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Review Article

Weed management strategies in wheat-A review

Rajender Singh Chhokar*, Ramesh Kumar Sharma and Indu Sharma

**Directorate of Wheat Research,
Karnal 132 001, India**

Abstract

Weed infestation is one of the major biotic constraints in wheat production. Wheat is infested with diverse type of weed flora, as it is grown under diverse agroclimatic conditions, different cropping sequence, tillage and irrigation regimes. The yield losses due to weeds vary depending on the weed species, their density and environmental factors. Among weeds, *Phalaris minor* Retz. is single most dominant grassy weed in northern Indian plains causing significant yield losses. For controlling weeds in wheat, growers mostly rely on herbicides due to cost and time effectiveness. For control of diverse weed flora in wheat combination of herbicides either as tank mixture, if compatible (sulfosulfuron + metsulfuron; mesosulfuron + iodosulfuron) or as sequential, if not compatible (fenoxaprop or clodinafop or pinoxaden with metsulfuron or 2, 4-D) are required. Further, the herbicide efficacy can be improved by use of adjuvants, safeners and proper spray technology. A greater focus on spray technology by imparting training to growers, field functionaries and industry personnel is required. However, sole dependence on herbicides is also not desirable as it contributes to shift towards difficult-to-control weeds and the rapid evolution of herbicide resistance, which is a threat for sustainable wheat production. Presently some of *P. minor* populations have shown the evolution of multiple herbicide resistance across three modes of action (Photosynthesis at photosystem II site A, ACCase and ALS inhibitor). Studies on the quantification and characterization of herbicide resistance in *P. minor* have revealed that some of the populations had GR_{50} (50% growth reduction) values for clodinafop > 12 times greater than that of the most S (susceptible) population. Population resistant to clodinafop exhibited cross-resistance to fenoxaprop (fop group), tralkoxydim (dim group) and pinoxaden (den group). Similarly, population resistant to sulfosulfuron showed cross-resistance to mesosulfuron and pyroxsulam. Management strategies must be developed to prevent selection and spread of herbicide resistant populations. For control of multiple herbicide resistant *P. minor* populations (resistant to isoproturon, clodinafop and sulfosulfuron) pendimethalin, trifluralin, pyroxasulfone, metribuzin and terbutryn are effective. Also, the multiple herbicide resistant populations showed sensitivity to glyphosate and paraquat. However, for efficient weed management, the non-chemical weed management tactics should be adopted in conjunction with chemicals (like herbicide mixture and rotation, optimum spray time, dose and methods). Some of the non-chemical agronomic strategies like tillage, sowing time, sowing methods, competitive crop cultivars, higher crop density, closer spacing, irrigation, fertilization, crop rotation and sanitation practices (weed-free crop seeds and manure) can be adjusted and adopted in such a manner that they provide the competitive edge to the crop over weeds. As the introduction of herbicide having new mode of action has slowed down, therefore, there is need to revive some of the old herbicides (*viz.* pendimethalin and trifluralin) as well as to develop wheat varieties tolerant to less selective herbicides like metribuzin and resistant to non-selective herbicides like glyphosate and glufosinate. Integration of knowledge of weed biology and non-chemical methods of weed control with chemical methods will help in increasing the life of existing herbicides and make the weed management cost-effective and efficient.

Introduction

Wheat is an important crop worldwide and in India, its production increased from a mere 11.0 million tons during 1960-61 to 93.9 million tons during 2011-12. This more than eight-fold increase in wheat production was mainly due to the adoption of short stature high yielding varieties, increased fertilizers use, irrigation and herbicides. 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. Weeds are regarded as most disdain to crop production and account for about one third of total losses caused by all the pests. Among various wheat based cropping system, rice-wheat is major one, occupying about 10.0 million hectare in India and worldwide this system occupies about 24 million hectare area (Ladha *et al*., 2000; Timsina and Connor, 2001). Weeds cause significant annual regional productivity losses in rice-wheat system (Harrington *et al*., 1992). Weed infestation is one of the major factors limiting crop productivity. For realizing full genetic yield potential of the crop, the proper weed control is one of the essential ingredients. Weeds not only reduce the yield but also make the harvesting operation difficult. Therefore, for sustaining food grain production to feed ever-increasing population and ensuring food security, effective weed management is very essential.

* Corresponding author email: *rs_chhokar@yahoo.co.in*

Weed competition

Introduction of high yielding dwarf wheat varieties changed the spectrum of weed flora from dominance of broadleaf weeds in the 1960s to mixed flora of broadleaf 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. Herbicides were introduced in 1979-80, weed flora changed in favour of complex weeds species in late 1980s and then again in favour of *P. minor* during the early 1990s with evolution of herbicide resistance

(Malik and Singh, 1993). 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.

Weeds compete with crop plants for moisture, nutrients, light and space, thereby depriving the crop of vital inputs. Therefore, weed competition is one of the most important constraints in crop production. Weed-crop competition begins when crop plants and weeds grow in close proximity and their root or shoot system overlaps. The competition becomes severe due to more smothering effect, when weeds emerge earlier than the crop. 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 zone ranges from 20 to 32 per cent. The yield losses (Fig 1) in North Western Plains Zone (NWPZ), Northern Hills Zone (NHZ) and North Eastern Plains Zone (NEPZ), are higher (Mongia *et al.,* 2005) compared to Peninsular Zone (PZ) and Central Zone (CZ). The losses depend on weed species and density, time of emergence, wheat cultivar, planting density, soil and environmental factor (Afentouli and Eleftherohorionos, 1996; Chhokar and Malik, 2002; Malik and Singh, 1993; Cudney and Hill, 1979; Khera *et al*., 1995; Malik and Singh, 1995; Mehra and Gill 1988). 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 herbicide 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). Wild oat is another grass weed, which is highly competitive.

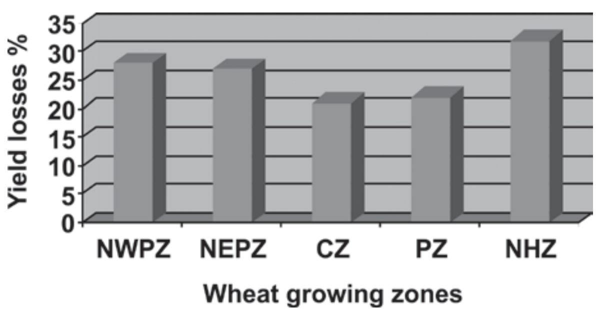

Fig 1. Yield losses in different wheat growing zones due to weeds (Mongia *et al*., 2005)

Before green revolution, weeds were not a serious problem in wheat cultivation because of the inherent better competing habit of wheat cultivar being tall and secondly because of the relatively less aggressive nature of weeds which were mostly broadleaf annuals. *P. minor* and wild oat which remained inconspicuous in the tall wheat assumed serious proportions in dwarf wheat in major wheat growing areas of the country. Both, wild oats and *Phalaris minor* belong to the grass family and have similar habit of growth and development as wheat. It is very difficult to distinguish them from the wheat plants in the vegetative phase. Moreover, these weeds grow much taller than the dwarf wheat, cause partial shading of wheat plants, lodge severely due to weak stem and smother the wheat plants causing heavy grain yield reductions. Depending on the intensity of these weeds, yield losses in the range of 10 to 80% may be affected. In most severe cases there may be complete crop failure especially where management of the crop is not good. Density and yield comparisons revealed that wheat and wild oat were equally competitive on per plant basis. This was true even though wild oat had less leaf area per plant than did wheat. Wild oat has a height advantage over wheat in late season which results in shading and yield reduction (Cudney *et al*., 1991).

The critical period of weed control in wheat is 30-45 days after sowing and crop should be kept weed free during this period. Majority of the farmers are not adhering to this critical period for the management of weeds and they mostly delay the herbicide application.

Weed flora and weed flora shift

Weed flora of crop differs from area to area and field to field depending on environmental conditions, irrigation, fertilizer use, soil type, weed control practices and cropping sequences (Anderson and Beck, 2007; Chhokar and Malik, 2002; Chhokar *et al*., 2007a&b; Dixit *et al*., 2008a&b; Froud-Williams *et al*., 1983). The predominant weeds associated with wheat crop in different wheat growing zones in India are mentioned in Table 1.

Although, both grass and broadleaf weeds infest wheat crop, however grass weeds pose more serious problem than broadleaf weeds. Yellow thistle (*Carthamus oxycantha* Beib) was main weed before green revolution but increased irrigation and tillage along with increased cropping intensity have almost eliminated this weed. Similarly, wild oat has been eliminated from heavy soils where rice is grown, although, maize-wheat rotation allows its gradual build up.

