the crop has further spread to more of non-traditional areas of the region.

Besides the one thousand plus corporate tea gardens in this region, tea has also found a place as a farmer's crop since the end of last century when the concept of small tea growers came into existence. At present, about 117 thousand acres of land (47,348 ha) is under small tea sector; 87% of the small tea farmers have less than 3 acres (1.21 ha) of plantation, further, 67% of such gardens are less than 10 years old (Barua and Nath 2015). Average productivity of the small sector is about 2379 kg made tea per ha (KMTH) while the average productivity of the gardens of corporate sector is about 1860 KMTH. The higher productivity in smaller tea gardens might be due to smaller holdings and thus a better individual bush care which is not possible in a large garden besides tea plantation is also done in marginal areas in a bigger garden.

Weeds are counted as one of most important critical factors limiting optimum productivity in tea plantations. Intensity of weed problem is primarily governed by agro-climatic conditions, type of tea culture, general management conditions, specific weed management schedule *etc*. Dominant weed flora in young tea in Assam comprises of *Scoparia dulcis*, *Borreria articularis*, *Mimosa pudica*, *Hyptis suaveolensis*, *Axonopus compressus*, *Cynodon dactylon*, *Paspalum conjugatum*, *P. longifolium*, *Ageratum hostonianum*, *Sida acuta*. Weeds like *Mikania micrantha*, *Paspalum* spp., *Borreria articularis*, *Gynura bicolor, Axonopus compressus*, *Cynodon dactylon*, *Hyptis suaveolensis*, *Melastoma malabathricum, Osbechia nepalensis, Sida acuta, Chromolaena odorata, Lantana camara, Mimosa diplotricha, Dicanthium* spp. mostly dominate in mature tea. In the seed *baris* (orchard) besides other terrestrial weeds, a parasitic weed, *Loranthus longifolius* has been noticed at many places. The organic tea cultivation is gaining popularity in recent times; the nature of weed is also changing. Other than the common weeds of tea, prevalence of several perennial grasses and bushy broadleaved weeds like *Urena lobata*, *Triumpfeta rhomboidea*, *Solanum torvum,* perennial climbers like *Lygodium flexuosum, L. japonica* and sedges belonging to *Carex, Scleria* etc. have also been recorded in organic tea plantations.

Like other agricultural and horticultural crops, tea also needs an adequate agronomic care for a high and sustained productivity. Uncontrolled weed growth can cause a loss of productivity to the extent of 50-70% in tea. Productivity losses due to weeds may accrue due to severe competition for growth factors, restricted branching and frame development, harbouring of disease pathogens and pests as alternate hosts, less plucking efficiency, contamination of plucked shoots, and water stagnation in the drainage outlets. Weed infestation and consequent damage to the crop is more severe in young tea up to two years before canopy closure and during the period of pruning at an interval every three to four years. Weed competition began at 8 weeks after weed emergence in tea plantation and was detrimental to young tea at 12 weeks or later (Prematilake *et al.* 2004). A period of 18 weeks of uncontrolled weed growth in young tea was enough for plant mortality. The period between April to September is very critical from tea productivity point of view and the season coincides high rainfall and temperature which provides a very favourable condition for weed growth and resultant menace for the crop. Different methods are used individually or integrated for an effective weed management in tea plantations. However, the use of herbicides still remains cheap and effective means for weed control. Model weed control schedules with combination of pre-emergence and post-emergence herbicides have been developed and followed. But option of herbicides (PPFs) in tea is very limited as number of herbicides registered for tea as per gazette notification of Ministry of Agriculture S.O. 2486 (E) dated 24th September, 2014 is few comprising only glyphosate 41 SL and 71 SG, glyphosate ammonium salt 5 SL, glufosinate amonium13.5 SL, oxyfluorfen 23.5 EC and paraquat dichloride 24 WSC. Cases of herbicide tolerance by specific weeds have been observed (AICRPWC, AAU, Jorhat 2006-07). Herbicide rotation, integrated weed management, vigilance on developing resistant ecotypes is some of the useful means to restrict herbicide resistance build up in weeds. Studies on herbicide residues till now have not indicated any residues above detectable level in context of standard herbicides in plant, soil or water in tea plantations. Developing clones with resistance to non-selective herbicides as in the case of some agricultural crops is also promising in tea.

A new challenge has emerged in recent time in regards to weed management in organic tea plantations. An effective and economically sound method is still eluding the organic tea planters.

Horticultural crops agro-ecosystem

Difficult terrain, wide variations in slopes and altitudes, land tenure systems and indigenous cultivation practices mark the North-East region of the country. The cereals dominate the rainfed hill ecosystem, dependence on horticulture as an alternative source of income is also remarkable. Banana, potato, vegetables, ginger, turmeric, citrus, apple are some of the major agro-ecosystems in the North East Himalayan region.

The predominant weeds of banana are listed in table 2 and these comprised of *Ageratum-Borreria-Commelina* combinations coupled with *Mikania micrantha*, of late *Mimosa diplotricha* throughout the states of Assam, Manipur, Tripura and foothills of the other hill states. Banana plantation is permanent and an ideal microclimate in these plantations favourably increases the weed problem and competition with the crop hampering its growth and productivity. Frequent inter-cultural operations and mulching are generally followed for weed control in addition to manual weeding operations. Further, growing an inter crop of cowpea and incorporation in soil followed by hand weeding at 30 days interval up to shoot stage help in managing the weed problem. Application of diuron 3 kg/ha or paraquat 1.5 kg/ha can check the weed problem in this crop (Anonymous 2005).

Pineapple is a major fruit crop of the entire north east India with an average productivity higher than the national average (15.3 t/ha). However, the crop cycle is long and it confronts severe competition from weeds. The weed flora has been surveyed under AICRP on Weed Control, and the dominant ones are presented in Table 2.

Vegetables are popularly grown by the farmers of north east India but various problems including seasonal and perennial weeds cause extensive damage to the crops and limit the productivity to a low level.

Table 2. Problem weed flora in horticultural crop-ecosystems of NER

Name of weed	Crop			
	Banana	Pineapple	Vegetables	Turmeric, ginger, chili
Ageratum houstonianum	v	v	v	v
Borreria articularis	v	v	v	v
Commelina diffusa	v			v
Mikcania micrantha	v	v	v	
Mimosa diplotricha	v			
Eleusine indica		v	v	
Digiteria setigera		v		v
Paspalum longifolium		v	v	
Chromolaena odorata		v		
Saccharum spontaneum		v		v
Imperata cylindrica		v	v	v
Cynodon dactylon			v	v
Panicum repens			v	v
Cyperus rotundus			v	v
Gnaphalium polycaulon			v	v
Colocasia esculenta			v	

Potato, cauliflower, cabbage, brinjal, coriander, tomato, okra and French bean are some of the very important commercial vegetables of the region. These crops are infested by numerous weeds; their type and intensity vary depending upon season, crop and management approach. The combination of broadleaved species like *Ageratum-Leucas-Gnaphalium* occur everywhere besides the weeds listed in table 2. Farmers mostly adopt cultural, manual or mechanical methods of weed control. Various herbicide recommendations have been made from AAU, Jorhat for different vegetable crops but they are yet to reach the field level in a big way.

Turmeric, ginger and chili are the most important spice crops of the region having large diversity. The region has enough surplus production and thus large scale exports are made from these states. Higher productivity and better quality of the produce could help the farmers to earn more from these crops. Adequate weed management is a priority in this respect. A number of grasses, broadleaved and sedges infest these crops and offer severe competition. Ginger and turmeric are long duration crops and a sustained management of weeds is very important. An integrated weed management approach involving chemical, cultural and mechanical methods will be cost effective as well as efficient in checking the weed problem for longer period. Pre-emergence application of herbicides like metribuzin 700 g/ha, atrazine 750 g/ha and pendimethalin 1000 g/ha or oxyfluorfen 20 g/ha followed by two hand weeding at monthly interval up to 60 days after planting has been found promising.

In recent years, infestation of *Parthenium hysterophorous* in citronella plantations has vigorously increased in Golaghat, Karbi Anglong and Dima Hasao districts of Assam and Dimapur district of Nagaland.

Forest and wetland ecosystems

Weeds are always a matter of concern in plantation forests, more particularly in first few years of their plantation. A good number of herbs, shrubs and climbers of invasive nature are the problem causing weeds, which vary from place to place and their pattern of dominance is governed by associated vegetation, availability of seeds and sources, and above all the elevation of the site. The most common sub-climax forming weeds amongst them are *Chromolaena odorata* in foothills and plains, whereas *Lantana camara* in lower elevations, and *Solanum xanthocarpum* and wild *Saccharum* spp. above the zone of *Lantana*. In disturbed lands, *Mikania micrantha* and *Imperata cylindrica* are the most common weeds all along the North Eastern Himalayan region except ice covered peaks in Arunachal Pradesh. Several Asteracean plants and species mostly belonging to *Borreria, Ficus* and reed grasses, along with climbers mostly belonging to Convolvulaceae and Fabaceae usually offered good competition to the newly planted seedlings of timber plants. Different climbers belonging to *Mukuna, Ipomoea* and *Merremea* were the problem weeds of teak and *sal* forests of this region.

In natural forests, the seriousness about weeds perhaps developed along with the problem created by the thorny and climbing straggler *Mimosa diplotricha* in the Kaziranga National Park. Since its appearance in around 2006, the weed is creating havoc in this park, by heavy smothering of associated vegetation, debarring wild animals from free grazing and passage besides cleverly escaping all kinds of mechanical and cultural management efforts taken up by the forest managements. Cutting and burning of *M. diplotricha* in the winter in the park area have damaged the grassy vegetation rather badly and encouraging its seed germination immediately after burning. Presently, this invasive weed has spread to newer areas, including Rajib Gandhi National Park, Assam many forests and non-forest areas of Arunachal Pradesh, Assam and Nagaland, and nearby settlement areas and crop fields. Consequently, another problematic and thorny invasive weed species, *Rosa bracteata* has also been found as newly introduced in the wetlands of Kaziranga National Park (Barua *et al.* 2014).

Mikania micrantha is another threat for the forests of Assam, mostly infesting the forest edges and open forests. Because of its excessive growth, the climber often covers the ground vegetation in the slope-lands, smothers the trees, bamboos and shrubby bushes, along the secondary forests and the edges of primary forests. Its smothering effect causes significant deterioration of the forest ecosystem and thus expansion of degraded area along the edges of primary forests; the ground vegetation in such damaged forest-lands is seen changing remarkably because of increasing predominance of other invasive weeds like *Chromolaena odorata, Hyptis suaveolensis, Lantana camara, Sida acuta,* etc. and several grasses belonging to *Cyrtococcum, Digitaria, Oplismenus,* etc. permanently replacing the autochthonous species. Thus, the smothering effect of *Mikania* not only triggered the shift of the indigenous vegetation of forests, but also seriously disturbed the food webs and micro-environments for faunal elements as well as opens up possibilities for human encroachment into the forest land as pioneer invader, in other words a driver species (Barua *et al.* 2013).

The riverine grasslands are another flagship vegetation of this region, more particularly of the Brahmaputra valley of Assam. This grassland is conserved by forest management machineries as these forest patches are the major source of food for the herbivores and birds and insects, which play an important role in energy flow system in the complex food web. These grasslands are usually subjected to partial burning during winter as a part of their management. Annual burning also destroyed its associated weed flora. Stumps of certain big trees, however, developed naturally because of annual burning or overgrazing, create trouble three to four years after their development, thus causing serious depletion of grasslands. *Oroxylum indicum, Dillenia pentagyna* and *Bombax ceiba* are such tree weeds in Manas Wild Life Sanctuary, Nameri Wild Life Sanctuary and many other forest areas. Out of these trees, the invasive migrants like *Mimosa diplotricha, Rosa bracteata, Mikania micrantha etc*. have also been recorded as serious weeds in several forest based grasslands. *Ludwigia peruviana*, the villous bush with tremendous seed production ability is one of the latest additions to this list, first sighted in the Dhansiri catchments of Assam and adjoining Nagaland. Satellite populations of this weed have also been developed in the eastern catchment of Kopili River, in and around the Lumding Reserve Forest and a few other districts of Brahmaputra valley.

Wetland of non-forest areas play very important role in nesting many indigenous and migratory avifauna and their foods, fishes and herpetofauna, leaches and reptiles, aquatic and semi-aquatic vegetation and ideal atmosphere for cultivation of deep water paddy, and other water-crops. Amongst the weeds, which damage the ecosystem are nothing but some invasive species, over-population of which have caused discomfort and harm to this ecosystem. *Mikania micrantha, Eichhornia crassipes, Ipomoea carnea*, several *Polygonum* species *etc*., parasites like *Cuscuta reflexa* and *C. campestris* and grasses like *Saccharum spontaneum* and *Leersia hexandra* have been recorded as serious weeds in majority of wetlands of NER.

REFERENCES

Adesina A, Johnson DE and Heinrichs EA. 1994. Rice pests in Ivory Coast, West Africa-farmers perceptions and management strategies. *International Journal Pest Management* **40**(4): 293-299.

AICRPWC. 1999-2000. *Annual Report*. All India Coordinated Research Programme on Weed Control, AAU, Jorhat, Assam.

AICRPWC. 2000-01. *Annual Report*. All India Coordinated Research Programme on Weed Control, AAU, Jorhat, Assam.

AICRPWC. 2002-03. *Annual Report*. All India Coordinated Research Programme on Weed Control, AAU, Jorhat, Assam.

AICRPWC. 2004-05. *Annual Report*. All India Coordinated Research Programme on Weed Control, AAU, Jorhat, Assam.

AICRPWC. 2005-06. *Annual Report*. All India Coordinated Research Programme on Weed Control, AAU, Jorhat, Assam.

AICRPWC. 2006-07. *Annual Report*. All India Coordinated Research Programme on Weed Control, AAU, Jorhat, Assam.

AICRPWC. 2009-10. *Annual Report*. All India Coordinated Research Programme on Weed Control, AAU, Jorhat, Assam.

AICRPWC. 2011-12. *Annual Report*. All India Coordinated Research Programme on Weed Control, AAU, Jorhat, Assam.

AICRPWC. 2012-13. *Annual Report*. All India Coordinated Research Programme on Weed Control, AAU, Jorhat, Assam.

AICRPWC. 2013-14. *Annual Report*. All India Coordinated Research Programme on Weed Control, AAU, Jorhat, Assam.

Ampong-Nyarko K. 1996. Weed management in rice in Africa, pp. 183-191. In: *Weed Management in Rice* (Eds. Auld BA and Kim KU), FAO, Rome.

Anonymous. 2005. *Package of practices- Horticultural Crops of Assam*. Assam Agricultural University, Jorhat. 4 p.

Anonymous. 2010. *Package of Practices Meeting for Kharif Crops of Assam*. Assam Agricultural University, Jorhat.

Barua IC, Barua KN and Gogoi AK. 2002. A study on the weed flora of pointed gourd fields under shifting cultivation in Assam. *Indian Journal of Weed Science* **34**(1&2): 104-109.

Barua IC, Deka J and Devi M. 2013. Invasive weeds and vegetation dynamics in Assam, pp 166-170. In: *Proceedings 24th Asia-Pacific Weed Science Conference* (Eds. Baker B, Kurniadie HD and Tjitrosoedirdjo S). APWSS, WSSI and Padjadjaran University, Bandung, Indonesia.

Barua IC, Devi M, Deka J, Vasu NK and Sarmah R. 2014. Invasiveness of wild *Rosa* in Kaziranga National Park,p. 61. In: *Proceedings of Biennial Conference*, Indian Weed Science Society, 15-17 Feb, ISWS and DWSR, Jabalpur.

Barua IC and Gogoi AK. 1995. Phytosociological studies of sugarcane weeds in Assam. *World Weeds* **2**: 107-115.

Barua IC and Gogoi AK.2002. Biodiversity of weed flora in upland direct seeded rice ecosystem in Assam, pp 108-116. In: *Biodiversity of Assam and its Conservation* (Eds. Bhattacharya MK, Dutta Choudhury and Mazumdar PB). Assam.

Barua IC and Talukdar PK. 2015. Assam's plant diversity conservation and utilization,pp. 269-298. In: *Agriculture in Assam* (Ed. Mishra P and Bhattacharjya A), Assam Agricultural University.

Barua Subhash C and Nath JC. 2015. Plantation crops of Assam-Conservation and Utilization, pp. 189-211. In: *Agriculture in Assam*. (Ed. Mishra P and Bhattacharjya A), Assam Agricultural University.

Becker M and Johnson DE.1999. Rice yield and productivity gaps in irrigated systems of the forest zone of Cte d'Ivoire. *Field Crops Res*, **60**(3): 201-208.

Chatterjee S, Saikia A, Dutta P, Ghosh D and Worah S. 2006. Review of biodiversity in North East India. *Background paper No.* 13, WWF, Delhi, India. p 45.

Chauhan BS and Johnson DE. 2010. Relative importance of shoot and root competition in dry competition in dry seeded rice growing with jungle rice and *Ludwigia*. *Weed Science* **58**: 295-299.

Chinnusamy C, Kandasamy OS, Sathyamoorthy K and Chandrasekhar CN. 2000. Critical period of crop weed competition in lowland rice ecosystems. In: *Proceedings of State level seminar on Integrated Weed Management in new millennium*, Ratnagiri, Maharashtra, 27-28 Feb, 2000.

Cutting CV, Wood RA, Brown P and Ambrose BB. 1959. Assessment of fertility status and the maintenance of productivity of soils in Nyasaland, pp. 817-824. In: *3rd International African Soils Conference*, Dalaba.

Fujisaka S. 1991. A diagnostic survey of shifting cultivation in northern Laos: targeting research to improve sustainability and productivity. *Agroforestry systems* **13**: 95-109.

Govindarasu R, Rammohan J, Ramamoorthi N and Hanifa AM. 1998. Direct seeding- a best substitute for transplanted rice cultivation in future. *Kisan World* **25**(11): 20-21.

Kushwaha SPS, Ramakrishnan PS and Tripathi RS. 1981. Population dynamics of *Eupatorium odoratum* L. in successional environments following slash and burn agriculture (*Jhum*). *Journal Applied Ecology* **18**: 529- 536.

Khuswaha SPS and Ramakrishnan PS. 1987. An analysis of some agro-ecosystem types of north eastern India, pp. 161-168. In:. *Proceedings of Indian National Science Academy*, B53 No.2.

Moody, K. 1990. Post planting weed control in direct-seeded rice. In*: Proceedings of Rice Symposium*, MARDI, Penang, Malayasia, 25-27 September, 1990.

Moorthy BTS and Saha S. 2005. Studies on crop weed competition in rainfed direct-seeded lowland rice (*Oryza sativa* L.). *Indian Journal. of Weed Science* **40**(3-4): 112-116.

Neogi B, Dey BP and Barua IC. 1992. Distribution pattern of some dominant weeds of East Khasi hills, Meghalaya. *Journal of National Botanical Society* **46**: 15-20.

Prematilake KG, Froud-Williams RJ and Ekanayake PB 2004. Weed infestation and tea growth under various weed management methods in a young tea (*Camellia sinensis* (L.) Kuntze) plantation. *Weed Biology and Management* 4: 239-248.

Ramakrishnan PS. 1992. *Shifting Agriculture and Sustainable Development: An Interdisciplinary Study from North-Eastern India*. Parthenon Publ. Group, Carnforth, U.K.

Rathore SS, Krose N, Naro M, Shekhawat K and Bhatt BP. 2012. Weed management through salt application: An indigenous method from shifting cultivation areas, Eastern Himalayas, India. *Indian Journal of Traditional Knowledge* **11**(2): 354-357.

Ravisankar N, Chandrasekaran B, Raja R, Din M and Chaudhari SG. 2008. Influence of integrated weed management practices on productivity and profitability of wet seeded rice (*Oryza sativa*). *Indian Journal of Agronomy* **53**(1): 57-61.

Rodenburg J and Johnson D E. 2009. Weed management in rice-based cropping systems in Africa. *Advances in Agronomy* **103**: 149-218.

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

Saraswat, V.N. 1999. Weed management in jute and jute based cropping system, pp. 193–200. In: *Jute and Allied Fibres: Agriculture and Processing* (Eds. Palit P, Pathak S and Singh DP). Central Research Institute for Jute and Allied Fibres, Barrackpore.

Sathyamoorthy K and Kandasamy OS. 1998. Critical period of crop weed competition in different rice culture (lowland transplanted and wet seeded rice). In*: Summary and Research Achievements-1998*. AICRPWC (ICAR), Coimbatore Centre, TNAU, Coimbatore.

Saxena KG and Ramakrishnan PS. 1984. Patterns of herbaceous vegetation development and weed potential under slash and burn agriculture (Jhum) in north-eastern India. *Weed Research* 24: 137-144.

Sehgal JL, Mandal DK, Mandal C and Vadivelu S. 1990. Agro-ecological regions of India. Technical Bulletin, NBSS Publ. 24, 73 p.

Singh P, Singh P and Singh SS. 2007. Response of aromatic rice (Pusa Basmati!) to establishment methods, fertility levels and weed management practices. *Indian Journal of Weed Science* **39**(1&2): 32-35.

Sridevi V, Jeyaraman S, Chinnusamy C and Chellamuthu V. 2013. Weed management in lowland rice (*Oryza sativa* L.) ecosystem a review. *International Journal of Agricultural Science and Research* **3**(3): 13-22.

Tewary AN and Singh RD. 1991. Crop-weed competition in direct seeded rainfed rice. *Indian Journal of Weed Science* **23**:51-52.

Thapa CB and Jha PK. 2002. Paddy crop weed competition in Pokhara, Nepal. *Geobios* **29**(1): 51-54.

Toky OP and Ramakrishnan PS 1981. Cropping and yields in agricultural systems of north–eastern hill region of India. *Agro-Ecosystems* **37**: 11-25.

Umapathy K and Sivakumar C. 2000. Studies on crop-weed competition in rice-rice cropping system, pp. 57. In: *Proceedings of State Level Seminar on Integrated Weed Management in New Millennium*. Ratnagiri, Maharashtra, 27-28 Feb, 2000.

Zinke PJ, Sabhasri S and Kunstadter P. 1978. Soil fertility aspects of the 'Lua' forest fallow system of shifting cultivation. In: *Farmers in Forest (*Eds. P. Kunstadter, E.C. Chapman and S. Sabhasri). Hawaii: East-West Centre.

Indian Journal of Weed Science **47**(3): 306–320, 2015

History, progress and prospects of classical biological control in India

Sushil Kumar
ICAR-Directorate of Weed Research, Jabalpur, Madhya Pradesh 482 004

Received: 25 June 2015; Revised: 30 July 2015

ABSTRACT

First successful classical biological control of a weed (prickly pear) was achieved unintentionally in India when cochineal insect, *Dactylopius ceylonicus* was mistakenly introduced from Brazil in place of *D. cacti* to produce dye from *Opuntia vulgaris*. This incident led to biological control of weeds. From 1863 to 1868, it was introduced to southern India, which was first successful intentional use of an insect to control a weed. In 1926, *D. opuntiae*, a North American species, was imported from Sri Lanka and its colonization resulted in spectacular suppression of *Opuntia stricta* and related *O. elatior*. So far in India, about 30 exotic biological control agents have been introduced against weeds, of which six could not be released in the field, 3 could not be recovered after release while 21 were recovered and established. From these established bioagents, 7 are providing excellent control, 4 substantial control and 9 partial control. Biological agents, mainly insects provided excellent biological control of prickly pear, *Opuntia elatior* and *O. vulgaris* by *D. ceylonicus* and *D. opuntiae*; *Salvinia molesta* by weevil, *Cyrtobagous salviniae*; water hyacinth by weevils *Neochetina bruchi* and *N. eichhorniae* and galumnid mite *Orthogalumna terebrantis*; and *Parthenium hysterophorus* by chrysomelid beetle *Zygogramma bicolorata*. Some introduced bioagents did not prove success but providing partial control like of *Lantana* by agromyzid seedfly, *Ophiomyia Lantanae*, tingid lace bug, *Teleonemia scrupulosa, Diastema tigris, Uroplata girardi, Octotoma scabripennis* and *Epinotia lantanae*; *Chromolaena odorata* by *Pareuchaetes pseudoinsulata*; *Ageratina adenophora* by gallfly, *Procecidochares utilis*; submerged aquatic weeds such as *Vallisneria* spp. and *Hydrilla verticillata* in fish ponds by grass carp. There are many bioagents which have been introduced in other countries and have shown varying degree of success through combined effect. In Australia, 9 bioagents have been introduced against *Parthenium* alone. Such successful bioagents need to be introduced in India against some of the problematic weeds like *Parthenium*, water hyacinth, *Pistia*, alligator weed *etc*.

Key words: *Ageratina adenophora*, Biological control, *Chromolaena odorata*, *Lantana*, *Parthenium*, water hyacinth, *Salvinia molesta*

Weeds play an important role in human affairs in most of the areas of the earth. The major characteristics of weeds are their unwanted occurrence, undesirable features and ability to adapt to a disturbed environment (Combellack 1992). Despite measures adopted for their control, weeds are estimated to reduce world food supplies by about 11.5% annually (Combellack 1992). Many of our problem weeds are of exotic origin, having been introduced accidentally or deliberately as ornamental plants, *etc*. They flourish in the new environment as they have escaped from the natural enemies, which suppress their vigour and aggressiveness in their native lands. Alien species are recognized as the second largest threat to biological diversity, the first being habitat destruction. Exotic pests cause unprecedented damage in the absence of their natural antagonists. Economic impact of invasive pests is tremendous. Exotic weeds (terrestrial, aquatic and parasitic) interfere with cultivation of crops, loss of biodiversity and ecosystem resilience, loss of grazing and livestock production, poisoning of humans and livestock, choking of navigational and irrigation canals and reduction of available water bodies. Biological control, *i.e.* introduction, augmentation and conservation of exotic natural enemies, has been accepted as an effective, environmentally non-degrading, technically appropriate, economically viable and socially acceptable method of pest management.

