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A REVIEW OF WEED MANAGEMENT IN INDIA: THE NEED OF NEW DIRECTIONS FOR SUSTAINABLE AGRICULTURE

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ABSTRACT

Weeds are the major deterrent to the development of sustainable crop production. Since weeds dictate most of the crop production practices and causes enormous losses (37 per cent) due to their interference. Farmers follow several practices for managing weeds in different crops/cropping systems, of which at present the use of herbicides are on the top due to the scarcity of labors. The sustainability of these systems is being questioned because of environmental, social, and economic concerns caused by global competition, production cost, soil erosion, environmental pollution, and concern over the quality of rural life. Enhancing the crop competitiveness through preventive methods, cultural practices, mechanical methods, plant breeding, biotechnology, biological control and crop diversification will be the central thesis in new paradigms of weed management. Integration of above techniques will be key to sustainable weed management that maintain or enhance the crop productivity, profitability and environmental quality. This article explores the scope of sustainable weed management, growing concerns over herbicide resistance, environmental and health hazards of pesticides including herbicides and declining profitability are the major challenges of 'high input' agriculture. The goal of this review is to facilitate the development of ecologically based alternative methods for sustainable weed management that will support crop production systems, which require less tillage, herbicide and other inputs. To accomplish this goal, research efforts must be radically expanded in crop ecology and in the development of ecologically based technologies for weed management. Adoption of sustainable agricultural practices reduces the intensity of soil manipulation thereby creates an unfavorable condition for weed seed germination, reduces the organic matter depletion and soil erosion. Thus, the sustainable approaches could be an option for weed and soil management which leads to sustainable crop production.

INTRODUCTION

As the global population expands, food demands placed on agricultural production systems will test the capabilities of current agriculture practices. Moreover, adequate food production in the future can only be achieved through the implementation of sustainable growing practices that minimize environmental degradation and preserve resources while maintaining high yield and profitability in the cropping systems. This paper illustrates how some peculiar features of sustainable agriculture suggest the need to undertake an efficient approach to manage weeds. It is important to have a long range strategy to help predict and avoid potential weed problems in the future. Effective weed management is critical to maintaining agricultural productivity (Ahmed *et al*., 2010; Verma, 2014). By competing for light, water, space and nutrients, weeds can reduce crop yield and quality and can lead to billions of dollars in global crop losses annually (Das, 2008; Srinivasrao *et al*., 2014). Because of their ability to persist and spread through the multiple reproduction and dispersal of dormant seeds/ vegetative propagules, for this reason weeds are virtually impossible to eliminate from any given field (Singh, 2014; Sharma, 2014). The importance of weed management to successful cropping is demonstrated by the fact that herbicides account for the large majority of pesticides used in agriculture, eclipsing inputs for all other major pest groups (Kewat, 2014). To no small extent, the success and sustainability of our weed management systems shapes the success and sustainability of agriculture as a whole (David *et al*., 2012).

Weeds are an important constraint in agricultural production systems, acting at same tropic level as the crop; weeds capture a part of the available resources that are essential for plant growth (Oerke, 2006; Ryan *et al*., 2009; Smith *et al*., 2010). Inevitably, leaving weeds uncontrolled will sooner or later lead to considerable reductions in crop yield and increase production cost (Sharma, 2014). Manual weed control is labour intensive and therefore limits the production area (Verma *et al*., 2008; Dubey, 2014). In many rural Indian communities it has becomes increasingly difficult to hire labour for weeding and other farming activities, due to a swindling labour force as consequence of outmigration of the male population. As a result farm operations are often delayed and labour costs have increases (Singh *et al*., 2012). The situation calls for labour saving weed management practices for sustainable crop production. Depending on weed type and crop weed competition, it reduces yield up to 96.5 percent and some time total crop failures reported by several researchers given in Table 1.

From the beginning of agriculture until the introduction of herbicides, weed management in agriculture depends largely on crop rotation, tillage and seed cleaning. The increased availability and acceptability of highly effective and selective synthetic herbicides in the decades following World War II diverted the focus of weed researchers and managers away from nonchemical weed management (Upadhyaya and Blackshaw, 2007). In this context, weeds were not considered components of agro-ecosystems and so sustainability issues were easily ignored and preventive or suppressive approaches to weed management were put aside (Rask and Kristoffersen, 2007; Moss, 2008), the lack of research on these options of weed management has made the weeds a serious problem, particularly where chemical weed management was avoided.

