Environmental Sustainability (2021) 4:51–61
https://doi.org/10.1007/s42398-020-00157-3

REVIEW

Ecological weed management approaches for wheat under rice–wheat cropping system

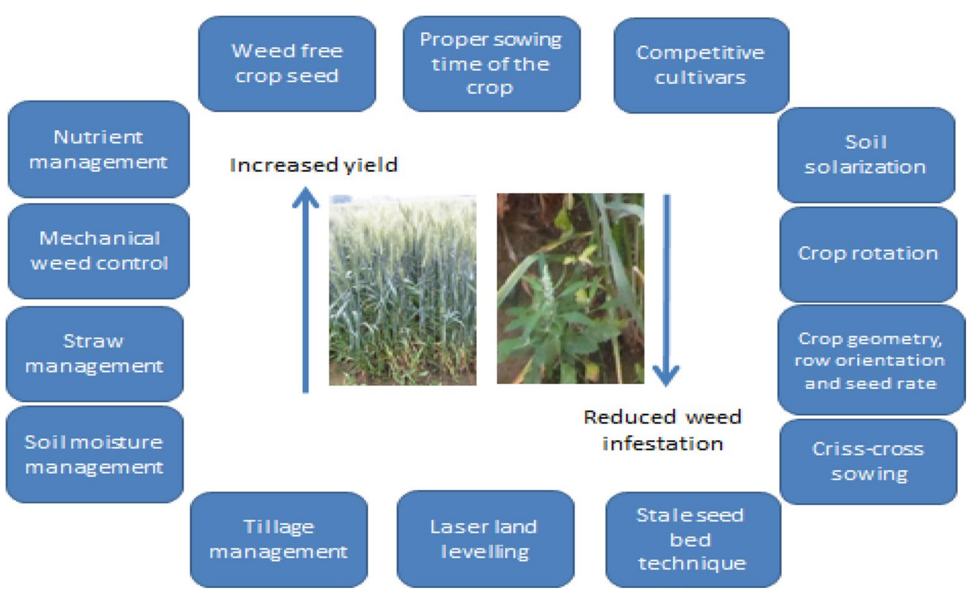
Vipin Kumar[1] · R. S. Bana[1] · Teekam Singh[1] · Ganpat Louhar[2]

Received: 29 July 2020 / Revised: 8 December 2020 / Accepted: 14 December 2020 / Published online: 27 January 2021

Abstract

Weeds are one of the most important yield limiting factor in wheat cultivation, causing a yield loss of 15–50% depending on relative proportion of weed flora, weed density and period of their infestation. To control the weeds effectively, the farmers of Indo-Gangetic Plains Region (IGPR) are mainly dependent on the chemical herbicides. However, the excessive herbicide use has led to development of resistance in many weed species and shift in weed flora besides negative residual effects on the succeeding crops and food quality as well. Therefore, there is an urgent need to look for alternate methods which are economically viable and ecologically stable. Several approaches like early sowing of wheat, soil solarization, adjustment in row spacing, sowing weed free seeds, adjusting seed rate, planting densities, crop rotations, competitive cultivars, stale seed bed technique, efficient nutrient management, proper irrigation scheduling, mechanical control, mulching, residue retention and tillage methods have been found effective in wheat in numerous field studies. Looking at the potential of such ecological approaches, there is need for in-depth research on various aspects of these methods. This paper reviews the available information on different ecological weed management approaches in wheat under rice–wheat cropping system of Indo-Gangetic plains.

Graphical abstract



Keywords Crop–weed competition · Soil solarization · Sowing time adjustment · Stale seed-bed · Wheat · Zero tillage

✉ R. S. Bana
rsbana@gmail.com

Extended author information available on the last page of the article

Wheat (*Triticum* spp.), grown over 220 m ha throughout the globe, is the major cereal crop of the world and along with rice forms the backbone of the global food security system. However, in India, it is the second most important cereal crop after rice with an area of 29.1 m ha and annual production of 102.2 mt (Economic Survey 2020). Wheat production in South Asian region had seen multi-fold increase after green revolution, mainly attributed to high yielding varieties (HYVs), use of recommended chemical fertilizers, irrigation infrastructure and improved production technologies. But, during recent past the growth rate of wheat production has started declining (Ray et al. 2013), which is mainly due to several emerging problems like weed infestation, delayed sowing after rice harvest, soil salinity build-up, soil compaction due to puddling in rice and outbreak of various diseases (Choudhary et al. 2018). Among above all the factors, weeds are the major threat for wheat cultivation (Nakka et al. 2019). Numerous weed species have been influencing the productivity of wheat which include mainly *Phalaris minor* Retz., *Chenopodium album* L., *Avena fatua* L., *Chenopodium murale* L., *Circium arvense* L., *Daucus carota* L., *Coronopus didymus* L., *Convolvulus arvensis* L., *Melilotus alba* Lamk., *Avena ludoviciana* Dur. and *Rumex dentatus* L. These weeds altogether cause a yield loss of ~ 15–50% to wheat (Jat et al. 2003) and sometimes above 60% if weeds are allowed to grow rampantly (Singh et al. 2015a). Due to weeds, India suffered a loss of wheat produce worth US$ 3376 million, across 18 states during 2003–2014 (Gharde et al. 2018). Although yield penalties due to weeds vary according to relative proportion of weed flora, weed density and period of weed infestation. Apart from yield losses, weeds like *R. dentatus* and *C. arvense* make the harvesting and threshing operations difficult, whereas, heavy infestation of *P. minor* during maturity period leads to severe lodging of wheat crop (Chhokar et al. 2012).

Chemical herbicides have been considered as the effective and economical method to control weeds in the cereals (Singh et al. 2017). However, herbicide usage has many negative effects like excessive and repeated use of same herbicide or herbicides of same mode of action; which led to development of resistance in many weed species across the Indo-Gangetic plains region (IGPR) (Bhowmik et al. 2010; Chhokar and Malik 2002; Malik and Singh 1995), weed flora shift (Chhokar et al. 2014) and carry-over effect on the succeeding crops, resulting in low productivity of the cropping systems (Grey et al. 2012). Herbicides also cause toxicity to crop plants and drift hazards if handled improperly. Herbicide residues can accumulate in plant parts and may enter the food chain (Bai and Ougbourne 2016). Therefore, there is a need to look for alternate weed management options. Ecological approaches of weed management can be a possible non-chemical option for weed management in wheat. Non-chemical/ecological methods of weed control include sowing weed free seeds, adjusting sowing time, cultivation of competitive cultivars, soil solarisation, adoption of scientific crop rotations, adjusting crop geometry, row orientation and seed rate, stale seed-bed technique, laser land levelling, newer tillage and crop establishment methods, proper irrigation scheduling, nutrient management, mechanical weed control methods and straw management. These technologies can also be successfully used for controlling weeds in organic agriculture in various crops including wheat. The present paper aims to identify the effective ecological practices for weed management in wheat crop, especially under rice–wheat cropping system (RWCS) in IGPR in general and western IGPR in particular.