Biological control of weeds involves the use of living organisms to attack a weed population to keep at or below desirable level without significantly affecting useful and wanted plants.It is evidently proved that biological control methods do best on large infestation of a single weed species, which usually occurred in rangelands or in water bodies. In spite of much good success in classical biological

***Corresponding author:** sknrcws@gmail.com

weed control in wasteland and fallow land or large water bodies, it has not developed to the point that it has any appreciable impact on to suppress weeds in cropping situations. Biological control includes the classical (inoculative), bioherbicides (inundative) approaches and herbivore management. Insects, mites, nematodes, plant pathogens, animals, fish, birds and their toxic products are major weed control biotic agents. Singh (2004) concluded that in India, maximum degree of success with classical biological control agents was achieved in biological control of aquatic weeds (55.5%); homopterous pests in crop situations (46.7%) followed by terrestrial weeds (23.8%). McFadyen (2000) listed 44 weeds, which were successfully controlled somewhere in the world using introduced insects and pathogens. Biological control programs have saved millions of dollars and, despite the high initial costs, are very cost-effective. This paper elucidates recent information on classical biological control research in India and prospects of this approach.

History of biological control in India

The history of biological control of weeds dates back to the seventeenth century and since then a great deal of success has been achieved in biological methods of weed control. In fact, the first unintentional outstanding success of biological control of prickly pear in India during 1795 by cochineal insect led the word to use natural enemies against exotic weeds (Sushilkumar 1993, Singh 2004).

Systematic biological control research in India, started with the establishment of the Indian station of Commonwealth Institute of Biological Control (CIBC) at Bengaluru in 1957 with need based 23 substations at various places in different states. The All-India Co-ordinated Research Project on Biological Control of Crop Pests and Weeds (AICRP-BC&W) was established in 1977 with 10 centres, which increased to 16 under the aegis of Project Directorate of Biological Control (PDBC), an institute of Indian Council of Agricultural Research. During XIth plan, PDBC was upgraded as National Bureau of Agriculturally Important Insects (NBAII) to act as a nodal agency for biological control of crop pests. In the XIIth five year plan, the Bureau was re-named as National Bureau of Agricultural Insect Resources (NBAIR) with changed mandate. Meanwhile, National Research Center for Weed Science (NRCWS) came into existence in 1989 at Jabalpur with a modest beginning of biologiocal control of weeds in 1990s. The centre upgraded to Directorate of Weed Science Research in 2009 and renamed as Directorate of Weed Research (DWR) in 2015. Now with the change in mandate of NBAIR, the DWR shall deal on issues related to weed management including biological control of weeds in India with the help of its 23 AICRP-WM centres.

In past, some attempts have been made to review the biological control of agricultural, forest and aquatic weeds of India (Sen-Sarma and Mishra 1986, Ahmad 1991, Singh 1989, Sushilkumar 1993, Jayanth 1994, Singh 2004, Sushilkumar 2009 and 2011).

Progress of classical biological control of weeds in India

Classical biological control aims at introducing the exotic natural enemies of inadvertently introduced alien organisms, which have become pests in the absence of natural checks in the new environment in order to re-establish the balance between the pests and natural enemies. Work on biological control of weeds in India in general and *Parthenium* and aquatic weeds in particular has been dealt by Sushilkumar (1993) and Singh (2004) and Sushilkumar (2009, 2011), respectively. So far in India, about 30 exotic biological control agents have been introduced against weeds, of which six could not be released in the field, 3 could not be recovered after release while 21 were recovered and established. From these established bioagents, 7 are providing excellent control, 4 substantial and 9 partial control. Singh (2004) concluded maximum degree of success of aquatic weeds (55.5%) followed by homopterous pests (46.7%) of crop pests and terrestrial weeds (23.8%) by classical biological control agents in India. Significant research and development efforts over a long period, have led to several successful case studies that have provided great impact in classical biological control of weeds in India. Such weed species are listed (Table 1) and are discussed below:

Prickly pear

The prickly pear (cacti), *Opuntia* spp., (cactaceae) native of North and South America were deliberately introduced into India for cochineal trade. *Opuntia* spp. (*O. vulgaris, O. stricta* (= *O. dillenii*) (Origin: Florida, USA and West Indies) and *O. elatior* gradually spread from the cultivated fields to other lands and eventually became a severe weed pest in North and South India. The first outstanding biological suppression of this weed in India occurred unintentionally by the insect *Dactylopius ceylonicus (=O. indicus)*. It was imported in 1795 from Brazil to produce commercial dye in believe that it is the true cochineal insect *D. cacti,* used to get high quality dye from *Opuntia* spp. The dye produced by *D. ceylonicus* was much inferior to *D. cacti,* hence the dye producing factories eventually stopped to produce dye due to its uneconomic yield. But, *D. ceylonicus* readily established on *Opuntia vulgaris* (its natural host) in North and Central India bringing about spectacular suppression. Gradually, areas that were impenetrable due to prickly pear, became suitable for cultivation within 6 years. Subsequently by 1865, *D. ceylonicus* was introduced into Sri Lanka from South India, where it controlled *O. vulgaris* in large area. This was the first intentional transfer of a natural enemy for biological control of weeds from one country to another country in the world (Sushilkumar 1993).

D. ceylonicus, being restricted to *O. vulgaris*, did not control *O. stricta*, an another species of cactus, which gradually became a problem in South India. In 1926, *D. opuntiae*, a North American species, was imported from Sri Lanka to India, which resulted spectacular suppression of *O. stricta* and related *O. elatior* within five to six years. Due to sustainable occurrence and attack, currently *O. vulgaris* and *O. stricta* are not a problem in India.

Lantana camara

Lantana camara Linnaeus (Verbenaceae), a Central and South American weed was introduced into India in 1809 as an ornamental plant. It spread soon into open areas in forest land, and pastures forming dense thickets. It is a perennial, straggling shrub with prickly stems, spreading by seed, but re-growing vigorously after cutting. It competes with young trees in the forest area and in plantations thus not allowing them to grow. *Lantana* flowers throughout the year in warm areas. The seeds are eaten by birds, which facilitate the rapid dispersal of the plant. Apart from several drawbacks of this plant such as competitive displacement, it has been reported to be a symptomless carrier of sandal spike disease.

In India, it has by now spread everywhere in all the states. Global Invasive Species Information Network (GISIN) now identifies *Lantana* among the top ten invasive species in the world based on the number of countries where these species are considered invasive (GISIN, 2012).Current estimates suggest that *Lantana* has invaded more than 5 Mha in Australia, 13 Mha in India and 2 Mha in South Africa (Bhagawat *et al,* 2012). *Lantana* is known to pose serious threat to biodiversity in several world Heritage sites and Endangered Ecological Communities in Australia (e.g. rainforest of Northern Queensland, Fraser Island and the Greater Blue Mountains), the Fynbos of South Africa, and biodiversity hotspots in India (*e.g.* the Western Ghats and Eastern Himalayas) (Shaanker *et al.* 2010). Consumption of leaves and berries of *Lantana camara,* which contains pentacyclic triterpenoids (akin to steroids) in starvation led to the death of the spotted deers (Naveen 2013). *Lantana* invasion and proliferation has resulted in loss of biodiversity and decline in other ecological services in Corbett Tiger Reserve, Kalesar National Park and Pachmarhi Biosphere Reserve (Babu 2009).

Great success of biological control of *Lantana* by exotic insects in Hawaii followed by Fiji and Australia between 1902-1910 opened the way for biological control throughout the world. In 1916. Government of India, appointed Dr. Rao to conduct an enquiry to know the efficiency of the indigenous insect fauna of *Lantana*. He recorded 148 insect species from India and Myanmar (Burma) (Rao, 1920). In 1921, the agromyzid seed fly, *Ophiomyia lantanae* was introduced from Hawaii (origin: Mexico) and released in South India for the suppression of *L. camara*. Though established, it did not provide spectacular suppression. It is now widely distributed in India. Thakur *et al.* (1992) identified three indigenous insect as potential biocontrol agent for *Lantana viz., Asphondylia lantanae* Felt (flower feeder), *Hypena laceratalis* (a flower and leaf defoliator) and *Archips micaceana (Homona micaceana, a* borer of ripe fruits, however, *H. laceratalis* was found to be hightly parasititzed in south India by two ichneumonid parasites *Casinaria* sp. and *Enicospilus xanthosephalus (*Visalakshy and Jayanath 1990). Sushilkumar and Saraswat (2001) concluded that as many as 9 exotic insect species were introduced in India against *Lantana*.

Tingid lace bug, *Teleonemia scrupulosa*, a native of Mexico, was introduced from Australia in 1941 at Dehra Dun by Forest Research Institute. During, host specificity test, the bug was reported to feed on teak flowers, hence the culture was destroyed in the quarantine. But the insect escaped from quarantine and was recovered later on after about 10 years. Gradually, the insect spread to all the *Lantana* stands in the country, but so far, it has not been found to attack teak or any other economic plant in India in spite of the abundance of teak (Sushilkumar, 1993, Sushilkumar and Saraswat, 2001). This is one of the examples of no risk magnitude by biological control agents as advocated by Suckling and Sfroza (1914) after rigorously analyzing biological agents releaes since inception of biological control programmes in the world. Till today, this bug is a partial success and is not able to kill the *Lantana* in spite of good defoliation during rainy season. Heavy parasitism (up to 85%) of *T. scrupulosa* eggs by *Erythmelus teleonemiae* in Bengaluru impaired the population build up of *T. scrupulosa*. Several other host specific insects such as *Diastema tigris*, *Salbia* (*Syngamia*) *haemorrhoidalis, Uroplata girardi, Octotoma scabripennis* and *Epinotia lantanae* have been introduced from time to time for the biological suppression of *Lantana*. *U. girardi and O. scabripennis* have established in India (Table 1).

Siam weed

Chromolaena odorata (Linnaeus) R. King and H. Robinson (Asteraceae), a native of West Indies and continental America, is a serious weed of pastures, forests, orchards and commercial plantations in South and North-East India. It was introduced in Assam during the First World War (1914-18), where it is locally known as Assam-lata or Assam-lota. It is now well distributed in North-Eastern and Southern states, particularly in Assam, Andhra Pradesh, Karnataka, Kerala, Maharashtra, Odisha, Tamil Nadu and West Bengal. By 1990s, its mild infestation was noticed in Jagdalpur area of Chhattisgarh, which achieved the status of one of the worst weeds of forest and wasteland by 1915 (Sushilkumar, personal observations). It has been rapidly spreading towards mainland of Chhattisgarh and it is feared that it may enter into Madhya Pradesh from this route. It has become a menace in coconut, cocoa, cashew, rubber, oil palm, tea, teak, coffee, cardamom, citrus and other plantation, orchards and forests. During the dry season, it can be a serious fire risk in the forests. The allelopathic effect of this weed in addition to other ill effects has been demonstrated (Ambica and Jayachandran 1980).

The CIBC Indian Station introduced defoliator *Pareuchaetes pseudoinsulata* and a flower and seed feeding weevil *Apion brunneonigrum* (Coleoptera: Apionidae) from Trinidad, but all attempts failed (Singh 2004). During October 1984, a nucleus culture of about 500 larvae of the Sri Lankan strain of *P. pseudoinsulata* was supplied to Kerala Agricultural University (KAU), Thrissur. Further mass multiplication and release of this insect in Kerala, Tamil Nadu and Karnataka brought initial success and large area of *C. odortata* was found defoliated in Kerala and Karnataka by 1988. But, gradually, this insect lost its potential and became non-effective due to heavy parasitism. Ahmad (1991) again tried to establish this bioagent in the forests of Tamil Nadu and Kerala, but he could find only faint recovery of larvae at some places of release. At present, *P. pseudoinsulata* is not considered a potential bioagent.

The Sri Lankan strain of *P. pseudoinsulata* was also supplied to the University of Guam through the CIBC Indian Station. Field releases of this insect in Guam resulted in immediate establishment and extensive defoliation. By 1989, *C. odorata* was reported to have lost its status as the predominant weed in Guam (Singh 2004).

A gall fly *Cecidochares connexa* was introduced from Indonesia in 2002. It was released at 2 locations in Bengaluru, Karnataka during July-October 2005 on naturally rowing *Chromolaena odorata*. The gall fly soon established and due to action of gall fly, plant height was reduced by 11.6 and 16.7% at 30 and 60 days after oviposition in galled plants over control. Significant reduction in number of branches per plant (35.6%), number of panicles per plant (45.4%), number of capitula per panicle (12.07%), and number of seeds per head (10.89%) was evident in galled plants over the control due to oviposition (Bhumannavar *et al.* 2007). The gall fly was also introduced in Kerala and Chhattisgarh (Sushilkumar, personal observations). In Kerala, it has been well established in dense patches and galls occurrence was common after 8 years of its introductions, however, only small number of galls have been recorded at Jagdalpur (Chhattisgarh) after three years of its introduction (Sushilkumar, personal observations). Survey made by the author in Bengaluru and Thrissur revealed good number of galls on each plants but complete killing of plants was not observed. It was concluded that although gall flyies are able to reduce branch formation, flower produciton up to some extent but are not able to bring substantial suppression of *C. odorata*.

Crofton weed

Ageratina adenophora (*Eupatorium adenophorum)* (Sprengel) R. King and H. Robinson (asteraceae), a native of Mexico has spread to the hilly areas of North and South India, forming dense thickets up to some 3 meters on valuable grazing land. The weed has also occupied vacant places in tea, teak, rubber and other forest plantations. Banerjee (1958) noted its presence throughout the Himalaya from Shimla to Bhutan including Nepal. It has assumed a serious status in Nepal (Kapoor and Malia 1978) and Himachal Pradesh (Singh *et al.* 1992)

The gallfly, *Procecidochares utilis* (origin: Mexico) was introduced from New Zealand in 1963 and released in the Nilgiris (Tamil Nadu), Darjeeling and Kalimpong areas (West Bengal) for biological control of *A. adenophora*. The insect has established

Table 1. Name of bioagents , source of country, year of introudciton in India and thier current status

).	Exotic natural enemies (Order: Family) imported in India	Source country/year of introduction and weed plant	Current status/Reference
.	*Dactylopius ceylonicus* (Hemiptera: Dactylopiidae)	Brazil, 1795, prickly pear	It was mistakenly introduced in the belief to produce good quality carmine dye but it was the species of *D. coccus*. It readily established on pear, *Opuntia vulgaris* (its natural host) in North and Central India and resulted spectacular suppression. Later on, introduced in South India during 1863-1868, where it also did excellent control of prickly pear (Sushilkumar 1993, Singh 2004).
2	*Dactylopius opuntiae* (Hemiptera: Dactylopiidae)	USA via Sri Lanka via Australia, 1926; pricly pear	Caused spectacular suppression of *Opuntia stricta* and related *O. elatior* (Singh 2004).
3	*Pareuchaetus pseudoinsulata* (Lepidoptera: Arctiidae)	Trinidad, West Indies via Sri Lanka, 1984 ; against weed species *Chromolaena odorata*	Established in 1988 in Dakshina Kannada district (Karnataka). Good suppression was recorded by 1990. Also recovered from Kerala and Tamil Nadu; partially successful (Ahmad 1991, Thakur *et al*. 1992, Sushilkumar 1993, Singh 2004).
4	*Procecidochares utilis* (Diptera: Tephritidae)	From Mexico via Hawaii, USA via Australia via New Zealand, 1963 ; against Crofton weed *Ageratina adenophora*	Released in the Nilgiris (Tamil Nadu), Darjeeling and Kalimpong areas (West Bengal) against Crofton weed; established and is spreading naturally, but efficacy hampered by indigenous parasitoids; has spread to Nepal, where it has become well distributed; partially successful (Swaminathan and Raman 1981, Bennet and Vanstaden 1986, Sushilkumar 1993, Singh 2004).
5	*Zygogramma bicolorata* (Coleoptera; Chrysomelidae)	From Mexico, 1983; against *Parthenium hysterophorus*	Released for control of *Parthenium;* established by natural spread and by concentrated efforts by Directorate of Weed Research (Jabalpur), established well in many states of India; naturally entered from India to Nepal and Pakistan; successful bioagent (Jayanth 1982; Sushilkumar 2005, 2009, 2014).
6	*Neochetina bruchi* (Coleoptera: Curculionidae)	Argentina via USA, 1982/1983; against water hyacinth	Well distributed and established on water hyacinth, spread to different parts of the country; doing good control of weed along with *N. Eichhorniae* (Jayanth 1988, Singh 2004, Sushilkumar 2011).
7	*Neochetina eichhorniae* (Coleoptera: Curculionidae)	Argentina via USA, 1983 agaisnt water hyacinth	Well distributed and established throughout India in different water bodies. It is successful in stagnated ponds and lakes but not effective in running water like river (Jayanth 1987, Singh 2004, Sushilkumar 2011).
8	*Orthogalumna terebrantis* (Acari: Orthogalumnidae)	Argentina via USA, 1986; against water hycienth	Well established in all released sites and is spreading on its own; doing good control of weed along with *Neochetina* spp. (Jayanth 1996, Singh 2004, Sushilkumar 2011).
9	*Epinotia lantanae* (Lepidoptera: Tortricidae)	Mexico, unintentional accidental introduction in 1919 on *Lantana*	Established on *Lantana camara* in several places, partially effective (Sushilkumar 2001, Singh 2004).
0	*Lantanophaga pusillidactyla* (Lepidoptera: Pterophoridae)	Mexico, unintentional accidental introduction, 1919 against *Lantana*	Established on *Lantana* but not effective (Sushilkumar 2001, Singh 2004).
1	*Octotoma scabripennis* (Coleoptera: Chrysomelidae)	Mexico via Hawaii via **Australia, 197;** against *Lantana*	Established on *Lantana* but not effective (Sushilkumar 2001, Singh 2004).
2	*Ophiomyia lantanae* (Diptera: Agromyzidae)	Mexico via Hawaii, 1921; against *Lantana*	Established on *Lantana* at several places, but not effective (Sushilkumar 2001, Singh 2004).
3	*Orthezia insignis* (Hemiptera: Ortheziidae)	Mexico, unintentional accidental introduction, **1915l** against *Lantana*	Established on *Lantana* at several places, partially effective (Sushilkumar 2001, Singh 2004).
4	*Teleonemia scrupulosa* (Hemiptera: Tingidae)	Mexico via Hawaii via Australia, 1941; against *Lantana*	Reported to feed on teak flowers at Dehradun, hence culture was destroyed in quarantine. But the insect 'escaped' quarantine and presently found on all *Lantana* stands in India; partially effective.
5	*Uroplata girardi* (Coleoptera: Chrysomelidae)	Brazil via Hawaii via Australia, 1969 to 1971; against *Lantana*	Established on *Lantana,* not effective (Sushilkumar 2001, Singh 2004).
6	*Cyrtobagous salviniae* (Coleoptera: Curculionidae)	Brazil via Australia, 1982/1983; against *Salvinia molesta*	Initially released in Bengaluru; later released at Kuttanad (Kerala), well established, did excellent control (Jayanth 1996, Singh 2004, Sushilkumar 2011).
7	*Ctenopharyngodon idella* (Pisces: Cyprinidae)	China via Hong Kong & Japan, 1959/1962; against submerged aquatic weeds	Introduced to control submerged aquatic weeds such as *Vallisneria* spp. and *Hydrilla verticillata* in fishponds; established in different parts of the country; very effective (Singh 2004, Sushilkumar 2011).

Sl. No.	Exotic natural enemies (Order: Family) imported in India	Source/year of introduction and weed plant	Current status
18	*Hypophthalmichthysmolitrix* (Pisces: Cyprinidae)	China via Hong Kong & Japan, 1959/1962	Released and established in different water bodies and feeds on various aquatic weeds and algae.
19	*Oreochromismoss ambicus* (Pisces: Cichlidae)	Africa, 1953; against submerged aquatic weeds	Established in different water bodies and feeds on various aquatic weeds and algae; partially effective (Singh 2004).
20	*Osphronemus goramy* (Pisces: Osphronemidae)	Java, Indonesia; Mauritius, 1916; against submerged aquatic weeds	Established in different water bodies and feeds on various aquatic weeds and algae partially effective (Singh 2004).
21	*Paulinia acuminata* West Indies, 1983 (Orthoptera: Acrididae)	West Indies, 1983; against *Salvinia molesta*	Released and recovered from water fern, *Salvinia molesta* in Thiruvananthapuram (Kerala); not effective (Singh 2004).
22	*Cecidochares connexa* (Diptera: Tephritidae)	South America via Indonesia, 2003 against *Chromolaena odorata*	Established at Bengaluru (Karnataka), Thrissur (Kerala); also released at Jagdalpur (Chhattisgarh); partially successful (Bhumannavar and Ramani 2007, Sushilkumar personal observations)
23	*Phytomyza orobanchia* (Diptera: Agromyzidae)	Yugoslavia, 1982; against broomrape *Orobanche* sp	Recovered occasionally. partially established (Singh 2004, Kannan *et al*, 2014).
24	*Dactylopius confuses* (Hemiptera: Dactylopiidae)	South America via South Africa, 1836; against prickly pear	Introduced but not recovered on *Opuntia vulgaris* (Singh 2004).
25	*Apion brunneonigrum* (Coleoptera: Apionidae)	Trinidad, West Indies, 1972-1983; against *Chromolaena odorata*	Introduced but not recovered on *Chromolaena odorata* (Singh 204).
26	*Salbia haemorrhoidalis* (Lepidoptera: Pyralidae)	Trinidad, West Indies, 1972-1983; against *Lanatana*	Introduced but not recovered on *Lantana camara* (Sushilkumar 2001, Singh 2004).
27	*Mescinia parvula* (Lepidoptera: Pyralidae)	Trinidad, West Indies, 1986 Mexico via Australia, 1985; *Chromolaena odorata*	Imported but failed in host specificity test; culture destroyed (Singh 2004)
28	*Epiblema strenuana* (Lepidoptera: Tortricidae)	Mexico, 1983; against *P. hysterophorus*	Did not breed in laboratory (Singh 1989, Sushilkumar 2005, 2009)
29	*Smicronyx lutulentus* (Coleoptera: Curculionidae)	Mexico, 1983; against *P. hysterophorus*	Failed in host specificity test hence culture destroyed (Singh 1989, Sushilkumar 2005, 2009)
30	*Leptobyrsa decora* (Hemiptera: Tingidae)	Peru & Colombia via Australia, 1971; against *Lantana*	Failed in host specificity test, culture destroyed (Mishra and Sen-Sarma 1986, Sushilkumar 2001).

and is spreading naturally. Its effectiveness is hampered by attack of indigenous parasitoids. *P. utilis* has spread into Nepal from India, where it has become well-distributed. Bennett and Vanstaden (1986) studied gall formation process in detail in this weed.The exit holes cut by the inhabiting larvae enable access by microorganisms that induce decay. High galling intensity results in plant mortality. In the high-altitude regions of Tamil Nadu (India) (2000–2300 masl), four hymenopteran parasitoids, *Diameromicru skiesenwetteri* (Meyr) (Hymenoptera: Torymidae), *Syntomopus* sp. (Hymenoptera: Pteromalidae), *Bracon* sp. (Hymenoptera: Braconidae) and *Eurytoma* sp. (Hymenoptera: Eurytomidae) were recorded on *P. utilis* (Swaminathan and Raman 1981). Parasitism by *Bracon* sp. was as high as 80% and was considered to be the primary cause for the failure of the gall fly to control crofton weed in India.

Carrot weed

Parthenium hysterophorus Linnaeus (Asteraceae), globally known as feverfew, ragweed or *Parthenium* is a weed of world significance. It is most popularly known as 'congress grass' throughout India while in Hindi speaking belt known by the popular name of 'gajarghas'(carrot grass). It degrades natural ecosystems by reducing biodiversity (Holm *et al*. 1997) and can cause serious allergic reactions in man and animals (Chippendale and Panetta 1994, Sushilkumar 2012). In India, it has invaded almost all types of crops and has become a serious threat for agricultural production. Sushilkumar and Varshney (2010) estimated infestation of *Parthenium* in 18.78, 14.25 and 2.0 Mha lands in barren, fallow, wasteland including land under non-agricultural uses, crop area under cultivation and forest areas, respectively. In India, this weed is a serious problem in states like, Andhra Pradesh, Bihar, Haryana, Karnataka, Madhya Pradesh,Tamil Nadu and Uttar Pradesh.

Parthenium is regarded as one of the worst weeds because of its immense capacity of reproduction and ability to thrive in varied climatic conditions. Its low photorespiration under arid conditions, photo and thermo-insensitivity, C_3/C_4 intermediate mechanism, more biomass production at elevated atmospheric CO_2 conc. compared to the normal in a rapidly changing climate make it more invasive (Pandey *et al.* 2003, Naidu and Paroha 2008, Tang *et al.* 2009, Naidu 2013, Sushilkumar 2014). Now, *Parthenium* has invaded about 35 Mha of land throughout India (Sushilkumar and Varshney 2010). After being established in India, *Parthenium* has gradually spread into most of its neighbouring countries like Pakistan (Shabbir and Bajwa 2006), Sri Lanka (Jayasurya 2005), Bangladesh (Rahman *et al.* 2008, Karim 2009) and Nepal (Adhikari and Tiwari 2004, Shrestha *et al.* 2014).

Manual, mechanical and chemical methods have been advocated for the control of this weed but these methods are expensive and provide only short-term control. Biological control has been considered most effective method against *Parthenium*. Now, much emphasis has been given to control *Parthenium* through various biological agents like pathogens, insects and plants. Sushilkumar (2009) has reviewed the status of biological control of *Parthenium* by insects, pathogens and competitive plants in India. Indigenous insect *Nupserha* sp. was reported to attack large number of *Parthenium* plants (5-95%), and caused reduction in flower production (Sushilkumar 2009, 2012).

Classical biological control of *Parthenium* in India started in 1983 with the import of three insects namely defoliating beetle *Zygogramma bicolorata* Pallister (Coleoptera: Chrysomelidae), the flower feeding weevil *Smicronyx lutulentus* Dietz (Coleoptera: Curculionidiae) and the stem boring moth *Epiblema strenuana* (Walker) (Lepidoptera: Tortricidae) (Singh 1989, Sushilkumar 1993, 2009). *S. lutulentus* could not be multiplied in the laboratory while *E. Strenuana* was found to complete its life cycle on a oil seed crop niger (*Guizotia abyssinica* L. (Asteraceae), hence its culture was destroyed (Jayanth 1987) in spite of the fact that this insect was considered to be a potential biocontrol agent in Australia (McFadyen 2000, Dhileepan 2009). After host specificity test, *Z. bicolorata* was released which spread over 2 million sq km area by 1994 (Jayanth and Visalakshy 1994). Soon after release, *Z. bicolorata* involved in controversy about its host specificity due to its occasional feeding on sunflower which forced Govt. of India to impose ban in 1991 for its intentional release (Sushilkumar and Bhan 1996). But, after in depth studies under the supervision of a Fact Finding Committee constituted by Government of India, the insect was declared safe and ban was lifted in 1999 for its release (Sushilkumar 2009).