Introduction of herbicidal control in the 1940s was one of the major triggers of the intensification of agricultural production systems, most notably characterized by a tremendous increase in labour productivity, but the heavy reliance on chemical weed control is nowadays considered objectionable (Das, 2008). This is first because a heavy reliance implies extensive use of compounds with a potential negative side effect on food safety, public health and the environment. Second, cropping systems with a narrow focus on herbicidal control are becoming increasingly vulnerable, as herbicide resistance are frequently creating situations where part of the weed community can no longer be controlled by chemical means (Kumar, 2014). Finally, the increased interest in organic agriculture calls for alternative solutions for weed management. As a result, number of directions has evolved, of which a more efficient use of herbicides is a first track (Anderson, 2003). This strategy can be implemented through improvements in application technology (Brown *et al.*, 2007), the use of factor adjusted dosages and patch spraying, which enhances efficiency of herbicides and save time (Gerhards and Christensen, 2003). A second strategy is to focus more on alternative curative control technologies, like cultural, biological and mechanical weed control (Singh and Singh, 2006; Das *et al.*, 2012). Preventive and cultural control can be described as any adjustment or modification to the general management of the crop or cropping systems that contributes to the regulation of weed populations and reduces the negative impact of weeds on crop (Dubey, 2014). As options for biological control are limited, a complete reliance on mechanical or agronomical control is undesirable and herbicidal control is prohibited, cultural control seems particularly relevant for organic agriculture. However, despite the existence of a large variety of cultural control measures, weeds are still mentioned as the major production related bottleneck in sustainable agriculture. Also, in conventional agriculture, cultural control has not managed to obtain firm footing, despite the desire to reduce the strong reliance on chemical control. Furthermore sustainability of our food production systems and the health and environmental consequences of pesticide use are rapidly becoming important global issues renewing interest on ecological approaches of weed management.

In the balance of this paper, I will present several areas of research that could facilitate the development of ecologically based methods of weed management and support the development of more sustainable crop production systems. These systems must support a system of agriculture that cover

Table 1: Yield reduction caused by weed in different crops

Name of crops	% Yield reduction	Reference
Direct seeded paddy	45-90	Singh (20140
Transplanted paddy	15-38	Singh (2014)
Maize	28-93	Malviya and Singh (2007); Singh (2014)
Sorghum	6-40	Singh (2014)
Finger millet	26-27	Pradhan *et al.* (2013)
Redgram	20-47	Singh (2014)
Soybean	40-60	Jha and Soni (2013); Singh (2014)
Wheat	26 - 38	Das (2008); Verma *et al.* (2008); Das *et al.* (2012) and Kewat (2014)
Oat	26-30	Kewat (2014)
Lucerne	50-90	Revathi *et al.* (2012)
Barley	20-25	Kewat (2014)
Chickpea	15-25	Kewat (2014)
Lentil	20-30	Kewat (2014)
Pea	20-30	Kewat (2014)
Mustard	15-30	Kewat (2014)
Linseed	30-40	Kewat (2014)
Safflower	35-60	Kewat (2014)
Groundnut	20 - 50	Rathore (2014)
Sesame	50-75	Bhadauria *et al.* (2012); Duary and Hazra (2013);Rathore (2014)
Sun flower	30-64	Sumathi *et al.* (2009); Rathore (2014)
Castor	15-25	Rathore (2014)
Cotton	74-96.5	Ayyadurai and Poonguzhalan (2011)
Niger	30-33	Rathore (2014)
Jute	58-70	Ghorai *et al.* (2013)
Coriander	20-50	Yadav *et al.* (2013)
Sugarcane	40-67	Chauhan and Srivastava (2002); Pratap *et al.* (2013)
Egyptian clover	30-40	Pathan *et al.* (2013)
Brinjal	49-90	Reddy *et al.* (2000); Kunti *et al.* (2012)
Tapioca	40-50	Lebot (2009); Prameela *et al.* (2012)

Table 2: Effect of crop sequences on Phalaris minor population in wheat

Crop sequence	Population of *Phalaris minor* (No/m^2)
Rice-wheat-rice-wheat -rice-wheat	253
Rice-potato-rice-wheat-rice-potato	54
Rice-potato-rice-berseem-rice-winter maize	16
Rice-sugarcane:-sugarcane-ratoon-ratoon-wheat	4
Maize-wheat-rice-wheat -maize-wheat	18
Soybean-wheat -maize-wheat-soybean-wheat	22

Table 3: Effect of crop sequences on Phalaris minor in wheat (Pooled data of three year)

Treatment	Dry matter of *Phalaris minor* (q/ha)	No. of seed/ m^2 in soil	
		Before sowing	After harvest
Rice-Wheat (Herbicide)	2.09	7.8	1.8
Rice-Wheat (Control)	45.5	8.0	10.3
Rice-Potato-Wheat	0.0	0.5	0.0
Rice-Potato-Sunflower	0.0	0.3	0.0
Rice-Berseem	0.0	0.3	0.0
Rice-Gobhi-sarson	0.13	0.8	0.5
CD at 5%	0.40	-	-

the long term improvement in environmental resources such as soil and water, creates a healthful and plentiful food supply, is not harmful to farmer health and fosters a system of agriculture that is supportive of economically viable for rural communities. The main objective of this paper is to outline the reasons for and the potential benefits of tackling sustainable weed management for maximum crop production.