Use of weed free seed

Crop seed contamination with weed seeds is primary mechanism of dispersal of weeds. Both monocot and dicots weed species have a unique capability of producing seeds in large quantities (Kurdyukova 2018). Weeds like *P. minor* show phenotypic and chronological mimicry with the host crop like wheat and get harvested and threshed with wheat, which results into mixing of *P. minor* seeds with wheat grains. Seeds of other weeds also get mixed with crop seeds during harvesting and threshing operations. Yadav et al. (2002) collected the seed and grain samples of wheat (each sample of 125 kg) from 5 districts of Haryana state (India) and found ~ 0.2–1.7 million and ~ 15–72 thousand seeds of *P. minor* in grain samples and seed samples respectively (Table 1). Most of the farmers use a part of the previously harvested grain as seed stock for next season crop sowing as evident by low seed replacement rate of wheat (32.6%) reported by the Seed Division, Department of Agriculture Cooperation, Government of India during 2011. Such practices multiply the weed seed contamination, thus regular replacing of old seed with high quality seed can reduce the weed infestation to a great extent and consequently save a

Table 1 Presence of *Phalaris minor* seeds in the wheat grain and seed samples in Haryana, India. Source: Yadav et al. (2002); Yadav and Malik (2005)

District	No. of *P. minor* seeds/125 kg wheat seed sample		No. of *P. minor* seeds/125 kg wheat grain sample	
	Mean	Maximum	Mean	Maximum
Kurukshetra	5000	15,000	3,79,896	9,40,847
Karnal	4766	25,000	3,30,687	17,00,003
Fatehabad	3462	28,750	3,02,818	15,37,547
Kaithal	5718	72,500	1,89,017	6,79,172
Hissar	6250	46,875	1,28,437	2,14,891

large amount of money by avoiding unnecessary weed control operations and herbicidal sprays for achieving higher wheat yields.

Time of sowing

Crop sown at optimum time always gives them competitive advantage over the weeds. Wheat sown in the last week of October generally experiences less infestation of *P. minor* as the prevailing temperature during this period is not favourable for its germination in western IGPR (Chhokar and Malik 1999). Modern rice cultivars like 'Pusa Basmati-1509' matures in 120 days duration thereby, gives opportunity to sow wheat crop timely in rice–wheat cropping system (Singh et al. 2014). However on the other hand, Singh et al. (1995) reported that infestation of *A. ludoviciana* is prominent in the early sown wheat crop. They observed that the density of wild oat at 60 days after sowing was 97, 27 and 9 plants/m^2 in November 10, 30 and December 30 sown wheat, respectively. Ibrahim et al. (1986) also found that dry matter accumulation (m^{-2}) by broad leaved weeds and narrow leaved weeds reduced from 33.3 to 11.4 g and 48.3 to 7.7 g, respectively, when the wheat sowing was delayed from October 21 to November 30, whereas the yield increased from 2.7 to 4.6 t ha^{-1}. Therefore, sowing time should be tinkered as per the intensity and target weed species in particular region.

Competitive cultivars

Crop varieties vary in growth habits which is mainly responsible for different weed competing ability (Choudhary et al. 2015). During past few decades high yielding dwarf wheat and rice varieties have become quite popular among farmers but many of these varieties lack the weed suppressing ability. Varieties with quick growing habit swiftly cover the ground and disfavor the growth of weeds early in the season, reducing the efforts required for controlling weeds at later crop stages. Weed-suppressive crop varieties have larger specific leaf area, uniformly distributed leaves along plant height, wider plants per unit biomass and their width and plant height get increased when shaded (Colbach et al. 2019).

Blackshaw (1994) found that yield reduction in wheat in western USA due to *Bromus tectorum*, an annual winter season grassy weed, was 14–30% higher in semi-dwarf varieties as compared to the tall growing varieties. Similarly, in India, Yaduraju and Ahuja (1997) observed that wheat variety C-306, which is a tall statured cultivar, has caused a significant decrease in dry matter accumulation (DMA) and plant height of *P. minor*, as compared with HD-2329 and Kundan cultivars. High weed suppressing ability of cultivar C-306 was attributed to its tall stature and quick growth. Chauhan et al. (2001) found that wheat varieties WH-542 and WH-157 are less competitive than HD-2687 and PBW-343. Whereas, Walia and Singh (2005) reported less DMA by *P. minor* in wheat varieties PBW-343, WH-283, PBW-373 and

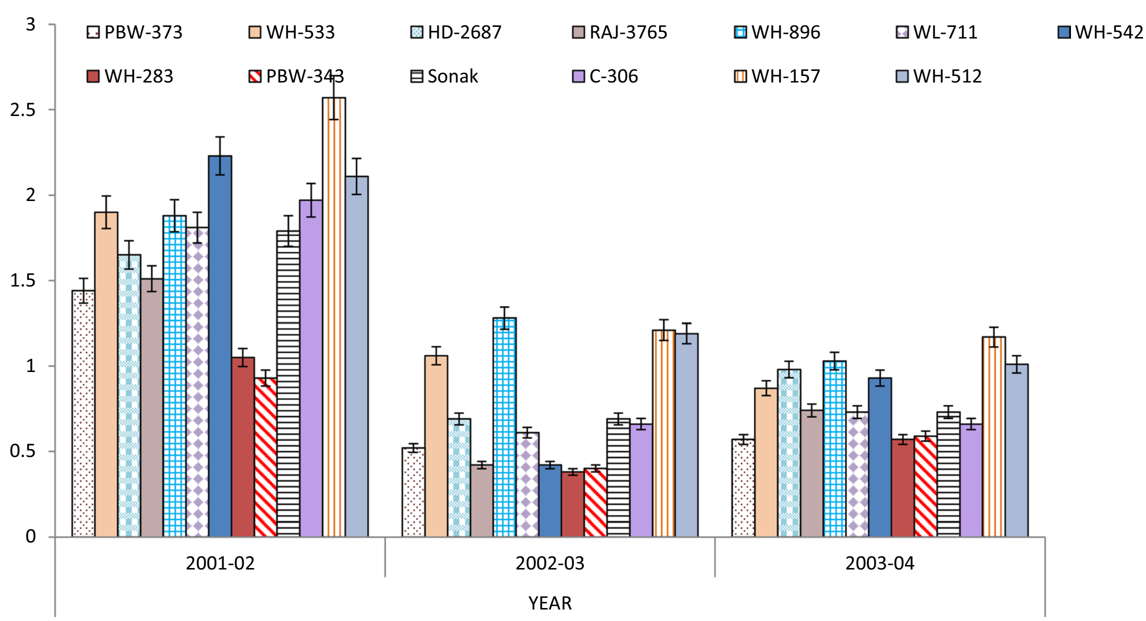


Fig. 1 Effect of wheat varieties on dry matter accumulation (DMA) of *Phalaris minor* in herbicide untreated crop. Source: Modified from Walia and Singh (2005)

Raj-3765 as compared to varieties WH-157, WH-896 and WH-512 (Fig. 1).