After first release of *Z. bicolorata* in Bengaluru in 1984 in India (Jayanth 1987) and later on due to its intensive introductions to different regions of the country after the year 2000 by Directorate of Weed Research (DWR), Jabalpur, it has widely spread across the country (Sushilkumar 2005, 2009 and 20014; Sushilkumar and Varshney 2007). Incidence of *Z. bicolorata* has been recorded mild to heavy in most of the states wherever it was introduced. An economic benefit of 12150% was recorded by 6^{th} years after its initial release comparing single application of herbicides (Sushilkumar 2006). Sushilkumar (2005) after observing the widespread establishment of *Z. bicolorata* in Ludhiana up to Bagha border (Punjab) forecasted the bioagent entry from this route to Pakistan. Later on, Javaid and Shabbir (2006) spotted this bioagent first time from Lahor and Changa Manga Forest area of Pakistan. In Nepal too, the bioagent was entered from the nearby released places of Uttar Pradesh (Shreshta *et al.* 2012).

In India, this widespread establishment of Z. *bicolorata* is in contrast to earlier predictions of Jayanth and Bali (1993), who suggested that *Z. bicolorata* would not be suitable for hot regions of Central and West India and cold regions of Himachal Pradesh, Uttarakhand, Punjab and Western Uttar Pradesh. Dhileepan and Senaratne (2009) and Sushilkumar (2014) have also found the occurrence of *Z. bicolorata* in very hot and cold regions of India. Diapause in *Z. bicolorata* was considered a negative attribute which hampers its activity (Jayanth and Bali 1993a). The diapause was broken by regulation of temperature and females were able to lay eggs normally after breaking of diapause (Sushilkumar and Ray 2010). In crop situations, *Z. bicolorata* was found to have limited scope due to disturbance of soil during agricultural activities. However, biological control approach may be viable through augmentation of the bioagent as was demonstrated by Sushilkumar and Ray (2011). The augmentation of bioagent may be achieved through large scale multiplication in net houses (Sushilkumar 2005).

Nefalata

The climber *Mikania micrantha* HBK (asteraceae), locally known as Refugee-lata is a perennial vine of Neotropical origin, with a native range from Mexico to Argentina. It has become an important invasive weed in many countries within the humid tropical zones of Asia and Pacific (Zhang *et al.* 2004). It started appearing in about 1948 in tea gardens in Bengal and in the forests of North-Eastern region (Jha 1959). Heavy flood in Bengal and Assam helped its dispersion into forests. Its menace was more in those plantation areas, which were clear felled. It has become a major menace in natural forests, plantations, agricultural systems in North-East and South-West India (Sushilkumar 1991, Ragubanshi *et al*. 2005). Palit (1981) estimated invasion of *Mikania* in about 11% area of high forests and 38% in plantation forests in West Bengal. *M. Micrantha* is posing a serious threat to unique eco system and biodiversity of Chitwan National Park in Nepal (CNP), which has been included in the World Natural heritage site by UNESCO. Its present infestation is estimated to be over 20% of the entire national park.

Under a biological control programme, Cock (1982) listed 8 major and 20 minor insect species from Latin America but none of these has been tried in South and South-East Asia. A tropical American rust fungus (*Puccinia spegazzinii*), collected in Trinidad, was selected and screened at CABI- UK against 175 plant species and was approved for release in six countries including India. Initial release was made in Assam and Kerala in 2005 in India. Initial symptoms of attack were noticed but it did not proof potential bioagent so far. Despite the rust failing to persist in the field in India and China, the potential of *P. spegazzinii* is recognised by Taiwan, Fiji where it has established and causing significant damage to *M. micrantha* (Ellison *et al.* 2014). Natural enemies of *M. micrantha* from Kerala have been reported by Abraham eta al. (2002).

Giant sensitive plant

Mimosa diplotricha C. Wright (fabaceae), also known as the giant sensitive plant, a native from Brazil, is a species in the Fabaceae family. The tangled and thorny growth of *Mimosa* hampers movement and access to food and other resources for wild animals like the one-horned rhinoceros (*Rhinoceros unicornis*) in Kaziranga National Park in North-East India. So far, no classical biological control has been tried in India.

In Australia in 1988 in North Queensland, a native insect species *Heteropsylla spinulosa* was imported from Brazil and released after host specificity test. During the 1988/89 summer, a dramatic reduction in the vigour of *M. diplotricha* was observed and seed production was suppressed by over 88%. Seedling establishment was reduced and some mature plants killed (Lockett and Ablin 1990). *H. spinulosa* is now well established (Willson and Garcia 1992), has spread significantly (Cullen and Delfosse 1990), and caused a dramatic reduction in vigour and seed production of *M. diplotricha* in Australia (Parsons and Cuthbertson 1992, Julien 1992). This species was intended to introduce in Kaziranga National Park by erstwhile Project Directorate of Biological control, Bengaluru, but authority of National Park refuged to give permission on the pretext that exotics are not allowed in National Park.

Water fern

Salvinia molesta D.S. Mitchell (salviniaceae), a native of South-Eastern Brazil has invaded many water bodies of Asia, Africa and Australia. It was introduced into India through Botanical gardens. *Salvinia*, first observed in 1955 in Vole Lake (Kerala), assumed the pest status since 1964 and affects large water bodies in Keral including rice fields. It choked rivers, canals, lagoons, and covered Kakki and Idukki reservoirs. In some areas cultivation of paddy had to be abandoned on account of *Salvinia* infestation (Joy 1978). In Australia, introduction of bioagent *Cyrtobagous salvinae* controlled *Salvinia* successfully and combined benfit: cost ratio was estimated 25.5:1, while it was 53:1 in Sri Lanka (Doeleman 1989). For the biological suppression of *S. molesta*, the weevil, *Cyrtobagous salviniae*, a native of Brazil, was imported from Australia in 1982 and released in Bengaluru in 1983-84. Within 11 months of the release of the weevil, *Salvinia* plants collapsed (Jayanth 1987a). Later on, bioagent was released in many parts of Kerala. Within a span of 3 years after its release, most of the canals abandoned due to the weed menace have become navigable once again (Joy et al. 1995). By 1988 in the case of paddy cultivation, where Rs. 235 had to be spent per hectare for manual removal, the savings on account of labour alone were about Rs. 6.8 million annually. The control of *Salvinia* has brought back the aquatic flora of Kerala back to the pre-*Salvinia* days (Singh 2004). The two isolates designated as '*WF(Sm)37'* and '*WF(Sm)38*' were identified as *Phoma glomerata* and *Nigrospora sphaerica* were found potential pathogen for the biological control of *Salvinia* (Sreerama *et al*. 2007).

Water hyacinth

Eichhornia crassipes (Martius) Solms-Laubach (Pontederiaceae), a free floating aquatic weed of South American origin, ranks among the top ten weeds and has spread to at least 50 countries around the globe. After first introduced into Bengal around 1896 as an ornamental plant, it has spread throughout India and occupies over 200,000 ha of water surface. Water hyacinth is considered to be the most damaging aquatic weed in India. It now occurs in all fresh water ponds, tanks, lakes, reservoirs, streams, rivers and irrigation channels. Water hyacinth has also become a serious menace in flooded rice fields, considerably reducing the yield. It has entered into major river systems–Brahmaputra, Cauvery, Ganges, Godavari, Satluj and Beas. Due to construction of dams on major river systems water hyacinth is no longer flushed out to sea. It interferes with the production of hydro-electricity, blocks water flow in irrigation projects (40 to 95% reduction), prevents the free movement of navigation vessels, interferes with fishing and fish culture and facilitates. The weed is responsible for great water loss (1.26 to 9.84%) due to evapo-transpiration from the luxuriant foliage of water hyacinth. In view of the high cost of manual control and water pollution problems associated with use of herbicides, attention has now been turned to biological control (Sushilkumar 2011).

Three exotic natural enemies were introduced in India, *viz*. hydrophilic weevils – *Neochetina bruchi* (Ex. Argentina) and *N. eichhorniae* (Ex. Argentina) and galumnid mite *Orthogalumna terebrantis* (Ex. South America) from their original home via USA in 1982 for the biological suppression of water hyacinth. Field releases of mass bred weevils in different water tanks in Karnataka and other parts of country were done which resulted in suppression of water hyacinth in many water bodies within 4 years. These efforts have resulted in establishment of the weevils in different parts of the country. The annual savings due to suppression of the weed by the weevils was estimated to be Rs. 11.2 lakhs in Bengaluru alone during 1987. In India spectacular success has been achieved at Hebbal tank in Bangalore causing 95% control within a span of two years (Jayanth 1988), Loktak lake in Manipur (Jayanth and Visalakshi 1989) and several ponds in Jabalpur (Sushilkumar 2011) and Hyderabad (personal observations). However, there were instances where weevil releases have been a total failure, for example, Kengeri tank in Bangalore (Anon. 1994). Wilson *et al*. (2007) were of the opinion that decline of water hyacinth in lake Victoria was due to the action of *Neocheitna* spp.

Kannan and Kathiresan (1999) reported varied numbers of weevils required to control different growth stages of water hyacinth. Ray *et al*. (2009) studied minimum required inoculation load of weevils of *Neochetina* spp. on three growth stages of water hyacinth, based on fresh biomass, plant height and number of leaves. The small growth stage was controlled early corresponding to the increase in number of weevils/plant. Four and eight weevils could control the small growth stage in 50 and 40 days while 8, 12, 16 and 20 weevils could control in 10 days only. Middle growth stage was completely killed in ten days by 16 and 20 weevils per plant while 4, 8 and 12 weevils per plant took 70, 60 and 50 days, respectively . The large plants could not be controlled even with the inoculation pressure of 20 weevils/plant and required more inoculation load. This study suggested that comparative high number of inoculation load of *Neochetina* spp. should be release for control of large size of water hyacinth in a water body.

Weeds can be controlled by pathogens like fungi, bacteria, viruses and virus like agents. Among the classes of plant pathogens, fungi have been used to a larger extent than bacteria, virus or nematode pathogens. In some cases, it has been possible to isolate, culture, formulate and disseminate fungal propagules as mycoherbicides. So far, not even a single successful mycoherbicide has been employed against any aquatic weed in India in spite of many reports of fungal pathogen infesting many aquatic weeds severly (Aneja *et al.* 1993, Kauraw and Bhan 1994, Ray *et al.* 2008b). Ray *et al*. (2008c) studied the combined impact of various pathogens for integrated management of *E. Crassipes* (Mart.) Solms. The combined effect of various pathogens was more effective than any of the pathogens tested alone. Martin *et al.* (2013) demonstrated that in water hyacinth (*Eichhornia crassipes*), weevil *Neochetina eichhorniae* reduced the photosynthetic rates almost equally to the 37% decrease due to entry of deleterious microbes into plant tissues on which they feed.

Biological and chemical integration was applied by Sushilkumar (2011) to achieve the early control as more time is taken by bioagents alone. After 9 months of biological and chemical integration, the first cycle of complete control was achieved. This early collapse of weed within a period of 9 month could be possible due to integration of herbicide and bioagents which would otherwise have taken minimum 24-36 months by the bioagents alone. After some time, again water hyacinth population increased due to new germination from buried seeds or from the left stolons of water hyacinth. This second wave of water hyacinth was again collapsed in 12 months due to integration of one spray of herbicides after one month of regrowth.

Biological control of submerged aquatic weeds

Submerged weeds are those that remain below water surface and may be rooted, *e.g. Hydrilla, Najas, Potamogeton, Vallisneria, Ottelia* and *Nechamandra* or rootless (*e.g. Ceratyphyllum* and *Utricularia*). Submerged aquatic weeds cause serious navigational problems in different water bodies particularly in lakes, which attract large numbers of tourists. The grass carp *Ctenopharyngodon idella*, a native of Siberia, Manchuria and China, was introduced from Japan in 1959 to control submerged aquatic weeds such as *Vallisneria* spp. and *Hydrilla verticillata* in fish ponds and it has since been distributed to different parts of the country. The grass carp was released in Rajasthan to control submerged aquatic weeds Mehta and Sharma 1972). The fish feeds primarily upon submerged plants but also consume small floating plants like *Spirodella, Lemna, Wolffia* and *Azolla*. Judicious manipulation of stock density and size depending on the nature of water body, type and quantum of weed infestation are important factors for successful control of weeds. Singh *et al*. (1967) found grass carp of 600 g size to be effective against most submerged weeds under stocking density of 250 to 500/ha. Fish of about 100 g size can be used to control most of the common water weeds in small farm ponds, if free from predators. Bigger fish of 0.5–1 kg can be employed to control weeds in larger waters.

The submerged weeds preferred by grass carp are *Hydrilla, Najas, Ceratophyllum, Potamogeton, Utricularia* and *Myriophyllum*. The fish will also control *Ottelia, Nechamandra, Vallisneria, Trapa, Limnophila* and *Salvinia* (to some extent). However, water hyacinth and *Pistia* are not completely consumed except small bites.

For control of floating weeds grass, carp of about 10 cm length (about 15 g) are stocked at 1000-2000/ha according to weed density. For other weeds use fish of about 20–30 cm (100–250g) and stocked at 200–1000/ha. Regular inspections are needed to determine whether control is proceeding satisfactorily and if required, more fish can be added. After the weed has been cleared the fish may be carefully netted out of the water and transferred for use elsewhere. As grass carp is good to eat, and easily caught by angling, precautions against poaching are necessary. If predatory fishes are present then the grass carp should be at least 1 kg in weight before being introduced (Anon. 1971).

The other fishes which are considered useful in controlling some aquatic weeds are *Puntius javanicus*, *Pulchellus pulchellus*, *Tilapia mossambica, T. melanopleura* and *Ophronemus gorami*. Grass carp normally consumes choiced aquatic weeds, at least 50% of their body weight in a day. About 300–400 fish, each of about 0.5kg weight, are enough to clear 1 ha of *Hydrilla* infested water body in about a month. Normally *Hydrilla* infestation density ranges from 5–25 kg/m^2 (Tyagi and Gireesha 1996).

Prospects of biological weed control in India

Although many attempts in past have been made in India to control exotic terrestrial and aquatic weeds, but so far, spectacular success could not be achieved to suppress or eradicate them as happened in case of *Dactylopius vulgaris* (prickly pear) by wrongly import of cochineal insect *D. ceylonicus* in place of *D. cacti*, intended to produce commercial dye. This is an eye opening example that how taxonomy plays an important role in selection of an appropriate species. The beetle *Zygogramma bicolorata* has also shown spectacular success in suppression of *Parthenium* in many states of India, but complete control of this weed is impossible due to immense reproductive and survival potential of the weed. In many countries, introduction of multiple species of bioagents against a single weed species has shown encouraging results. For example, introduction of 9 bioagents against *Parthenium* in Australia contributes to suppress the weed significantly at different time of the year.

Although rate of success of classical biological control in India is low but still there are well founded hopes that the rate of success will increase in future projects. It is a well documented fact that classical biological control is especially suited to control of alien weed species which dominate the native vegetation in relatively stable environment. In Indian situation, following research areas on biological weed control have high prospects.

1. In India, relatively little work has been done on new introduction of bioagents against weeds after 1980s. Therefore, there is a great scope of introduction of natural enemies against invasive weeds of terrestrial and aquatic situations.
2. Weeds like C. *odorata, A. adenoforum, M. mikarantha* and *Miomosa diplotricha* have assumed serious status in forestry plantations and

now spreading their tentacles to agricultural and wastelands. There is urgent need to explore the introduction of new bioagent against these weeds.

3. The use of native biotic agents may be of high value against those weeds on which there is no scope for introduction of additional and more effective biocontrol agents from other geographical areas. Some indigenous insects do extremely well to suppress weeds hence they need encouragement by augmenting their population in a particular locality. For example, indigenous *Lantana* gall fly *Asphondylia lentenee* and defoliator *Hypena laceralata* are slow in dispersal. There is need to introduce and disseminate them to newer areas where they may prove more effective under new environment. Therefore, extensive survey for indigenous natural enemies of weeds from different climatological zones of India is required to enhance the biotic pressure.

4. In India, there is great scope of introduction of some well proven exotic insect enemies like dipterous leaf minor *Coteomvze lanatanae* from Australia and noctuid *Neogulea esula* from Hawaii against *Lantana.*

5. Many alien weeds are great problems in protected forests. The problem may be reduced by release of proven bioagents under classical biological control. The authorities of protected areas such as National Parks do not give permission to release bioagents in the pretext of ban to introduce exotics in PA, in spite of the fact that bioagent had already been introduced in the country by due permission of Government of India. It is also true that in due course, an introduced bioagent will reach on its suitable host inside the protected areas, without man's efforts. This need retrospection by the forest authorities to hasten the biological control process.

6. Although, in other countries great emphasis is being given to use plant pathogens but in India this potential field has been totally neglected hence there is an urgent need to explore the use of pathogens and their products (bioherbicides) against problematic weeds. Many pathogens gave promising results as biological control agents of water hyacinth in different countries. Among them are *Uredo eichhorniae*, suitable as a classical biocontrol agent and *Acremonium zonatum, Alternaria eichhorniae, A. alternata, Cercospora piaropi, Myrothecium roridum,* and *Rhizoctonia solani*, which are widely distributed in different continents, as bioherbicides.

7. Integrated weed management (IWM) approach is lacking in India. It has been seen that the effect of biological agents can be greatly enhanced through augmenttion as has been demonstrted by Sushilkumar and Ray (2010) to manage Parthenium in crops. Therefore, it seems desirable that there should be a close collaboration between biological weed control workers, silviculturists, agronomists, plant breeders and crop protection entomologists in order to utilize full advantage of the potential of biological agents.

8. There are known bioagents, which have shown promising results in suppression of weeds like water hyacinth, alligator weed, *Pistia* etc. in the countries of their introduction. Many of such bioagents have not been introduced yet in India, which need immediate attention. Some of these like *Listronotus setosipennis, Smicronyx latulentus, Stobaero concimma, Buccalatrix parthenica, Epiblema strenuana, Puccinia abrupt* on *Parthenium*; a flea beetle *Agasicles hygrophila* for alligator weed *Alternanthera philoxeroides*; *Sameodes albiguttalis* Warren (Lepidoptera: Pyralidae) on water hyacinth, *Neohydronomous affinis* (Hustache) on *Pistia stratiotes*, *Heteropsylla spinulosa* (Homoptera: Psyllidae) on *M. diplotricha* have been effective in controlling aquatic growth of the weed in many areas in USA and Australia.

Conclusion

Being a mega diversity country, India has contributed significantly in classical biological control at global level by providing Indian biological control agents to other countries. In fact classical biological control of weeds in the world had its beginning in India. Overall, the classical biological control offers highly effective and environment friendly solutions to the problem of invading alien weeds. A strong national and regional policy is required to accelerate the effective implementation of biological control programmes. Some pest species are widely distributed in different continents, but their natural enemies are effective in one area and absent in others, hence suitable species could be considered for study and introduction from one area to another.

REFERENCES

Ambika SR and Jayachandra. 1980. Suppression of plantation crops by *Eupatorium* weed. *Current Science* **49**(22): 874-875.

Abraham M, Abraham CT and Joy PJ. 2002. Natural enemies on *Mikania micrantha* H.B.K. in Kerala. *Journal of Tropical Agriculture* **40**: 39-41.

Anonymous. 1971 Use grass carp for weed control. *Indian Farming* **21**(5): 45-47.

Anonymous. 1987-2002. *Annual Reports for 1987-2002*. Project Directorate of Biological Control, Bangalore, India.

Anonymous. 1994. *Annual Progress Report*. Project Directorate of Biological Control, Bangalore, India

Ahmad M. 1991. Attempts on biological control of *Chromolaena odorata* in India. *Myforest* **27**: 179-186.

Adhikari B and Tiwari S. 2004. *Parthenium hysterophorus* L.: highly allergic invasive alien plant growing tremendously in Nepal. *Botanica Orientalis* **4**: 36–37.

Aneja KR, Srinvas B and Kaur M. 1993. Evaluation of *Fusarium chlamydosporum* as a biocontrol agent of water hyacinth (*Eichhornia crassipes*) (Mart.) Solms, pp. 145-149. In: *Integrated Weed Management for Sustainable Agriculture. Proceedings of Indian Society of Weed Science International Symposium, Hisar, India,* 18-20 November 1993. Vol. II, Hisar, Haryana, India.

Babu Suresh, Babu Amit and Raghavendra Cherukuri. 2009. Ecological restoration of *Lantana*-invaded landscapes in Corbett Tiger Reserve, India. *Ecological Restoration* **27** (4): 467-477.

Bennett PH and Van Staden J. 1986. Gall formation in Crofton weed, *Eupatorium adenophorum* Spreng. (syn. *Ageratina adenophora*), by the *Eupatorium* gall fly *Procecidochares utilis* Stone (Diptera: Trypetidae). *Australian Journal of Botany* **34**: 473–480.

Banerji NL. 1958. Invasion of *Eupatorium glandulosum* (*E. adenophorum*) in east Nepal. Bulletin of Botanical society, University of Saugar 10 (1 and 2): 14-18.

Bhagwat SA, Breman E, Thekaekara T, Thornton TF and Willis KJ. 2012. A battle lost? Report on two centuries of invasion and management of *Lantana camara* L. in Australia, India and South Africa. *PLoS ONE* **7**(3): e32407. doi:10.1371/journal.pone.0032407.

Bhumannavar BS, Ramani S, Rajeshwari SK. 2007. Field release and impact of *Cecidochares connexa* (Macquart) (Diptera: Tephritidae) on *Chromolaena odorata* (L.) King and Robinson. *Journal of Biological Control* **21**(1): 59–64.

Chippendale JF and Panetta FD. 1994. The cost of Parthenium weed to the Queensland cattle industry. *Plant Protection Quarterly* **9**: 73–76.

Cock MJW. 1982. Potential biological control agents for *Mikania micrantha* HBK from the Neotropical Region. T*ropical Pest Management* **28**(3): 242-254.

Combellack JH. 1992. The importance of weeds and ways of reducing concerns about methods for their control,pp43-63. In: *Proceedings of the First International Weed Control Congress,* Melbourne.

Cullen JM and Delfosse ES. 1990. Progress and prospects in biological control of weeds, pp..452-476. *Proceedings of the 9th Australian Weeds Conference.*

Dhileepan K. 2009. Managing Parthenium across diverse landscapes: prospects and limitations, pp. 227-259. In: *Management of Invasive Weeds* (Ed. Inderjit), Springer Science Business Media, Knoxville, USA

Dhileepan K and Senaratne Wilmot KAD. 2009. How widespread is *Parthenium hysterophorus* and its biological control agent *Zygogramma bicolorata* in South Asia? *Weed Research* **49**: 557–562.

Doeleman JA. 1989. Biological control of *Salvinia molesta in* Sri Lanka: an assessment of costs and benefits. *ACIAR Technical Reports 12*, Canberra

Ellison Carol A, Day Michael D and Witt Arne. 2014. Overcoming barriers to the successful implementation of a classical biological control strategy for the exotic invasive weed *Mikania micrantha* in the Asia-Pacific region, pp 135-141. In: *Proceedings of the XIV International Symposium on Biological Control of Weeds,*. (Eds. Impson FAC., Kleinjan CA and Hoffmann JH, 2-7 March 2014, Kruger National Park, South Africa.

Gupta OP. 2008. *Weedy Aquatic Plants: their Utility, Mmenace and Management*. Agrobios, Jaipur. 286p.

GISIN. 2013. *Global Invasive Species Information Network* http://www.niiss.org/cwis438/Websites/GI SINDirectory/ SpeciesStatusTop Invasives. php?WebSiteID=4. Accessed 2013 June 23.

Holm L, Doll J, Holm E, Pancho J, Herberger J. 1997. *World Weeds: Natural Histories and Distribution*. John Wiley & Sons, Inc, New York: 1129 p.

Jayanth KP. 1987. Introduction and establishment of *Zygogramma bicolorata* on *Parthenium hysterophorus* at Bangalore, India. *Current Science* **56**: 310–311.

Jayanth KP and Singh SP. 1993. Biological control of aquatic weeds. *Indian Farming* **42**: 25-30.

Jayanth KP. 1987. Suppression of water hyacinth by the exotic insect *Neochetina eichhoriae* in Bangalore, India. *Current Science* **56**: 494-495.

Jayanth KP. 1987a. Biological control of the water fern Salvinia molesta infesting a lily pond in Bangalore (India) by Cyrtobagous salviniae. *Entomophaga* **32**: 163-165.

Jayanth KP . 1988. Biological control of water hyacinth in India by release of the exotic weevil *Neochetina bruchi. Current Science* **57**(17): 968-970.

Jayanth KP and Bali G. 1993. Temperature tolerance of *Zygogrammabicolorata* (Coleoptera: Chrysomelidae) introduced for biological control of *Parthenium hysterophorus* (Asteraceae) in India. *Journal of Entomological Research* **17**(1): 27-34

Jayanth KP and Ganga Visalakshy PN. 1994. Dispersal of the *Parthenium* beetle *Zygogramma bicolorata* (Chrysomelidae) in India. *Biocontrol Science and Technology* **4**: 363–365.

Jayanth KP. 1996. Biological control of aquatic weeds in India - progress and prospect, 122-129. In: *Aquatic Weed-Problem and Management*" (Ed. Varma, CVJ).Proceedings of Workshop on held at Bangalore (Karnataka), 5-7 June 1996.

Jayanth KP and Visalakshi PNG. 1989. Introduction and establishment of Neochetina eichhorniae and Neochetina bruchion water hyacinth in Loktak Lake, Manipur. Sci. Cult. **555**: 505-506.

Jha R. 1959. Distribution of *Mlkania seandens* Willd (*Eupatorium scandens* L.I in India lietter to editor. *Indian Forester* **85**(41): p268.

Joy PJ. 1978. Ecology and control of *Salvinia* (African Payal) the molesting weed of Kerala. *Technical bulletin* No. 2. Kerala Agricultural University 40 pp.

Joy PJ, Varghese KC and Abraham CC. 1981. Studies on biology and host range of *Paulinia acuminata* De Geer (Orthoptera: Acrididae) and its efficacy for the control of *Salvinia molesta* Mitchell—an aquatic floating weed in Kerala, pp. 201-206. In: *Proceedings of the Eighth Asian-Pacific Weed Science Society Conference*, 22-29 November 1981, Bangalore, India.

Joy PJ, Sathesam NV, Lyela KR and Joseph D.1985. Successful biological control of floating weed *Salvinia molesta*, using the weevil, *Cyrtobagous salvinae* in Kerala (India), pp. 622-629. In: *Proceedings of 10th Asian Pacific Wed Science Society Conference*, Bengaluru.