After a reasoned analysis of the literature on this subject published recently along with the description of the following common techniques is given to achieve sustainable weed management including

Preventive methods

Weed prevention embodies all measures to deny the entry and establishment of new weeds in an area not infested with it yet. This can be achieved by use of weed free crop seeds, seed certification, weed laws, and by quarantine laws. In general, spread of weeds within country can be reduced by clean seed laws, cleaning farm equipment and produce, cleaning irrigation water, cleaning sand and gravel and reducing the number of weed seeds returned to the soil (Das, 2008). Introduction of weed in crop field can be prevented by using weed free seed, not using fresh or partially decomposed FYM or compost, proper cleaning of farm machinery before sowing and keeping farm bund and irrigation/drainage channel free from weeds (Verma and Singh, 2008).

Cultural methods

Cultural methods provide competitive advantage to crop against weeds by reducing weed establishment (Singh, 2014), and through selective stimulation, facilitating faster crop growth to smother weeds (Das *et al.*, 2012). Globally, cultural control has been one of the most widely used control options and includes stale seedbed techniques, crop rotation, increase the competitive ability of the crop, time of seeding and irrigation, inclusion of cover crops, and intercropping (Kumar and Rathore, 2014), conscious use of crop interference, use of cropping pattern, and tillage systems (Zimdhal, 2007); employing time, method, rate of sowing, rate of fertilizer, inter and mixed cropping, tolerance cultivars and spacing (Verma and Singh, 2008); smother crop, summer ploughing or following (Dubey, 2014) have carried out for successful weed management.

Stale seedbed technique

In stale seedbed technique, after seedbed preparation, the field is irrigated and left unsown to allow weeds to germinate and which are killed either by a non-selective herbicide or by carrying out tillage prior to the sowing (Singh, 2014). This technique reduces weeds emergence (Singh *et al.*, 2012), delaying early crop-weed competition and also reduces weed seeds bank (Sindhu *et al.*, 2010). The success of stale seedbed depends on several factors like method of seedbed preparation, method of killing emerged weeds, weed species, duration of the stale seedbed, environmental condition (Singh, 2014).

Crop rotation/crop diversification

Rotating crops with different life cycles can disrupt the development of weed crop associations, through different planting and harvest dates preventing weed establishment and therefore weed seed production (Das *et al.*, 2012), mainly by smothering and allopathic effect (Dwivedi *et al.*, 2012). According to Teasdale *et al.* (2004), growing of wheat, maize and soybeans in rotation tends to decrease the weed seed bank and abundance of broadleaf weeds. The shift from rice-wheat to rice-potato, rice-potato-wheat sequence or any other sequence reduced the population Table 2 (Verma and Singh, 2008) and soil seed bank of *Phalaris minor* (Singh and Singh, 2006) and other weeds (Table 3). Singh *et al.* (2012) studied that when rice- wheat cropping system is changed, there is reduction in weed density and weed dry matter production. Rice - wheat- greengram sequence recorded lowest population of all the three groups of weeds followed by rice-wheat, rice-chickpea and rice-pea sequence.

In diversified cropping systems, use of different grain crops, forage legumes as green manure and livestock manure to provide organic sources of nutrients and organic matter that can reduce weeds, by affecting weeds through suppression and the release of allelochemicals or by providing substrates for other organisms that inhibit weed seedling growth and potentially influencing the colonization and decay of weed seeds (Mohler *et al.*, 2012; Gomez *et al.*, 2014).

Sowing/planting time

Sowing time is a nonmonetary input, but greatly affects the crop productivity (Verma and Singh 2008). Early planting provides a competitive edge to adapted crop cultivars (Sindhu *et al.*, 2010) because crop emerged before the weeds and therefore the weeds did not receive sufficient sun light for their emergence and growth (Cici *et al.*, 2008). Whereas, several studies have shown that sowing of rice after onset of monsoon gave higher grain yield and recorded less weed density (Kumar *et al.*, 2012) whereas, late planting of wheat reducing *Phalaris*

Table 4: Effect of cultivars and herbicides on weeds and wheat yield (Mean data of two year)