Hossain et al. (2010) compared the competitiveness of eight different wheat varieties against various weed species, and ranked those varieties for their weed suppressing ability. 'Prodip' cultivar was the most competitive and ranked first while 'Bijoy' was least competitive. Yenish and Young (2004) compared tall and dwarf winter wheat cultivars for their competing ability against jointed goat grass (*Aegilops cylindrica*) and found that tall wheat varieties are superior to dwarf wheat varieties in suppressing the grass. Different species of wheat also differ in weed competing potential and *Triticum aestivum* is more suitable in curbing weeds as compared with durum wheat. Among different wheat varieties throughout the world, varieties of South America and Eastern Europe are more competitive against weeds than Indian, Mediterranean and Australian varieties (Lemerle et al. 1996). There is no doubt that dwarf wheat varieties have high yield potential as compared to tall varieties, but in high weed infestation fields tall varieties should be preferred over dwarf ones, owing to their better weed suppressing capability. Thus, selection of cultivars should be location specific depending upon weed dynamics is important for effective weed management.

Soil solarization

Cultivated soils are full of weed seeds as every year weed plants shed huge quantum of seeds. Weed seeds possess variable dormancy which helps them to germinate repeatedly over several years. Even if we are able to fully control the weeds for numerous years, the seed bank having variable dormancy will contribute to continuous appearance of weeds over the years (Rana et al. 2014b). Therefore, any technique which can destroy weed seed bank can act as very powerful tool for controlling weeds. Soil solarization is one such technique which can reduce the weed seed bank. Soil solarization is not a new technique; rather it is an age-old practice widely followed by ancient Indian farmers for restricting the growth of various harmful biological agents in soil as well as plants (Raghaven 1964). In soil solarization, whole field is covered with transparent plastic sheet during hot summer months. Covering of soil with plastic sheets increases the soil temperature to a level where it has a lethal effect on underlying weed seeds, spores of various pathogenic microorganisms and pupae and eggs of insects. Soil temperature in different layers increases by ~ 12–15 °C under soil solarized plots (Abd-Elgawad et al. 2019). Egley (1983) reported a soil temperature of 40–50 °C during soil solarization, and this temperature may reach above 60 °C in upper soil layers during full sunlight conditions. The major reasons for this rise in soil temperature under plastic sheet are greenhouse effect and restriction of evaporative cooling (Avissar et al. 1986).

Increase in soil temperature is more in soils which are irrigated before laying plastic sheets as compared to the non-irrigated soils because in irrigated soils a thin layer of water is formed underside the plastic sheet, which allows the incoming short-wave radiations to pass through it but blocks the outgoing long-wave radiations. This thin water layer also keeps the plastic sheet adhered to the ground, whereas in non-irrigated soils, without such water layer formation plastic sheet does not stick with the soil, making it prone to damage due to high speed winds (Arora and Yaduraju 1998). In soil solarization two major mechanisms govern the weed control, first, the weed seeds present near the soil surface are directly killed due to higher temperature in upper soil layer and second, the weed seeds present in relatively deeper layers are not subjected to very high temperature that will be able to kill the weed seeds but the temperature in deeper soil layers reaches up to an extent that the dormancy of those seeds gets broken, resulting into their germination. But due to small size and lesser stored energy in the weed seeds, the germinated seedlings fail to emerge and die within the soil (Rana et al. 2014a).

Arora and Yaduraju (1998) reported a reduction in germination of *A. fatua* up to 85 and 78% in top 5 and 15 cm soil depths, respectively. The same trend was also shown by *P. minor* seeds, but seeds of *Melilotus indica* remained unaffected by high temperature during soil solarization, attributed to their hard seed coat. Das and Yaduraju (2008) also reported decrease in overall weed population in wheat owing to soil solarization. Another major broad leaved weed of wheat i.e. *R. dentatus* is also very susceptible to soil solarization (Patel et al. 2005). Besides controlling weeds, soil solarization also increases the available nitrogen (Arora and Yaduraju 1998) and organic matter content of the soil (Khan et al. 2012). Therefore, soil solarization can act as an effective non-chemical method for controlling weeds in wheat but its suitability is limited to tropical and sub-tropical regions only, where temperature remains higher during summer months.

Crop rotation

Periodical rotation of crops of different life cycles, growth habits and requiring different management practices offers several advantages as compared to growing the same crop year after year. Several weeds are favored by growing same crop repeatedly, and mostly crop associated weeds (weeds which have similar climatic requirement, growth habits and life cycle to the crop) are most benefitted due to monoculture (Rana et al. 2018). Crop rotation interrupts the growth and development of weeds which are associated with a particular crop by changing the micro-climate of the field and the crop management practices. Stacked rotation is an emerging concept in the field of crop rotation. In stacked crop rotation one crop is grown for more than one year and after that some other crop is grown for the same number of years and this cycle continues. Stacked crop rotation is more effective than alternating crops each year in terms of weed control (Garrison et al. 2014). There are several weeds which exhibit phenotypic mimicry with crop plants like *P. minor* and *A. fatua* with wheat, *Echinochloa colonum* and *Echinochloa crus-galli* with rice. These weeds are difficult to control through hand weeding and various mechanical methods, but can be easily distinguished in the field of crop plants other than wheat and rice and can be controlled by hand weeding. Monoculture of wheat favors the infestation of *P. minor* which is the major concern for sustaining wheat productivity under rice–wheat cropping system (RWCS). Mono-cropping promotes the buildup of the weed-seed bank, which can be reduced to a manageable level if wheat is substituted with some other crops for 2–3 years. Altering wheat in RWCS by some other *rabi* crops like mustard, chickpea, lentil, sugarcane, sugar beet, fenugreek, cauliflower and cabbage might provide successful control of weeds associated with wheat (Brar 2002; Om et al. 2004). Growing fodder crops like oat and berseem instead of wheat for 2–3 years offers a wide spectrum weed control as weed plants get mowed during cutting of fodder crops. Fodder crops are cut 2–3 times in a single cropping season and weeds are also cut along with fodder crops and thereby minimize their seed production, subsequently a major portion of weed seed bank gets exhausted (Choudhary et al. 2018).