Table 1. Major weeds infesting in different wheat growing zones

Zone	Weed species generally infesting
NHZ [J&K (except Jammu and Kathua distt.); H.P. (except Una and Paonta Valley); Uttaranchal (except Tarai area); Sikkim and hills of West Bengal and N.E. States]	*Anagallis arvensis* L., *Avena fatua* L., *Avena ludoviciana* Dur., *Capsella bursa-pastoris* (L.) Medik., *Chenopodium album* L., *Convolvulus arvensis* L., *Coronopus didymus* L., *Fumaria parviflora* Lamk., *Juncus bufonius* L., *Lathyrus aphaca* L., *Lolium temulentum* L., *Medicago denticulata* L., *Melilotus alba* Lamk., *Phalaris minor* Retz., *Poa annua* L., *Polygonum nepalense* Meissn., *Ranunculus spp.*, *Sorghum halepense* (L.) Pers., *Stellaria media* (L.) Vallars, *Veronica persica* Poir., *Vicia sativa* L.
NWPZ [Punjab, Haryana, Delhi, Rajasthan (except Kota and Udaipur divisions) and Western UP (except Jhansi division), parts of J&K (Jammu and Kathua distt.) and parts of HP (Una distt. and Paonta valley) and Uttaranchal (Tarai region)]	*Alhagi pseudoalhagi* (Beib.) Desv., *Anagallis arvensis* L., A*rgemone mexicana* L., *Avena fatua* L., *Avena ludoviciana* Dur., *Asphodelus tenuifolius* Cav., *Carthamus oxycantha* Beib, *Chenopodium album* L., *Chenopodium murale* L., *Convolvulus arvensis* L., *Coronopus didymus* L., *Circium arvense* L., *Daucus carota* L., *Euphorbia helioscopia* L., *Fumaria parviflora* Lamk., *Lathyrus aphaca* L., *Malva neglecta, Malva parviflora*, *Medicago denticulata* Willd, *Melilotus alba* Lamk., *Melilotus indica* All., *Phalaris minor* Retz., *Poa annua* L., *Polygonum plebejum* R. Br., *Polypogon monsplensis* (L.) Desf., *Rumex dentatus* L., *Solanum nigrum*, *Spergula arvensis* L., *Stellaria media* (L.) Vallars, *Trigonella incise* Benth., *Trigonella polycerata*, *Veronica agrestis* L., *Vicia sativa* L., *Vicia hirsute* Koch.,
NEPZ (Eastern UP, Bihar, Jharkhand, Orissa, West Bengal, Assam and plains of N.E. States)	*Ageratum conyzoides* L., *Alternanthera sessilis* (L.), *Anagallis arvensis* L., A*rgemone mexicana* L., *Asphodelus tenuifolius* Cav., *Avena fatua* L., *Brachiaria mutica*, *Brachiaria ramose*, *Cannabis sativa* L., *Celosia argentea* L., *Chenopodium album* L., *Chenopodium ficifolium*, *Chenopodium murale* L., *Cirsium arvense* (L.), *Commelina benghalensis* L., *Convolvulus arvensis* L., *Coronopus didymus* (L.), *Cyanotis cuculata*, *Cynodon dactylon* Pers., *Cyperus iria* L., *Cyperus rotundus* L., *Desmodium triflorum* (L.) DC., *Digitaria ciliaris* (Retz) Koel., *Digitaria sanguinalis* (L.) Scop., *Drymaria vilosa*, *Echinochloa colona* (L.) Link, *Eclipta alba*, *Eclipta prostrate* L., *Eleusine indica* Gaerts., *Eragrostis ferroginia* Beauv., *Euphorbia dracunculoides*, *Fibristylis miliacea*, *Fumaria indica* Pugsley, *Fumaria parviflora*, *Galinsoga parviflora* Cav., *Gnaphalium pensylvanicunm* Willd., *Gnaphalium purpureum* , *Grangea maderaspatana* (L.) Poir., *Lathyrus aphaca* L., *Lathyrus sativa* L., *Leucas aspera*, *Ludwigia perennis*, *Medicago denticulata*, *Melilotus alba* Lamk., *Melilotus indica* All., *Mimosa pudica* L., *Murdannia nudiflora*(L.) Brenan, *Oxallis carniculata* L., *Panicum repens* L., *Parthenium hysterophorus* L., *Paspalum scorbiculatam* L., *Phalaris minor* Retz., *Physalis minima*, *Poa annua* L., *Polygonum barbatum* L., *Polygonum erectum*, *Polygonum plebejium* R. Br., *Polypogon monsplensis* (L.) Desf., *Rumex dentatus* L., *Scirpus articulates*, *Solanum nigrum, Spergula arvensis* L., *Sporoboles indicus* (L.) R.Br. Var.diader, *Stellaria media* (L.) Vallars, *Vicia hirsute* Koch., *Vicia sativa*, *Xanthium stumarium*,
CZ (Madhya Pradesh, Chhattisgarh, Gujarat, Kota and Udaipur divisions of Rajasthan and Jhansi division of Uttar Pradesh)	*Achyranthus aspera* L., *Alhagi pseudolhagi* (Beib.) Desv., *Amarantus viridis* L., *Anagallis arvensis* L., *Argemone maxicana* L., *Asphodelus tenuifolius* Cav., *Avena fatua* L., *Avena ludoviciana* Dur., *Boerhaavia* spp., *Brassica kaber , Brassica sinensis, Chenopodium album* L., *Chenopodium murale* L., *Chrozophera perviflora* L., *Cichorium intybus* L., *Cirsium arvense* L., *Convolvulus arvensis* L., *Cynodon dactylon* Pers., *Cyperus iria* L., *Cyperus rotundus* L., *Dactyloctenium aegyptium* L., *Digera arvensis*, *Digitaria adscendens, Dinebra retroflexa* (Vahl.) Panzer, *Echinochloa colona* (L.) Link, *Eclipta alba*, *Eleusine indica* Gaerts., *Eragrostis cilienensis* (All) Link., *Eragrostis major, Euphorbia geniculata* Ortega, *Euphorbia hirta* L., *Fumaria parviflora, Lathyrus aphaca* L., *Launaea asplenifolia* (willd.) Hook. f., *Medicago denticulata, Melilotus alba* lamk., *Melilotus indica* All., *Melilotus parviflora, Melilotus sativa, Melotropicum indicum, Parthenium hysterophorus* L., *Phalaris minor* Retz., *Phyllanthus fraternus* Webster., *Physalis minima*, *Ranunculus acutus, Rumex dentatus* L., *Solanum nigrum*, *Sonchus asper* (L.) Hill., *Spergula arvensis* L., *Sphaeranthus indicus* L., *Stellaria media* (L.) Scop., *Suaeda maritime* (L.) Dum., *Tephrosia pururea*, *Tribulus terrestris* L., *Tridax procumbens* L., *Vicia hirsute* Koch., *Vicia sativa, Xanthium strumarium*,
PZ (Maharashtra, Karnataka, Andhra Pradesh, Goa, plains of Tamil Nadu)	*Alternanthera sessilis* L., *Amarantus graceizans* L., *Anagallis arvensis* L., *Argemone mexicana* L., *Asphodelus tenuifolius* Cav., *Avena fatua* L., *Bidens pilosa*, *Brachiaria eruciformis* L., *Brassica arvensis* L., *Cassia spp.*, *Celosia argentia*, *Chenopodium album* L., *Commelina benghalensis* L., *Convolvulus arvensis* L., *Chrozophera perviflora* L., *Cynodon dactylon* Pers., *Cyperus rotundus* L., *Digera arvensis*, *Digitaria adscendens, Dinebra retroflexa, Echinochloa colona* (L.) Link, *Euphorbia hirta* L., *Lactuca runcinata* DC., *Lagascea mollis*, *Leucas aspera, Melilotus alba* Lamk., *Parthenium hysterophorus* L., *Phyllanthus spp.*, *Portulaca oleracea* L., *Physalis minima*, *Setaria verticillata*, *Sonchus wightianus* DC., *Spergula arvensis* L., *Sphaeranthus senegalensis* DC., *Trianthema portulacastrum*, *Zizipus jujube* Lamk.

Among grass weeds, *Phalaris minor* Retz. and among broad-leaved weeds, *Rumex dentatus* L. and *Medicago denticulata* are of major concern in irrigated wheat under rice-wheat system in India (Singh *et al.*, 1995a; Chhokar *et al.*, 2006; Balyan and Malik, 2000). *P. minor* is major problem in heavy soils, whereas, wild oat is more prevalent in light textured soil. Both *P. minor* and *Rumex 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 made it a single weed species limiting wheat productivity in the North Western plains of India.