Treatment	Weed density at 90 DAS (M^2)	Weed dry weight at 90 DAS (g/m^2)	Weed suppressing/WCE (%)	Grain yield (kg/ha)
Varieties				
PBW- 343	193.5	19.8	40.8	3055
NW- 1014	157.6	16.9	51.9	2862
HP- 2733	173.4	18.6	46.1	2978
HP- 1731	201.8	21.9	38.2	2900
K-9107	142.4	15.4	56.4	2888
LSD(P=0.05)	15.2	1.62	-	78.0
Herbicides				
Control	326.4	35.1	0.0	1964
Weed free	0.0	0.0	100.0	3484
Isoproturon (1 kg/ha)	103.3	10.4	68.4	2610
Sulfosulfuron (25g/ha)	69.0	6.4	78.9	2898
Fenoxaprop (100 g/ha)	74.6	6.7	77.2	2825
Pendimethalin (1 kg/ha)	108.5	9.8	67.0	2655
LSD(P=0.05)	24.3	3.0	5.7	242.0

Table 5: Effect of tillage and weed control methods on weeds and yield of maize

Treatment	Weed density (m^2)		Weed dry weight (g/m^2)		Grain yield (kg/ha)
	60 DAS	At harvest	60 DAS	At harvest	
Tillage methods					
Zero tillage	16.5	11.1	11.4	8.7	5799
Conventional tillage	16.1	10.6	11.1	8.5	6779
Raised seed bed	15.3	9.9	9.8	7.7	6595
LSD (P=0.05)	0.5	0.4	0.3	0.4	341
Weed control methods					
Unweeded	21.2	14.8	16.3	11.9	4275
Acetachlor 0.75 kg ai/ha	16.2	11.0	10.8	8.4	6462
Acetachlor 1.25 kg ai/ha	13.5	8.1	8.1	6.4	7339
Atrazine 1.5 kg ai/ha	13.2	8.3	7.8	6.4	7487
LSD (P=0.05)	0.6	0.7	0.3	0.4	300

minor infestation (Das and Yaduraju, 2007).

Cultivars

The role of crop genotype in weed management has received growing attention over the past several years. Competitive cultivar can suppress weed seed production, limit future weed infestation, and become a safe, environmentally benign and low cost tool for weed management (Kumar *et al.*, 2013). The competitive ability of a crop cultivar can be measured both as weed suppression and weed tolerance are important characters for identification of efficient cultivars for weed management (Verma and Singh, 2008). Cultivars within species differ in competitiveness with weeds (Verma *et al.*, 2008). This phenomenon is due to morphological and physiological differences between types and can also interact strongly with environmental factors. The cultivar with faster seedling emergence, canopy establishment, early fast growth, maximum number of leaf, tall stature and more tillering capacity have better competitive ability against weeds Table 4 (Ahmed *et al.*, 2010; Bhan *et al.*, 2012).

Sowing/planting methods

Weed population and its dry weight are significantly influenced by methods of sowing and planting of crops (Dev *et al.*, 2013). Zero-till and FIRB sowing recorded lower weeds density with higher grain yield in wheat (Ahmed *et al.*, 2010; Jat, *et al.*, 2013) over conventional tillage and strip till drill system, in maize Table 5 (Chopra and Angiras, 2008) over conventional tillage and flat bed system and in lentil (Manjunath *et al.*, 2010) over flat sowing. This is because of avoidance of wetting of whole cropped soil surface in bed sowing and the weed did not find congenial moisture conditions at the surface to germinate (Sharma, 2014).

In zero till seeding by Happy Seeder machine with stubble mulching, undisturbed inter row space, where seeds lying at lower depths did not germinate (Bhullar *et al.*, 2006) and it saves time and energy (Yadav *et al.*, 2013). BBF method of sowing provides favorable environment for the growth and development of crop and reducing weed population over flat bed and ridge furrow methods (Jha and Soni, 2013). Bidirectional sowing in wheat gives fewer weeds compared to unidirectional sowing although seed rate is same (Singh *et al.*, 2012). Transplanting under puddle condition had given detrimental impact on weed growth and resulted lowest producer of weed dry weight over direct sowing with zero till drill under unpuddled wet seed bed, direct drum seeding of pre-germinated seeds under puddle conditions, unpuddled transplanting (Singh *et al.*, 2013), SRI (Hassan *et al.*, 2010), whereas, drum seeding + green manure significantly reduced weed density in direct seeded rice over drum seeding alone and broad casting (Sangeetha *et al.*, 2009).