Malik and Singh (1995) reported higher resistance development in *P. minor* against isoproturon under RWCS as compared to rice–sunflower/vegetables/clover/pigeon pea. *P. minor* infestation remained higher in wheat grown after rice (Om et al. 2004) therefore, replacing rice with some other crop can also reduce the *P. minor* menace. However, replacing rice or wheat with some other crop on a large scale is not feasible as both are the major food crops. Small size of land holdings in India (~0.14 ha) also disfavors the adoption of the appropriate crop rotations. Some other negative factors like marketing and risk of crop failure are also associated with alternate crops. But intensification of RWCS by inclusion of short-duration vegetable crops like potato or vegetable pea can help in controlling weeds like *P. minor* without use of any herbicide (Chhokar et al. 2008). In addition to weed control, these crops also enhance the overall system productivity (Bana et al. 2015).

Crop geometry, row orientation and seed rate

Plant spacing and seed rate are two important factors which determine the plant density and affect the crop growth and yield. For reaping good harvest seed rate and row spacing should be optimum. Besides influencing crop growth and yield, these two factors also affect the weed population. Increasing the planting density increases the competitiveness of crops against weeds but one should be aware of intra-specific competition between the crop plants as well. Higher planting density decreases the spaces available for weed plants to grow. Higher seed rate and narrow spacing between crop plants facilitate early ground cover by crop plants and deprive the weeds from sunlight which is the basic requirement for proper growth. In a field study, decreasing the row to row spacing of wheat from 20 and 18 cm to 16 cm decreased the biomass of narrow-leaved weeds by 19.5 and 17.2%, and broad-leaved weeds by 20.7 and 19.9% respectively (Table 2), but grain yield was higher with 18 cm spacing (Devi et al. 2017).

There is significant reduction in *P. minor, M. indica and Rumex acetosella* densities by increasing wheat seed rate from 120 to 150 kg/ha (NATP Report 2001). There was a significant improvement in wheat yield with ~15% reduction in total DMA by different weed species in wheat after reducing the row spacing from 22.5 to 15 cm (Brar 2002). Likewise, the tiller density of wheat increased, by increasing wheat seed rate from 100 to 150 kg/ha and number of productive tillers and grains per spike decreased by increasing the seed rate, but overall, there was an increase in yield of wheat by ~7–8% (Duary and Yaduraju 2006). At low density of *P. minor,* increase in wheat yield by increasing seed rate from 100 to 150 kg/ha was only 4–5% but at higher densities of *P. minor,* wheat yield increase were up to 16% (Duary and Yaduraju 2006). Criss-cross sowing is a popular technique of wheat sowing. It helps in control of weeds and results into higher yield as compared to conventional line sowing method. Chhokar et al. (2017) reported 2.4% higher yield in criss-cross sown wheat as compared to the line sown wheat. Hussain et al. (2017) found that weed density and weed biomass at the time of wheat harvest was lower by ~18.4 and ~23.4%, respectively, in criss-cross sown wheat as compared to line sown wheat when 100 kg ha^{-1} seed rate was

Table 2 Effect of row spacing on weed biomass and grain yield in wheat

Row spacing (cm)	Weed density (m^{-2})	Grain yield (t/ha)	Reference
15	182.27	2.07	El-Samie et al. (2018)
20	242.60	1.99	
25	315.44	1.94	
LSD (P = 0.05)	0.08	0.03	
16	48.84	4.94	Devi et al. (2017)
18	59.07	5.33	
20	59.83	5.20	
LSD (P = 0.05)	0.19	0.24	

used. Criss-cross sowing of wheat at a spacing of 22.5 cm can control the weeds equal to the unidirectional sowing at 15 cm, but yield is 5% higher in criss-cross sown wheat (Mongia et al. 2005). In addition to crop geometry and seed rate, orientation of crop rows is also an effective weed management tool which is not well explored. Crop orientation decides the amount of solar radiations intercepted by a plant. Borger et al. (2010) reported reduced weed biomass and increased grain yield in east–west oriented wheat crop as compared to north–south oriented one.

Stale seed bed technique

In this weed management approach, the seed-bed is prepared for sowing of wheat crop, but before sowing of crop, light irrigation is applied which stimulates the germination of weed seeds present in upper soil surface and these germinated seeds can be controlled through a light tillage operation or hand-weeding or by a heavy planker. After the control of weeds, the wheat is then sown, having less weed infestation. Thus, stale seed-bed technique reduces the weed seed bank in upper soil layers drastically (Johnson and Mullinix 2000). Rasmussen (2004) also reported a decrease in weed seed bank by stale seed-bed technique in winter wheat. Although it is very effective weed control method but a good management skill is required for planning of these operations timely, otherwise sowing of wheat gets delayed.

Laser land-leveling

Laser land leveling is a novel resource conservation technology which reduces the irrigation duration in wheat by 20–25% and can increase the wheat grain yield by 6–9% in rice–wheat rotation (Aryal et al. 2015). Laser leveling is also useful in reducing the weed population and cost of weeding by ~ 10% (Hussain et al. 2020). Labour required for weeding operation reduces up to 75% owing to precise levelling of the field (Rickman 2002). In uneven fields germination of crops is less and ungerminated patches in the field become conducive for weed growth. Whereas, in laser levelled fields, uniform moisture distribution promotes even crop stand and growth, resulting in lower weed menace (Jat et al. 2006).

Tillage management

Tillage is the physical manipulation of soil, to form a good seed-bed for optimum germination of crops. Tillage influenced the physical (bulk density, soil moisture, temperature and aggregation), chemical (pH and cation exchange capacity) and biological (microbial population and organic matter) properties of soil (Busari and Salako 2013; Stanek-Tarkowska et al. 2018). Tillage also has a role in distribution of weed seeds in soil profile (Clements et al. 1996). Tillage methods adopted for rice cultivation also influence the vertical distribution of *rabi* season weeds. Due to puddling, numbers of *R. dentatus* seeds in upper soil layers were found to be more as compared to *P. minor* seeds. This can be attributed to low seed density of *R. dentatus* (16.2 kg/hectolitre) than *P. minor* (61.3 kg/hectolitre) (Chhokar et al. 2007a). Infestation of broad-leaved weed like *C. arvense, C. arvensis, Malva parviflora* and *R. dentatus* increases (Catizone et al. 1990; Chhokar et al. 2007b; Koch and Hess 1980), whereas *P. minor* population remains low under zero tillage (ZT) wheat as compared to conventional tillage (Usman et al. 2012). Lower infestation of *P. minor* under ZT wheat is attributed to higher soil strength in furrow slice of soil (top 15 cm) under ZT as compared to conventional tillage (Chhokar et al. 2007a). Therefore, due to adoption of ZT in wheat, the weed flora is shifted from narrow-leaved to broad-leaved weeds. But broad-leaved weeds can be easily distinguished from wheat plants and their mechanical control is possible, whereas it is very hard to control narrow-leaved weeds especially *P. minor* and *A. fatua* due to their phenotypic similarity with wheat plants. If weeds are effectively controlled for initial few years in ZT wheat and are not allowed to set seeds, weed seed bank is significantly reduced as the ZT soil is not disturbed and movement of weed seed from lower soil layer towards upper layer is drastically restricted. Besides weed control, the ZT in wheat also reduce the operational cost by ~ 25% and fuel cost by ~ 90% and permit timely sowing of wheat after rice, cotton or pigeon pea harvest (Chauhan et al. 2003; Sharma et al. 2002).