Julien MH and Griffith MW 1999. Biological Control of Weeds: A World Catalogue of Agents and Their Target Weeds (Fourth Edition). CAB International, Wallingford, Oxon, UK, 223 pp.

Javaid A and Shabbir A. 2006. First report of biological control of *Parthenium hysterophorus* by *Zygogramma bicolorata* in Pakistan. *Pakistan Journal of Phytopathology* **18**: 199–200.

Jayasurya AHM. *Parthenium* weed - status and management in Sri Lanka, p. 36-43. In: *Proceedings of 2nd International Conference on-Parthenium Management,* University of Agricultural Sciences, Bangalore, India, 5-7 December, 2005.

Kannan C, Aditi Pathak and Sushilkumar. 1914. Natural incidence of agromyzid fly on broomrape. *Indian Journal of Weed Science* **46**(3): 296-297.

Kannan C and Kathiresan RM. 1999. Biological control at different growth stages of water hyacinth, pp.1–8. In: *Proceedings of the First IOBC Global Working Group Meeting for Biological and Integrated Control of Water Hyacinth.* (Eds. Hill MP, Julian MH, Center TD). Harare, Zimbabwe, November16–19, 1998. PPRI Pretoria South Africa.

Karim SMR. 2009. *Parthenium* weed: A new introduction to Bangladesh, pp. 43-44.In: *21st Bangladesh Science Conference.*Bangladesh Agricultural Research Institute, Gazipur, 18-20 February, 2009.

Kumar PS, Rabindra RJ and Ellison CA. 2008. Expanding classical biological control of weeds with pathogens in India: The way forward. *Proceedings XII International Sympoium on Biological Control of Weeds,* La Grande Motte, France.

Kapoor VC and Malla YK. 1979. New record of *Dimeromicrusvibidia* (Walker) (Hymenoptera: Torymidae), a parasite of the gall fly *Procecidocharesutilis* (Stone) (Diptera: Tephritidae) from Nepal. *Journal of Bombay Natural History* Society **75**: 932.

Kaul S and Bansal GL. 2002. Allelopathic effect of *Ageratina adenophora* on growth and development of *Lantana camara*. *Indian Journal of Plant Physiology* **7:**195–197.

Kauraw LP and Bhan VM. 1994. Efficacy of *Cassytha* powder to water hyacinth and of marigold to *Parthenium* population. *Weednews* **1**(2): 3-6

Lockett CJ and Ablin MP. 1990. Heteropsylla sp. - a biological control agent for giant sensitive plant (*Mimosa invisa* Mart.) in north-eastern Queensland,,pp.138-142.In: *Proceedings of the 9th Australian Weeds Conference.* Adelaide, Australia: Crop Science Society of South Australia.

Martin Nic Venter, Hill P, Hutchinson Sarah-Leigh, Ripley Brad S. 2013. Weevil borne microbes contribute as much to the reduction of photosynthesis in water hyacinth as does herbivory. *Biological Control* **64**: 138–142.

Mehta I and Sharma RK. 1972. Control of aquatic weeds by the white amur in Rajasthan, India. *Hyacinth Control Journal* **10**:16–9.

Mcfadyen Cruttwell RE. 2000. Successes in biological control of Weeds, pp. 3-14. In: *Proceedings of the X International Symposium on Biological Control of Weeds.* (Ed. Spencer NR), 4-14 July 1999, Montana State University, Bozeman, Montana, USA.

Mishra SC and Sen-Sarma PK. 1986. Host specificity test and note on life histroy of *Leptobyrsa decora* Drake (Hemipttera: Tingidae) on teak. Bulletin of Entomology **27**: 81-86.

Muniappan R, Reddy GVP and Raman A. 2009. Biological control of weeds in tropics and sustainability, pp. 1-16. In: *Biological Control of Tropical Weeds Using Arthropods*. (Eds. Muniappan R, Reddy GVP and Raman A), Cambridge University Press.

Muniappan R, Reddy GVP and Lai PY. 2005. Distribution and biological control of *Chromolaena odorata,* pp. 223–233. In: *Invasive Plants: Ecological and Agricultural Aspects*. (Ed. Inderjit), Birkha¨userVerlag, Basel, Switzerland.

Naidu VSGR. 2013. Invasive potential of C_3-C_4 intermediate *Parthenium hysterophorus* under elevated CO_2. *Indian Journal of Agricultural Sciences* **83**(2): 176–179.

Naidu VSGR and Paroha Seema. 2008. Growth and biomass partitioning in two weed species, *Parthenium hysterophorus* (C_3) and *Amaranthus viridis* (C_4), under elevated CO_2. Ecology, *Environment and Conservation* **14**(4): 515–518.

Naveen P. 2013. Poisonous plant killed 51 cheetals in Kanha, *Times of India,* Jan 23, 2013.

Pandey SP, Joshi BD and Tiwari LD. 2003. First report of a new predator, *Andrallus spinidens* (Far.), on Mexican beetle *Zygogramma bicolorata* (Pallister) from Uttaranchal, India. *Indian Journal of Entomology* **64** (1): 113-116.

Pandey DK, Kauraw LP and Bhan VM. 1993. Inhibitory effect of *parthenium* (*Parthenium hysterophorus* L.) residue on growth of water hyacinth (*Eichhornia crassipes* Mart Solms). I. Effect of leaf residue. *Journal of Chemical Ecology* **19**(11): 2651–2662.

Palit S. 1981. *Mikania* - a growing menace in plantation forestry in West Bengal. *Indian Forester* **107**: 96-101.

Parsons WT and Cuthbertson EG. 1992. *Noxious Weeds of Australia*. Inkata Press, Melbourne/Sydney, Australia, 692 p.

Rahman A, Alam MS and Khan SK. 2008. Taxonomic studies on the family Asteraceae (Compositae) of the Rajshahi division. *Research Journal of Agriculture and Biological Sciences* (Bangladesh) **4**: 134-140.

Raghubanshi AS, Rai LC, Gaur JP and Singh JS. 2005. Invasive aliens species and biodiversity in India. *Current Science* **88**(4): 539-540.

Ray Puja, Pandey AK and Sushilkumar 2008a. *Alternaria alternata*: a potential biocontrol agent of water hyacinth. *Journal of Basic Applied Mycology* **7**: 43-45.

Ray P, Sushil K and Pandey AK. 2008b. Survey and selection of potential pathogen for biological control of water hyacinth. *Indian Journal of Weed Science* **40**: 75-78.

Ray Puja, Sushilkumar and Pandey AK. 2008c. Efficacy of pathogens of water hyacinth (*Eichhornia crassipes*), singly and in combination for its biological control. *Journal of Biological Control* **22**(1): 173-177.

Ray Puja, Sushilkumar and Pandey AK. 2009. Impact evaluation of *Neochetina* spp. on different growth stages of water hyacinth. *Journal of Plant Protection Research* **49**(1): 7-13.

Rao VR. 1920. *Lantana* in India. *Indian Ent. Memories of Agriculture* **5**: 239-314.

Sankaran T. 1974. Natural enemies introduced in recent years for biological control of agricultural pests in India. *Indian Journal of Agricultural Sciences* **44**(7): 425-433.

Sankaran KV. 2001, *Mimosa invisa*: A growing menace in south India, *Biocontrol News and Information* **22**: 4-5.

Sen-Sarma PK and Mishra SC. 1986. Biological control of forest weeds in india-retrospect and prospects. *Indian Forester* **112**: 1088-1093.

Shaanker UR, Joseph G, Aravind NA, Kannan, R and Ganeshaiah KN. 2010. Invasive plants in tropical human-dominated landscapes: Need for an inclusive management strategy, pp. 202-219. In: *Bioinvasions and Globalization: Ecology, Economics, Management and Policy*. (Eds. Perrings C, Mooney H and Williamson M). Oxford: Oxford University Press.

Shabbir A and Bajwa R. 2006. Distribution of *Parthenium* weed (*Parthenium hysterophorus* L.), an alien invasive weed species threatening the biodiversity of Islamabad. *Weed Biology and Management* **6**: 89-95.

Shrestha Bharat Babu. 2012. *Parthenium* weed in Chitwan National Park, Nepal. *International Parthenium News Letter*. **5**: 8-9

Singh CM, Mohanty RK and Kumar S. 1992. Biology and control of *Eupatorium adenophorum* in Himachal Pradesh. *Indian Journal of Weed Science* **24**(1&2): 62-64.

Singh SB, Banarjee SC and Chakrabarti PC. 1967. Preliminary observations on the resonse of young ones of Chinese carps to various physiological factors of water. *Proceedings of National Academy of Science, India* **37**(B): 320-324.

Singh SP. 1989. Biological suppression of weeds. NCIPM, Faridabad: *Technical Bulletin No.1*. 15-16.

Singh SP. 1998. A review of biological suppression of *Chromolaena odorata* K&R in India, pp. 86-92. In: *Proceedings of . 4th International Workshop on Biological Control and Management of Chromolaena odorata (*Eds. Fessar *et al.*), USA, University of Guam.

Singh SP. 2001. Biological control of invasive weeds in India. 11-19. In: *Alien Weeds in Moist Tropical Zones: Banes and Benefit*s, (Eds. KV Sankaran, ST Murphy and HC Evans) Workshop Proceedings, 2-4 November, 1999, Kerala Forest Research Institute, India and CABI Bioscience, UK Centre (Ascot), UK.

Singh SP. 2004. *Some Success Stories in Classical Biological Control in India*. Asian and Pacific Coconut Community, APCC.

Singh SP. 1997. Perspectives in biological control of *Parthenium* in India, pp. 22-32. *In*: *First International Conference on Parthenium Management.* (Eds. Mahadevappa M. and Patil VC.), UAS, Dharwad, Karnataka, India, 107 pp.

Singh SP. 1995. Experiences in classical biological control in India, pp. 121-154. In: *Biological Control as a Cornerstone of Integrated Pest Management for Sustainable Agriculture in Southeast Asia*. Proceedings of a Workshop on Biological Control (Eds. Paul Ferrar, LokeWai Hong, A. Sivapragasam, Ahmad Anwar Ismail, LumKengYeant, Lim Guan Soon and JannyVos. Kuala Lumpur, Malaysia, September 11-15, 1995. MARDI, Malaysia/ACIAR, Australia.

Sreerama KP, Ramani S and Singh SP. 2007. Natural suppression of the aquatic weed, *Salvinia molesta* D.S. Mitchell by two previously unreported fungal pathogens. *Journal of Aquatic Plant Management* **43**: 105–107.

Suckling DMl and Sforza RFH. 2014. What magnitude are observed non-target impacts from weed biocontrol. *PLoS One*(1): e84847;doi: 10.1371/journal.pone.0084847.

Sushilkumar.1993. Biological control of forests and waste land weeds in India. *Annals of Entomology* **11**(2): 131-153.

Sushilkumar. 2005. Biological control of Parthenium through *Zygogramma bicolorata*. National Research Centre for Weed Science, Jabalpur, India, 88 p.

Sushilkumar. 2006. Economic benefits in biological control of *Parthenium* by Mexican beetle, *Zygogramma bicolorata* Pallister (Coleoptera: Chrysomelidae) in India. *Annals of Entomology* **24**(1&2): 75-78.

Sushilkumar. 2009. Biological control of *Parthenium*in India: status and prospects. *Indian Journal of Weed Science* **41**(1&2): 1-18.

Sushilkumar. 2011. Aquatic weeds problems and management in India. *Indian Journal of W eed Science* **43**(3&4): 118-138,

Sushilkumar. 2012. Current spread, impact and management of *Parthenium* weed in India. *International Parthenium News* **5**: 1-6.

Sushilkumar. 2013. Weed problems in protected areas and prospects of their management, pp. 105-116. In: *Protected Areas in India: Prospects and Retrospect*. Proceedings of National Workshop on Grassland Management. Bandhavgarh Tiger Reserve, Madhya Pradesh, 4-6 July 2013, Organized by State forest Research nstitute, Jabalpur.

Sushilkumar and Bhan VM. 1996. *Parthenium* control by insects in India: retrospect and prospects. *Journal of Applied Zoological Researches* **6**(2): 109-115.

Sushilkumar and Ray P. 2010. Activity enhancement of *Zygogramma bicolorata*, a biocontrol agent of *Parthenium hysterophorus*, by temperature regulated diapause aversion. *Biocontrol Science and Technology* **20**(9): 903-908.

Sushilkumar and Ray P. 2011. Evaluation of augmentative release of *Zygogramma bicolorata* Pallister (Coleoptera: chrysomelidae) for biological control of *Parthenium hysterophorus* L. *Crop Protection* **30**: 587-591.

Sushilkumar and Saraswat VN. 2001. Integrated management: The only solution to suppress *Parthenium hysterophorus*, pp.150-168. In: *Alien Weeds in Moist Tropical Zones: Banes and Benefit*s, (Eds. KV Sankaran, ST Murphy and HC Evans) Workshop Proceedings, 2-4 November, 1999, Kerala Forest Research Institute, India and CABI Bioscience, UK Centre (Ascot), UK.

Sushilkumar and Varshney Jay G. 2010. *Parthenium* infestation and its estimated cost management in India. *Indian Journal of Weed Science* **42(**1&2): 73-77.

Sushil Kumar and Varsheny Jay G. 2007. *Gajar Ghas ka jaivik Niyantrana: Vartman sthathi avamn sambhavnayn (in Hindi) [Biological Control of Parthenium: Present Situation and Prospects]*.National Research Centre for Weed Science: 157 pp.

Swaminathan S and Raman A. 1981. On the morphology of the stem-galls of *Eupatorium adenophorum* Spreng. (Compositae) and the natural enemies of the cecidozoan, *Procecidochares utilis* Stone (Tephritidae, Diptera). *Current Science* **50:** 294-295.

Tang SQ, Wei F, Zeng LY, Li XK, Tang SC, Zhong Y and GengYP. 2009. Multiple introductions are responsible for the disjunct distributions of invasive *Parthenium hysterophorus* in China: evidence from nuclear and chloroplast DNA. *Weed Research* **49**: 373-380.

Thakur ML, Anmad A and Thakur RK. 1992. Lantana weed *Lantana camara* var. *aculeata* Linn and its possible management through natural insect-pests in India. *Indian Forester* **118**(7): 466-488.

Tyagi AC and Gireesha O. 1996. Successful management of submerged weeds in the power canal and Hampi foreway pf the Tungabhadra board. pp.185-190. *In*: *Proceedings of Workshop on "Aquatic Weed-Problem and Management* (Ed. Varma, CVJ) held at Bangalore (Karnataka), 5-7 June 1996.

Visalakshy PNG and Jayanth KP. 1990. Studies on the biology and seasonal abundance of *Hypena laceratalis* walker lepidoptera noctuidae on *Lantana camara* in India. *Entomon* **15**(3-4): 231-234

Willson BW and Garcia CA. 1992. Host specificity and biology of *Heteropsylla spinulosa* (Hom.: Psyllidae) introduced into Australia and western Samoa for the biological control of *Mimosa invisa*. *Entomophaga* **37**(2): 293-299.

Wilson John RU, Ajuonu Obinna, Center Ted D, Hill Martin P, Julien Mic H, Katagira Francisca F, Neuenschwander Peter, Njoka Stephen W, Ogwang James, Reeder Rob H. and Van Thai. 2007. The decline of water hyacinth on Lake Victoria was due to biological control by *Neochetina* spp 2007. *Aquatic Botany* **87**(1): 90-93.

Zhang LY, Ye WH, Cao HL and Feng HL. 2004. *Mikania micrantha* H.B.K. in China - an overview. *Weed Research* **44:** 42-49.

Indian Journal of Weed Science **47**(3): 321–328, 2015

Allelochemicals from *Parthenium* for water hyacinth control

D.K. Pandey*

ICAR-Directorate of Weed Research, Jabalpur, Madhya Pradesh 482 004

Received: 23 June 2015; Revised: 27 July 2015

ABSTRACT

Water hyacinth is an aquatic plant coined to multifarious activities including its role as an obnoxious weed with tremendous economic and aesthetic implications. *Parthenium* (*Parthenium hysterophorus* L.) is a terrestrial weed often put in the category of world's worst weeds now assuming status of India's national weed affecting human health, agriculture, environment and natural biodiversity with tremendous economic implications. The weed has toxic and phytotoxic constituents comprising of phenolics and terpenoids- two major chemical classes implicated in toxic and allelopathic interactions of the species. The species has wide range of constituents in its plant parts, but a few allelochemicals have been investigated for water hyacinth control. Many phenolic acids have been investigated for inhibitory activity on water hyacinth, of which *p*-hydroxybenzoic acid appeared to be of potential herbicidal activity at 100 ppm, a lethal level for the aquatic weed. Major sesquiterpene lactone parthenin is another allelochemical which has been shown to be a potential herbicidal for water hyacinth at 100 ppm, which killed the weed irrecoverably. Investigations undertaken on the aspect of control of water hyacinth by *Parthenium* allelochemicals showed that allelochemical crude and constituent allelochemicals and other secondary metabolites from *Parthenium* leaf herbicidal for the water hyacinth. The allelochemicals could be used under certain situations for managing a weed (water hyacinth) by another weed (*Parthenium*) fostering a concept of weed against weed. The little work undertaken so far on screening of *Parthenium* constituents including allelochemicals for herbicidal activity on water hyacinth and other aquatic weeds pointer to necessity of taking up the investigations on these lines intensively, which might facilitate the development of natural herbicides and their formulations and provide lead for the development of newer synthetic herbicides with novel chemistry for more effective and environment friendly management of water hyacinth and other aquatic weeds.

Key words: Allelochemicals, Managment, Parthenin, *Parthenium*, Phenolics, Water hyacinth

Water hyacinth (*Eichhornia crassipes* Mart. Solms) is one of the worst aquatic plants in the world. It is native to South America, but has been naturalized in most of the parts of the world's subtropical and tropical climates. Water hyacinth plants have tremendous growth and reproductive rates and the free-floating mats cause substantial problems. Plant managers and water front residents spend millions of dollars per year for its management. The plant reproduces by seeds and vegetatively through daughter plants that form on rhizomes and produce dense plant beds. A single plant can produce as many as 5,000 seeds and waterfowl eat and transport seeds to new locations. The best way to manage water hyacinth is to prevent it from ever becoming established (Anonymous 2014). Water hyacinth reproduces sexually by seeds and vegetatively by budding and stolon production. Daughter plants sprout from the stolons and doubling times have been reported of 6-18 days. The seeds can germinate in a few days or remain dormant for 15-20 years. They usually sink and remain dormant until periods of stress (droughts). Westerdahl and Getsinge (1988) reported excellent control of water hyacinth by the use of the aquatic herbicides 2,4-D or diquat. Mechanical controls such as harvesting have been used for nearly 100 years in Florida, but are ineffective for large scale control, very expensive, and cannot keep pace with the rapid plant growth in large water systems. Three insects have been released for the biological control (Grodowitz 1998) of water hyacinth. These include two weevil species (*Neochetina* spp.) and a moth (*Sameodes albiguttalis*). Unfortunately large scale reductions in water hyacinth populations did not occur.

Parthenium hysterophorus L. is commonly known as American feverfew, white top, white head, carrot grass (for resemblance of its leaves with that of carrot) or congress-grass. The species is a herbaceous annual or ephemeral of Asteraceae with world-wide occurrence and is a major crop and

***Corresponding author:** dayapandey@hotamail.com

pasture weed of India and Australia in particular (Towers *et al.* 1977, Navie *et al.* 1996, Pandey *et al.* 2003, Sushilk umar and Varshney 2007). It has been asserted that photo- and thermo-insensitivity and adaptability to contrasting ecological conditions enable it to thrive from sea level to altitudes of 3000 m above mean sea level (amsl) (Lomniczi de Upton *et al.* 1999) in Argentina and to altitudes of more than 2080 m amsl in the Central Himalaya in India (Pandey *et al.* 2003). In the absence of effective natural enemy, its much publicized than verified probable allelopathic effects on other species and rapid growth allow it to grow luxuriantly all through the year, except in extreme winter, especially with spells of freezing temperatures, and summer drought, suppressing native vegetation and threatening biodiversity (Krishnamurthy *et al.* 1977, Towers *et al.* 1977, Kanchan and Jayachandra 1979a, b, 1980a, b, c, Williams and Groves 1980, Jayanth and Bali 1994, Pandey *et al.* 2003). This may threaten quality and quantity of agricultural production, human and animal health, biodiversity and the environment resulting in serious socio-economic implications (Towers *et al.* 1977, Narasimhan *et al.* 1977, Pandey *et al.* 2003). The biological interactions of the species are due to its allelochemicals comprised of phenolics and terpenoids including sesquiterpene lactone parthenin as a major constituent (Rodriguez *et al.* 1971, Picman *et al.* 1979, Picman *et al.* 1980, Kanchan and Jayachandra 1980b, Picman *et al.* 1981, Das and Das 1995). Economic potential of the secondary metabolites including allelochemical constituents remains to be speculative, and descriptive rather than drawing practical advantage for use in agriculture and agricultural pest management.

Allelochemicals in *Parthenium*

Investigations on natural product chemistry of *Parthenium* have been confined to major nutrients (Dutta *et al.* 1979), phenolics, organic acids, sesquiterpene lactones (Rodriguez *et al.* 1971, Rodriguez *et al.* 1976, Picman *et al.* 1979, Picman *et al.* 1980, Kanchan and Jayachandra 1980b, Picman *et al.* 1981, Das and Das 1995) and leaf oils (Kumamoto *et al.* 1985) (Table 1 and Table 2).

Though the *Parthenium* plant has a vast array of secondary metabolites, yet nature of most of the constituents as to being allelochemicals is to be ascertained. It is likely that many yet to be investigated constituents might show allelopathic potential of varying degrees and many may have high herbicidal activity to control water hyacinth. Phenolic acids identified from *Parthenium* plant parts with reference to allelochemic-interactions include caffeic acid, vanilic acid, ferulic acid, chlorogenic acid, *p*-coumaric acid and *p*-hydroxybenzoic acid and among the organic acids, fumaric acid (Kanchan and Jayachandra 1980b, Das and Das 1995). Among pseudoguaianolides reported are parthenin, coronopilin, damsin, hymanin, 8-b-hydroxyparthenin, anhydroparthenin, hysterin, tetraneurin, ambrosanolides and p-methoxybenzoic acid, a sterol b-sitosterol, a triterpenoid betulin, flavonoides quercetagetin-3,7-dimethyl ether, 6-hydroxykempferol 3, 7-dimethyl ether, kaempferol 3-0-glucoside, quercetin 3-0 glucoside and kaempferol-3-0-glucoarabinoside, and a rare lignan (+)-syringaresinol (Rodriguez *et al.* 1971, Rodriguez *et al.* 1976, Picman *et al.* 1980, Towers *et al.* 1977, Kanchan and Jayachandra 1980b, Das and Das 1995, Lomniczi de Upton *et al.* 1999, Venkataiah *et al.* 2003). Occurrence and concentration of various constituents depended on plant parts, geographical distribution and specific populations (Towers *et al.* 1977, Lomniczi de Upton *et al.* 1999). Fresh leaves of *Parthenium* yielded about 0.033% oil which comprised of µ-pinene, camphene, b-pinene, sabinene, b-myrcene, a-terpinene, limolene, b-ocimene, ocimene, *p*-cymene, linalool, cary-ophyllene, humulene, terpinene-4-ol and many unidentified components (Kumamoto *et al.* 1985). Parthenin and related sesquiterpene lactones form adducts with cysteine and glutathione (Picman *et al.* 1979). The plant and its residue owe a range of biological activities to constituent phenolics and major sesquiterpene lactone parthenin.

Parthenium plant parts herbicidal to water hyacinth

Initial exploratory studies showed that *Parthenium* plant was inhibitory to water hyacinth. Investigations were undertaken to study inhibitory activity of different plant parts of the *Parthenium* on this and other floating and submerged aquatic weeds. Experimental results revealed that residue of *Parthenium* plant and its parts were herbicidal to water hyacinth at 0.1-2.0% (dry w/v) (Pandey *et al.* 1993a, b). The herbicidal activity of the plant and plant parts residue appeared to be due to allelochemicals comprising phenolics and terpenoids, major groups of secondary metabolites implicated in its allelopathy (Kanchan and Jayachandra 1979a).

Effect of *Parthenium* leaf residue and its allelochemicals: *Parthenium* dry leaf powder (DLP) was inhibitory to water hyacinth (Pandey et al. 1993a). The DLP caused wilting starting from the margins of the older leaves and desiccation of above-

Table 1. Phenolics and alkaloid secondary metabolites (including allelochemicals) in *Parthenium* and their reported biological activities

Constituent	Reference	Reported biological activity of the constituent	Reference
Phenolic acids			
Occurrence: leaf, stem, root, flower, pollen and trichomes, depending on plant parts and other factors. Usual cellular localization is in vacuoles.			
1. Caffeic acid 2. Vanillic acid 3. Ferulic acid 4. Chlorogenic acid 5. *p*-Coumaric acid 6. *p*-Hydroxy benzoic acid	Kanchan and Jayachandra (1980b), Das and Das (1995)	allelopathy, phytotoxicity, herbicidal activity, growth regulation / inhibition; and nitrification and nitrifying bacteria	Gross 1975, Lodhi and Killingbeck 1980, Patterson 1981, Rice 1984, Mersie and Singh 1988, Pandey 1994b, Pandey 1996b, Pandey and Mishra, 2002, Pandey and Mishra 2005
Flavonoids			
Occurrence: leaf, stem, flower and pollen, depending on plant parts and other factors. Usual cellular localization is in vacuoles.			
1. Quercetagetin-3,7-dimethyl ether 2. 6-Hydroxy kempferol-3,7-dimethyl ether 3. Kaempferol 3-O-glucoside 4. Quercetin 3-O-glucoside 5. Kaempferol-3-O-glucoarabinoside 6. Lignan (+) - syringaresinol	Rodriguez *et al.* (1971), Rodriguez (1977), Towers *et al.* (1977)	antioxidant activities, scavenging effects on activated carcinogens and mutagens, action on cell cycle progression, altered gene expression, UV-B protection in plants, warding off microbial infections, and protection of plants from herbivores, etc.	Harborne and Williams 2000, Rusak *et al.* (2002)
Alkaloids			
Occurrence: leaf, stem, root, flower. Usual cellular localization is in vacuoles.			
Alkaloids-2 (Unidentified)	Rodriguez 1977	-	-

water plant parts (shoot). Appearance, persistence, and disappearance of symptoms depended on the level and duration of the treatment and recovery of the treated plants, if it occurred. The treatment drastically reduced the number of healthy leaves (HLN) and the plant biomass at 0.25% (w/v) DLP; the treated plants recovered in about one month. At and above 0.50% (w/v) DLP, the plants were killed in about one month, resulting in sinking of the dead mass in water. The results indicated that the inhibitors leached out of the DLP affected the water hyacinth plants through changes in macromolecules: protein, lipid, and nucleic acid, resulting in root dysfunction and other inhibitory activities both in the root and shoot. Phenolic and other inhibitors including those found in the *Parthenium* plant (except sesquiterpene lactones which had not been tested) at 50 ppm, except *p*-hydroxybenzoic acid, did not affect the treated plants. Such a high concentration of the allelochemicals was unlikely to be present in the medium at the lethal dose (0.50% w/v) of the DLP. Even with *p*-hydroxybenzoic acid, the plants recovered subsequently and grew normally. Thus, it appeared that other allelochemicals including sesquiterpene lactones were mainly responsible for the inhibitory activity of the DLP on water hyacinth plants.