Intercropping

Intercropping can be used as an effective weed control strategy. Growing of different plant types together which enhances weed

Table 6: Effect of intercropping and weed control treatment on weed dry weight and cane yield

Treatment	Dry matter of weeds (kg/ha)			Cane yield (t/ha)
	Cyperus rotundus	Annual weeds	Total	
Cropping system				
Sole sugarcane	1450	810	2250	56.2
Sugarcane + greengram	1350	730	2080	57.0
Sugarcane + blackgram	1440	860	2300	55.2
Sugarcane + okra	1660	750	2410	51.6
CD (P=0.05)	NS	NS	NS	4.3
Weed control treatment				
Weedy check	2010	1510	3510	44.7
Two hand hoeing	740	170	910	61.0
Pendimethalin 0.75 kg/ha	1520	400	1920	57.7
Trifluralin 1.0 kg/ha	1600	660	2260	56.7
CD (P=0.05)	57	53	121	4.3

Table 7: Effect of green manuring (In-situ) on weeds and grain yield of rice

Treatment	Dry matter of weeds /m^2 (g) at 60 DAS	Grain yield (kg/ha)
Paired row planting of direct sown rice 15/30 cm	152.0	710
Paired row planting of direct sown rice + one row of *Sesbania*	107.3	1190
Paired row planting of direct sown rice weed free (3 HW)	38.4	3820
Paired row planting of direct sown rice + one row of *Sesbania* weed free (3 HW)	27.5	3970
CD (p=0.05)	12.67	51.0

Table 8: Weed seed population in the top 20 cm as affected by tillage sequence and weed management

Tillage sequence	Weed seed as affected by weed management			Mean
	Weedy check	Herbicide	Herbicide + one hand weeding	
Zero tillage- Zero tillage	70	89	20	60
Zero tillage- conventional tillage	92	92	34	72
Conventional tillage- Zero tillage	80	43	31	51
Conventional tillage-conventional tillage	112	81	25	73
Mean	88	76	27	

control by capturing a great share of available resources (Shah *et al.*, 2011) and probability by increasing shade and crop competition with weeds in tighter crop spacing (Praveen and Bhanu, 2005). Besides, intercropping also reduces weeding cost and realizes higher total productivity of the system and monetary returns (Bhullar *et al.*, 2006). Intercropping, preferentially spreading types of crops, legumes, cucurbits, sweet potatoes, contributes to a faster and denser ground cover suppresses weed growth and reduces erosion (Giri *et al.*, 2006). But this system alone is not sufficient to ensure adequate weed control because of varied canopy coverage (Dwivedi *et al.*, 2012). Evidence of better weed suppression was reasonably clear where intercropping provides a more competitive effect against weeds either in light, time or space than monocropping (Dwivedi *et al.*, 2012). Sugarcane + greengram intercropping recorded lower weed dry weight and the highest cane yield (Table 6) over sole sugarcane, sugarcane + blackgram and sugarcane + okra (Singh and Yadav, 2002; Bhullar *et al.*, 2006).

Planting pattern

Planting pattern, which modifies the crop canopy structure and micro climate, in combination with weed management practices, may influence the weed infestation to a great extent (Dwivedi *et al.*, 2012) and hypothesized that increased crop density (Kewat, 2014), reducing row spacing (Singh and Singh, 2006) and spatial uniformity can increase weed suppression, because the competitive ability of crops with weeds is improved (Singh, 2014). In a perfectly uniform grid pattern, where the distance between individual crop plants within the row and between the rows is equal, competition with weeds will begin sooner than in a row pattern and competition between individual crop plants will be delayed as long as possible (Olsen *et al.*, 2005; Singh and Singh, 2006). Closer row spacing will improve crop competition for limited resources due to a rapid canopy closure (Nagamani *et al.*, 2011), reducing weed seedling growth and soil weed seed bank (Arvadiya *et al.*, 2012). Dry matter of weeds in wheat was significantly the lowest under bi-directional row orientation followed by North-South row orientation, cross sowing at 22.5x22.5 cm and highest under normal 22.5cm (Chaudhary *et al.*, 2013), this might be due to better smothering effect (Singh, 2014).

Cover crops/green manures

Growing cover crops, have potential as an important component of a system oriented ecological weed management strategy for sustainable agriculture (Kruidhof *et al.*, 2008), because it conserve soil and moisture, enhancing soil nutrient status (Malviya and Singh, 2007), total biomass production,

Table 9: Effect of allelochemicals present in different plants on weeds and rice yield

Plant species	Weed reduction (%)	Increase in rice yield (%)
Ageratum conyzoides L.	80.8	20.9
Azadirachta indica L.	91.0	NR
Bidens pilosa L.	81.8	23.3
Euphorbia hirta L.	87.9	23.3
Eupatorium canabium L.	75.8	23.3
Heliantus tuberosus L.	70.1	17.0
Leucaena glauca L.	85.9	23.3
Medicago sativa L.	80.0	8.6
Morus alba L.	72.7	23.3
Oryza sativa L.		
Hull	51.7	19.4
Bran	25.1	6.5
Hull+ Rasen	88.3	77.4
Bran+Yuba	53.1	29.0
Herbicide (5L/ha)	77.8	11.6
Hand weeding	71.7	25.6

and lowering temperature within the crop canopy (Norsworthy, 2004), suppress weed growth due to allelopathic effects (Das, 2008) or by shading (Mohler *et al.*, 2012). Besides the allelopathic effects, crop covers reduces the sunlight exposure of weeds and compete with the weeds for water, nutrient and space (Singh *et al.*, 2012). Use of the cover crops and organic amendments promotes the fungal, bacterial and mycorrhizal communities that may be detrimental to weeds and beneficial for the crops (Norris and Kogan, 2000). Growing of non-legume crops in the rotation as a cover crop utilize the surplus nitrogen from the soil that prevent nitrate nitrogen removal and also reduce the available nutrients for weed germination and its growth (Dinesh *et al.*, 2009; Kewat, 2014).