Soil moisture management

Soil moisture is a critical factor which governs the germination and growth of crop as well as weed plants. Wheat is able to germinate in slightly drier soils but germination of weeds like *P. minor* and *R. dentatus* is discouraged in dry soils (Kumar et al. 2013). Singh and Singh (2004) found that pre-sowing irrigation reduced total weed density from 45 to 32 plants m^{-2}, weed dry matter accumulation from 63 to 43 g m^{-2} and increased the wheat grain yield by 12% as compared to the post-sown irrigation. So, managing the soil moisture in such a way that it favors the wheat germination and disfavor the germination of weeds might be an affective ecological technique for controlling weeds in wheat. Sowing of bold-seeded crops at a slightly deeper moist layer, where upper surface is dry can give an initial advantage to crop plants over weeds (Liebman and Mohler 2001).

Nutrient management

Optimum nutrient application is necessary for higher crop yield (Bana et al. 2016). Both crop and weed plants compete for limited amount of nutrients present in the soil. Amount, method and time of fertilizer application are major factors which affect the crop-weed competition. Singh et al. (2015b) found that increasing nitrogen (N) application rate from 120 to 160 kg/ha reduces the total weed density and biomass in wheat (Table 3). Basal application of 50% nitrogen, and then two-split applications of 25% each at crown root initiation (CRI) and flowering stage resulted into lesser weed population and biomass in wheat as compared to 33.3% N, each as basal, at CRI and flowering (Singh et al. 2015b). Therefore, amount, time and method of fertilizer application should be managed properly to give a competitive edge to wheat crop over weeds. Sub surface application of nitrogenous fertilizers disfavors the growth of weeds, whereas, broadcasting encourages weed growth (Blackshaw et al. 2004). Weed growth was also influenced by type of nutrient; nitrogen favors the growth of grassy weeds, whereas, growth of broad leaved weeds were enhanced by phosphatic fertilizers (Chhokar et al. 2012). Seeds of many weed species do not lose their viability even after passing through animal alimentary canal (Pleasant and Schiather 1994; Rahimi et al. 2016), therefore, whenever farm yard manure (FYM) has to be applied it should be well decomposed.

Mechanical weed control

It includes the removal of weed plants through hand-weeding or use of machinery. It is very effective weed control method if properly exercised. In addition to weed control it also aerates the soil. But it requires a lot of energy, time and cost. Along with these requirements, mechanical weed control is very difficult in wheat as weeds like *P. minor* and *A. fatua* look like the wheat plants. Wheel hand hoe with slight modification to match the inter-row spacing can be used to control weeds in wheat grown on light soils, but it is not suitable for heavy soils where wheat is grown after rice harvest. Before tillering, mechanical weed control through spring-tyne harrow was satisfactory in organically grown wheat (Graziani et al. 2012; Rasmussen and Svenningsen 1995). Line-sown flat-bed and furrow irrigated raised bed system (FIRBS) of wheat cultivation are quite suitable for mechanical control of weeds through wheel hoe. Along with possibility of mechanical weeding, weed population remains inherently low in FIRBS system as compared with conventional method (Mollah et al. 2009).

Table 3 Effect of nitrogen scheduling on total weed density and biomass, and wheat yield

Treatments	Total weed density (plants/m^2)	Total weed biomass (g/m^2)	Grain yield (t/ha)	References
Nitrogen rates				Singh et al. (2015a, b)
120 kg/ha	10.04	8.54	4.00	
160 kg/ha	9.19	7.76	4.52	
LSD (P = 0.05)	0.26	0.26	0.11	
Time of nitrogen application				
50% basal + 50% crown root initiation	9.63	8.14	4.30	
50% basal + 25% crown root initiation + 25% flowering	9.4	7.90	4.46	
33.3% basal + 33.3% crown root initiation + 33.3% flowering	9.76	8.41	4.02	
LSD (P = 0.05)	0.31	0.32	0.14	
75% NPK	7.23	5.47	3.69	Prasad (2016)
100% NPK	6.57	4.98	4.24	
125% NPK	5.91	4.50	4.47	
LSD (P = 0.05)	0.25	0.18	2.71	
50 kg N/ha	12b		3.82c	Modhej and Kaihani (2013)
100 kg N/ha	14b		4.72bc	
150 kg N/ha	15ab		5.96ab	
200 kg N/ha	17a		6.08a	

Means followed by a similar lowercase letter within a column are not significantly different ($P < 0.05$) according to Tukey's HSD test

Straw management

Rice residues management particularly in combine-harvested fields is a serious issue for farmers of IGPR who practice RWCS. Burning rice residues for making field ready for sowing of wheat is environmentally unsound practice followed by large number of farmers (Rana et al. 2014b). Moreover, burning of rice residues also facilitates germination of *P. minor*, as after rice harvesting humidity and soil moisture is high and atmospheric temperature is low (20–25 °C in Oct–Nov months). These conditions prevent the soil temperature during straw burning to reach a level that can prove lethal for *P. minor* seeds. Germination of *P. minor* increases by ~ 31% and ~ 82% by burning of rice residues @ 6 t/ha and 12 t/ha, respectively as compared to no burning (Chhokar et al. 2009).

In a field study, the total biomass of three important weed species i.e. *P. minor, R. dentatus* and *Medicago denticulata*, reduced in ZT wheat by 28 and 40% through retention of 5 and 7.5 t/ha rice residues, respectively, as compared to no rice residues. Bana et al. (2020) also observed less weed infestation in direct seeded rice due to residue retention in rice–wheat rotation. ZT wheat with 7 t/ha residues recorded ~ 10% less total weed biomass as compared to conventional tilled wheat (Chhokar et al. 2009).