For the control of isoproturon-resistant *P. minor,* clodinafop, fenoxaprop and sulfosulfuron have been found effective (Chhokar and Malik, 2002; Chhokar *et al.*, 2006). Clodinafop and fenoxaprop control only grasses, whereas, sulfosulfuron controls grasses and some of the broadleaf weeds. The continuous dependence on a single herbicide for a long time, besides resistance development, also leads to a shift in the weed flora (Chancellor, 1979). In areas where the farmers are continuously using graminicides like clodinafop, fenoxaprop or pinoxaden, and not supplemented with broad-leaf weed herbicides (Chhokar and Malik, 2002; Chhokar *et al.*, 2008b), the broad-leaf weed flora particularly *Rumex* spp. have increased. Continuous use of isoproturon also led to increased infestation of *Medicago denticulata, Convolvulus arvensis, Cirsium arvense.* Therefore, for broad-spectrum weed control combination of herbicides as well as weed control methods is essential.

Weed control measures

The various weed management practices can be grouped into three broad categories namely cultural and preventive; physical or mechanical; and chemical weed control. These practices are discussed as under.

A preventive and cultural measures

Preventive measures such as use of clean seed and manures and cultural practices such as time and method of sowing, crop density and geometry, crop rotation, crop varieties, dose, method and time of fertilizer application, time and method of irrigation have pronounced effect on weed-crop interference.

Use clean wheat seed free from weed seeds: Crop seed contaminated with weed seeds is a major factor responsible for the spreading of weeds. Recent drill box surveys revealed that majority of the farmer's wheat seeds contain weed seeds particularly *P. minor*. Farmers should use cleaned seed or certified seed. Contaminated seeds reduces crop seed rate thereby reducing yield.

Sowing time: Date of sowing should be adjusted in such a manner that it is unfavorable for the weed seed germination without hampering the crop yield. Early sown wheat (Last week of October) reduces *P. minor* infestation compared to late sown. In early sown wheat temperature is not optimum for *P. minor* germination (Chhokar *et al*, 1999). Contrary to it, population of wild oat (*Avena ludoviciana*) is more in early sown wheat compared to late sown (Singh *et al.*, 1995c). However, it is important not to deviate wheat seeding much from optimum planting time otherwise yields will be reduced.

Crop rotation: Crop rotation is an important component of integrated weed management. Weeds with the same life cycle as the crop tend to increase under monoculture. Inserting crop having different seeding and maturity time can break the life cycle of some economically important annual weeds. An important reason for rotating crops is to deplete the soil weed seed bank. Growing alternate crops in place of wheat for two or more years, soil weed seed banks decline to low levels where they can be more easily managed. Weeds having more longevity require more cycles of crop rotation. Crop rotation has been found a very effective cultural practice in breaking the association of problematic weeds like *P. minor* in wheat. Rotating the wheat fields with other crops like sunflower, sugarcane or berseem helps in reducing the population of *P. minor*. Also, inclusion of berseem or oats for fodder once in three year reduces the weed infestation. Replacement of wheat by an alternative crop, or substituting short duration crops, such as potato and vegetable pea in between rice and wheat sequence can also help in *P. minor* management (Fig. 2). Besides lower weed population, rice-pea/potato-wheat, cropping sequence provides higher system productivity leading to greater profit.

A survey has shown that resistance to isoproturon in *P. minor* was observed in 67% of fields under rice-wheat rotations, compared to 8, 9 and 16% when rice-berseem-sunflower-wheat, sugarcane-vegetables-wheat and cotton-pigeonpea-wheat, respectively, were rotated (Malik and Singh, 1995). However, implementation of crop rotation on a large area is impossible due to certain constraints (marketing of produce, risk of crop failure or food security).

Row spacing and seeding rate: The increased competitive ability of wheat plant with weeds can be achieved by increasing plant population by increasing the seed rate or reducing the space for weeds by closer spacing and cross sowing. The higher density and closer spacing smother weeds due to better early canopy coverage. When moisture is not a limiting factor, narrow rows and increased crop density offer advantages for weed control. Narrow row spacing can improve weed control because weeds are smaller and more easily controlled with herbicides than they are in wide row spacing (Table 2). Closer row spacing of 15 centimetre with 50 per cent higher seed rate and cross sowing showed distinct advantage in reducing the weed population and dry weight. Moreover, cross sowing has been found to have favourable effect on crop yield by providing better orientation of plants. Closer or criss-cross sowing can further reduce the requirement of herbicides.

Table 2. Smothering of weeds through plant geometry (mean of 15 trials)

Sowing pattern	Grain yield q ha^{-1}	Weed density Number m^{-2}
Normal sowing (22.5 cm)	35.1	186.6
Closer sowing (15 cm)	38.3	143.9
Cross sowing (22.5 cm)	40.4	144.8

Mongia *et al.*, 2005

Prakash *et al.*, 1986 found closer row spacing (15 cm) and reduced dose of herbicide effective in reducing weeds and increasing grain yield. Ahuja and Yaduraju (1989) also reported cross sowing of wheat and placement of fertilizer below seed more effective in controlling weeds and increasing yield compared to unidirectional sowing and broadcast fertilizer application. The use of competitive cultivar coupled with closer or cross sowing can further reduce the herbicide usage.

Fig 2. Effect of cropping system on *P. minor* density. Vertical bars represent ± SEM. Means are significantly different at P=0.01 using "Fischer's t test" (Chhokar *et al.*, 2008a)

Row direction: It is hypothesized that the north-south rows shade the ground better than east-west rows and may be useful in reducing the weed emergence.

Competitive varieties: Crop cultivars vary in their growing habit, which can substantially affect crop- weed balance. Fast growing or early canopy forming and spreading types during early stages are less susceptible to weed competition. Taller wheat genotypes are more competitive (Table 3). Although, the competitive ability in wheat is negatively associated with yield potential under weed free environments, the magnitude of yield loss under weedy conditions is greater in high yielding less competitive dwarf wheat cultivars than in tall competitive cultivars (Challaiah *et al.*, 1986). With the instances of herbicide resistant weeds on the increase, the need to develop more competitive winter or spring cultivars has also become a necessity. Paul and Singh, 1979 reported effectiveness of tall wheat genotypes (115 cm) in suppressing the *P. minor* compared to shorter wheat genotypes. For cereals, the ideal genotype should have a plant height of at least one metre, and quick germination, early seedling vigour and good tillering to smoother the weeds.

Table 3. Effect of crop height on weed competitiveness

Wheat genotypes	Dry weight of *P. minor* (q ha^{-1})	Height of *P. minor* (cm)
Tall (115 cm)	5.3	57
Medium (85 cm)	12.5	92
Dwarf (60 cm)	17.0	90

Source: Paul and Gill, 1979

Fertilization: Adequate fertilization increases the vigour and competitiveness of the wheat crop. By altering the time and method of fertilizer application, competitive advantage can be shifted in favour of wheat crop. The initial crop growth will be better if fertilizer is made more available to crop instead of weeds. Fertilizer placement 2-3 centimetre below the seed instead of broadcasting helps in providing the competitive edge to crop over weeds. By adopting FIRBS, fertilizers are banded close to the crop rows thus enhancing crop's accessibility to nutrient and competitiveness over weeds. The higher fertilizer use efficiency through better placement of fertilizer and faster drying of the top portion of beds in FIRBS is responsible for reduced weed infestation.

Generally the phosphatic fertilizers promote the growth of broadleaved weeds, whereas higher nitrogen rates increase the grass weeds growth. Higher nitrogen rates help in suppressing the leguminous weeds like *Lathyrus aphaca* L (Fig 3). Some times the efficacy of herbicides is increased when it coincide with the application of fertilizer. Tutt and Call (2006) reported that topdressing of nitrogen fertilizer on the same day as spraying AE F130060 has the potential to injure wheat and limit grain yield, particularly with 28 per cent liquid N. To avoid crop injury and possible yield reduction, mesosulfuron and N applications Urea Ammonium Nitrate (UAN) should be separated by at least 7 to 14 days (Sosnoskie *et al.*, 2009). Where, farm yard manure is used, it should be well rotten as it is also a source of increasing weed infestation. The seeds of many weeds remain viable even after passing through the digestive tract of the animals (Pleasant and Schiather, 1994).