Relative effect of flower, leaf, stem, and root residue allelochemicals

Since other plant parts of *Parthenium* also showed inhibitory effects on water hyacinth, relative effect of residue of leaf, flower, stem, and root of *Parthenium* on growth of water hyacinth was studied. The inhibitory activity of the residue as shown by its effect on biomass and healthy leaf number (HLN) of treated plants was in the order: leaf and flower >stem >root (Pandey *et al.* 1993b). Total phenolic acids in the medium after 72 hr of suspending the plant part residue were maximum in flower followed by leaf, root, and stem, successively. The DLP and dry flower powder (DFP) at and above 0.50% (w/v) and dry stem powder (DSP) at 1.0% (w/v) killed water hyacinth in about one month. Dry root powder (DRP) at the highest dose (1.25% w/v) reduced the growth of the treated plants drastically, but the plants recovered after about one month. The DSP at 0.50% (w/v) and DRP at 0.25–0.75% (w/v) supported growth of treated plants, probably due to lower levels of inhibitors, allowing utilization of constituents of the residue as nutrients. Using wheat seedling as a reference material, it was observed that in aquaculture at different levels of *Parthenium* plant parts residue, water hyacinth plants were much more sensitive to inhibitory activity. Thus, water hyacinth

Talbe 2. Pseudoguaianolide and oils (including allelochemicals) in *Parthenium* and their reported biological activities

Constituent	Reference	Reported biological activity of the constituent	Reference
Occurring in shoots (mainly leaves and flowering heads), trichomes and seedlings in their first true leaves which bear trichomes, depending on plant parts and other factors. Located in the cytoplasm of the plant cells.			
Pseudoguaianolides			
1. Parthenin 2. Anhydroparthenin 3. Ambrosin 4. Coronopilin 5. Damsin 6. Hymanin 7. 8-β-Hydroxyparthenin 8. 2β-Hydroxycoronopilin 9. Tetraneurin-A 10. Ambrosanolides 11. Charminarone 12. 8-β-Acetoxyhysterone C 13. Deacetyltetraneurin A 14. Hysterin 15. Hysterone E 16. Hysterone D 17. Conchasin A 18. Acetylated pseudoguaianolides 19. Scopoletin (belongs to coumarin) 20. Dihydroxyparthenin	Herz and Hogenauer 1961, Romo de Vivar *et al.* 1966, Rodriguez *et al.* 1976, Towers *et al.* 1977, Picman *et al.* 1980, Picmn *et al.* 1982, Picman 1986, Venkataiah *et al.* 2003, Ramesh *et al.* 2003, Das *et al.* 2005, Das *et al.* 2006, Das *et al.* (2007)	Cytotoxic, antitumor, antibacterial, antifungal, phytotoxic, anti-protozoan, activity against human and animal parasites (including intermediate hosts), insecticidal, moluscicidal, vertebrate feeding deterrence and toxicity, allergic contact dermatitis, mitochondrial oxidative phosphorylation inhibition, allelopathic, anti-inflammatory, and antimalarial	Fay and Duke (1977), Narasimhan *et al.* (1985), Picman (1986), Pandey (1996b), Warshaw and Zug (1996), Sharma and Bhutani (1988), Hooper *et al.* (1990), Tefera (2002), Verma *et al.* (2002), Ramesh *et al.* (2003), Verma *et al.* (2004), Sharma *et al.* (2005), Lakshmi and Srinivas (2007), Regina *et al.* (2007), Das *et al.* (2007), Krenn *et al.* (2009)
Oils			
1. ∝-Pinene 2. Camphene 3. β-Pinene 4. Sabinene 5. β-Myrcene 6. ∝-Terpene 7. Limolene 8. β-Ocimene 9. Ocimene 10. p-Cymene 11. Linelool 12. Caryophyllene 13. Humulene 14. Terpinene-4-ol 15. Many unidentified compounds	Kumamoto *et al.* (1985)	Antifungal, antibacterial, antimicrobial, virucidal, antiparasitical, insecticidal, medicinal and with cosmetic applications; and cytotoxic	Uribe *et al.* (1985), Lima *et al.* (1993), Velickovic *et al.* (2002), Damjanoviae - Vratnica *et al.* (2008), Bakkali*et al.* (2008), Ogendo *et al.* (2008)

was suggested as a material for bioassay of inhibitory activity of the *Parthenium* plant residue. Simultaneously, the results implicated occurrence of potential herbicidal activity in *Parthenium* plant parts residues tempting exploration of the materials for search for natural molecules with potential herbicidal activity. However, probably tedious efforts and resources required for isolation and characterization of the allelochemicals and secondary metabolites, systematic studies are still lacking on screening of individual constituents of *Parthenium* plant parts for their herbicidal activity.

Allelochemical crude herbicidal to water hyacinth

Allelochemical crude prepared by suspending the *Parthenium* plant parts residue in water and evaporating to dryness showed potential herbicidal activity on water hyacinth. Some of the plant parts had much higher herbicidal potential than others. For instance, inflorescence and leaf allelochemical had higher herbicidal activity than stem and root allelochemical crude (Pandey, unpublished work).

In general the allelochemical crude had a yield of about one fourth to one fifth of dry residue of the plant parts. The allelochemicals could be further concentrated by using appropriate solvents and the isolated constituents in final purification can be potential herbicidal to water hyacinth inhibiting and killing it at as low as 12-25 ppm under certain outdoor environmental conditions (Pandey, unpublished work). The concentration of allelochemicals to potential herbicidal formulation is being intensively investigated in the laboratory of the author.

Allelochemicals and their inhibitory activity status to water hyacinth

Phenolics (caffeic acid, vanilic acid, ferulic acid, chlorogenic acid, *p*-coumaric acid and *p*-hydroxybenzoic acid) and organic acids (fumaric acid) identified from *Parthenium* plant parts with reference to allelochemic interactions (Kanchan and Jayachandra 1980b, Das and Das 1995) were investigated for their toxicity on water hyacinth (Pandey 1996a). Caffeic acid stopped biomass increment in water hyacinth plants at 100 ppm but showed little or no effect at 25 and 50 ppm. Vanillic acid had inhibited water hyacinth growth at 100 ppm but was not effective inhibitor at 25 and 50 ppm. Ferulic acid reduced biomass growth over the initial values at 100 ppm and reduced the growth over controls at 50 ppm but was not inhibitory at 25 ppm. Chlorogenic acid was inhibitory at 100 ppm but was obviously not inhibitory at 25 and 50 ppm. *p*-Coumaric acid was inhibitory at 100 ppm but was not so at 20 or 50 ppm. *p*-Hydroxybenzoic acid was lethal at 100 ppm, considerably inhibitory at 50 ppm and was not inhibitory at 25 ppm. Fumaric acid was inhibitory at 100 ppm but was not so at 25 and 50 ppm.

The sesquiterpene lactone parthenin, one of the major secondary metabolites and often considered as an allelochemical of *Parthenium* plant, has been shown to be potential phytotoxic to water hyacinth (Pandey 1996b). Parthenin killed water hyacinth at 100 ppm. The concentration just below the lethal level reduced biomass of the plants. Higher concentrations of parthenin killed the treated plants quicker. At lethal level, the treated plants were killed in about 10 days. Parthenin reduced water use by water hyacinth plants. This was apparent as early as two days after initiation of the treatment. The reduction in water use in treated plans was drastic by six to seven days. The massive increase in solute leakage from the roots of water hyacinth plants grown at the lethal dose of parthenin for two, four, and eight days showed damage to cellular membranes that resulted in loss of cellular structures and constituents. Total dehydrogenase activity in the roots of water hyacinth allowed to grow in 100 ppm parthenin (lethal dose) solution declined rapidly. Enzyme activity declined by about 50% in two days. Parthenin at lethal dose markedly reduced chlorophyll a, b and total chlorophyll contents in water hyacinth leaves. It was interesting that parthenin phytotoxicity dissipated rapidly.

Parthenin appeared to be a potent phytotoxin in an aquatic environment and it was deduced that it might play a decisive role in determining population dynamics and shifts in weed flora in natural ecosystem if it reached the 100 ppm. Sesquiterpene lactones have been reported to be phytotoxic. They react with –SH groups of cysteine, glutathione, and many proteins (Picman 1986). Some have been reported to be novel uncouplers of oxidative phosphorylation (Chefurka 1978).

The mode of action of parthenin on water hyacinth was unknown, but a variety of toxic actions, including some of those previously reported may have combined to cause the stalled growth and development of the weed. Parthenin reduced water use by water hyacinth and caused desiccation of the above-water plant parts consequent to root dysfunction and death. Massive damage to cellular membrane was shown by excessive leakage of solutes from the roots of the treated plants, loss of dehydrogenase activity in roots, and loss of chlorophyll contents in the leaves. These effects suggested that parthenin phytotoxicity may be mediated though affecting macromolecules like proteins, lipids and nucleic acids. The physiological effects of parthenin on water hyacinth resembled those found with *Parthenium* plant residue on water hyacinth and salvinia (Pandey *et al.* 1993a, Pandey 1994a).

Parthenin appears to be a potential herbicidal molecular lead for development of a novel herbicide as it dissipated relatively rapidly in about a month under outdoor conditions (Pandey *et al.* 1993b, Pandey 1994b). The high levels of parthenin in the leaves and flowers largely determine the inhibitory activity of the residue.

Allelochemicals from *Parthenium* for water hyacinth control

A molecule active at 50 ppb to 5 ppm is considered to be of direct commercial herbicidal use. The work undertaken so far showed that *Parthenium* allelochemicals can serve as herbicides for control of water hyacinth at 100 ppm. Since much of stock of secondary metabolites and allelochemicals occurring in the species have not been investigated so far, it is likely that more potential herbicidal allelochemical molecules or secondary compounds are likely in *Parthenium* and the constituents which are likely to be herbicidal for the aquatic weed water hyacinth at much lower levels than the currently known ones (Pandey *et al.* 1993a, b, Pandey and Mishra 2005, Pandey 1997). It is interesting to note that in these studies the allelochemicals in *Parthenium* appeared to have killed water hyacinth primarily by causing root dysfunction which rendered the treated plants unworthy of keeping pace with the massive evapotranspiratory loss of water and succumbed to desiccation involving massive damage to physiological processes with time leading to death by starving, loss of metabolites and metabolism, in a span of few days (Pandey *et al.* 1993a, Pandey 1996b). This information could be utilized for making the formulations and making them more effective.

Research needs / future thrusts

From the foregoing treatise, it appears that the allelochemicals from *Parthenium* for control of water hyacinth has not been adequately investigated. Our understanding at present has been restricted to display of herbicidal activity of *Parthenium* plant and its parts residue, allelochemical crude and crude fractions obtained from the plant parts by using solvents belonging to a range polarity spectrum (Pandey, unpublished work) and a few phenolics and organic acids and major sesquiterpene lactone parthenin. However, it is obvious from Table 1and 2 that most of the secondary metabolites and allelochemicals reported from *Parthenium* have not been systematically investigated for herbicidal use, more so for the control of water hyacinth. Investigations on herbicidal allelochemicals in *Parthenium* are essentially needed in the wake of the fact that safer herbicides are rare for the aquatic ecosystems and that herbicides with new modes of action are badly needed due to the rapidly evolving resistance to commercial herbicides, but a new modes of action has not been introduced in over 20 years (Dayan and Duke 2014).

The greatest pest management challenge including for organic agriculture and keeping in view environmental considerations especially in aquatic environment is the lack of effective natural product based herbicides. The structural diversity and evolved biological activity of natural phytotoxins in the plants like *Parthenium* offer opportunities for the development of both directly used natural compounds and synthetic herbicides with new target sites based on the structures of natural phytotoxins. Natural phytotoxins are also a source for the discovery of new herbicide target sites that can serve as the focus of traditional herbicide discovery efforts. There are many examples of strong natural phytotoxins with new modes of action other than those used by commercial herbicide with new modes of action (Dayan and Duke 2014). Though the allelochemical crude from *Parthenium* leaves show promise for development of a circumstantial herbicidal preparation, yet it needs to be investigated for more effective utilisation of the allelochemicals optimally, which may reduce the rate of application and off course the details of toxicity or toxin persistence would have to be investigated beforehand.

REFERENCES

Anonymous. 2014. http://www.ecy.wa.gov/programs/wq/plants/weeds/hyacinth.html (accessed on 6.6.2015).

Bakkali F, Averbeck S, Averbeck D and Idaomar M. 2008. Biological effects of essential oils – a review. *Food and Chemical Toxicology* **46**: 446-475.

Chefurka W. 1978. Sesquiterpene juvenile hormones: novel uncouplers of oxidative phosphorylation. *Biochemical and Biophysical Research Communication* **83**: 571-578.

Damjanoviae-Vratnica B, Dakov T, Sukoviae D, Damjanoviae J. 2008. Chemical composition and antimicrobial activity of essential oil of wild-growing *Salvia officinalis* L. from Montenegro. *Journal of Essential Oil Bearing Plants* **11:** 79-89.

Das B and Das R. 1995. Chemical investigation in *Parthenium hysterophorus* L. - an allelopathic plant. *Allelopathy Journal* **2:** 99-104.

Das B, Mahender G, Rao YK, Ramesh C, Venkateswarlu K, Ravikumar K, Geethangili M, Tzeng YM. 2006. Pseudoguaianolides from the flowers of *Parthenium hysterophorus*. *Helvetica Chimica Acta* **89:** 285-290.

Das B, Reddy VS, Krishnaiah M, Sharma AV, Ravi Kumar K, Rao JV and Sridhar V. 2007. Acetylated pseudoguaianolides from *Parthenium hysterophorus* and their cytotoxic activity. *Phytochemistry* **68:** 2029-2034.

Das R, Geethangili M, Majhi A, Das B, Rao YK and Tzeng YM. 2005. A new highly oxygenated pseudoguaianolide from a collection of the flowers of *Parthenium hysterophorus*. *Chemical and Pharmaceutical Bulletin (Tokyo)* **53**: 861-862.

Dayan FE and Duke SO. 2014. Natural compounds as next-generation herbicides. *Plant Physiology* **166**: 1090-1105.

Dutta TR, Gupta RK and Patil BD. 1979. A study on the control and possible utilisation of *Parthenium hysterophorus* L. pp. 628-633. In: *Proceeding of the 6th Asian-Pacific Weed Science Society Conference,* Jakarta, Indonesia, vol. 2: .

Fay PK and Duke WB. 1977. An assessment of allelopathic potential in *Avena* germ plasm. *Weed Science **25:** 224-228.*

Grodowitz, MJ. 1998. An active approach to the use of insect biological control for the management of non-native aquatic plants. *Journal of Aquatic Plant Management* **36**: 57-61.

Gross D. 1975. Growth regulating substances of plant origin. *Phytochemistry* **14**: 2105-2112.

Harborne JB and Williams CA. 2000. Advances in flavonoid research since 1992. *Phytochemistry* **55**: 481-504.

Herz W and Hogenauer G. 1961. Isolation and structure of coronopilin, a new sesquiterpene lactone. *Journal of Organic Chemistry* **26**: 5011–5013.

Hooper M, Kirby GC, Kulkarni MM, Kulkarni SN, Nagasampagi BA, O'Neill MJ, Phillipson JD, Rojatkar SR and Warhurst DC. 1990. Antimalarial activity of parthenin and its derivatives. *European Journal of Medicinal Chemistry* **25**: 717-723.

Jayanth KP and Bali G. 1994. Biological control of *Parthenium hysterophorus* by the beetle *Zygogramma bicolorata* in India. *FAO Plant Protection Bulletin* **42:** 207-213.

Kanchan SD and Jayachandra.1979a. Allelopathic effects of *Parthenium hysterophorus* L. I. Exudation of inhibitors through roots. *Plant and Soil* **53:** 27-35.

Kanchan SD and Jayachandra. 1979b. Allelopathic effects of *Parthenium hysterophorus* L. III. Inhibitory effects of the weed residue. *Plant and Soil* **53:** 37-47.

Kanchan SD and Jayachandra. 1980a. Allelopathic effects of *Parthenium hysterophorus* L. II. Leaching of inhibitors from aerial vegetative parts. *Plant and Soil* **55**: 61-66.

Kanchan SD and Jayachandra. 1980b. Allelopathic effects of *Parthenium hysterophorus* L. IV. Identification of inhibitors. *Plant and Soil* **55:** 67-75.

Kanchan SD and Jayachandra. 1980c. Pollen allelopathy – a new phenomenon. *New Phytologist* **84:** 739-746.

Krenn L, Wollenweber E, Steyrleuthner K, Görick C and Melzig MF. 2009. Contribution of methylated exudate flavonoids to the anti-inflammatory activity of *Grindelia robusta*. *Fitoterapia* **80:** 267-269.

Krishnamurthy K, Ramachandraprasad TV, Muniyappa TV and Venkata Rao BV. 1977. Parthenium, a new pernicious weed in India, p. 46. In: *Technical Series No. 17*. University of Agricultural Sciences, Bangalore, India. pp. 46.

Kumamoto J, Scora RW and Clerx WA. 1985. Composition of leaf oils in the genus *Parthenium* L., Compositae. *Journal of Agricultural and Food Chemistry* **33**: 650-652.

Lakshmi C and Srinivas CR. 2007. *Parthenium* a wide angle view. *Indian Journal of Dermatology, Venerology and Leprology* **73**:296-306.

Lima EO, Gompertz OF, Giesbrecht AM and Paulof MQ. 1993. In vitro antifungal activity of essential oils obtained from officinal plants against dermatophytes. *Mycoses* **36**: 333-336.

Lodhi MAK and Killingbeck KT. 1980. Allelopathic inhibition of nitrification and nitrifying bacteria in a ponderosa pine (*Pinus ponderosa* Dougl.) community. *American Journal of Botany* **67**: 1423-1429.

Lomniczi de Upton IM, Fuente JR de la, Esteve Romero JS, Garcia Alvarez Coque MC, Carda Broch S and de la Fuente JR. 1999. Chromatographic detection of sesquiterpene lactones in *Parthenium* plants from northwest *Argentina*. *Journal of Chromatography and Related Technologies* **22**: 909-921.

Mersie W and Singh M. 1988. Effect of phenolic acids and *Parthenium* (*Parthenium hysterophorus* L.) extracts on tomato (*Lycopersicon esculentum*) growth and nutrient and chlorophyll content. *Weed Science* **36**: 278-281.

Narasimhan TR, Ananth M, Narayana Swamy M, Rajendra Babu M, Mangola A and Subba Rao PV. 1977. Toxicity of *Parthenium hysterophorus* L. to cattle and buffaloes. *Experientia* **33**: 1358.

Narasimhan TR, Harindranath N, Ramakrishna Kurup CK and Subba Rao PV. 1985. Effect of parthenin on mitochondrial oxidative phosphorylation. *Biochemistry International* **11**: 239-244.

Navie SC, McFadyen RE, Panetta FD and Adkins SW, 1996 The biology of Australian Weeds 27. *Parthenium hysterophorus* L. *Plant Protection* **11**: 76-88.

Ogendo JO, Kostyukovsky M, Ravid U, Matasyoh JC, Deng AL, Omolo EO, Kariuki ST and Shaaya E. 2008. Bioactivity of *Ocimum gratissimum* L. oil and two of its constituents against five insect pests attacking stored food products. *Journal of Stored Products Research* **44**: 328-334.

Pandey DK and Mishra N. 2002. Phytotoxicity of phenolics allelochemicals to aquatic weeds with reference to conservation, restoration and management of aquatic ecosystems. *wgbis.ces.iisc.ernet.in/energy/lake2002*.

Pandey DK and Mishra N. 2005. Phytotoxicity of phenolics allelochemicals to aquatic weeds, pp. 249-266. In: *Aquatic ecosystems: conservation, restoration and management.*(Eds.: Ramchandra TV, Ahalya N and Rajasekara Murthy C). Capital Publishing Company, New Delhi.

Pandey DK, Palni LMS and Joshi SC. 2003. Growth, reproduction, and photosynthesis of *Parthenium* (*Parthenium hysterophorus* L.). *Weed Science* **51:** 191-201.

Pandey DK. 1994a. Inhibition of salvinia (*Salvinia molesta* Mitchell) by *Parthenium* (*Parthenium hysterophorus* L.). I. Effect of leaf residue and allelochemicals. *Journal of Chemical Ecology* **20**: 3111-3122.

Pandey DK. 1994b. Inhibition of salvinia (*Salvinia molesta* Mitchell) by *Parthenium* (*Parthenium hysterophorus* L.). II. Relative effect of flower, leaf, stem and root residue on salvinia and paddy. *Journal of Chemical Ecology* **20**: 3123-3131.

Pandey DK. 1996a. Relative toxicity of allelochemicals to aquatic weeds. *Allelopathy Journal* **3**: 240-246.

Pandey DK.1996b. Phytotoxicity of sesquiterpene lactone parthenin on aquatic weeds. *Journal of Chemical Ecology* **22**: 151-160.

Pandey DK, Kauraw LP and Bhan VM. 1993a. Inhibitory effect of parthenium (*Parthenium hysterophorus* L.) residue on growth of water hyacinth (*Eichhornia crassipes* Mart Solmns.). I. Effect of leaf residue. *Journal of Chemical Ecology* **19**: 2651- 2662.

Pandey DK, Kauraw LP and Bhan VM. 1993b. Inhibitory effect of parthenium (*Parthenium hysterophorus* L.) residue on growth of water hyacinth (*Eichhornia crassipes* Mart Solmns.). II. Relative effect of flower, leaf, stem and root residue. *Journal of Chemical Ecology* **19**: 2663-2670.

Patterson DT. 1981. Effects of allelopathic chemicals on growth and physiological responses of soybean (*Glycine max*). *Weed Science* **29**: 53-59.

Picman AK, Balza F and Towers GHN. 1982. Occurrence of hysterin and di-hydroisoparthenin in *Parthenium hysterophorus*. *Phytochemistry (Oxford)* **21**: 1801-1802.

Picman AK, Panfil I and Towers GHN. 1981. Separation and identification of stereoisomers of lactones by multiple development of thin layer chromatograms. *Journal of Chromatography* **212**: 379-381.

Picman AK, Rodriguez E and Towers GHN. 1979. Formation of adducts of parthenin and related sesquiterpene lactones with cysteine and glutathione. *Chemical and Biological Interactions* **28**: 83-89.

Picman AK, Towers GH and Subbarao PV. 1980. Coronopillin - another major sesquiterpene lactone in *Parthenium hysterophorus*. *Phytochemistry* **19**: 2206-2207.

Picman AK. 1986. Biological activities of sesquiterpene lactones. *Biochemical Systematics and Ecology* **14**: 255-281.

Ramesh C, Ravindranath N, Prabhakar A, Gharatam J, Tavikumar K, Dashinatham A and McMorris TC. 2003. Pseudoguaianolides from the flowers of *Parthenium hysterophorus*. *Phytochemistry* **64:** 841-844.

Regina GB, Reinhardtb CF, Foxcroftc LC and Hurlea K; 2007. Residue allelopathy in *Parthenium hysterophorus* L. – Does parthenin play a leading role? *Crop Protection* **26**:237-245.

Rice EL. 1984. *Allelopathy*, 2nd ed. Academic Press, Orlando, Florida, USA.

Rodriguez E, Dillon MO, Mabry TJ, Mitchell JC and Towers GHN. 1976. Dermatologically active sesquiterpene lactones in trichomes of *Parthenium hysterophorus* L. (Compositae). *Experientia* **32**: 236-237.

Rodriguez E, Yoshioka H and Marby TJ. 1971. The sesquiterpene lactone chemistry of the genus *Parthenium* (Compositae). *Phytochemistry* **10**: 1145-1154.

Rodriguez E. 1977. Ecogeographic distribution of secondary constituents in *Parthenium* (Compositae). *Biochemical Systematics and Ecology* **5**: 207-218.

Romo de Vivar A, Bratoeff EA, Ríos T. 1966. Structure of hysterin, a new sesquiterpene lactone. *Journal of Organic Chemistry* **31**: 673–677.

Rusak G, Gutzeit HO and Ludwig-Muller J. 2002. Effect of structurally related flavonoids on hsp gene expression on human promyeloid leukaemia cells. *Food Technology and Biotechnology* **40**: 267-273.

Sharma GL and Bhutani KK. 1988. Plant based antiamoebic drugs; Part II. Amoebicidal activity of parthenin isolated from *Parthenium hysterophorus*. *Planta Medica* **54**: 120-122.

Sharma VK, Sethuraman G and Bhat R. 2005. Evolution of clinical pattern of *Parthenium* dermatitis: A study of 74 cases. *Contact Dermatitis* **53**: 84-88.

Sushil Kumar and Varshney JG. 2007. Biological control of *Parthenium*: Present status and prospects, pp. 110. National Research Centre for Weed Science, Jabalpur (in Hindi).

Tefera T. 2002. Allelopathic effects of *Parthenium hysterophorus* extracts on seed germination and seedling growth of *Eragrostis tef*. *Journal of Agronomy and Crop Science* **188**: 306-310.

Towers GHN, Mitchell JC, Rodriguez E, Bennett FD and Subbarao PV. 1977. Biology and chemistry of *Parthenium hysterophorus* L., a problem weed in India. *Journal of Scientific and Industrial Research* **36:** 672-684.

Uribe S, Ramirez J and Peña A. 1985. Effects of beta-pinene on yeast membrane functions. *Journal of Bacteriology* **161**: 1195-1200.