Future prospects

Rice–wheat cropping system covers around 18 mha worldwide, where an alternative strategy for weed management is needed to overcome excessive herbicidal use problem, particularly in wheat. Though, various ecological approaches discussed in the present review have the potential to overcome weed menace in wheat, but still farmers are largely dependent on herbicidal weed management. Poor productivity of weed competitive cultivars, long duration Basmati varieties delaying wheat planting, non-availability of information on long-term effect of new tillage and crop establishment techniques on weed dynamics and yield stability, less information on newer scientific advancement like use of allelopathy for weed control, nano-technology, and biological weed control are biggest bottlenecks in adoption of ecological weed management approaches. Therefore, future research should focus on developing high yielding weed suppressing wheat cultivars (Worthington and Reberg-Horton 2013), short-duration rice varieties (Akhter et al. 2019), long-term studies for better understanding of weed dynamics under new tillage and crop establishment techniques (Bana et al. 2020), use of allelopathy in weed management (Jabran 2017), nanotechnology (Balah and Pudake 2019) and biological weed control (Schwarzländer et al. 2018) in wheat. Moreover, majority of ecological approaches have been studied in isolation. Combined studies on ecological weed management approaches can be done for developing integrated weed management strategy.

Conclusion

To overcome the emerging threats of excessive herbicide uses and to face the herbicide resistance development problems, there is an urgent need to explore the alternative ways/methods of weed management especially for wheat. Various ecological approaches have the potential to effectively and efficiently manage the weed problem in wheat, but there are several bottlenecks in their adoption. Therefore, these ecological approaches of weed management need further in-depth research, location specific farming system based fine-tuning and refinement including suitable adjustment with modern agronomic advancements. In addition, the researchers should focus on interaction of diverse ecological approaches and their environmental impacts vis-à-vis conventional weed management practices in wheat under rice–wheat cropping system in Indo-Gangetic Plains.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interests.

References

Abd-Elgawad MMM, Elshahawy IE, Abd-El-Kareem F (2019) Efficacy of soil solarization on black root rot disease and speculation on its leverage on nematodes and weeds of strawberry in Egypt. Bull Natl Res Cent 43:175

Akhter M, Mahmood A, Haider Z, Saleem U (2019) Development of an aromatic high yielding basmati rice variety having extra long grains and short duration. J Rice Res 7:204

Arora A, Yaduraju NT (1998) High-temperature effects on germination and viability of weed seeds in soil. J Agro Cr Sci 181:35–43

Aryal JP, Mehrotra MB, Jat ML, Sidhu HS (2015) Impacts of laser land leveling in rice–wheat systems of the north–western indo-gangetic plains of India. Food Sec 7:725–738

Avissar RY, Mahrer L, Margulies KJ (1986) Field ageing of transparent polyethylene mulches: photometric properties. Soil Sci Soc Am J 50:202–205

Bai SH, Ogbourne SM (2016) Glyphosate: environmental contamination, toxicity and potential risks to human health via food contamination. Env Sci Pol Res 23:18988–19001

Balah MA, Pudake RN (2019) Use nano tools for weed control and exploration of weed plants in nanotechnology. In: Pudake R,