Green manuring is a cost and labour efficient practice, and therefore sometime it called the "herbicides" of small farmers (Bhambri and Kolhe, 2006). Green manure incorporated during tillage can inhibit weed seedling emergence (Kruidhof *et al.*, 2011) and it efficiently suppress the weed growth (Dhawan, 2007). Suppression of seedling emergence by incorporated green manure has been attributed to three potential mechanisms: (i) the release of allelopathic chemicals, (ii) reduced nitrate because of nitrogen tie-up by soil microbes and (iii) the promotion of seed and seedling pathogens (Kumar *et al.*, 2008). Green manuring of *Sesbania* significantly suppresses weeds in rice due to shading and allelopathic effect (Yadav *et al.*, 2010).

Brown manuring

This is simply a 'no-till' version of green manuring, using an herbicide to desiccate the crop before flowering instead of using cultivation. The plant residues are left standing. This may also be a preferred option on lighter soils prone to erosion and reduce weeds (Sharma, 2014; Singh, 2014). Butachlor + brown manuring + 2, 4- D was able to reduce weed pressure, as brown manuring acted as a cover crop in suppressing weed growth effectively (Kumar and Mukherjee, 2011; Dubey, 2014). Drum seeding alone or drum seeding + *dhaincha* brown manure (Prabhakaran and Chinnusamy, 2006) or growing of one row of *Sesbania rostrata* between two paired rows of rice (Bhambri and Kolhe, 2006) was found effective in reducing density and dry matter accumulation of weeds and increased yield (Table 7).

Seed treatment

Ensuring good plant population through better land preparation and employing approaches like seed treatments with growth stimulants (KCl and GA_3), pre-heat treatment, soaking and drying of seed etc. may helps minimizing weed population. A vigorously growing crop aids weed control by weakening the weeds by offering competition (Singh *et al.*, 2012). Coating sorghum seeds with *Fusarium oxysporum* for control of the root parasitic weed *Striga* (Elzein *et al.*, 2006).

Seeding rate

Crop density is an important component of the crop's ability to compete with weeds (Sindhu *et al.*, 2010; Arvadiya *et al.*, 2012). Variation in the seed rates and high seed rate significantly influenced weed population and their dry weight by securing an optimum plant population (Meena *et al.*, 2010), which shows excellent smothering effect on weeds (Verma & Singh, 2008; Sharma and Singh, 2011) and improving productivity and profitability of the crop.

Methods and Levels of Fertilizer Application

Fertilizers alter the nutrient level in the agro-ecosystems and therefore they may directly affect weed population dynamics and crop weed competitions (Robert *et al.*, 2004; Babu and Jain, 2012). Nevertheless, nutrients clearly promote crop growth but benefit weeds more than crops (Upasani *et al.*, 2013). Strong effects can be observed by manipulating fertilizer timing, dosage, and placement in order to reduce weed interference in crops (Dubey, 2014). Appropriate timing of N mineral fertilization has been proposed in integrated cropping systems as a mean to unbalance nutrient competition between crop and weeds to the benefit of the former (Das and Yaduraju, 2007). Placement of fertilizer significantly reduced the density and dry biomass of weed and produced higher grain yield than broadcast method of fertilizer application (Pandey *et al.*, 2006; Lodha *et al.*, 2010).

Irrigation

Optimum time and number of irrigation reduces the density and weight of weeds (Das and Yaduraju, 2007; Verma, 2014). Singh and Singh (2004) reported that pre-sowing irrigation reduced the dry weight of *C. album* and *C. murale* by 21 and 25%, respectively, and subsequently grain yield was 12% higher over post sowing irrigation. Wheat irrigated at CRI+tillering+flowering stage reduced the dry weight of *Phalaris minor* over crop irrigated at CRI+tillering+flowering+ dough, CRI+tillering, CRI+flowering and at CRI stage, respectively (Das and Yaduraju, 2007). Irrigation at 0.4 IW: CPE in *Isabgul* (Parmar *et al.*, 2010), 1.25 IW: CPE in wheat (Nadeem *et al.*, 2010) and 0.6 IW: CPE ratio in fenugreek (Mehta *et al.*, 2010) resulted lower weed population and higher yield over 0.8 and 1 IW: CPE.