Stale seed bed technique/ Dab system: In this technique, weed emergence is stimulated by applying irrigation then followed weed control either with non-selective herbicides like glyphosate or cultivation before sowing. It is a very effective method but it delays the sowing operation. The emerged weed seedlings can also be uprooted or destroyed using a heavy planker and then wheat drilled in moist layer. The use of non-selective herbicide is of particular importance in zero tillage (ZT) sown crop. Therefore, stale seed bed technique can also be used for reducing the weed seed bank.

Soil moisture: Soil moisture affects the weed control efficiency through its effect on herbicide efficacy and weed germination and growth. Moisture should be modified in such a manner that it favour crop not weeds. Wheat crop can germinate from slightly drier zone (Chhokar *et al.*, 1999) whereas some of weeds (*P. minor and Rumex dentatus*) fail to germinate from dry soil. These results can be utilized for management of such moisture loving weeds by seeding wheat crop at slightly lower moisture such that wheat crop establishment is not affected.

Tillage: Tillage influences soil bulk density, penetration resistance, aggregate mean weight diameter and surface roughness (Carman, 1996). Therefore, the changes in mechanical characteristics of the seedbed due to tillage can influence the crop and weed emergence. Tillage affects weed seed distribution in soil profile (Pareja *et al.*, 1985; Yenish *et al.*, 1992 and 1996) and the differential distribution of the seed in soil profile has the potential to change weed population dynamics (Buhler, 1991, 1995, 1997; Froud-Williams, 1983; Harper, 1957). Tillage also affects soil properties, such as organic matter, microbial populations, soil moisture, temperature and pH (Blevins *et al.*, 1983), which can affect herbicide activity by influencing herbicide adsorption, movement, persistence and efficacy.

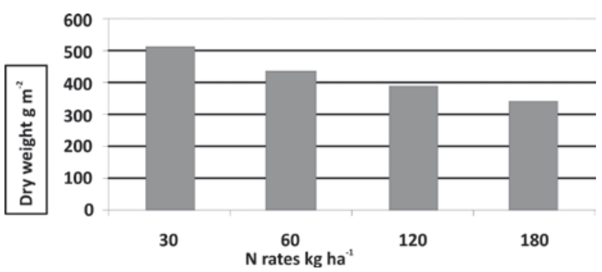

Fig 3. Effect of nitrogen rates on wild pea (*Lathyrus aphaca* L.) dry weight in wheat *(Malik and Singh, 1993)*

A shift from an intensive tillage to reduced/no tillage system cause major changes in weed dynamics (Buhler, 1995; Chhokar *et al.*, 2007b), ultimately affecting the herbicide efficacy due to change in microclimate and weed flora. The differential distribution of weed seeds during puddling in transplanted rice as well as changes in microclimate (soil structure, moisture, diurnal temperature fluctuations and light exposure) due to tillage in wheat can influence the weed seedling recruitment.

Reduced tillage favours the growth of *Cirsium arvense* and *Convolvulus arvensis* (Koch and Hess, 1980; 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 (Chhokar *et al.*, 2007b; Franke *et al.*, 2007).

With ZT, *P. minor* can also be effectively managed through integration of pre seeding non-selective herbicides (like glyphosate/paraquat) under rice-wheat system when encouraged to germinate through pre sowing irrigation. The subsequent populations will be less due to minimum disturbance of soil. An integrated approach consisting of ZT with slightly advanced sowing (last week of October) with higher seed rate and narrow row spacing of competitive cultivars can drastically reduce *P. minor* population. Further, if ZT is practised with residue retention then weed infestation will be lesser. Such an integrated approach, consisting of multi-tactic can offer a viable solution if the choice for selective herbicides is restricted.

The less *P. minor* problem under ZT system (Fig 4) was due to less soil disturbance as a result *P. minor* seeds present in lower soil layer fail to germinate due to mechanical impedance. Besides lower *P. minor* problem, adopting ZT technology in wheat reduces the expenditure on field preparation and saves more than 90 per cent fuel and time as well as advances the sowing time compared to conventional tillage practices. (Chauhan *et al.*, 2003; Sharma *et al.*, 2002). The sowing of wheat in India is generally delayed when sown after either *Basmati* rice or two crops of rice (rice-rice-wheat) or after sugarcane or cotton harvesting. The extent of yield reductions in different zones in India varies with an average loss of about 26.8 kilogram per hectare per day, when sowing is delayed beyond recommended optimum period (Tripathi *et al.*, 2005). Although, reduced/ZT tillage may not always accompany yield increase, but savings in fuel, equipment and labour costs along with its role in conservation of soil and water (Unger and Cassel, 1991) makes it a viable economic option. Therefore, ZT is a cost effective and sustainable weed management system but continuous use of ZT may shift the weed flora in favour of other weeds such as *Rumex dentatus* (Fig 5) and *Malva parviflora* (Chhokar *et al.*, 2007a). Therefore, to avoid undesirable shift in weed flora, other weed control measures should also be integrated with ZT that can offer a more economic and sustainable options of wheat cultivation. Also, If no-till in wheat in conjunction with no-till in previous and succeeding crops is adopted than this double/triple no-till system may enhance the natural loss of weed seeds by maintaining seeds on the soil surface through exposure to environment extremes and predation (Sagar and Mortimer, 1976; Roberts, 1981; Anderson, 2005).

Straw management: Straw burning, besides affecting germination of weeds (Singh, 1996; Wilson and Cussans, 1975; Morris, 2000), also affects herbicide efficacy (Moss, 1979; Embling *et al.*, 1983; Toth *et al.*, 1981). The straw ash drastically reduces the efficacy of pendimethalin and isoproturon (Fig 6). Therefore instead of burning, it should be retained on the surface which has multi benefits like moisture conservation, weed suppression and improvement in soil physio-chemical properties. Retaining a residue load of 5.0 and 7.5 t ha^{-1} can reduce the weed infestation by 27.2 and 40.2 per cent, respectively (Table 4). Crop residue, physically impede seedling growth or inhibit germination and growth by allelopathy (Crutchfield *et al.* 1986; Wicks *et al.* 1994). It was reported by Wicks *et al.*, 1994 that each 1000 kg ha^{-1} of winter wheat residue on the soil surface reduced 14 per cent weed seedling establishment. Therefore, ZT with residue retention is more beneficial.

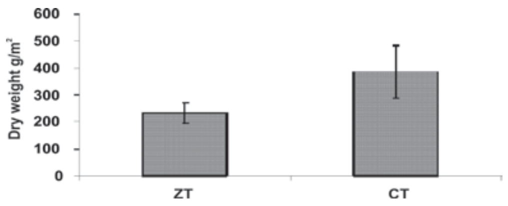

Fig 4. Effect of tillage on P. minor dry weight. Vertical bars represent ± SEM. Means are significantly different at P=0.10 using "Fischer's paired t test" *Source: Chhokar et al., 2007b*

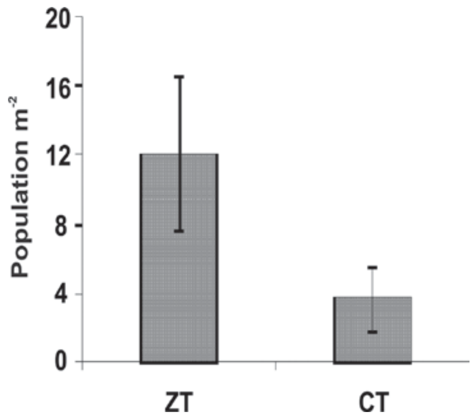

Fig. 5. Effect of tillage on *R. dentatus* population. Vertical bars represent ± SEM. Means are significantly different at P=0.05 using "Fischer's paired t test" *Source: Chhokar et al., 2007b*

Table 4. Effect of residue retention on weeds in wheat under rice-wheat system

Treatment	Total Weed dry weight (g m^{-2})		Wheat yield (t ha^{-1})	
	2006-07	2007-08	2006-07	2007-08
ZT + residue removal (RR)	672.3	803.4	0.75	1.58
ZT + 2.5 t ha^{-1} residue	682.4	790.0	1.05	1.72
ZT + 5.0 t ha^{-1} residue	514.9	559.6	2.58	2.31
ZT+ 7.5 t ha^{-1} residue	433.3	449.0	2.46	2.12
ZT (RR) with sulfosulfuron +metsulfuron at 25+3 g ha^{-1}	19.8	2.9	5.48	4.54
CT without herbicide and residue	462.9	518.9	1.22	1.86
CT with sulfosulfuron +metsulfuron at 25+3 g ha^{-1}	5.6	0.3	5.61	4.70
LSD (0.05)	83.5	122.2	0.39	0.56

Source: Chhokar et al., 2009

B. Mechanical control

It involves the removal of weeds by various tools and implements including hand weeding and uprooting. Manual weeding though effective but involves considerable amount of man-power and time (Table 5). Due to costly and scarce labour its feasibility is very less. Mechanical weeding is also difficult, where weeds resemble morphologically to crop *eg. P. minor* and *Avena ludoviciana* before flowering in wheat. Also, mechanical weed control becomes difficult in broadcast sown wheat. However, mechanical control can be practiced effectively when wheat is sown in FIRBS or in lines under flat bed system. Further the efficiency of mechanical weed control is increased in FIRB system when two rows are planted on each bed. Weeding with the help of adjustable hand cultivator or wheel hoe can be done in line sown wheat crop. Besides feasibility of mechanical weeding, FIRBS also reduces weed competition (Chauhan *et al.*, 2003).