Chauhan N, Kole C (eds) Nanoscience for sustainable agriculture. Springer, Cham, pp 207–231
Bana RS, Shivay YS, Tyagi VK (2015) Effect of summer forage crops and phosphogypsum–enriched urea on soil quality, nitrogen-use efficiency and quality of Basmati rice (*Oryza sativa*) and their residual effect on succeeding wheat (*Triticum aestivum*). Ind J Agri Sci 85:531–538
Bana RS, Pooniya V, Choudhary AK, Rana KS, Tyagi VK (2016) Influence of organic nutrient sources and moisture management on productivity, bio-fortification and soil health in pearlmillet (*Pennisetum glaucum*) + clusterbean (*Cyamopsis tetragonaloba*) intercropping system of semi-arid India. Ind J Agri Sci 86:1418–1425
Bana RS, Deepak S, Nain MS, Hement K, Vipin K, Seema S (2020) Weed control and rice yield stability studies across diverse tillage and crop establishment systems under on-farm environments. Soil Till Res 204:104729
Bhowmik PC (2010) Current status of herbicide resistant weeds around the globe. J Cr Weed 6:33–43
Blackshaw RE (1994) Differential competitive ability of winter wheat cultivars against downy brome. Agro J 86:649–654
Blackshaw RE, Molnar LJ, Janzen HH (2004) Nitrogen fertilizer timing and application method affect weed growth and competition with spring wheat. Wd Sci 52:614–622
Borger CP, Hashem A, Pathan S (2010) Manipulating crop row orientation to suppress weeds and increase crop yield. Weed Sci 58:174–178
Brar LS (2002) Current status of herbicide resistance in Punjab and its management strategies. In: Proceedings of International Workshop on Herbicide Resistance and zero-tillage in Rice–wheat cropping system, March 4–6, CCS HAU, Hisar, India, pp 6–10
Busari MA, Salako FK (2013) Effect of tillage, poultry manure and NPK fertilizer on soil chemical properties and maize yield on an Alfisol at Abeokuta, south-western Nigeria. Nig J Soil Sci 23:206–218
Catizone P, Tedeschi M, Baldoni G (1990) Influence of crop management on weed population and wheat yield. Proceeding of a EWRS Symposium, Helsinki and Finland 4–6
Chauhan BS, Yadav A, Malik RK (2001) Competitive wheat genotypes under zero tillage-an important tool to manage resistant *Phalaris minor*. Ind J Weed Sci 33:75–76
Chauhan DS, Sharma RK, Chhokar RS (2003) Comparative performance of tillage options in wheat (*Triticum aestivum*) productivity and weed management. Ind J Agri Sci 73:402–406
Chhokar RS, Malik RK (1999) Effect of temperature on the germination of *Phalaris minor* Retz. Ind J Weed Sci 31:73–74
Chhokar RS, Malik RK (2002) Isoproturon resistant *Phalaris minor* and its response to alternate herbicides. Weed Tech 16:116–123
Chhokar RS, Sharma RK, Jat GR, Pundir AK, Gathala MK (2007a) Effect of tillage and herbicides on weeds and productivity of wheat under rice–wheat growing system. Crop Prot 26:1689–1696
Chhokar RS, Sharma RK, Pundir AK, Singh RK (2007b) Evaluation of herbicides for control of *Rumex dentatus*, *Convolvulus arvensis* and *Malva parviflora*. Ind J Weed Sci 39:214–218
Chhokar RS, Sharma RK, Singh RK, Gill SC (2008) Herbicide resistance in little seed canary grass (*Phalaris minor*) and its management. In: Proceedings of 14th Australian Agronomy Conference Adelaide, South Australia. pp 106
Chhokar RS, Singh S, Sharma RK, Singh M (2009) Influence of straw management on *Phalaris minor* control. Ind J Weed Sci 41:150–156
Chhokar RS, Ramesh KS, Sharma I (2012) Weed management strategies in wheat—a review. J Wheat Res 4:1–21
Chhokar RS, Ram H, Kumar V (2014) Integrated weed management. In Shukla RS, Mishra PC, Chatrath R, Gupta RK, Tomar SS, Sharma I (eds), Recent trends on production strategies of wheat in India: Jawaharlal Nehru Krishi Vishwa Vidyalaya (JNKVV), Jabalpur and ICAR-Indian Institute of Wheat and Barley Research, pp 155–171
Chhokar RS, Sharma RK, Gill SC, Kumar R (2017) Influence of tillage, cultivar, seed rate and planting geometry on wheat yield. J Wht Res 9:12–20
Choudhary AK, Rana DS, Bana RS, Pooniya V, Dass A, Rana KS, Kaur R (2015) Agronomy of oilseed and pulse crops. [ISBN: 978-93-83168-21-7]. Post Graduate School, IARI, New Delhi and ICAR, New Delhi, India, pp 218
Choudhary AK, Bana RS, Pooniya V (2018) Integrated crop management practices for enhancing productivity, resource-use efficiency, soil health and livelihood security (ISBN 978-93-83168-32-3), ICAR–Indian Agricultural Research Institute, New Delhi, pp 217
Clements D, Benoit D, Murphy S, Swanton C (1996) Tillage effects on weed seed return and seed-bank composition. Weed Sci 44:314–322
Colbach N, Gardarin A, Moreau D (2019) The response of weed and crop species to shading: Which parameters explain weed impacts on crop production? Fl Cr Res 238:45–55
Das TK, Yaduraju NT (2008) Effect of soil solarization and crop husbandry practices on weed species competition and dynamics in soybean-wheat cropping system. Ind J Weed Sci 40:1–5
Devi S, Hooda VS, Singh J, Kumar A (2017) Effect of planting techniques and weed control treatments on growth and yield of wheat. J App Nat Sci 9:1534–1539
Duary B, Yaduraju NT (2006) Effect of sowing date, seed rate of wheat and different densities of little seed canary grass. J Cr Weed 2:5–8
Economic survey. 2020. Economic survey report 2019–20 Ministry of Finance, Government of India, New Delhi. https://www.indiabudget.gov.in/economicsurvey/.
Egley GH (1983) Weed seed and seedling reductions by soil solarization with transparent polyethylene sheets. Weed Sci 31:404–409
El-Samie FS, Abd Megawer Ekram A, Mekdad AAA, Mohamed Sara M (2018) Effect of inter row spacing with or without weed control in Wheat (*Triticum aestivum* L.). Egypt J Agron The 15th Int Conf Crop Science, pp 41 – 48.
Garrison AJ, Miller AD, Ryan MR, Roxburgh SH, Shea K (2014) Stacked crop rotations exploit weed-weed competition for sustainable weed management. Weed Sci 62:166–176
Gharde Y, Singh PK, Dubey RP, Gupta PK (2018) Assessment of yield and economic losses in agriculture due to weeds in India. Crop Prot 107:12–18
Graziani F, Onofri A, Pannacci E, Tei F, Guiducci M (2012) Size and composition of weed seed bank in long-term organic and conventional low-input cropping systems. Europ J Agro 39:52–61
Grey T, Braxton L, Richburg J (2012) Effect of wheat herbicide carryover on double-crop cotton and soybean. Weed Tech 26:207–212
Hossain A, Chowdhury MAS, Jahan T, Sarker MAI, Akhter MM (2010) Competitive ability of wheat cultivars against weeds. Bang J Weed Sci 1:65–72
Hussain I, Khan EA, Hassan G, Gul J, Ozturk M, Alharby H, Hakeem KR, Alamri S (2017) Integration of high seeding densities and criss cross row planting pattern suppresses weeds and increases grain yield of spring wheat. J Env Bio 38:1139–1145
Hussain M, Latif MT, Ahmad I, Sher F, Bajwa HM, Asghar M, Faisal N, Ullah S, Sanaullah BA (2020) Economic evaluation of laser land leveling on direct seeded rice in rice–wheat cropping system: a field survey. Gl Sci J 8:105–117
Ibrahim AF, Kandil AAA, El-Hattab H, Eissa AK (1986) Effect of sowing date and weed control on grain yield and its components in some wheat cultivars. J Agro Cr Sci 157:199–207
Jabran K (2017). Wheat allelopathy for weed control. In: K. Jabran, Manipulation of Allelopathic Crops for Weed Control. Springer Briefs in Plant Science, Springer International Publishing AG, Switzerland. pp. 13–20

Jat RS, Nepalia V, Chaudhary PD (2003) Influence of herbicide and methods of sowing on weed dynamics in wheat (*Triticum aestivum*). Ind J Weed Sci 35:18–20

Jat ML, Chandna P, Gupta R, Sharma SK, Gill MA (2006) Laser land leveling: a precursor technology for resource conservation. Rice–wheat consortium technical bulletin series 7. Rice–wheat consortium for the Indo-Gangetic Plains, New Delhi, India pp 48

Johnson WC, Mullinix B (2000) Evaluation of tillage implements for stale seedbed tillage in peanut (*Arachis hypogaea*). Weed Tech 14:519–523

Khan MA, Khan BM, Anees A, Nawaz A, Khan R, Khan H, Shah HU (2012) Soil solarization: an organic weed-management approach in cauliflower. Comm Sl Sci Pl Anal 43:1847–1860

Koch W, Hess M (1980) Weeds in wheat. Wheat Documenta, Ciba-Geigy. Ciba_Geigy Ltd., Basle, Switzerland, pp 33–40

Kumar V, Singh S, Chhokar R, Malik R, Brainard D, Ladha J (2013) Weed management strategies to reduce herbicide use in zero-till rice–wheat cropping systems of the Indo-Gangetic plains. Weed Tech 27:241–254

Kurdyukova OM (2018) Seed production capability of monocotyledonous and dicotyledonous weeds in segetal and ruderal habitats. Ukr J Eco 8(1):153–157

Lemerle D, Verbeek B, Cousens RD, Coombes NE (1996) The potential for selecting wheat varieties strongly competitive against weeds. Weed Res 36:505–513

Liebman M, Mohler CL (2001) Ecological management of agricultural weeds. pp 210–269.