Mechanical weed control

Most mechanical weed control methods, such as hoeing, tillage, harrowing, torsion weeding, finger weeding and brush weeding, are used at very early weed growth stages (Singh, 2014; Kewat, 2014). Hoeing can be effective on older weeds, and remains selective, many mechanical control methods become difficult after the cotyledon stage and their selectivity decreases with increasing crop and weed age. Thus, if the weeds have become too large, an intensive and aggressive adjustment of the implements is necessary to control the weeds, and by doing this one increases the risk of damaging the crop severely (Carter and Ivany, 2006). Stopping tillage practices has a positive impact on weed populations, because it can influence the weed seed viability and distribution and it has a strong impact on weed emergence by burying weeds in the soil (Vasileiadis *et al.*, 2006). Continuous zero tillage reduced the total weed seed bank over continuous conventional tillage (Mishra and Singh, 2008) in soybean- linseed cropping system Table 8.

Conservation tillage (low disturbance) leaves more weed seeds on the surface, whereas high disturbance systems bury weeds. Weed seeds left on the surface are generally more susceptible to decay and ultimately reduce weeds seed banks (Chauhan *et al.*, 2006), it allowed early sowing and thus the competitive advantage remains in favour of crop not for weeds (Mishra *et al.*, 2010; Sharma, 2014), lower emergence in conservation tillage might be due associated with higher soil strength (Dev *et al.*, 2013).

Slashing

This is normally done as a pre-planting operation. Just before making planting pits or planting in furrows, any plants growing in the field are slashed. In-row slashing, a practice known to farmers in some countries, is the preferred for conservation agriculture, as it does not disturb the soil. Weeds should be slashed even after crop harvest and during the dry season to prevent seed formation (Senarathne and Perera, 2011).

Mulching

In environmental production and ecological farming, there is increasing interest in herbicide free weed control. Mulching is one of the possible ways to control weeds without using herbicides (Verma and Singh, 2008; Awasthy *et al.*, 2014). Besides this it also reduce soil erosion, evaporation suppressant, increasing infiltration and population if beneficial micro-organisms (Arentoft *et al.*, 2013), improve soil moisture status, nutrient utilization, disease control, soil temperature regulation and can suppress weeds, due to delayed emergence and smothering effect on weeds (Sharma and Singh, 2010; Manahas *et al.*, 2011). Black polythene (Goswami and Saha, 2006) and news paper (Singh, 2014) mulch recorded significantly lower density and dry biomass of weeds over water hyacinth, paddy straw and wheat straw mulch, respectively.

Residue management

Crop residues are defined as crop or its parts left in field for decomposition after it has been thrashed or harvested. Earlier these were regarded merely as waste, but now because of their usefulness they are considered an important resource that can bring significant physical, chemical, biological changes into the soil after amendment and suppresses weeds directly (Sharma, 2014). Residue retention has significantly influenced weed emergence (Verma *et al.*, 2008), although several interacting factors may determine the extent of this influence including residue nature, height, type and quantity, prevailing weed flora, soil type and weather conditions (Khankhane *et al.*, 2009). Surface application of rice residue 6 to 7 t/ha significantly reduce the growth and development of weeds as compared to incorporation and no-residue treatments (Brar and Walia, 2010).

Thermal weed control

Thermal weed control includes use of fire, flaming, hot water, steam and freezing (Ascard *et al.*, 2007), which provide rapid weed control without leaving chemical residues in the soil and water, selective towards the weeds, they do not disturb the soil as in the case of cultivation methods (Zimdhal, 2007), but its effectiveness depends on the temperature, exposure time and energy input (Ascard *et al.*, 2007). Thermal weed control methods kills above ground plant parts, they may regenerate and repeated treatments may be required.

Flame weeding

Flame weeding uses the heat generated from one or more propane burners to kill weeds. Intense heat sears the leaves of the weeds, causing the cell sap to expand, damaging cell walls (Singh, 2014). This causes leaves to wilt and prevents water from moving from the roots to the leaves. In a short period of time, the plant withers and dies (Cohen, 2006).

Soil solarization

Soil solarization is a special technique in which moist soil is covered by polyethylene film (usually black or clear plastic sheet) to trap solar radiation and cause an increase in soil temperatures for several weeks to levels that kill weeds, weed seeds, plant pathogens, and insects for economic crop production (Ascard *et al.*, 2007; Singh, 2014). For effective weed control there should be warm, moist soil and intense radiation needed throughout the day in order to raise the soil temperature, may cause damaging changes in enzyme activity, membrane structure and protein metabolism and ultimately kill weed seeds and seedlings of heat sensitive species (Arora and Tomar, 2012), because the effect of solarization varies with weed species (Singh, 2014). Research has shown the negative impact of solarization on weeds, including parasitic weed *Orobanche* in tobacco and vegetable crops and better control of noxious *Cyperus rotundus* has been achieved where other methods failed (Das and Yaduraju, 2008; Kumar *et al.*, 2012). In view of growing concern for environmental safety and sustainability of agricultural production, integration of solarization practices would provide an eco-friendly and sustainable system (Arora and Tomar, 2012).