Table 5. Comparative cost and time taken in various weed management strategies

Weed control method	Time required hours ha^{-1}	Time saving (%)	Cost ha^{-1} (Rs)	Cost saving (%)
Manual weeding-*Khurfi* (Hand held tyne)	250	-	7500	-
Manual weeding-Hand Hoe (*Kasola*)	100	60	3000	60.0
Knapsack sprayer (Chemical control)	3.5-5.0	98-98.6	950 (200 + 750*)	87.3
Tractor mounted sprayer (Chemical control)	0.3-0.5	99.8-99.9	900 (150+750*)	88.0

*Cost of herbicide= Rs 750/- ha^{-1}

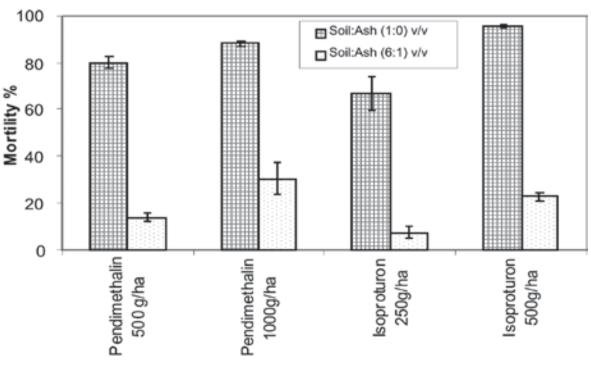

Fig. 6. Effect of paddy straw ash on herbicide efficacy against *P. minor* in pot study. The vertical bars represent the SEM, *Source: Chhokar et al., 2009*

C. Chemical weed control

Chemical weed control is preferred because of its better efficiency along with less cost and time involvement (Table 5). Also, it causes no mechanical damage to the crop that happens during manual weeding. Moreover, the control is more effective as the weeds even within the rows are killed, which invariably escape, because of morphological similarity to crop, during mechanical control. Effective weed control depends on the proper selection of herbicides depending on the type of weed flora infesting the crop and further herbicide should be applied at optimum dose and time using proper application technology. Wheat crop is generally invaded by both grass and broad-leaved weeds but the major challenge offered is by grass weeds. This is due to narrow selectivity between grassy weeds and wheat crop being both of grass in nature exhibits similar physiology and reaction to herbicides compared to broad-leaved weeds.

In wheat, generally post-emergence herbicides are adopted by the growers, which are mainly applied 7-10 days after first irrigation using knapsack sprayer. The optimum dose of herbicides and their effectiveness against target group are given in Table 6.

The efficacy of herbicides can be improved by applying at optimum dose and time with proper application method. Balyan *et al.*, 1988 observed that control of weeds was excellent, when isoproturon was applied up to 35 days after sowing (DAS) and poor control was observed with delay in application. Similarly, Malik, *et al.*, 1984 reported better control of wild oat with isoproturon when applied 25 DAS compared to its application at 35 DAS. Further, the efficacy of foliar active herbicides can be improved by lowering carrier volumes, which concentrates the herbicide per volume of the spray solutions (Buhler and Burnside, 1984). Herbicide application in small droplets is more toxic than large ones because of their greater numerical coverage and translocation (Prasad and Cadogan, 1992).

Herbicides effective against isoproturon resistance biotypes of *P. minor* are sulfosulfuron, clodinafop, fenoxaprop, tralkoxydim, pendimethalin, Atlantis and pinoxaden. Sulfosulfuron, Atlantis and pendimethalin are effective against both grass and non-grass weeds, whereas, clodinafop, fenoxaprop, tralkoxydim and pinoxaden are specific to grasses. However, sulfosulfuron and pendimethalin are not effective against *Rumex dentatus* and *Avena ludoviciana,* respectively. For control of broad-leaved weeds in wheat, three major herbicides used are metsulfuron, 2,4-D and carfentrazone (Chhokar *et al.*, 2007a ; Singh *et al.*, 2004 a&b). For control of broad-leaved weeds, 2,4-D has been used for a long time, however, the application of 2,4-D at inappropriate time as well as on sensitive cultivar can lead to yield reduction due to malformation (Pinthus and Natowitz, 1967; Bhan *et al.*, 1976; Balyan and Panwar, 1997). In addition, 2,4-D butyl ester application often results in injury to adjacent sensitive broadleaf crops, due to its volatilization and solution drifting (Li *et al.*, 2002; Zhang *et al.*, 2005) as a result it is less preferred by the growers.

Table 6. List of wheat herbicides, their optimum doses and target group

Herbicide	Dose g ha^{-1}	Weed Control	
		Grasses	Broad leaf
Clodinafop	60	√	
Fenoxaprop-ethyl	100-120	√	
Pinoxaden	35-40	√	
Sulfosulfuron	25	√	√
Isoproturon	1000	√	√
Atlantis (Mesosulfuron + iodosulfuron)	12 +2.4	√	√
Total (Sulfosulfuron + metsulfuron)	30+2	√	√
2,4-D-E	500		√
Metsulfuron	4		√
Chlorsulfuron	25	√	√
Carfentrazone	20		√
Ally Express (Metsulfuron+carfentrazone)	25 (5+20)		√
Pendimethalin	1000-1500	√	√
Trifluralin	1000-1500	√	√
Terbutryn	1000-1500	√	√
Pyroxasulfone	125-150	√	√
Pyroxsulam	18	√	√
Flufenacet	300	√	
Dicamba	360		√
Tralkoxydim	350	√	
Metoxuron	1500	√	√
Chlorotoluron	750-1500	√	√
Methabenzthiazuron	750-1500	√	√

Recently, carfentrazone has been recommended for broad-leaved weed control and the added advantage with this herbicide is that it has very fast action and control *Malva spp and Solanum nigrum.* Generally a herbicide is more effective against some of the weeds and less or not effective against the others. Metsulfuron and 2,4-D are ineffective against some of the weeds like *Malva parviflora* (Chhokar *et al.*, 2002; Chhokar *et al.*, 2007a) and *S. nigrum* (Mukerjee *et al.*, 2011). Also, 2,4-D is not effective against *Rumex spinosus (*Singh *et al.*, 2011*)*. It is also poor against some of the broad-leaved weeds such as *Anagallis arvensis*, *Melilotus indica*, *Medicago denticulata etc.* (Singh *et al.*, 2004a&b). Isoproturon is also poor against some of the weeds like *Convolvulus arvensis, Rumex spp, Lathyrus aphaca, Vicia sativa, Cirsium arvensis, Anagallis arevensis and Melilotus spp.* (Mustafee, 1991; Malik and Singh, 1993). To overcome these problems, evaluation of alternative herbicides alone or in combination becomes imperative. One of the ready mixture to control the hardy weeds as well as diverse spectrum of broadleaf weeds is Ally Express (Metsulfuron+carfentrazone).

The advantage of combination of metsulfuron and carfentrazone over alone application of metsulfuron and carfentrazone will be in situations having the diverse infestation of broad-leaved weeds particularly the *M. parviflora, S. nigrum and L. aphaca*. Metsulfuron and 2,4-D are not effective against *M. parviflora* and *S. nigrum*, whereas, carfentrazone is not effective against *L. aphaca.* The ready mix combination of metsulfuron + carfentrazone will provide the control of these weeds. Similarly, Singh *et al.*, 2011 reported better control of *R. spinosus* (92%) with metsulfuron + carfentrazone tank mixture compared to sole application of either metsulfuron (85%) or carfentrazone (78%). This mixture was better than 2,4-D formulations as none of the 2,4-D formulations was effective against *R. spinosus.* Similarly, Singh 1999, reported improved control of hard weed Canada thistle (*C. arvense*) with tank mix application of herbicides.