Velickovic DT, Ristic MS, Randjelovic NV and| Smelcerovic AA. 2002. Chemical composition and antimicrobial characteristic of the essential oils obtained from the flower, leaf and stem of *Salvia officinalis* L. originating from Southeast Serbia. *Journal of Essential Oil Research* **14**: 453-458.

Venkataiah B, Ramesh C, Ravindranath N and Das B. 2003. Charminarone, a *seco*-pseudoguaianolide from *Parthenium hysterophorus*. *Phytochemistry* **63:** 383-386.

Verma KK, Manchanda Y and Dwivedi SN. 2004. Failure of titer of contact hypersensitivity to correlate with the clinical severity and therapeutic response in contact dermatitis caused by *Parthenium*. *Indian Journal of Dermatology, Venereology and Leprology* **70**:210-213.

Verma KK, Sirka CS, Ramam M and Sharma VK. 2002. *Parthenium* dermatitis presenting as photosynsetive lichenoid eruption: A new clinical variant. *Contact Dermatitis* **53**: 84-88.

Warshaw EM and Zug KA. 1996. Sesquiterpene lactone allergens. *American Journal of Contact Dermatitis* **7**:1-23.

Wickham K, Rodriguez E and Arditti J. 1980. Comparative phytochemistry of *Parthenium hysterophorus* L. (Compositae tissue cultures). *Botanical Gazette* **141**: 435-439.

Westerdahl HE and Getsinger KD. 1988. Efficacy of sediment-applied herbicides following drawdown in Lake Ocklawaha, Florida. *Information Exchange Bulletin. A-88-1*. US Army Corps Engineers, Vicksburg, MS.

Williams JD and Groves RH. 1980. The influence of temperature and photoperiod on growth and development of *Parthenium hysterophorus* L. *Weed Research* **20**: 47-52.

Indian Journal of Weed Science **47**(3): 329–344, 2015

Herbicide residues and their management strategies

P. Janaki*, Neelam Sharma[1], C. Chinnusamy, N. Sakthivel and C. Nithya
Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu 641 003

Received: 15 June 2015; Revised: 4 September 2015

ABSTRACT

Herbicides have become obligatory for increasing the agricultural production and to maintain the non-cropped area free from weeds and pests. In general, herbicides are formulated in such a way that they degrade from the environment after completion of their intended work, but a few of them persist in the environment and pose a serious hazard to the succeeding crop and also to the surroundings. Mostly the triaizines, isoxazolidinones, imidazolinones and a few of sulfonylureas are persistent herbicides. Hence, it is essential to compile the available literature on the management of herbicide residues in the soil environment. In this review, the management aspects were covered under five broad categories, *viz*. cultural and mechanical, enhanced degradation, deactivation, reducing the availability in soil, and removing from the site of contamination. From the review, it was found that the integration of mechanical and cultural management practices with herbicides for managing weeds is a viable protecting option since the safeners exhibit varying behaviour in soil on influencing the herbicide persistence. Further, the combination of bioaugmentation and biostimulation along with the organic matter addition might be a promising technology to accelerate the biodegradation. Although it requires extensive field evaluation studies, biostimulation in conjunction with other tools like crop rotation and increasing the organic matter content is definitely a promising technique for managing the herbicide persistence minimizing its residue in the soil.

Key words: Biostimulation, Deactivation, Enhanced Degradation, Herbicide, Management

Herbicide usage becomes inevitable in the present day intensive agricultural system to obtain large harvests and minimize the yield loss due to weeds. The herbicide demand in India is rising sharply and could double in the next three years as an acute labour shortage makes them a cheaper option and a rally in farm goods prices prompts farmers to grow crops with extra care (Mukherjee 2011). Usage of herbicides occupy 44% of the total agrochemicals globally and 30% in India (Sondhia 2014).

Herbicides are a group of organic compounds that possess far-reaching environmental consequences when persistent in the soil. A persistence problem arises when the herbicides are applied scrupulously or continuously; the crop failure necessitates replanting; a susceptible crop follows a short term crop which received a persistent herbicide; and the decomposition of the applied herbicide proceeds very slowly (Sankaran *et al*. 1993). The longer persistence of a herbicide poses a hazard to subsequent land use and is undesirable. Recent concerns of ground and surface water contamination by some of the herbicides has led to renewed interest on persistence and dissipation behavior of herbicides in the environment. Several monitoring programmes have also been implemented by different countries to check the environmental contamination and for ecological risk assessment of herbicides. However, the information on managing herbicide persistence in the soil saving the crop from those situations are limited. Though the studies are conducted around the world and a few places in India, there is a lack in the published information. This article aims to hoard the information on herbicide persistence and its management across the world.

***Corresponding author:** janakibalamurugan@rediffmail.com
[1]AICRP-WM, Department of Agronomy, CSK Himachal Pradesh Krishi Vishvavidyalaya, Palampur, Himachal Pradesh 176 062

Persistence and residue of herbicides

A herbicide is said to be persistent if it is present in the soil in its original or closely related but phytotoxic forms even after its mission is accomplished (Sankaran *et al.* 1993, Sondhia 2014) and the quantity that exists is referred to as residue. Herbicides vary in their potential to persist in soil. Herbicide families that have persistent members include the triazines, uracils, phenylureas, sulfonylureas, dinitroanilines, isoxazolidinones, imidazolinones, and certain plant growth regulators belonging to the pyridine family (Curran 2001). The relative persistence of some common herbicides in soil when applied at recommended rates for weed control are given in the table 1.

The chemical properties of the herbicide affect its persistence in soil and the important factors include water solubility, vapor pressure, and susceptibility to chemical and microbial alteration or degradation (WSSA 2002). Besides the climatic conditions prevailing in the locations, the physicochemical properties of the soil have influences on the persistence of an herbicide (Sharma and Angiras 2004, Janaki *et al.* 2013, Sondhia 2014) in soil and its carry over potential. Detailed review on the degradation and residue of different herbicides in soil and health concerns are already published by Sondhia (2014).

Management of herbicide residues in soil

There are several ways to avoid herbicide persistence and carryover problems. Literatures available on various management techniques to minimize the persistence and residue hazards in soil and carryover problems are reviewed under five different categories for the ease of understanding.

Cultural and mechanical management practices

Integrated weed management: Integrated weed management (IWM) involves the application of a variety of management practices to control weeds. Herbicides are used only when weed populations exceed an economic threshold level that justifies their application. Field scouting is required to monitor weed populations. Nonchemical weed control methods, such as crop rotation, cultivation, competitive hybrids, rotary hoeing and altered planting dates, are emphasized as management practices that can reduce the need for herbicides. The effectiveness of the integrated weed management using chemical and mechanical means in different crops has been studied vastly in India and also at world level. Vaishya *et al.* (2003) found that the pre-emergence application of pendimethalin 1.0 kg/ha or pre-plant incorporation of fluchloralin 1.0 kg without phytotoxicity on crop. Sathiyavani and Prabhakaran (2014) reported that the pre-emergence application of metribuzin 0.7 kg/ha on 3 day after planting (DAP) of turmeric plus hand weeding on 45 and 75 DAP for effective weed management and higher yield without phytotoxicity to crop and carryover problems. Similarly, Sharma *et al.* (2013) found that the application of 2,4-D at three levels of 0.5, 1.0 and 2.0 kg/ha in wheat crop at 35 days after sowing persisted in soil up to 15, 45 and 75 days, respectively, however, residues of 2,4-D were found below detectable level (0.02 ppm) in wheat grain and wheat straw. Nalini *et al.* (2010) found that the pre-emergence application of pendimethalin (38.7%) at 2.0 kg/ha 3 day after sowing (DAS) + hand weeding (HW) on 45 DAS showed effective weed control in cotton without leaving any residues in the soil at the time of harvest and carryover problems to the succeeding crops, *viz.* pearl millet, cowpea and sunflower grown in sequence. Sharma *et al.* (2014) reported that pre-emergence application of pendimethalin did not leave any residues in soil beyond harvest of the garlic at any of the applied dose. Sharma and Angiras (1996) found that the residue of pendimethalin 1.5 kg/ha applied in wheat + sarson intercropping system was only 0.001 ppm in soil after harvest of these crops.

Ploughing or cultivating the land: Tillage operations help in bringing deep present herbicide residues to soil surface which would aid in decontamination by volatilization. Ploughing with disc plough or intercultivators reduce the herbicide toxicology, as the applied herbicide is mixed to a large volume of soil and get diluted. Olson *et al.* (1998) stated that the atrazine loss was low in the chisel-disk system with incorporation compared to no till and ridge till systems. Zablotowicz *et al.* (2007) observed

Table 1. Relative persistence of some herbicides in soil

< 1 month	1-3 months	3-6 months	> 6 months
2,4-D, Glyphosate, MCPA	Alachlor, acetochlor, ametryn, anilofos, bispyribac-sodium, butachlor, carfentrazone-ethyl, dalapon, fluzifop-butyl, halosulfuron, metribuzin, metamifop, metsulfuron-methyl, metolachlor, oxyfluorfen, propachlor, pyrazosulfuron-ethyl, thiobencarb	Clomazone, chlorimuron-ethyl, diallate, dithiopyr, ethofumesate, fluchloralin, imazethapyr, isoproturon, metamitron, oxadiazon, linuron, pendimethalin, pyrazon	Atrazine, bromacil, chlorsulfuron, diuron, diquat, imazapyr, methazde, picloram, simazine, sulfometuron, sulfentrazone, trifluralin, paraquat

Source: Loss (1975); Sankaran *et al.* (1993); Hager *et al.* (2000); Sharma and Angiras (2003); Sharma *et al.* (2006); Chinnusamy *et al.* (2008); Sharma *et al.* (2013); Sharma *et al.* (2014); Ramprakash *et al.* (2014); Sondhia (2014); Tandon (2014)

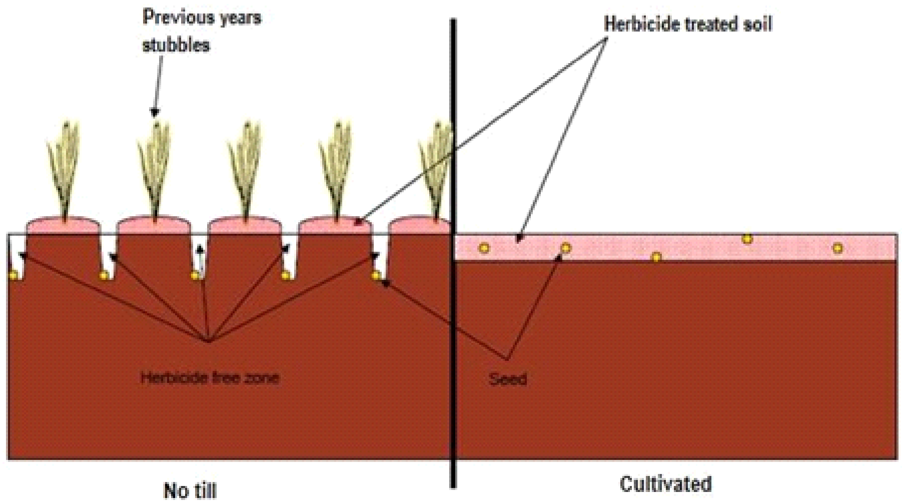


Fig. 1. Difference between the distribution of herbicides in soil under no-till and cultivated conditions (Source: Barry 2012)

the rapid degradation of fluometuron in conventional tillage (CT) compared to no-tillage (NT) soils in the 2 to 10 cm depth and found that the ryegrass cover crop systems, under NT or incorporated under CT, stimulated microbiological soil properties and promoted the herbicide degradation in surface soils. Since, most herbicide transformations in soil are mediated by microbial metabolism, modification of the soil environment and microbial populations by reduced tillage and/or cover crops can affect herbicide fate (Levanon *et al.* 1994, Locke and Zablotowicz 2003).

According to Gaston and Locke (2000) the herbicides degradation was faster in the surface layers than deeper layers of soil and is faster at CT than NT. In compliance with a study on the behavior of atrazine in the soil at no-till by Hang *et al.* (2010), only in a few isolated cases the faster herbicide degradation was in deeper soil layers than in the surface layers. Dao (1991) found unbalanced degradation of metribuzin and S-ethylmetribuzin due to slow herbicide release fixated in the crop residues. Straw affinity is able to reduce efficiency of herbicides that were activated in the soil, if they were applied into soil surface at no-till. Alletto *et al.* (2009) reviewed in detail the impact of tillage practices on the sorption, degradation and movement of herbicides and found that depending on the nature of crop residues, the degradation of molecules can be affected by the presence of mulch, but in contrasted ways. In no-tillage, vetch residues accelerated the degradation of metolachlor by from 1.5 to 3 times, but had no effect on the degradation of atrazine (Teasdale *et al.* 2003). On the contrary, according to laboratory studies, vetch residues seemed to slow down fluometuron degradation compared with soil samples without vetch residues (Brown *et al.* 1994, Zablotowicz *et al.* 1998) or other types of residues such as wheat residues (Gaston *et al.* 2001), rye residues (Zablotowicz *et al.* 1998), etc. This slowdown could be due to the abundance of nitrogen in legumes.

Incorporation of herbicides: Mechanical incorporation of a herbicide by placing it below the mixing zone (eg., atrazine) helps to reduce runoff loss, which takes place through the solution or water phase and not much with soil particles. Some herbicides are sensitive to sunlight and need to be mixed into the soil to minimize losses. Some herbicides are volatile and can be lost through evaporation, especially from wet soil. Application of pre-emergent herbicides as pre-sowing and then incorporating them into the seed bed during the sowing process will often increase safety to crops because the sowing operation removes a certain amount of herbicide away from the seed row (Fig. 1). This can conversely reduce weed control for the very same reason, as chemical is moved out of the seed row. Hence, it is wise to include a water soluble herbicide into the mix aiming to have a portion of it into the seed furrow (Barry 2012).

Use of crop residue from the previous year and mulch can reduce sediment concentrations and losses. With the development of special tools, subsurface herbicide application can provide incorporation with minimal disturbance of surface residue. Mickelson *et al.* (2001) found that the soil incorporation and subsurface herbicide application with the Mulch Master can reduce herbicide losses through surface runoff when compared to surface application with no-till (Table 2).

Crop rotation: Soil can be decontaminated of herbicide residues by deliberately including crop plants that are resistant to the particular herbicide. Crop rotation spreads the planting and herbicide application season, reducing the risk of encountering widespread herbicide runoff during a single runoff event. Suzer and Byuk (2010) found that the rape seed and sugar beet are highly sensitive to the imidazolinones (imazamox + imazethapyr) and should be avoided in the rotation as a succeeding crop when the previous crop was applied with these herbicides. While they also reported that the maize, winter wheat and barley were unaffected and can be used in rotation. Bresnahan *et al.* (2000) also reported that the recropping with canola and sugar beet should be avoided in the growing season if the previous crop sunflower received mixture of imazamox and imazethapyr to avoid carryover problems.

Cobucci *et al.* (1998) reported that the sensitivity of rotational crops to fomesafen and imazamox residues was in decreasing order from sorghum to corn, millet, and then rice and to acifluorfen from sorghum to corn, rice, and then millet. For com, rice, and millet injury is possible under certain environmental conditions (i.e., low soil moisture content and high clay and organic matter soil) but appears to be low with high precipitation conditions. Verma *et al.* (2014) reported that the maintenance of appropriate crop rotation with legume and non-legume crops, and growing of cover crops during fallow period helps to suppress the weed population by smothering without applying the herbicides.

Growing herbicide tolerant crops: Certain herbicide tolerant crops can reduce herbicide residues in a soil by absorbing and deactivating these in their tissues. Maize and millets, for instance, are very good consumers of triazine herbicides. Vetiver was not affected by exposure to the herbicides, atrazine and diuron, at concentrations as high as 2,000 mg/L which are likely to be encountered in the environment only in situations of accidental spillage, or direct application to waterways (Cull *et al.* 2000). Singh and Walia (2005) reported that the crops like methi, turnip, berseem and gobhi-sarson were not affected by the carryover effect of sulfosulfuron and hence can be grown in soil have sulfosulfuron residue. Sathiyavani (2014) found that the spraying of glyphosate from 1.04 to 1.56 kg/ha as post-emergence on 25 days after planting in the turmeric field did not affect the main crop and provided a broad spectrum of control of all weeds and also does not show any phytotoxicity symptoms on turmeric at 30 days after application. Bandana *et al.* (2015) reported that in soil, the glyphosate persisted up to 30, 45 and 60 days at application doses of 0.5, 1.0 and 2.0 kg/ha, respectively and in tea leaves, residues were detected for up to 15 days at all doses, however, concentration was found to be below the maximum residue limit (1 mg/kg).

Light irrigation after application: Continuous moist soils often result in a more rapid breakdown of herbicides due to creation of favorable conditions for microbial activity. While controlled irrigations enhance all modes of deactivation, heavy irrigations leach herbicides out of the root zone of the crop. Rice *et al.* (2002) stated that the saturated soil favored the dissipation of metolachlor and the formation of soil-bound residues. Significantly greater quantities of a dechlorinated metabolite were measured in the saturated surface soil compared to the unsaturated soil. Lovell *et al.* (2002) found that the degradation of isoxaflutole was faster in soil maintained at -100 or -1500 kPa compared to that in air-dry soil. At 25°C, the half-lives for isoxaflutole were 9.6, 2.4, and 1.5 days

Table 2. Herbicide losses with water and sediment as influenced by the method of incorporation

Treatment	Chemical losses with water (g/ha)			Chemical losses with sediment (g/ha)		
	Atrazine	Metolachlor	Cyanazine	Atrazine	Metolachlor	Cyanazine
Surface application and incorporation using mulch master	0.94b	1.32b	1.43b	0.09b	0.06c	0.07b
Sub surface application an incorporation using mulch master	7.61b	10.1b	9.05b	0.35b	1.13b	0.48b
Surface application and no incorporation (no-till)	148a	112a	231a	1.70a	1.93a	2.64a
Surface application and incorporation using dines	1.87b	1.30b	2.25b	0.20b	0.31c	0.20b

[a] Means with the same letters are not significantly different at 10% confidence level

in air-dry, -1500 kPa and -100 kPa moisture regimes, respectively.

Site specific application using variable rate applicator: The interaction between herbicide chemistry and soil properties greatly affects its weed control efficacy and the potential for crop injury. Because of this, fields with significant variability in soil properties are good candidates for variable rate of application of soil-applied herbicides. The combination of automatic tractor steering and variable rate technology is well suited for site-specific application of pre-emergence herbicides. With tractor guidance control and variable rate controllers, growers can increase the efficiency of chemical application by applying optimum rates based on soil texture. These technologies have primarily been adopted by growers of major crops such as corn, wheat and soybeans (Koch and Khosla 2007). Bauer and Schefcik (1994) found that recommended application rates of pre-emergence soil applied herbicides can vary as much as 50% in a given field due to varying soil textures. Kurt *et al.* (2011) studied the effectiveness of benefin herbicides in controlling weeds on vegetable crops using the variable rate technology in different textured soils and found that the use of this technology resulted in significantly less crop injury and significantly more marketable yield as compared to uniform application. In the portions of the lettuce field with loamy sand textured soils, 35% less herbicide was applied and up to 40% more heads were harvested. Furthermore, there was no significant difference in weed control efficacy found between the two application methods examined (Table 3).

In soils with high clay content, a greater amount of the herbicide is required for adequate weed control as compared to sandy soils. If higher rates necessary for good weed control in high clay content soils are used on sandy soils, excessive herbicide concentrations in soil solution can cause injury to lettuce seedling roots (Tickes and Kerns 1996).

Enhancing the herbicide degradation

Biostimulation: The term “biostimulation” is often used to describe the addition of electron acceptors, electron donors, or nutrients to stimulate naturally occurring microbial populations (Scow and Hicks 2005). Comprehensively, biostimulation could be perceived as including the introduction of adequate amounts of water, nutrients, and oxygen into the soil, in order to enhance the activity of indigenous microbial degraders (Couto *et al.* 2010) or to promote cometabolism (De Lorenzo 2008). The concept of biostimulation is to boost the intrinsic degradation potential of a polluted matrix through the accumulation of amendments, nutrients, or other limiting factors and has been used for a wide variety of xenobiotics (Kadian *et al.* 2008).

The dearth of adequate decomposable organic matter in the soil gives insufficient substrate to stimulate microorganisms in the decomposition of herbicides (Felsot and Dzantor 1990) and thus leaves herbicides recalcitrant in the soil for years without degradation. The addition of organic matter, bioprocessed materials or compost naturally initiates the microbial activity in the soil and could be utilized to treat contaminated soils Buyuksonmez *et al.* (1999). Fresh bioprocessed materials serve as rich source of nitrogen, carbon, and other nutrients and make excellent candidates for flourishing the microbial growth (Kadian *et al.* 2008). The general conclusion from the studies involving organic amendments in the soil was that the herbicide concentrations in the soil were reduced to significantly lower levels within short spans of time when compared to the unamended treatments (Kanissery and Sims 2011). Durga Devi *et al.* (2005) found that the continuous application of FYM to the rice crop enhanced the degradation of butachlor, pretilachlor and 2,4-D in the soil through enhanced microbial activity.

Table 3. Influence of standard and variable-rate application treatments of benefin on cumulative weed emergence per plot at two and four weeks post-germination

Soil texture	Rate technology application (lb/acre)		Total weeds (no./plot) on 14 days after germination		Total weeds (no./plot) 28 days after germination	
	Standard	Variable	Standard	Variable	Standard	Variable
Sandy clay	2.0	2.5	3.63[a]	4.21[a]	2.43[a]	2.62[a]
Sandy clay loam	2.0	2.0	4.35[a]	3.52a	3.06[a]	2.83[a]
Loamy sand	2.0	1.5	4.73[a]	4.13[a]	2.45[a]	6.05[a]

[a]Means followed by the same letter in each column are not significantly different at P=0.05 according to the analysis of variance and the Fisher’s LSD means separation test. (*Source:* Kurt *et al.* 2011)

Nutrients addition

Mostly, nutrients in the soil stay below optimal concentration for microbial activity. Supplementing such soils with the necessary nutrients instigates the biodegradation of the pollutants and is a promising technique to enhance the bioremediation of contaminated sites. Nutrients like carbon, nitrogen, and phosphorus stimulate microbes to create the essential enzymes to break down the contaminants. Hance (1976) demonstrated the consequence of inorganic nutrient addition on the breakdown of atrazine in the soil. Thereafter, the concept of nutrient supplementation for enhanced degradation of contaminants was brought into the limelight by various researchers, and the prospects of microbial biostimulation through the manipulation of organic and inorganic nutrient status in the soil have since been investigated (Table 4). In some cases, inorganic nitrogen starvation may be more effective in promoting degradation and has been reported for atrazine and other heterocyclic compounds (Bichat *et al*. 1999, Sims 2006). This can potentially be accomplished by supplying excess carbon to make nitrogen limiting.

Recently, Qiu *et al.* (2009) confirmed that P was a limiting nutrient during the degradation of coexisting dichlobenil and atrazine by bacterial degraders in soil. Dichlobenil was completely degraded in 60 hours in the P-supplemented soil extract, in comparison to less than 40% degradation without P supplement. It is noteworthy that the degree of enhancement of atrazine degradation was even greater, in that it was completely degraded in P-supplemented extract within 40 hours, compared to less than 10% degradation without the P supplement.

Bioaugmentation: The process of bioaugmentation is the introduction of specific microorganisms (indigenous or non-indigenous) aiming to enhance the biodegradation of target compound or serving as donors of the catabolic genes. Usually this goes in pair with the biostimulation (Kanissery and Sims 2011). Microorganisms are capable of degrading the herbicide compounds in the soil by utilizing them as a supply of nutrients and energy. Increasing the population of particular herbicide degrading pure culture bacteria by artificial means may solve such type of problem. Mandelbaum *et al*. (1993) found that the instead of pure cultures, mixing pure cultures restored atrazine-mineralizing activity and also observed increased rates of atrazine metabolism with the repeated transfer of the mixed cultures even at the elevated concentrations. Radosevich *et al.* (1995) isolated an atrazine-degrading bacterial culture from an agricultural soil previously impacted by herbicide spills and used to enhance the its degradation in soil and found that these organisms were capable of using atrazine under aerobic conditions as the sole source of C and N. Jaya *et al.* (2014) reported, *Rhizopus oryzea* is a potential fungal isolate and can be used for the bioremediation of alachlor from soil and the half life values in sterile and non-sterile soil incubated with *Rhizopus oryzea* were found to be 7.2 and 8.6 days, respectively. Mukherjee *et al.* (2005) found that the

Table 4. Stimulating the biodegradation of herbicides in soil through nutrient supplements

Herbicides targeted atrazine	Nutrients and influence	References
	Ammonium nitrate, potassium nitrate and ammonium phosphate	Hance (1973)
Dichlobenil, Atrazine	Phosphorus	Qiu *et al*. (2009)
2,4-D, Mecoprop	Glucose, phosphate	De Lipthay *et al.* (2007)
Isoproturon	Nitrate and phosphoruous	Perrin-Ganier *et al.* (2001)
Atrazine	Mannitol	Assaf and Turco (1994)
Atrazine	Glucose	Abdelhafid *et al.* (2000)
Pretilachlor, 2,4-D ethyl ester	Enhanced 2,4-D degradation due to the combined application of organic and inorganic source of N in transplanted rice-rice system. However, the pretilachlor degradation was stimulated and enhanced by the 100% organic sources of nitrogen.	Shanmughasundaram *et al.* (2005) Janaki *et al.* (2009 and 2010a, b)
Butachlor	Dissipation was rapid due to the combined application of organic and inorganic sources of N in the rice soil continuously for ten years and has been attributed to the enhanced population of microbes in soil as influenced by the organic matter addition.	Chinnusamy *et al.* (2012)
2,4-D, MCPA	Application of combined NPK fertilizers enhanced their degradation from soil	McGhee and Burns (1995)
MCPA	Nitrate is not suitable as an alternative electron acceptor for MCPA degradation and, in certain circumstances, inhibits aerobic catabolism of the herbicide in the soil	McBain *et al.* (1997)

dissipation of lactofen was faster in soil solarization technique and was enhanced by the straw amendment to the tune of 90% and suggested that this technique is promising one remediating the herbicide residues from the site of persistence.