Hand tools

Removing weeds or patch of weeds by hand is often the most effective way to prevent that weed from spreading and therefore from becoming a serious problem (Zimdhal, 2007). Hand weeding is more effective for annual rather than perennial weeds due to its capacity of vegetative reproduction. Hand hoes, push hoes and other traditional methods of hand weeding are still used worldwide in many agricultural crops.

Cutting/mowing

These methods are commonly used in turf and can be used in vineyards, in orchards, in pastures and in forage crops if used in the appropriate way (Cloutier *et al.*, 2007). Although, cutting and mowing techniques control weeds by reduces their leaf area, slows their growth and decreases or prevents their seed production and to minimize the competition between weeds and crops (Zimdhal, 2007).

Allelopathy

The term allelopathy, from the Greek words 'allelon' and 'pathos' and meaning mutual harm or affection, is generally used to express growth inhibition of a plant through the release of chemicals into the environment from another plant. In agro ecosystems crops, weeds, trees and microbes constitute the biotic components, which not only interact among them but also with the abiotic environment. The allelopathic interactions among various biotic components have a great potential in improving crop production, maintaining ecosystem stability, nutrient conservation, and above all in management of weeds and pests (Kong *et al.*, 2004). The exploitation of crop allelopathy against weeds may be useful to reduce issues related to the use of herbicides because in recent years, allelopathic suppression of weeds is receiving greater attention ((Inderjit *et al.*, 2005). Several crop, such as alfalfa (Xuan *et al.*, 2005), barley, black mustard, buckwheat, rice (Kirn and Shin, 2005), sorghum, sunflower (Khanh *et al.*, 2005) and sesame (Kumar and Varshney, 2008), demonstrate strong weed suppression ability, either by exuding allelochemical compounds from living plant parts or from decomposing residues. The introduction in agronomic rotations of allelopathic crops, their use as a mulch to smother crops or as a green manure may also be helpful in reduction of weeds and other agricultural problems, such as environmental pollution, use of unsafe products and human health concerns, through a reduction in chemical inputs (Tesio and Ferrero, 2010). Xuan *et al.* (2005) evaluated allelopathic potential of different crops and plant parts against rice weeds and observed 25 to 91% reduction in weed population and 20 to 80% increase in rice yield due to allelochemicals present in different plants (Table 9).

Biological weed management

In general weeds are managed either manually or by using herbicides but for the former is costly, time consuming and regenerates soon and thus not feasible and later on creates soil and water pollution, forces heavy financial burden and needs technical know-how for its application. To overcome these problems, biological control appears pollution free and economic option for weeds control. Insects, mites, nematodes, plant pathogens, animals, fish, birds and their toxic products are major weed controlling biotic agents and among these insects are one of the important groups (Tiwari *et al.*, 2013; Kumar, 2014).

Pioneering works on biological control of weeds was carried in India for control of *Parthenium hysterophorus* (Kumar and Ray, 2011). The primary focus of the biological weed management efforts in South-East Asia has been on two aquatic weeds, water hyacinth (Ray *et al.*, 2009) and water fern. 'BIOMAL' a dry formulation of *Colletotrichum gloeosporioides* f.sp. malvae, was used in Canada for the control f *Malva pusilla* in flax and lentils and *Colletotrichum gloeosporioides* f.sp. Cuscutae, for the control of *Cuscuta sp.* in soybean (Das, 2008).

Integrated weed management

Integrated weed management, defined as the combination of two or more weed-control methods at low input levels to reduce weed competition in a given cropping system below an economical threshold level. Integrated weed management system is basically an integration of effective, dependable and workable weed management practices that can be used economically by the producers as a part of sound farm management system (Riemens *et al.*, 2007). Integrated weed management relies on weed management principles that have proved to be suitable for long term weed management by combining the use of cultural, mechanical, thermal, biological and chemical means based on ecological approaches (Singh, 2014; Kewat, 2014), that will prevent weed reproduction, emergence, promote weed seed bank depletion and minimize weed competition (Malviya and Singh, 2007), which is the key component of sustainable agriculture. Under such circumstances, to get effective control of composite weed flora, a logical combination of several weed control methods is likely to prove the most effective approach (Kumar *et al.,* 2012). These alternative approaches to suppressing weed growth and reproduction below the economic threshold level are called "ecological approaches of weed management".

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