For the control of complex weed flora (grass and broadleaf weeds) and to provide long term residual weed control, combination of herbicides are needed. Tank mix combinations or ready mixtures are advantageous over sequential application due to saving in application timing and cost. Herbicide mixture besides providing control of complex weed flora will also help in managing and delaying the herbicide resistance problem (Wruble and Gressel, 1994). The possibility of evolution of herbicide resistance as well as shift towards difficult to control weed are more common with continuous usage of single herbicide. Therefore, for sustaining wheat production, we have to evaluate new herbicide and herbicide mixtures with different mechanism of action. The effectiveness of grass herbicides are generally reduced when mixed with broad-leaved herbicides (Vidrine 1989; Holshouser and Coble, 1990; Grichar 1991; Vidrine *et al.*, 1995; Damalas and Eleftherohorinos, 2001). About 80 per cent of the interactions that has been observed in species of the family Poaceae (grasses) refer to cases of antagonism (Zhang *et al.*, 1995). Whereas, synergism/compatibility has been found to occur more frequently in mixtures where the companion herbicides belong to the same chemical groups (Damalas, 2004). Sulfosulfuron + metsulfuron are compatible (Chhokar *et al*., 2007b) but tank mix application of grass herbicides (clodinafop, fenoxaprop, tralkoxydim and pinoxaden) with either 2,4-D or metsulfuron is antagonistic (Mathiassen and Kudsk, 1998). Antagonism between herbicides can be avoided by altering the application timing of herbicides. Ideally, it is desirable to select herbicide combinations that have synergistic effect on weeds and antagonistic effect on crop. To avoid antagonism the grass and broad-leaved herbicides should be applied sequentially.

Pendimethalin, trifluralin and pyroxasulfone are pre-emergence herbicides in wheat. Trifluralin provides selective weed control in wheat (Rahman and Ashford 1972; Malik *et al.,* 1995) but its adverse effect on germination of wheat (Malik *et al.,* 1995), needs to be addressed by adjusting the application timing or by increasing seed rate.

It was also found that advancing the time of application of isoproturon from 5 week to 3 week after sowing can help in reducing the herbicide dose. The results indicated that efficiency of isoproturon mixed with soil or urea was found some what low in comparison to spray method (Table 7). Therefore herbicide spraying is the best. Moreover, the time of application also affects the herbicide efficacy (Table 8 and 9). Some of the herbicide having good soil activity (sulfosulfuron) can be targeted as early post emergence application (just before first irrigation). Early post emergence (EPOST) and post emergence (POST) herbicides were applied before and after first irrigation at 19-21 DAS and 31-33 DAS, respectively

Table 7. Effect of herbicide application methods (Mean of 21 trials)

Method	Grain Yield (q ha^{-1})	Weed dry Wt. (g m^{-2})
Unweeded Check	32.6	139.6
Hand weeding between 30 and 35 DAS	40.4	47.7
Isoproturon post emergence @ 0.75 kg/ha, 5 WAS	43.7	29.9
Isoproturon @ 1.0 kg ha^{-1} +soil mixed broadcasting 30-35 DAS	41.8	32.1
Isoproturon @ 1.0 kg ha^{-1}+Urea(1/2 N dose) mixed broadcasting 30-35 DAS	41.5	42.0
Pendimethalin @ 1.00 kg ha^{-1} Pre - emergence	40.9	43.0
2-4 D @ 0.4 kg ha^{-1}at 30-35 DAS	39.9	59.7
Fluroxypyr @ 0.10 kg ha^{-1} + Isoproturon @ 0.5 kg ha^{-1} a day before irrigation	43.8	37.0

Source: Mongia et al., 2005

Table 8. Effect of time of herbicide application on herbicide performance in wheat

Herbicide	Dose	TOA*	Dry Weight, g m^{-2}			Grain Yield t ha^{-1}	
			P. minor		Others		
	g ha^{-1}	DAS	2001-02	2002-03	Pooled	2001-02	2002-03
Flufenacet	240	19	14.0	61.7	168.8	5.28	4.63
Flufenacet	360	19	5.6	30.2	180.8	5.11	4.80
Flufenacet	240	31	238.0	280.7	86.7	3.73	3.35
Flufenacet	360	31	208.4	243.3	99.2	3.55	3.23
Sulfosulfuron + S**	25 + 0.3%	31	10.3	17.1	13.8	6.23	5.77
Weedy check			594.0	453.3	33.7	1.50	2.33
LSD (P=0.05)			32	34.2	17.1	0.49	0.35

*TOA – Time of application, DAS= Days after sowing; **Cationic surfactant
Source: Chhokar et al., 2006

Spray technology: The application of herbicide using proper spray technology is a must to get the desirable results of herbicides. Majority of the farmers are using cut nozzles for herbicide spraying which is causing uneven distribution of herbicides. This may also increase the selection pressure for resistance to alternate herbicides. Therefore, there is great need to educate farmers on proper spray technology. Pre emergence application can also be done with tractor mounted sprayer. Care should also be taken to have fine tilth and good soil moisture for better performance of pre-emergence herbicides like pendimethalin and trifluralin. Self propelled sprayer fitted with multiple nozzles boom should be developed and promoted for herbicide application. It will save application time and will improve weed control due to better coverage.

Table 9. Effect of time of herbicide application on herbicide performance for weed control in wheat

Herbicide	Dose g ha^{-1}	TOA*	*P. minor* control (%)	Grain yield % of weed free control
			Mean	Mean
Flufenacet + metribuzin	96+144	EPOST#	75.5	85.4
Flufenacet + metribuzin	96+144	POST##	60.9	75.4
Sulfosulfuron + S**	25 + 0.3%	EPOST	97.8	99.0
Sulfosulfuron + S	25 + 0.3%	POST	94.8	97.8
Weed free			100	100
Weedy check			0	27.7

*TOA – Time of application; **S= Surfactant; # = EPOST-Early post emergence ; ## = POST-Post emergence
Source: Chhokar et al., 2006

Role of surfactant and adjuvant: Some of the herbicides require surfactants for better efficacy (Table 10). Surfactants help in better penetration and spread over leaf surface by reducing the surface tension thereby increasing the contact area. The efficacy of herbicide and herbicide mixtures can be improved with the use of surfactant and can reduce the dose of herbicides with increased spectrum of weed control (Malik *et al.,* 1988; Malik *et al.,* 1989b). Many workers (Chhokar *et al.*, 2010; Chhokar *et al.*, 2011; Green and Green, 1993; Singh *et al.*, 2002) have reported improvement in the efficacy of sulfonylurea herbicides with surfactant. Many adjuvants also alter the cuticular waxes on the leaf surface which may enable herbicide to penetrate the cuticle (Malik *et al.*, 1993). Some times foliar crop injury may occur with the use of surfactants. So, enough care should be taken while selecting surfactants. Further, the role of certain fertilizer salts {urea ammonium nitrate (28% UAN) and ammonium sulfate (AMS)} in combination with different surfactants in improving the efficacy of herbicides need to be evaluated as, these additives increase the herbicide absorption into plants (Wills *et al.*, 1998; Young and Hart, 1998; Miller *et al.*, 1999). Urea fertilizer at 0.25 per cent w/v enhances the efficacy of sulfosulfuron (Woznica *et al.,* 2001*)*. It has also been observed that AMS overcomes the decreased herbicide activity due to antagonism caused by the presence of metal cations (Ca, Na, K and Mg) in water used as spray solution (Nalewaja and Matysiak, 1993; McMullen, 1994; Nalewaja *et al.*, 1995).

Table 10. Efficacy of sulfosulfuron and ready mixture of sulfosulfuron+carfentrazone-45 (25+20) WDG with and without surfactant against weeds in wheat

Treatment	Dose Herbicide g a.i. ha^{-1}	Weed dry weight g m^{-2}						Wheat grain yield q ha^{-1}	
		P. minor		*A. ludoviciana*		Total			
		2007-08	2008-09	2007-08	2008-09	2007-08	2008-09	2007-08	2008-09
Sulfosulfuron	25	19.0 b*	206.7 b	62.4 b	161.1 b	176.8 b	380.3 a	49.2c	34.4c
Sulfosulfuron +S*	25+S	3.8 c	21.9 c	7.2 c	18.2 c	106.2 c	50.4 d	53.6b	50.1a
Sulfosulfuron +Carfentrazone	45 (25+20)	24.2 b	188.2 b	53.7 b	144.0 b	79.9 c	332.1 c	55.4b	37.1b
Sulfosulfuron+ Carfentrazone +S	45 (25+20)+S	6.3 c	28.7 c	11.1 c	20.1 c	19.3 d	48.8 d	59.1a	51.1a
Weedy Check	-	149.7 a	652.7 a	123.1 a	670.4 a	357.6 a	1325.7 b	41.8d	2.7d

*S= Cationic surfactant; Data within columns having same letter were not significantly different
Source: Chhokar et al., 2011

Crop safener: Crop safener plays an important role in improving the selectivity of herbicide in the crop. The selection of safener should be such that it only improves the crop safety but not decrease the efficacy against weeds. Topramezone applied in wheat causes large scale crop phytotoxicity but when applied either in combination with clodinafop/pinoxaden or with a safener *cloquintocet* significantly improved the wheat tolerance to topramezone. The improved crop tolerance with tank mix application of topramezone with clodinafop/pinoxaden is due to presence of safener in these grass herbicides.