Malik RK, Singh S (1995) Little seed canary grass (*Phalaris minor* Retz.) resistance to isoproturon in India. Weed Tech 9:419–425

Modhej A, Kaihani A (2013) Effect of nitrogen fertilizer and herbicides on weed control and wheat grain yield under subtropical conditions. Int J Biosci 3:1–7

Mollah MIU, Bhuiya MSU, Kabir MH (2009) Bed planting—a new crop establishment method for wheat in rice–wheat cropping system. J Agric Rural Dev 7(1 & 2):23–31

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

Nakka S, Jugulam M, Peterson D, Asif M (2019) Herbicide resistance: development of wheat production systems and current status of resistant weeds in wheat cropping systems. The Cr J 7:750–760

NATP (2001) Annual Report of NATP Project on conservation tillage in rice–wheat cropping system (2000–2001). CCS HAU Rice Research Station, Kaul publication, Haryana, India, p 24

Om H, Kumar S, Dhiman SD (2004) Biology and management of *Phalaris minor* in rice–wheat system. Crop Prot 23:1157–1168

Patel RH, Shroff J, Dutta S, Meisheri TG (2005) Weed dynamics as influenced by soil solarization—a review. Agric Rev 26:295–300

Pleasant JM, Schlather KJ (1994) Incidence of weed seed in Cow (*Bos* sp.) manure and its importance as a weed source for crop land. Weed Tech 8:304–310

Prasad KM (2016) Effect of fertility levels and different herbicides on weeds and yield of wheat (*Triticum aestivum* L.). PhD thesis submitted to Sardar Vallabhbhi Patel Universiy of Agriculture and Technology Meerut, Uttar Pradesh, India, pp 274.

Raghaven D (1964) Agriculture in ancient India. ICAR-publication, ICAR, New Delhi, India, p 164

Rahimi S, Mashhadi HR, Banadaky MD, Mesgaran MB (2016) Variation in weed seed fate fed to different holstein cattle groups. PLoS ONE 11:1–15

Rana KS, Choudhary AK, Bana RS, Sepat S (2014b) Natural resource management for sustainable agriculture. [ISBN: 978–93–83168–06–4]. Post Graduate School, IARI, New Delhi 110 012, India, pp 342

Rana KS, Choudhary AK, Sepat S, Bana RS (2014a) Advances in field crop production. [ISBN: 978–93–83168–08–8]. Post Graduate School, IARI, New Delhi 110 012, India, pp 475.

Rana KS, Choudhary AK, Bana RS (2018) Climate resilient agro-technologies for enhanced crop and water productivity under water-deficit agro-ecologies' (ISBN 978-93-83168-31-6). ICAR-Indian Agricultural Research Institute, New Delhi, p 214

Rasmussen IA (2004) The effect of sowing date, stale seedbed, row width and mechanical weed control on weeds and yields of organic winter wheat. Weed Res 44:12–20

Rasmussen J, Svenningsen T (1995) Selective weed harrowing in cereals. Bio AgricHorti 12:29–46

Ray DK, Mueller ND, West PC, Foley JA (2013) Yield trends are Insufficient to double global crop production by 2050. PLoS ONE 8:1–8

Rickman JF (2002) Manual for laser land leveling, Rice–wheat Consortium Technical Bulletin Series 5. New Delhi-12, India: Rice–wheat Consortium for the Indo-Gangetic Plains, pp 24.

Schwarzländer M, Hinz HL, Winston RL (2018) Biological control of weeds: an analysis of introductions, rates of establishment and estimates of success, worldwide. Biocontrol 63:319–331

Sharma RK, Chhokar RS, Rani V, Gathala MK, Kumar A (2002) Productivity, economics and energy requirement of rice–wheat system. In: Malik RK, Balyan RS, Yadav A, Pahwa SK (eds) Herbicide resistance management and zero tillage in rice–wheat cropping system. CCSHAU, Hisar, pp 127–130

Singh R, Singh B (2004) Effect of irrigation time and weed management practices on weeds and wheat yield. Ind J Weed Sci 36:25–27

Singh S, Malik RK, Panwar RS, Balyan RS (1995) Influence of sowing time on winter wild oat (*Avena ludoviciana*) control in wheat (*Triticum aestivum*) with isoproturon. Weed Sci 43:370–373

Singh AK, Gopala Krishnan S, Nagarajan M, Vinod KK, Bhowmick PK, Atwal SS, Seth R, Chopra NK, Chander S, Singh VP, Prabhu KV, Singh D, Kumar S, Ravindran G (2014) Basmati rice variety, Pusa Basmati 1509. Ind J Gen Pl Bre 74:123

Singh AP, Bhullar MS, Yadav R, Chowdhury T (2015) Weed management in zero-till wheat. Ind J Weed Sci 47:233–239

Singh M, Singh MK, Singh SP, Sahu R (2015) Herbicide and nitrogen application effects on weeds and yield of wheat. Ind J Weed Sci 47:125–130

Singh T, Satapathy BS, Gautam P, Lal B, Kumar U, Saikia K, Pun KB (2017) Comparative efficacy of herbicides in weed control and enhancement of productivity and profitability of rice. ExpAgri 54:363–381

Stanek-Tarkowska EA, Czyż AR, Sławiński DC (2018) Effects of reduced and traditional tillage on soil properties and diversity of diatoms under winter wheat. Int Agrophys 32:403–409

Usman K, Ullah I, Khan SM, Khan MU, Ghulam S, Khan MA (2012) Integrated weed management through tillage and herbicides for wheat production in rice–wheat cropping system in North-western Pakistan. J Int Agri 11(6):946–953

Walia US, Singh M (2005) Competitive ability of wheat cultivars with associated weeds. J Pl Sci Res 21:32–39

Worthington M, Reberg-Horton C (2013) Breeding cereal crops for enhanced weed suppression: optimizing allelopathy and competitive ability. J Chem Ecol 39(2):213–231

Yadav A, Malik RK (2005) Herbicide resistant *Phalaris minor* in wheat—a sustainability issue. Department of Agronomy and Directorate of Extension Education, CCSHAU, Hisar, p 152

Yadav A, Sirohi RM, Chauhan BS, Bellinder R, Malik RK (2002) Alarming contamination of wheat produce with resistant *Phalaris minor*. Pestology 26:41–44

Yaduraju NT, Ahuja KN (1997) Effect of planting methods and seed rates on grass weed competition in tall wheat cultivars. Ind J Weed Sci 29:43–45

Yenish JP, Young FL (2004) Winter wheat competition against jointed goat grass (*Aegilops cylindrica*) as influenced by wheat plant height, seeding rate, and seed size. Weed Sci 52:996–1001

Authors and Affiliations

Vipin Kumar[1] · R. S. Bana[1] · Teekam Singh[1] · Ganpat Louhar[2]

[1] Division of Agronomy, ICAR-Indian Agricultural Research Institute, New Delhi 110 012, India

[2] Division of Soil Science and Agricultural Chemistry, ICAR-IARI, New Delhi, India