Deactivation of herbicides

Addition of organic matter: Pesticides are inactivated by plant residues or organic matter incorporated into soil. The organic matter acts in two ways. Primarily, the application of FYM adsorbs the herbicide molecules in their colloidal fraction and makes them unavailable for crops and weeds and after a lag phase, microbial population thriving on organic matter starts decomposing the herbicide residues at a faster rate due to high moisture holding capacity of organic matter in soils. Meena *et al.* (2007) reported that the FYM application at 12.5 t/ha reduced the atrazine residue significantly followed by compost (12.5 t/ha) and phosphoric acid (50 ppm) application. Residual toxicity of atrazine to the sensitive crop soybean was overcome by the application of farm yard manure at 12.5 t/ha or compost 12.5 t/ha or charcoal 5.0 kg/ha along the seed line (Chinnusamy *et al.* 2008). Randhawa *et al.* (2005) found that the residues of isoproturon, 2,4-D and butachlor in the soil under rice-wheat cropping was not built up when the organic matter was continuously applied for five years. Janaki *et al.* (2014) reported the influence of clay and organic matter on the sorption and persistence of pyrazosulfuron-ethyl in rice growing soils and suggested that the persistence of the herbicide and its residue depended on the above properties of the soil. Similarly, Arora (2014) also found that the leaching and persistence of oxyfluorfen depended on the organic matter addition through FYM in sandy clay loam soil. Sharma and Angiras (2004) observed that higher the organic matter content in soils, lesser was the persistence of atrazine and *vice versa*.

The effectiveness of FYM was evaluated and reported by Rathod *et al.* (2010) in reducing persistence of three dinitroaniline herbicides, *viz.* pendimethalin, trifluralin and fluchloralin from a field, cropped with Indian mustard (*Brassica juncea* L.) in sandy loam soil of middle-west Indian agro-climatic conditions. They found that the persistence of all three dinitroaniline herbicides was decreased with addition of FYM and observed a reduction of the half-life of all three herbicides when FYM incorporated. Decreased residues of dinitroaniline herbicides with an incorporation of FYM and faster degradation of herbicides in soil with organic matter have also been reported by Jacques and Harvey (1979) and Patel *et al.* (1996). Senesi and Testini (1984) stated that the H-bonding, London-Van der Walls forces and cation exchange are responsible for the adsorption of herbicides by organic materials. Pritchard and Stobbe (1980) revealed that phytotoxicities of dinitroanilies decreased with increased organic matter but persistence of fluchloralin and trifluralin was increased with increased organic matter, which may cause crop injury a year later. The effectiveness of different organic amendments on enhancing the herbicides degradation in soil has been reviewed by Kanissery and Sims (2011). While Topp *et al.* (1996) observed a significantly shortened lag period in dairy manure-treated plot prior to atrazine herbicide degradation. Gan *et al.* (1996) identified dairy manuring as a successful technique to enhance the remediation of atrazine-contaminated soil. Though the addition of organic matter reduces the residues on herbicides in soil, the type of organic sources plays a role in influencing the herbicide degradation in soil especially under low moisture conditions and also under conservation practices (Zablotowicz *et al.* 1998). Mukherjee (2009) used different organic amendments, *viz.* rice straw, FYM, saw dust, and charcoal and found FYM was the most effective for the degradation of atrazine to the extent of 89.5% within 60 days. However, Felsot and Dzantor (1997) observed that the use of organic amendments as an inexpensive option for the disposal of herbicide (alachlor, metolachlor, atrazine, and trifluralin) waste.

Use of non-phytotoxic oil, adjuvants and surfactants*:* Non-phytotoxic oil, adjuvants and surfactants reduce the residual hazard besides enhancing the weed killing potency. Adjuvants modify certain physical characteristics of the spray solution like surface tension and wetting ability, which may modify the spray solution's response to move in the soil (Walker 1980, Singh and Tan 1996). One of the beneficial effects of adjuvants, especially surfactants is a reduction in the amount of water available for evaporation from the soil surface (Bayer 1967). Addition of olejan to the trifluralin applications caused a significant increase in of the herbicide degradation rate, both in laboratory and pot-field experiments (Swarcewicz *et al.* 1998). Application of cationic adjuvants may have led to the formation of neutral species by binding to certain anionic molecules in the soil system. The resultant complex may have dissolved the herbicide rendering it less mobile in soil. Surfactants are important small group of chemicals among adjuvants. They act as emulsifiers as well as wetters and spreaders (Hall *et al.* 1993). The addition of adjuvants could influence the speed of degradation and increase herbicide residues in soil and plant, but usually adjuvants are applied with herbicides in reduced doses (70–80% of recommended one) and herbicidal residues determined at harvest time are lower than those obtained from treatments, where recommended doses of herbicide (without adjuvant) were applied (Kucharski 2003). Further the influence of adjuvants on herbicide residues in soil and plant, degradation rate and leaching depend on the kind of adjuvant (Kucharski and Sadowski 2009a).

Kucharski and Sadowski (2009b) found that the addition of oil adjuvant slowed down degradation and increased the level of ethofumesate residue in soil. Reddy and Singh (1993) evaluated bromacil and diuron herbicides lixiviation in soil columns and found the significantly lower vertical movements of bromacil, while there was no such effect on diuron. These two herbicides present distinct physicochemical characteristics that explain their differential movement abilities in the soil. From the environmental point of view, the adjuvant effect was positive in the case of bromacil, but the agronomic efficacy was restricted. Cabrera *et al.* (2010), in laboratory studies affirmed that metazachlor herbicide added to oil and surfactant showed reduced degradation rates and increased residues in the soil. Similarly, in a field experiment, Kucharski *et al.* (2011) observed a 43% increase in lenacil herbicide residues in the superficial soil layer, with the addition of adjuvants (oil and surfactant). Kucharski *et al.* (2012) found that the DT_{50} values for the mixture of chloridazon + oil and surfactant was about 8–14 days higher in comparison to the DT_{50} for chloridazon applied alone (43 days) and no significant differences were observed between degradation rates of chloridazon.

Use of adsorbents, protectants and antidotes: They are applied to the soil, crop seed or transplanted plant to protect the crop from herbicide injury. The mode of action may be due either to deactivation or adsorption of the herbicide, preventing its absorption and translocation by the crop. Activated charcoal has a high adsorptive capacity because of its extremely large surface area and may either be broadcasted or applied as narrow band over the seed at the time of planting. Yelverton *et al.* (1992) reported that the application of activated carbon 8 and 18 kg /ha to the tobacco along with imazaquin and chlorimuron reduced the phytotoxicity besides increasing the yield from two to four fold.

Table 6. Biochars and herbicide dissipation in soil

Herbicide	Finding	Reference
Atrazine	A lag phase of 11 days in the dissipation of atrazine in the non-amended and biochar amended silt loam soil. Later, dissipation was greater in the unamended soil.	Spokas *et al.* (2009)
Atrazine	Increase in the degradation in a clay soil adapted to atrazine, and amended with biochar and attributed to the stimulation of the soil microflora by the nutrients provided by biochar.	Jablonowski *etal.* (2010)
Acetochlor	Amending soil with biochar resulted in a DT_{50} of 34.5 days	Spokas *et al.* (2009)
Isoproturon	Biochar amendment increased the isoproturon persistence in soil with the DT_{50} of 2.2 days in the unamended soil to 5.6 days in the 2% (w/w) biochar amended soil.	Soperia *et al*. (2010)
Atrazine and trifluralin	Decreased bioavailability of the chemicals by the wheat straw biochar. Hence, choosing the appropriate application rates for biochar amended soils is essential.	Nag *et al.* (2011)
Pyrazosulfuron-ethyl	Biochar (0.5%) amendment did not have significant effect on herbicide degradation. Half-life values in the control, 0.5% biochar amended and rice planted soils were 7, 8.6, and 10.4 days, respectively.	Manna and Singh(2015)
Fluometuron and MCPA	Not all biochar amendments will increase sorption and decrease leaching of fluometuron and MCPA. The amount and composition of the organic carbon (OC) content of the amendment, especially the soluble part (DOC), can play an important role in the sorption and leaching of these herbicides. Biochar and surface area are other important parameters to be considered for sorbent election.	Cabrera *et al.* (2011)
MCPA	Enhanced MCPA persistence and soil toxicity in sandy soil amended with straw biochar. Also, significantly more MCPA remained after 100 days if amended with straw-derived biochar in comparison to wood-derived biochar.	Muter *et al.* (2014)

Biochar addition: Application of biochar is also a very good option to temporarily immobilize the herbicide residues in soil and allow the crop to escape from toxicity. The source of material used for biochar production also affects the sorption of herbicide residues. Biochar additions, even in small quantity, increased diuron sorption. Thus, the presence of carbonaceous material, even in small amounts, can dominate sorption of organic compounds in soils (Cabrera and Spokas 2011). Similar results were obtained by Yu *et al.* (2010) for the sorption of pyrimethanil on the same soil and using the same amendments at similar rates.The influence of biochar and its sources on herbicide dissipation is presented in table 6.

Use of safeners: Herbicide safeners are a group of structurally diverse synthetic chemicals with the unique ability to protect crop plants from injury by certain herbicides (Farago *et al.* 1994). They are used commercially to improve herbicide selectivity between crops and weed species and can be either as a mixture with the herbicide (Table 7) or as a seed treatment to the crop seed prior to sowing. They act as *"bioregulators"* controlling the amount of a given herbicide that reaches its target site in an active form. A safener-induced enhancement of the metabolic detoxification of herbicides in protected plants is the most apparent mechanism for the action of all commercialized safeners. Herbicide-detoxifying enzymes such as glutathione transferases (GST), cytochrome P-450 monooxygenases (Cyt P450), esterases, and UDP-glucosyltransferases are induced by herbicide safeners. At the molecular level, safeners appear to act by activating or amplifying genes coding for these enzymes like GST (Hatzios and Wu 1996).

Reducing the availability of herbicides in soil

Use of optimum and reduced dose of herbicide: The indiscriminate use of herbicides leaves behind residues in food and produce. Hence, the hazards of herbicide residues can be minimized by the application of chemicals at the least possible dosage by which the desired weed control is achieved. Applying herbicides in bands rather as broadcast will reduce the total amount of herbicide to be applied. This will be practicable in line sown crops or crops raised along ridges, such as cotton, sugarcane, sorghum, maize etc. Several workers have been reported that the optimum dose of herbicides did not leave any residues in soil grown with different crops. Jayakumar and Mohammed Ali (1984) reported that the recommended dose of atrazine and 2,4-D did not persist in soil and confirmed through growing the sensitive crops like finger millet, sunflower etc. Shanmugasundram *et al.* (2005a) observed that more than 90% of the applied atrazine degraded from the sugarcane grown soil on 90th day at 2.0 kg/ha while it took 180 days at 5.0 kg/ha. The influence of quantity of application on the persistence and dissipation of herbicides like metsulfuron, imazethapyr, metamifop, oxyfluorfen, metamitron, atrazine, pendimethalin, metribuzin, metolachlor, pretilachlor, alachlor etc in different soils under various situations were reported by many researchers (Janaki *et al.* 2009, 2010b, 2012a, 2012b, 2013a, 2013b, 2015; Sondhia 2009, 2013). They found that the increase in quantity of application increased the residue and persistence of herbicides in soil irrespective of locations and soil types.

Use of herbicides in combination and split doses: The use of herbicides in combinations can reduce the rates of application of highly persistence molecules in soil and in turn reduced their concentration. Similarly, applying herbicide in splits will reduce the amount of herbicide available to runoff at any one given time. Kalaichelvi *et al.* (2010) reported that the tankmix application of chlorimuron-ethyl (Kloben 25% WP) + quizalofop-P-tefuryl (Pantera 4.41% EC) + 0.2% surfactant at 9 + 40 g a.i./ha had a satisfactory weed control and did not have severe phytotoxicity symptom on soybean crop. Further, this combination did not have any residual effect on succeeding crops. Janaki *et al.* (2010c) reported that the split application of metamitron for sugarbeet weeds, reduced the persistence time of that herbicide in soil when compared to single application. Similarly, the split application of ethofumesate for weed control in sugar beet increased the dissipation of it with the DT_{50} values to 5.2 days as against 7.5 days under single application (Janaki *et al.* 2014). Punia and Yadav (2014) reported that the use of 1% ammonium sulphate as surfactant with the post-emergence application of pinoxaden 40 g/ha at 35 DAS and carfentrazone 25g/ha at 42 DAS enhances the weed control efficiency and yield of wheat without any phytotoxic injury.

Method and time of application: Band application is the process by which herbicide is applied in a narrow band varying in width. In the area in-between the treated bands, weed control is maintained through mechanical cultivation (Hansen *et al.* 2000). Applying atrazine in a narrow band in crop rows is an effective method of reducing the total amount of atrazine applied. One or more well-timed cultivations are necessary to prevent inter-row weeds from establishing and competing with the crop. Both the pre-emergence and post-emergence herbicides may be applied in the band.

Alternative use of herbicides: Avoid repeated use of herbicides with similar modes of action to reduce the potential development of herbicide resistance. Shanmugasundaram *et al*. (2005b) found that the rotational use of butachlor with pretilachlor along with 2,4-D as a POE for rice-rice cropping system for four years did not leave the residue of any herbicides in soil at the time of harvest.

Match rates to weed infestation levels and using suitable formulations: In many fields, most weeds are clustered, with as much as 70-90% of the land having very few weeds. At harvest it is possible to map these areas, so herbicide can be applied only where needed. Rate and site specific technology, although in the developmental stages, will enable adjustment of herbicide rates according to soil organic matter, soil pH, soil texture, and weed type and location within a field. Cuevas *et al*. (2007) found a high persistence and low mobility of lenacil in a clayey soil in southwest Spain, where lenacil residues in top layer were detected even after 60 days of herbicide application. Grey and Webster (2013) compared the EC to microencapsulated (ME) pendimethalin formulation in controlling the weeds in cotton crop and found that the ME formulation consistently reduced cotton injury, either as spray or fertilizer impregnated application. Hence, by utilizing the ME formulation, supplementing, or even delaying pendimethalin application to in-season timings impregnated on fertilizer, growers could extend residual weed control until cotton can develop canopy and suppress weed growth. While pendimethalin has lower volatilization than other dinitroaniline herbicides such as trifluralin (Savage and Jordan 1980), the ME formulation decreases volatilization and provides extended activity. This has been observed with another ME formulated herbicide, alachlor (Vasilakoglou and Eleftherohorinos 1997).

Table 7. Commonly used herbicide safeners

Safners	Crop	Herbicide	Application method	References
Naphthalic anhydride	Maize	Thiocarbamate	Seed treatment	Hatzios (1983), Parker (1983), Stephenson and Ezra (1983)
Naphthalic anhydride	Maize	Phenylcarbamates, Dithiocarbamates, Chloroacetanilides, Sulfonylureas, Imidazolinones, Cyclohexenones, Arylophenoxyalkanoic acids	Seed treatment	Hatzios (1983), Parker (1985)
Naphthalic anhydride	Maize, Oats	Chlorsulfuron, Diclofop-methyl	Seed treatment	Parker (1983)
Dichlormid	Maize	Tthiocarbamate herbicides	Seed dressing	Pallos *et al.* (1977), Stephenson and Chang (1978)
Dichlormid	Maize	Chloroacetanilide herbicides, Sethoxydim, Clomazone	Seed dressing	Leavitt and Penner (1978), Hatzios (1984), Devlin and Koszanski (1987a,b)
Dichlormid	Wheat	Diallate	Seed dressing	Mullison (1979)
Substituted N-Dichloroacety1-1,3 oxazolidines	Maize	Thiocarbamate herbicides	Seed dressing	Dutka and Komives (1987), Gorog *et al.* (1982), Hatzios (1983)
Oxime ether	Grain Sorghum	Chloroacetanilide herbicides	Seed dressings	Chang and Merkle (1982, 1983)
Benoxacor	Maize	Metolachlor	Spray as mixture with herbicide	Sankaran *et al.* (1993)
Cloquintocet-mexyl	Wheat	Clodinafop-progaryl	Spray as mixture with herbicide	Sankaran *et al.* (1984)
Cyometrinil	Sorghum	Metolachlor	Seed treatment	Turner *et al.* (1982)
Fenclorim	Rice	Pretilachlor	Spray as mixture with herbicide	Pyon (1986), Quadranti and Ebner (1984)
Flurazole	Sorghum	Alachlor, Acetochlor, Thiocarbamate	Seed treatment	Schafer *et al.* (1981), Ketchersid and Merkle (1985)
Fluxofenim	Sorghum	Metolachlor	Seed treatment	Rao (2000)
Flurazole	Cereals	Halosulfuron-methyl	Spray as mixture with herbicide	Hatzios and Hoagland (1989)
Mefenpyrdiethyl	Wheat, Rye, Triticale, Barley	Fenoxaprop-ethyl	Spray as mixture with herbicide	Hatzios and Hoagland (1989)
Oxabetrinil	Sorghum	Metolachlor	Seed treatment	Hatzios and Hoagland (1989)

Based on the history of weed flora and soil type, the herbicide application rate may be increased or decreased. Many times, if field preparation is done well, the weed flora competition at initial period won't be there, hence the pre-emergence herbicides and dose must be chosen in such a way that it can control the late emerging weeds also. Kanagam *et al*. (2005) reported that later emerging weeds in ground nut can be managed with the application of either metolachlor or fluchloralin 1.0 kg/ha.

Removal from site of contamination

Phytoremediation: The *in situ* use of vegetation in bioremediation schemes is termed as phytoremediation which is an emerging technology for the cleanup of contaminated environments such as soil, water and sediments. Different tolerant plants are planted at the contaminated sites which uptake the main pollutant along with other nutrients and thus changing the soil chemistry and increases microbial activity. Success of phytoremediation technique mainly depends upon the selection of proper tolerant plant and suitable soil (Arthur and Coats 1998). Rice and Sikka (1973) observed atrazine (^{14}C) removal of about 59% by submerged aquatic plant. Poplar trees seemed to be effective in the rapid assimilation of ring leveled atrazine (90%) from sandy soil in less than 9 days (Burken and Schnoor 1996) whereas, in clayey soil the assimilation was very poor. Similarly, transgenic poplars, over expressing ã-glutamylcysteine synthetase (ãECS), could be used for phytoremediation of herbicides due to the increased GSH levels. The suitability of poplars for phytoremediation of soils artificially contaminated with the chloroacetanilide herbicides, acetochlor or metolachlor was studied by Gullner *et al*. (2001) and found that the transgenic plants showed increased herbicide tolerance, due to elevated endogenous ã-ECS and GSH levels, resulting in rapid herbicide degradation.

Future research needs

In India, most of the research has been done pertinent to cultural and mechanical management of herbicide residues in soil and to some extent on the split application or rotational use of herbicides. However, the research works on the deactivation of herbicides utilizing the various organic sources; enhancing the degradation by biostimulation and removal of contaminants from the site using the phytoremediation techniques are scanty or nil. Similarly, the effect of crop residues on the behavior of herbicide residues in soil and environment is also very little. Hence, extensive site specific field studies will be essential to develop holistic measures for the management of herbicide residue in soil environment.

Conclusions

Herbicides have been identified as an indispensable part of the crop production programme. However, to sustain the soil environment, the indiscriminate use of them should be avoided. While using herbicides, all the prevention and management aspects should be kept in mind for huge harvest as well as for quality food production without deteriorating the environment. Hence, integrating the mechanical and cultural management practices with herbicides for managing weeds is a viable option. The combination of bioaugmentation and biostimulation along with organic matter addition might be a promising technology to accelerate the biodegradation. Although it requires extensive field evaluation studies, biostimulation in conjunction with other tools like crop rotation and increasing the organic matter content is definitely a promising technique for managing the herbicide persistence and residue in the soil.

REFERENCES

Abdelhafid R, Houot S and Barriuso E. 2000. How increasing availabilities of carbon and nitrogen affect atrazine behavior in soils. *Biology and Fertility of Soils* **30**(4): 333– 340.

Alletto L, Coquet Y, Benoit P, Djilali H and Barriuso E. 2009. Tillage management effects on pesticide fate in soils - A review. *Agronomy for Sustainable Development* **30**: 367–400.

Arora A. 2014. Evaluation of leaching behavior of oxyfluorfen in FYM amended and un-amended sandy clay loam soil, pp. 276. In: Proceedings of the Biennial Conference of Indian Society of Weed Science on Emerging Challenges in Weed Management, 15-17 February, 2014. Directorate of Weed Science Research, Jabalpur.

Arthur EL and Coats JR. 1998. Phytoremediation, pp. 251-283. In: Pesticide Remediation in Soils and Water. Eds. P. Kearney and T. Roberts. John Wiley & Sons Ltd., Chichester, U.K.

Assaf NA and Turco RF. 1994. Influence of carbon and nitrogen application on the mineralization of atrazine and its metabolites in soil. *Pesticide Science* **41**(1): 41–47.

Bauer WD and Schefcik M. 1994. Using differential GPS to improve crop yields. *GPS World* **5**(2): 38-41.

Bayer DE. 1967. Effect of surfactants on leaching of substituted urea herbicides in soil. *Weeds* **15**(1): 249-252.

Bichat F, Sims GK and Mulvaney RL. 1999. Microbial utilization of heterocyclic nitrogen from atrazine. *Soil Science Society of America Journal* **63**(1): 100–110.

Bresnahan GA, Koskinen WC, Dexter AG and Lueschen WE. 2000. Influence of soil pH sorption interactions on imazethapyr carryover. *Journal of Agricultural and Food Chemistry* **48**(5): 1929-1934.

Brown BA, Hayes RM, Tyler DD and Mueller TC. 1994. Effect of tillage and cover crop on fluometuron adsorption and degradation under controlled conditions. *Weed Science* **42**: 629–634.

Burken JG and Schnoor JL.1996. Phytoremediation: plant uptake of atrazine and role of root exudates. *Journal of Environmental Engineering* **123**(11): 958-963.

Buyuksonmez F, Rynk R, Hess TF and Bechinski E. 1999. Occurrence, degradation and fate of pesticides during composting part I: composting, pesticides, and pesticide degradation. *Compost Science & Utilization* **7**(4): 66–82.

Cabrera D, Lopez-pineiro A, Albarran A and Pena D. 2010. Direct and residual effects on diuron behaviour and persistence following two-phase olive mill waste addition to soil. *Geoderma* **157**(3/4): 133–141.

Cabrera MA and Spokas KA. 2011. Impacts of biochar (black carbon) additions on the sorption and efficacy of herbicides, pp. 315-340. In: Herbicides and Environment. Ed. A. Kortekamp. In Tech: Rijeka, Croatia.

Cabrera MA, Cox L, Spokas KA, Celis R, Hermosin MC, Cornejo J and Koskinen WC. 2011. Comparative Sorption and leaching study of the herbicides fluometuron and 4-chloro-2-methylphenoxyacetic acid (MCPA) in a soil amended with biochars and other sorbents. *Journal of Agricultural and Food Chemistry* **59**: 12550–12560.

Chang TS and Merkle MG. 1982. Oximes as seed safeners for grain sorghum (*Sorghum bicolor* L.) to herbicides. *Weed Science* **30**: 70–73.

Chinnusamy C, Prabhakaran NK, Janaki P and Govindarajan K. 2008. Compendium on Weed Science Research in Tami Nadu (25 years). Dept. of Agronomy, TNAU, Coimbatore. 220 p.

Chinnusamy C, Janaki P, Muthukrishnan P and Jeyaraman S. 2012. Long term herbicidal weed management integrated with nitrogen nutrient in transplanted rice-rice cropping system of Tamil Nadu, India. *Pakistan Journal of Weed Science Research* **18**: 95-103.

Cobucci T, Prates HT, Falcao CLM and Rezende MMV. 1998. Effect of imazamox, fomesafen and acifluorfen soil residues on rotational crops. *Weed Science* **46**: 258-263.

Couto MNPFS, Monteiro E and Vasconcelos MTSD. 2010. Mesocosm trials of bioremediation of contaminated soil of a petroleum refinery: comparison of natural attenuation, biostimulation and bioaugmentation. *Environmental Science and Pollution Research* **17**(7): 1339–1346.

Cull RH, Hunter H and Hunter M. 2000. Application of vetiver grass technology in off-site pollution control. II. Tolerance of vetiver grass towards high levels of herbicides under wetland conditions, pp. 407-410. In: Proceedings of the Second International Conference on Vetiver. Office of the Royal Development Projects Board, Bangkok.

Curran WS. 2001. Persistence of herbicides in soil. Agronomy Facts 36. Published by Penn State College of Agricultural Sciences research and extension programs. Available online at http://extension.psu.edu/pests/weeds/control/persistance-of-herbicides-in-soil/extension_publication_file.

Cuevas MV, Cox L, Calderon MJ, Hermosin MC and Fernandez JE. 2007. Chloridazon and lenacil dissipation in a clayey soil of the Guadalquivir river marshes (southwest Spain). *Agriculture Ecosystems and Environment* **124**(3-4): 245-251.

Dao TH. 1991. Field decay of wheat straw and its effects on metribuzin and S-ethyl metribuzin sorption and elution from crop residues. *Journal of Environmental Quality* **20**(1): 203.

De Lipthay JR, Sorensen SR and Aamand J. 2007. Effect of herbicide concentration and organic and inorganic nutrient amendment on the mineralization of mecoprop, 2,4-D and 2,4,5-T in soil and aquifer samples. *Environmental Pollution* **148**(1): 83–93.

De Lorenzo V. 2008. Systems biology approaches to bioremediation. *Current Opinion in Biotechnology* **19**(6): 579–589.

Devlin RM and Koszanski ZK. 1987a. R-25788 as an antidote for SC-0774 in corn. In: Proceeding on Annual Meeting of Northeast Weed Science Conference. **41**: 74-77.

Devlin RM and Koszanski ZK. 1987b. Effect of FMC-57020 on plant growth and pigment synthesis. In: Proceeding on Annual Meeting of Northeast Weed Science Conference. **41**: 95-99.

Durga Devi KM, Muthukannan M, Abraham CT and Kochurani Kurian, pp. 293-295. 2005. Persistence of herbicides in rice-rice cropping system. In: Proceedings of National Biennial Conference of ISWS6-9 April, 2005. PAU, Ludhiana.

Dutka F and Komives T. 1987. MG-191: a new selective herbicide antidote, pp. 201–204. In: Pesticide Science and Biotechnology. Eds. R. Greenhalgh and T.R. Roberts. Blackwell Scientific Publications, Oxford.

Farago S, Brunold C and Kreuz K. 1994. Herbicide safeners and glutathione metabolism. *Physiologia Plantarum* **91**: 537–542.

Felsot AS and Dzantor EK. 1990. Enhancing biodegradation for detoxification of herbicide waste in soil. *ACS Symposium Series* **426:** 249–268.