Residual effect of wheat herbicides on succeeding crops: The use of herbicides may have the carry over effect on the succeeding crops because of their high persistency (Table 11 and Fig 7). The persistence of herbicide can not be considered a positive or a negative characteristic in the absolute sense. In-fact herbicides, especially those used as pre-emergence or early post emergence should have a certain persistence level in order to keep the crop weed free for a sufficient period and to give the crop a competitive advantage. If the herbicide remains active for too long, it can create serious problems for the production of succeeding crops due to its residual effects.

Sulfonyl urea herbicides have long persistency and may affect the sensitive succeeding crops (Chhokar *et al.*, 2006). Sulfosulfuron and chlorsulfuron applied in wheat were found to have their residual effect on succeeding maize and sorghum crops (Chhokar *et al.,* 2002; Chhokar *et al.,* 2008c). Sulfosulfuron applied in wheat @ 25 g ha^{-1} caused an average reduction of 65 and 73.4 per cent in maize and sorghum fresh biomass due to its carry over effect indicating very high persistence of this herbicide. Sulfosulfuron is preferred by farmers over ACC-ase graminicides (clodinafop and fenoxaprop), due to its broad-spectrum weed control. However, due to its longer persistence, growers should be cautious about the potential danger of carryover injury to succeeding crops, like sorghum and maize. Sulfosulfuron and chlorsulfuron have no carry over effect on rice following wheat, however these should not be used in crop sequences where cotton, sorghum and maize are to follow wheat. Therefore, selection of herbicides for a crop should be in a system perspective.

Soil pH and climatic conditions in the intervening periods and duration between herbicide application and following crops are important in determining the potential for herbicide carryover (Anderson and Barrett, 1985; Hatzios, 1998; Moyer and Esau, 1996). The chances of herbicide carryover injury can be reduced either by increasing the turnaround time or by application of FYM along with frequent tillage and irrigation, which will reduce the bio-availability of herbicide to succeeding crop because of increased adsorption and degradation.

Table 11. Residual effect of sulfosulfuron on succeeding crops and weeds

Crop	Residual effect
Maize (Fodder)	Yes
Sorghum (Fodder)	Yes
Green gram	No
Horse purslane (*Trianthema portulacastrum*)	Yes
Sesbania aculeata	no
Cotton	Yes

Weed management in wheat based intercropping system: Wheat is generally grown with mustard and under such system clodinafop, fenoxaprop, isoproturon and pendimethalin can be used depending on the type of weed flora. In situations where wheat is intercropped with sugarcane in bed planting system, broad-spectrum weed can be controlled with combination of sulfosulfuron with metsulfuron. Isoproturon can also be used in areas having no resistance problem. Do not use sulfosulfuron, Atlantis, metsulfuron, 2,4-D in mixed cropping system of wheat with mustard or lentil or linseed.

Quarantine measure: Wheat is an important crop in India and in event of shortfall in its production, it is being imported to support our Public Distribution System (PDS) and to control the price escalation. In the past, India imported wheat from Argentina, Australia, Canada and USA. There is a possibility that it may contain weed seeds. Earlier a consignment imported from Australia contained seeds of 13 weed species, which are in the list of herbicide resistant weeds in Australia (Mool Chand *et al.*, 2000). Although imported wheat is meant for milling purpose and not for seed but still there is risk of dispersal to fields. To avoid the introduction of these weeds necessary quarantine measures must be taken.

Integrated weed management

The dependence on single method of weed control can not give the desired results in all situations. The best approach is integrated weed management in which all suitable methods of weed control are used in a compatible manner to reduce weed population and maintain them at levels below the threshold causing economic injury. Plant density, time of sowing, variety, seed rate, spacing, tillage practices, quantity and time of fertilizer and irrigation water are some of important factors, which influence the weed-crop competition. Regulation of these factors should be such that they give the competitive edge to crop over weeds. The integration of these factors with chemical measure is advisable to avoid the ill effects caused by the sole dependence on the herbicides. Some of the negative impacts of sole dependence on herbicides are evolution of herbicide resistance, weed flora shift and soil and environmental pollution. Also, the continuous dependence on single method of weed control leads to shift of weed flora in favour of more tolerant and difficult to control species and to tackle this problem, there is need to adopt integrated weed management practices. The rising cost of labour and input will wipe out the profits of farmers unless an integrated approach with focused attention of ecology and herbicides is adopted.

Multiple herbicide resistance in *Phalaris minor*- A threat to wheat production

Littleseed canarygrass (*Phalaris minor)* is the most troublesome winter season grass weed of irrigated wheat in India. This weed was not a problem before "green revolution" (mid seventies). The green revolution witnessed in India was due to adoption of dwarf high yielding varieties, improved irrigation and fertiliser facilities. Large scale adoption of high yielding dwarf wheat varieties, which are less competitive with this weed under increased fertilisation and irrigation practices favoured its dominance (Balyan and Malik, 1989; Mehra and Gill, 1988). Further, intensive rice-wheat cropping system and consequently changes in wheat production practices after the green revolution are responsible for elimination of some of the broadleaf weeds and increased infestation of *P. minor*. (Chhokar and Malik 1999; Chhokar *et al.,* 1999; Malik and Singh 1993; Singh *et al.*, 1999). During the late 1970s, Indian wheat farmers were so troubled by heavy infestations of this weed that many farmers ploughed down their immature wheat crop or harvested as forage. For its control in the late seventies different herbicides recommended were nitrofen, methabenzthiazuron, metoxuron and isoproturon (Gill and Brar, 1975; Gill *et al*., 1978; Malik *et al.,* 1995). Indian wheat farmers opted isoproturon mainly because of its cost effectiveness, wider application window, flexibility in method of application and broad-spectrum weed kill along with its selectivity under wheat and mustard intercropping. From 1980 to 1990, isoproturon kept *P. minor* and other weeds under control and farmers realised the full advantage of the high yielding albeit less competitive, dwarf wheat. The use of herbicides further allowed wheat breeders to develop less competitive varieties of wheat with a greater Harvest Index (HI), thus making wheat producers more dependent on this herbicide. The majority of farmers successfully relied on isoproturon or isoproturon + 2,4-D for weed control in wheat over a period of 10 to 15 years. However, during early nineties, the situation degraded as *P. minor* populations escaping isoproturon treatment were reported to be the resistant biotypes (Malik and Singh, 1995). Farmer's continued reliance on isoproturon or isoproturon + 2, 4-D in resistance prone area further increased the selection pressure for R populations (due to removal of competition from S populations of *P. minor* and broad-leaved weeds). This allowed *P. minor*'s complete dominance in wheat. After isoproturon resistance evolution, there were again instances when wheat farmers were forced to harvest their immature wheat crop as fodder in the absence of effective alternate herbicides (Malik and Singh, 1995).

For resistance to evolve, genetic variation for resistance trait(s) must exist within population and selection events must take place (Maxwell and Mortimer, 1994). There is no evidence to suggest that mutations result from herbicide application (Holt and Thrill 1994). It is generally accepted that genetic variation for resistance occurs due to spontaneous gene mutation (Jasieniuk and Maxwell, 1994). Based on these considerations, Cotterman (1995) has argued that depending on the initial frequency of resistance alleles, the selection intensity of R populations from sensitive weed might be due to continuous use of herbicide at a higher rate than the required rate for adequate weed control. However, the evidence based on the research by Malik and Singh (1995) suggests that farmers in Haryana (India) commonly used less than the recommended rate of isoproturon due to cost consideration. Further most of the farmers adopted burning of rice straw for its rapid disposal (paddy straw is not suitable for animal consumption in north India) and to speed up the seed bed preparation. Since less turn around time is left for wheat following rice. The straw burning reduces the herbicide efficacy because of more herbicide adsorption as a result of the ash formed from burning. There is some evidence that burning of rice straw increased the *P. minor* infestations by reducing the efficacy of isoproturon (Singh, 1996; Chhokar *et al.*, 2009). Rice-wheat areas normally have heavy soils, which also causes more herbicide adsorption leading to sub-optimal performance. Inappropriate methods of application (mixing herbicide with soil or fertilizer and then broadcasting it could also be responsible for sub-optimal performance of isoproturon. Singh *et al.*, 1995b reported that spraying herbicide is more effective than mixing with urea or sand. Perhaps all these factors substantially lowered the effectiveness of isoproturon resulting in development of metabolic resistance (Malik *et al.*, 1995; Singh *et al.*, 1997) since metabolic resistance evolves readily in low dose situations (Wrubel and Gressel, 1994; Gressel, 1995).