Felsot AS and Dzantor EK. 1997. Potential of biostimulation to enhance dissipation of aged herbicide residues in land-farmed waste, pp. 77–91. In: Phytoremediation of Soil and Water Contaminants. Eds. E. L. Kruger, T. A. Anderson, and J. R. Coats. 1997.

Gan J, Becker RL, Koskinen WC and Buhler DD. 1996. Degradation of atrazine in two soils as a function of concentration. *Journal of Environmental Quality* **25**(5): 1064–1072.

Gorog K, Muschinek G, Mustardy LA and Faludi-Daniel A. 1982. Comparative studies of safeners for prevention of EPTC injury in maize. *Weed Research* **22**: 27-33.

Gaston LA and Locke MA. 2000. Acifluorfen sorption, degradation and mobility in a Mississippi delta soil. *Soil Science Society of America Journal* **64**(1): 112.

Gaston LA, Boquet DJ and Bosch MA. 2001. Fluometuron wash-off from cover crop residues and fate in a loessial soil. *Soil Science* **166**: 681–690.

Grey T and Webster T. 2013. Cotton (*Gossypium hirsutum* L.) Response to pendimethalin formulation, timing, and method of application, pp. 26-46. In: Herbicides - Current Research and Case Studies in Use. Available online at http://dx.doi.org/10.5772/56184.

Gullner G, Komives T and Rennenberg H. 2001. Enhanced tolerance of transgenic poplar plants over expressing g-glutamylcysteine synthetase towards chloroacetanilide herbicides. *Journal of Experimental Botany* **52**(358): 971-979.

Hager A, Sprague C and McGlamery M. 2000. Factors Affecting Herbicide Persistence, pp. 323-326. In: Illinois Agricultural Pest Management Handbook. Available online at http://web.aces.uiuc.edu/vista/pdf_pubs/iapm2k/chap20.pdf.

Hall FR, Chapple AC, Downer RA, Kirchner LM and Thacker JRM. 1993. Pesticide application as affected by spray modifiers. *Pest Management Science* **38**: 123-133.

Hance RJ. 1973. The effect of nutrients on the decomposition of the herbicides atrazine and linuron incubated with soil. *Pest Management Science* **4**(6): 817–822.

Hang S, Andriulo A, Sasal C, Nassetta MM, Portela S and Canas AI. 2010. Integral study of atrazine behavior in field lysimeters in argentinean humid pampas soils. *Chilean Journal of Agricultural Research* **70**(1): 104-112.

Haskins B. 2012. Weed management using pre-emergent herbicides in conservation farming systems. NSW Department of Primary Industries, Department of Trade and Investment, Regional Infrastructure and Services 2012. (ISBN 978 1 74256 278 0).

Hatzios KK. 1983. Herbicide antidotes: Development, chemistry and mode of action. *Advances in Agronomy* **36**: 265–316.

Hatzios KK and Hoagland RE. 1989. Crop safeners for herbicides: development, uses, and mechanisms of action. Academic Press, London (ISBN: 978-0-12-332910-8).

Hatzios KK. 1984. Biochemical and physiological mechanisms of herbicide antidotes, pp. 7–30. In: Biochemical and Physiological Mechanism of Herbicide Action. Ed. S.O. Duke.Tallahassee, Florida.

Hatzios KK and Wu J. 1996. Herbicide safeners: Tools for improving the efficacy and selectivity of herbicides. *Journal of Environmental Science and Health, Part B: Pesticides, Food Contaminants, and Agricultural Wastes* **31**(3): 545-553.

Jablonowski ND, Hamacher G, Accinelli C, Berns AE, Meng F, Martinazzo R, Langen U, Walraf C, Linden A and Burauel P. 2010. Influence of biochar and activated char amendment on the biodegradation of 14C-atrazine in atrazine adapted soils from Belgium and Brazil. In: Setac Europe 20th Annual Meeting, Seville, May 2010.

Jacques ML and Harvey RG. 1979. Adsorption and diffusion of dinitroaniline herbicides in soils. *Weed Science* **27**(4): 450–455.

Janaki P, Meena S, Chinnusamy C and Muthukrishnan P. 2009a. Long term application of herbicides on its fate and persistence behavior in the soil under rice-rice cropping system: effect of nitrogen sources, pp. 133. In: Proceedings of the National Symposium on Weed Threat to Environment, Biodiversity and Agriculture Productivity, 2-3 August, 2009, TANU, Coimbatore.

Janaki P, Meena S and Chinnusamy C. 2009b. Persistence and degradation of herbicides in Rrice, maize and soybean grown vertisols of Tamil Nadu, Southern India. In: Proceedings of the 2nd International Conference on Novel and Sustainable Weed Management in Arid and Semi-Arid agro Ecosystem, 7-10 September, 2009, Santorini, Athens, Greece. Available online at http://slideplayer.com/slide/3843757/.

Janaki P, Chinnusamy C, Meena S and Shanmugasundaram R. 2010a. Persistence and degradation behavior of butachlor and 2,4-D in rice soil under continuous and rotational use: Effect of nitrogen sources and seasons, pp. 3817. In: Proceedings of International Rice Research Conference, 8-12 November, 2010, Hanoi, Vietnam.

Janaki P, Rathika S, Vellaikumar R, Prabhakaran NK and Chinnusamy C. 2010b. Persistence and residue of ethofumesate and metamitron herbicides in sugar beet grown soil, pp. 240-241. In: Proceedings of National Conference on Challenges in Weed Management in Agro-Ecosystems-Present Status and Future Strategies.

Janaki P and Chinnusamy C. 2012a. Determination of metamifop residues in soil under direct-seeded rice. *Toxicological and Environmental Chemistry* **94**(6): 1043-1052.

Janaki P, Meena S and Chinnusamy C. 2012b. Field dissipation of herbicides under different crops in tamil nadu. *Madras Agricltural Journal* **99**(10-12): 794-798.

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

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

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

Janaki P and Mohana Sundram H. 2014a. Sorption of pyrazosulfuron-ethyl in different soils of Tamil Nadu, pp. 278. In: Proceedings of the Biennial Conference of Indian Society of Weed Science on *Emerging Challenges in Weed Management*. 15-17 February, 2014. Directorate of Weed Science Research, Jabalpur.

Janaki P, Chinnusamy C, Radhika S, Prabhakaran NK and Senthil K. 2014. Field dissipation of ethofumesate under different methods of application in sugar beet field, pp. 285. In: Proceedings of the Biennial Conference of Indian Society of Weed Science on *Emerging Challenges in Weed Management*. 15-17 February, 2014. Directorate of Weed Science Research, Jabalpur.

Janaki P, Mohana Sundram K, Chinnusamy C and Sakthivel N. 2015. Determination of residues of metribuzin in soil and sugarcane by QuEChERS. *Asian Journal of Chemistry* **27**(10): 3692-3696.

Jaya M, Singh SB, Kulshrestha G and Arya S. 2014. Microbial degradation of alachlor using a native fungal strain, pp. 279. In: Proceedings of the Biennial Conference of Indian Society of Weed Science on *Emerging Challenges in Weed Management*. 15-17 February, 2014. Directorate of Weed Science Research, Jabalpur.

Jayakumar A and Mohamed Ali. 1984. Response of cucumber, fingermillet, foxtail millet and sunflower to soil residues of atrazine and 2,4-D. *Indian Journal of Weed Science* **16**: 133-135.

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

Kalaichelvi K, Janaki P, Chinnusamy C and Muthukrishnan P. 2010. Bio-efficacy evaluation of early POE tank-mix application of kloben 25% WP + Pantera 4 % EC on weed control in soybean and its residual effect on succeeding crops, pp.181-182. In: Proceedings of National Conference on Challenges in Weed Management in Agro-Ecosystems-Present status and Future Strategies.

Kanagam P, Chinnamuthu CR, Chinnusamy C and Shanmugasundram R. 2005. Screening of pre-emergence herbicides for managing the late emerging weeds (LEW) in irrigated groundnut, pp. 99-100. In: Proceedings of National Biennial Conference of ISWS, 6-9 April, 2005, PAU, Ludhiana.

Kanissery RG and Sims GK. 2011. Biostimulation for the enhanced degradation of herbicides in soil. *Applied and Environmental Soil Science* (doi:10.1155/2011/843450). Available online at http://dx.doi.org/10.1155/2011/843450

Ketchersid ML and Merkle MG. 1985. R-30228 as a safener for sorghum against thiocarbamate herbicides. *Proceedings of South Weed Science Society* **38**:439.

Koch B and Khosla R. 2007. The role of precision agriculture in cropping systems. *Journal of Crop Production*. **9**: 361-381.

Kucharski M. 2003. Influence of herbicide and adjuvant appli-cation on residues in soil and plant of sugar beet. *Journal of Plant Protection Research* **43**(3): 225–232.

Kucharski M and Sadowski J. 2009a. Influence of adjuvants on behavior of phenmedipham in plant and soil environment. *Polish Journal of Agronomy* **1**(1): 32-36.

Kucharski M and Sadowski J. 2009b. Degradation of ethofumesate in soil under laboratory conditions. *Polish Journal of Environmental Studies* **18**(2): 243–247.

Kucharski M, Sadowski J, Wujek B and Trajdos J. 2011. Influence of adjuvants addition on lenacil residues in plant and soil. *Polish Journal of Agronomy* **5**(5): 39-42.

Kucharski M, Sadowski J and Domaradzki K. 2012. Degradation rate of chloridazon in soil as influenced by adjuvants. *Journal of Plant Protection Research* **52**(1): 114-117.

Kurt DN, Siemens MC and Sanchez PA. 2011. Integrating variable rate technologies for soil-applied herbicides in Arizona vegetable production. Available online at www.cals.arizona.edu/pubs/crops/az1538.pdf.

Leavitt JR and Penner D. 1978. Prevention of EPTC induced epicuticular wax aggregation on corn (*Zea mays* L.) with R-25788. *Weed Science* **26**: 47–50.

Levanon DJ, Meisinger J, Codling EE and Starr JL. 1994. Impact of tillage on microbial activity and the fate of pesticides in upper soil. *Water Air Soil Pollution* **72**: 179–237

Locke MA and Zablotowicz RM. 2003. Pesticides in soil: benefits and limitations to soil quality, pp. 239–260. In: Managing Soil Quality. Eds. P. Schjonning, B.T. Christenson, S. Elmholt. C.A.B.I., Oxon, UK.

Loss MA. 1975. In: Herbicides: Chemistry, Degradation and Mode of Action. Eds. P.C. Kearney and D.D. Kaufman. Vol. I. Marcel Dekker Inc., New York.

Lovell ST, Sims GK and Wax LM. 2002. Degradation of isoxaflutole in soil. *Journal of Agricultural and Food Chemistry* **50**(20): 5626–5633.

Mandelbaum RT, Wackett LP and Allan DL. 1993. Mineralization of the s-triazine ring of atrazine by stable bacterial mixed cultures. *Applied and Environmental Microbiology* **59**(3): 1695-1701.

Manna S and Singh N. 2015. Effect of wheat and rice straw biochars on pyrazosulfuron-ethyl sorption and persistence in a sandy loam soil. *Journal of Environmental Science and Health, Part B: Pesticides, Food Contaminants, and Agricultural Wastes* **50**(7): 463-472.

McBain ADK, Senior E, Paterson A, du Plessis CA and Watson-Craik IA. 1997. Bioremediation of 4-chloro-2-methylphenoxyacetic acid (MCPA)-contaminated soil: microcosm and pilot field studies. *South African Journal of Science* **93**(5): 226–230.

McGhee I and Burns RG. 1995. Biodegradation of 2,4-dichlorophenoxyacetic acid (2,4-D) and 2-methyl-4-chlorophenoxyacetic acid (MCPA) in contaminated soil. *Applied Soil Ecology* **2**(3): 143–154.

Meena S, Chinnusamy C and Varsney JG. 2007. Status report on herbicide residue. Dept. of Agronomy, TNAU, Coimbatore.1-30 p.

Mickelson SK, Anton S, Baker JL and Ahmed SI. 2001. Subsurface herbicide application with the modified John Deere mulch master. *Transactions of the ASAE* **44**(4): 807–812.

Mukherjee I. 2009. Effect of organic amendments on degradation of atrazine. *Bulletin of Environmental Contamination and Toxicology* **53**(6): 832–835.

Mukherjee I, Gopal M and Das TK. 2005. Soil remediation by use of soil amendment, pp. 313-314. In: Proceedings of National Biennial Conference of Indian Society of Weed Science, 6-9 April, 2005, PAU, Ludhiana.

Mukherjee K. 2011. http://www.reuters.com/article/2011/02/24/india-herbicides-idUKSGE71N04220110224.

Muter O, Berzins A, Strikauska S, Pugajeva I, Bartkevics V, Dobele G, Truu J, Truu M and Steiner C. 2014. The effects of woodchip- and straw-derived biochars on the persistence of the herbicide 4-chloro-2-methylphenoxyacetic acid (MCPA) in soils. *Ecotoxicology and Environmental Safety* **109**: 93-100.

Nag SK, Rai Kookana, Smith L, Krull E, Lynne M, Macdonald and Gill G. 2011. Poor efficacy of herbicides in biochar-amended soils as affected by their chemistry and mode of action. *Chemosphere* **84**(11): 1572-1577.

Nalini K, Muthukrishan P, Chinnusamy C and Janaki P. 2010. Pre-emergence herbicide pendimethalin residue in cotton cultivated soil, pp. 189.In: Proceedings of the Biennial Conference of Indian Society of Weed Science on Recent Advances in Weed Science Research, 25-26 February, 2010, Indira Gandhi Krishi Vishwa Vidyalaya, Raipur.

Olson BLS, Regehr DL, Janssen KA and Barnes PL. 1998. Tillage system effects on atrazine loss in surface water runoff. *Weed Technology* **12**: 646- 651.

Pallos FM, Gray A, Arneklev DR and Broke ME. 1977. Antidotes protect corn from thiocarbamate herbicides injury, pp. 15–20. In: Chemistry and Action of Herbicide Antidote. Eds. F.M. Pallos and J.E. Casida. Academic Press, New York.

Parker C. 1983. Herbicide antidote. A review. *Pest Management Science* **14**: 40–48.

Patel RB, Patel BK and Barevadia TN. 1996. Minimization of herbicide residues through farmyard manure in soil. *Weed News* **3**(1-2): 15–17.

Perrin-Ganier C, Schiavon F, Morel JL and Schiavon M. 2001. Effect of sludge-amendment or nutrient addition on the biodegradation of the herbicide isoproturon in soil. *Chemosphere* **44**(4): 887–892.

Pritchard MK and Stobbe EH. 1980. Persistence and phytotoxicity of dinitroaniline herbicides in Manitoba soils. *Canadian Journal of Plant Science* **60**: 5–11.

Punia SS and Yadav D. 2014. Carfentrazone and pinoxaden with and without surfactant against grasses and broad-leaf weeds in wheat. *Indian Journal of Weed Science* **46**(3): 283–285.

Qiu Y, Pang H, Zhou Z, Zhang P, Feng Y and Sheng GD. 2009. Competitive biodegradation of dichlobenil and atrazine coexisting in soil amended with a char and citrate. *Environmental Pollution* **157**(11): 2964–2969.

Radosevich M, Traina SJ, Hao YL and Tuovinen OH. 1995. Degradation and mineralization of atrazine by a soil bacterial isolate. *Applied and Environmental Microbiology* **61**(1): 297–302.

Ramprakash T, Madhavi M and Yakadri M. 2014. Influence of bispyribac-sodium on soil properties and persistence in soil, plant and grain in direct seeded rice (wet), pp. 281. In: Proceedings of the Biennial Conference of Indian Society of Weed Science on *Emerging Challenges in Weed Management*. 15-17 February, 2014. Directorate of Weed Science Research, Jabalpur.

Randhawa SK, Singh T and Singh S. 2005. Effect of organic matter on the persistence of herbicide in rice-wheat cropping system, pp. 283-284. In: Proceedings of National Biennial Conference of Indian Society of Weed Science, 6-9 April, 2005, PAU, Ludhiana.

Rao VS. 2002. Principles of Weed Science. 2nd edition. Taylor & Francis, 555 p.

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

Reddy KN and Singh M. 1993. Effect of Acrylic polymer adjuvants on leaching of bromacil, diuron, norflurazon, and simazine in soil columns. *Bulletin of Environmental Contamination and Toxicology* **50**(3): 449-457.

Rice CP and Sikka HC. 1973. Fate of dieldrin in selected species of marine algae. *Bulletin of Environmental Contamination and Toxicology* **9**: 116-123.

Rice PJ, Anderson TA and Coats JR. 2002. Degradation and persistence of metolachlor in soil: effects of concentration, soil moisture, soil depth, and sterilization. *Environmental Toxicology and Chemistry* **21**(12): 2640-2648.

Sankaran S, Jayakumar R and Kempuchetty N. 1993. Herbicide residues, pp. 211-224. Gandhi Book House, 218, Cowly Brown Road (West), Coimbatore.

Sathiyavani E. 2014. Evaluation of integrated weed management with pre and post emergence herbicides in turmeric. Ph.D. thesis submitted to Dept. of Agronomy, TNAU, Coimbatore.

Sathiyavani E and Prabhakaran NK. 2014. Performance of pre and post-emergence herbicides on weed flora and yield of turmeric. *Trends in Biosciences* **7**(12): 1350-1353.

Savage KE and Jordan TN. 1980. Persistence of three dinitroaniline herbicides on the soil surface. *Weed Science* **28**: 105-110.

Scow KM and Hicks KA. 2005. Natural attenuation and enhanced bioremediation of organic contaminants in groundwater. *Current Opinion in Biotechnology* **16**(3): 246–253.

Senesi N and Testini C. 1984. Theoretical aspects and experimental evidence of the capacity of humic substances to bind herbicides by charge transfer mechanisms (electron donor acceptor process). *Chemosphere* **13**: 461–468.

Shanmugashundram R, Chinnusamy C, Senthil A and Kandasamy OS. 2005a. Fate of atrazine in sugarcane ecosystem, pp. 292. In: Proceedings of National Biennial Conference of Indian Society of Weed Science, 6-9 April, 2005, PAU, Ludhiana.

Shanmugasundaram R, Kandasamy OS and Chinnusamy C. 2005b. Impact of herbicide application on soil physico-chemical properties and its residue in rice-rice cropping system, pp. 290-291. In: Proceedings of National Biennial Conference of Indian Society of Weed Science, 6-9 April, 2005, PAU, Ludhiana.

Sharma N and Angiras NN. 2003. Estimation of metribuzin residues in wheat fields through bioassay technique. *Crop Research* **26:** 219-220.

Sharma N, Angiras NN and Ruchi. 2006. Dissipation behaviour of butachlor in rice cropped soils of Himachal Pradesh. *Crop Research* **32**(3): 149-152.

Sharma N and Angiras NN. 2004. Effect of organic matter content on persistence of atrazine. *Agricultural Science Digest* **24**: 227-228.

Sharma N and Angiras NN. 1996. Studies on standardization of bioassay technique and its use in estimation of pendimethalin residues in soil under wheat + sarson intercropping system. *Indian Journal of Weed Science* **28**(1&2): 82-84.

Sharma N and Angiras NN. 1996. Residues studies of butachlor in soils of direct seeded upland rice by bioassay technique. *Indian Journal of Weed Science* **28**(1& 2): 98-100.

Sharma N and Savita. 2007. Isoproturon persistence in field soil and its impact on microbial population under North-Western Himalayan conditions. *Pesticide Research Journal* **19**(1)**:** 116-118.

Sharma N, Kumar Suresh, Angiras NN and Sehgal S. 2014. Evaluation of pendimethalin residues in garlic. *Indian Journal of Weed Science* **46**(4): 374–377.

Sharma N, Sharma Swati, Kumar Suresh and Joshi Robin 2013. Dissipation and harvest time residue studies of 2,4-D in soil and wheat crop. *Indian Journal of Weed Science* **45**(1): 68-70.

Bandana, Sharma N, Joshi R, Ashu Gulati and Sondhia S. 2015. Dissipation kinetics of glyphosate in tea and tea-field under northwestern mid-hill conditions of India. *Journal of Pesticide Science* DOI: 10.1584/jpestics.D14-085.

Sims GK. 2006. Nitrogen starvation promotes biodegradation of N-heterocyclic compounds in soil. *Soil Biology and Biochemistry* **38**(8): 2478–2480.

Singh M and Tan S. 1996. Herbicide leaching and its prevention, pp. 297-322. In: Pesticide Formulation and Adjuvant Technology. Eds. C.L. Foy and D.W. Pritchard.CRC Press, Boca Raton, Florida.

Singh M and Walia US. 2005. Studies on carryover effects of sulfosulfuron on the succeeding crops, pp. 300-301. In: Proceedings of National Biennial Conference of Indian Society of Weed Science, 6-9 April, 2005, PAU, Ludhiana.

Singh SB, Lata and Sharma D. 2014. Herbicide residues and their microbial remediation in soil, pp. 35. In: Proceedings of the Biennial Conference of Indian Society of Weed Science on *Emerging Challenges in Weed Management*. 15-17 February, 2014. Directorate of Weed Science Research, Jabalpur.

Sondhia S. 2008. Persistence of metsulfuron-methyl in wheat crop and soil. *Environmental Monitoring and Assessment* **147**(1-3): 463-469.

Sondhia S. 2009. Persistence of metsulfuron-methyl in paddy field and detection of its residues in crop produce. *Bulletin of Environmental Contamination and Toxicology* **83**(6): 799-802.

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

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

Sondhia S. 2014. Herbicides residues in soil, water, plants and non-targeted organisms and human health implications: an Indian perspective. *Indian Journal of Weed Science* **46**(1): 66–85.

Soperia F, Semple K, Sohi S and Bending GD. 2010. Isoproturon bioavailability in soil amended with biocharcoal. In: Setac Europe 20th Annual Meeting, Seville, May 2010.

Spokas K, Koskinen WC, Baker JM and Reicosky DC. 2011. Impacts of wood biochar additions on greenhouse gas production and sorption/degradation of two herbicides in a Minnesota soil. *Chemosphere* **77**: 574–581.

Stephenson GR and Chang FY. 1978. Comparative activity and selectivity of herbicide antidotes, pp. 35-61. In: Chemistry and Action of Herbicide Antidotes. Eds. F.M. Pallos and J.E. Casida. Academic Press, New York.

Stephenson GR and Ezra G. 1983. Use of subtoxic pretreatment to improve crop tolerance to herbicides. *American Chemical Society* **276**: 96–104.

Suzer S and Byuk H. 2010. Residual effects of spraying Imidazolinone-family herbicides on clearfield sunflower production from the point of view of crop rotation. *Helia*, **33**(52): 25-36.

Swarcewicz MK, Mulinsk Z and Zbiec I. 1998. Influence of spray adjuvants on the behavior of trifluralin in the soil. *Bulletin of Environmental Contamination and Toxicology* **60**:569-576.

Tandon 2014. Dissipation of anilofos in soil and its harvest residue analysis in rice, pp. 275. In: Proceedings of the Biennial Conference of Indian Society of Weed Science on *Emerging Challenges in Weed Management*. 15-17 February, 2014. Directorate of Weed Science Research, Jabalpur.

Teasdale JR, Shelton DR, Sadeghi AM and Isensee AR. 2003. Influence of hairy vetch residue on atrazine and metolachlor soil solution concentration and weed emergence. *Weed Science* **51**: 628–634.

Tickes BR and Kerns DL. 1996. Lettuce injury from preplant and herbicides. IPM Series 9. Publ. No. 196007. University of Arizona, College of Agriculture and Life Sciences, Cooperative Extension, Tucson, Arizona. 4 p. Available online at http://valueaddedag.org/crops /vegetables/weeds/ lettuceinjury.html.

Topp E, Tessier L and Gregorich EG. 1996. Dairy manure incorporation stimulates rapid atrazine mineralization in an agricultural soil. *Canadian Journal of Soil Science* **76**(3): 403–409.

Turner C, Clark DR, Helseth W, Dill TR, King J and Seifried EB. 1982. CGA-92194 a new safener to protect sorghum from metolachlor injury. Proc. South. *Weed Science* **35**: 388–390.

Vaishya RD, Srivastava BK and Singh G. 2003. Integrated weed management in summer urdbean. *Indian Journal of Pulses Research* **16**: 161-162.

Vasilakoglou IB and Eleftherohorinos IG. 1997. Activity, adsorption, mobility, efficacy and persistence of alachlor as influenced by formulation. *Weed Science* **45**: 579-585.

Verma S, Lokesh Dubey and Arvind Verma. 2014. Management of weeds under organic farming through conservation agriculture, pp. 318. In: Proceedings of the Biennial Conference of Indian Society of Weed Science on *Emerging Challenges in Weed Management*. 15-17 February, 2014. Directorate of Weed Science Research, Jabalpur.

Walker A. 1980. Activity and selectivity in the field, pp. 203-235. In: *Interactions between Herbicides and the Soil*. Ed. R.J. Hance. Academic Press, New York.

WSSA. 2002. *Herbicide Handbook*, pp. 405-408. Ed. W.K. Vencill. Eighth Edition. Weed Science Society of America, Lawrence, U.S.A.

Yelverton FH, Douglas worsham A and Peedin GF. 1992. Activated carbon reduces tobacco (*Nicotiana tabacum*) injury from soil applied herbicides. *Weed Technology* **6**: 310-316.

Yu XY, Pan LG, Ying GG and Kookana RS. 2010. Enhanced and irreversible sorption of pesticide pyrimethanil by soil amended with biochars. *Journal of Environmental Science* **22**: 615-620.

Zablotowicz RM, Locke MA and Smeda RJ. 1998. Degradation of 2,4-D and fluometuron in cover crop residues. *Chemosphere* **37**: 87–101.

Zablotowicz RM, Locke MA and Gaston LA. 2007. Tillage and cover effects on soil microbial properties and fluometuron degradation. *Biology and Fertility of Soils* **44**(1): 27-35.

Pyon JY. 1986. Effect of 1,8-napthalic anhydride and CGA-123407 on reducing injury of rice in subirrigated seedbed. *Abstract of Weed Science Society of America* **26**:4

Quadranti M and Ebner L. 1984. Sofit, a new herbicide for use in direct –seeded rice (Wet-sowing in rice), pp. 405-412. In*:* Proceedings of Asia-Pacific Weed Science Society Conference, 1983.

Schafer DE, Brinker RJ and Rahdke RO. 1981. Evaluation of the behavior and performance of MON-4606 for alachlor in grain sorghum. *Abstract of Weed Science Society of America* **21**: 26.