Although, the selection duration of 10 year was almost same as has been reported with other herbicides. However, the development of isoproturon resistance with its frequent use at lower doses (either intensely or by wrong method of herbicide application) seems to differ from various models explaining herbicide resistance based on high efficiency and high doses (Cotterman, 1995)

Cases of herbicide resistance evolution are more frequent with continuous usage of a herbicide or herbicides belonging to the same group (Beckie, 2006). Similar might have happened with isoproturon resistance in *P. minor*, because isoproturon alone at reduced doses was used continuously in uninterrupted rice-wheat system. The factors which favoured the development of isoproturon resistance in India are mono-cropping (Rice-wheat), mono-herbicide (Isoproturon use only) and under dosing.

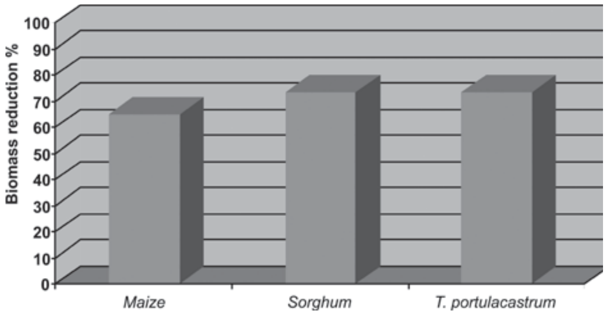

Fig.7. Residual effect of sulfosulfuron applied in wheat on succeeding maize, sorghum and *Trianthema portulacastrum*, *Source: Chhokar et al., 2008c*

Resistant *P. minor* biotypes required about 5-10 times more isoproturon compared to susceptible biotypes for 50 per cent growth reduction (Chhokar and Malik 2002; Malik and Singh 1993; Malik and Singh 1995). For the control of isoproturon resistant P. *minor*, five herbicides (tralkoxydim, diclofop, sulfosulfuron, clodinafop and fenoxaprop) were recommended during late nineties but farmers mainly used sulfosulfuron and clodinafop. Now again the *P. minor* has evolved resistance against these herbicides (Table 12, 13 and 14). The multiple resistance problems at few locations are so severe that it is causing huge grain yield reductions. If the problem of resistance is not tackled, it may lead to serious consequences leading to decrease in wheat production in rice-wheat sequence.

Table 12. Effect of sulfosulfuron on isoproturon and clodinafop resistant (R) and susceptible (S) populations of *P. minor* and wheat yield

Herbicide	S (DWR) Mean of two years		R (Mean of three locations/populations)	
	P. minor dry weight * g m^{-2}	Wheat yield t ha^{-1}	*P. minor* dry weight g m^{-2}	Wheat yield t ha^{-1}
Clodinafop 60 g ha^{-1}	*0.2^{a}*	*5.27^{a}*	*342.2^{a}*	2.53^{a}
Sulfosulfuron 25 g ha^{-1}	*1.3^{a}*	5.43^{a}	*3.4^{b}*	5.04^{b}

*Mean with in column followed by same letters are not significantly different using "paired t test", *Source: Chhokar and Sharma, 2008*

Table 13. Herbicide resistance profile of *P. minor* populations

Population	GR$_{50}$, g ha^{-1}					Resistance Index = GR$_{50}$ R / GR$_{50}$ S				
	CLD*	FNP*	SSN*	PDN*	IPU*	CLD	FNP	SSN	PDN	IPU
PATBI	10.3	36	3.31	7.7	162	1.00	1.00	1.00	1.00	1.00
DWR	12.8	34.4	3.22	8.0	186	1.24	0.96	0.97	1.04	1.15
SAKAR-1	>120	>240	4.63	37.7	1135	>11.65	>6.67	1.40	4.90	7.01
HALUD	>120	>240	14.79	36.1	1676	>11.65	>6.67	4.47	4.69	10.35
BAKAI-1	>120	>240	8.42	40.0	2224	>11.65	>6.67	2.54	5.19	13.73
NAKAR	18.3	38.4	4.63	11.0	1527	1.78	1.07	1.40	1.43	9.43
UCKAR	33.1	87.7	5.8	8.1	986	3.21	2.44	1.75	1.05	6.09

*CLD= Clodinafop, FNP= fenoxaprop, SSN= sulfosulfuron, PDN= pinoxaden, IPU= isoproturon
Source: Chhokar and Sharma, 2008

Table 14. Herbicide resistance profile of *P. minor* populations

Population	GR$_{50}$, g ha^{-1}				Resistance Index = GR$_{50}$ R / GR$_{50}$ S			
	CLD*	SSN*	PDN*	IPU*	CLD*	SSN*	PDN*	IPU*
HALUD	>240	12.97	41.5	1902	>11.65	2.41	5.04	8.27
DWR	20.6	5.38	8.2	230	1.00	1.00	1.00	1.00
CHKUR	>240	8.37	25.5	586	>11.65	1.56	3.09	2.55
KAKAR	>240	6.92	17.3	1217	>11.65	1.29	2.09	5.29
UCKAR	61.5	21.89	18.5	1762	2.99	4.07	2.25	7.66
DHKUR	96.3	15.1	24.5	2364	4.67	2.81	2.97	10.28
BHKAI	>240	12.7	37.1	1997	>11.65	2.36	4.50	8.68
SAKAR	47.5	16.9	14.6	737	2.31	3.14	1.77	3.20
DAKAR	29	5.36	11.6	2106	1.41	1.00	1.41	9.16
TEKAI	21.5	6.48	9.7	1856	1.04	1.20	1.18	8.07

*CLD= Clodinafop, SSN= sulfosulfuron, PDN= pinoxaden, IPU= isoproturon
Source: Chhokar and Sharma., 2008

Management strategies must be developed to prevent selection and spread of herbicide resistant populations. The different ways by which we can reduce the selection pressure for R populations are alternative herbicide, herbicide mixture, crop rotation and other agronomic practices providing the crop with a competitive edge over the weed (Cavan *et al*., 2000; Gressel, 1990; Wrubel and Gressel, 1994).

Crop rotation and herbicide rotation helps in lowering the selection pressure (Gressel and Segel, 1990). Crop rotations do not merely delay resistance by allowing use of different management options, but they also restore diversity in weed flora. Some crop rotations [growing Egyptian clover *(Trifolium alexandrinum)* for two years] may even be able to exhaust the soil seed bank of *P. minor,* thus providing a long term solution (Banga *et al*., 1997; Malik and Singh, 1995).

The morphological similarity of *P. minor* with wheat makes it difficult to remove manually within crop rows. Consequently, alternative herbicides play a key role in managing herbicide R *P. minor,* thereby curtailing the economic losses incurred by the farmers due to the resistance problem. For control of isoproturon resistant *P. minor*, clodinafop, fenoxaprop-p-, pinoxaden, mesosulfuron, flufenacet, metribuzin, pendimethalin, trifluralin and sulfosulfuron can be used. For control of clodinafop resistant populations of *P. minor*, sulfosulfuron, mesosulfuron, flufenacet, metribuzin, pendimethalin and trifluralin can be used. For controlling sulfosulfuron resistant populations, clodinafop, fenoxaprop-p-, pinoxaden, flufenacet, metribuzin, pendimethalin, trifluralin can be used. However, major concern is where *P. minor* has evolved resistance against clodinafop and sulfosulfuron and under such conditions we have limited options and effective herbicides are flufenacet, metribuzin, pendimethalin and trifluralin. Pyroxasulfone is another herbicide that controls the multiple resistant populations (resistant to isoproturon, clodinafop and sulfosulfuron) of *P. minor*. However, the metabolic nature of isoproturon resistance can make most of the herbicides as ineffective by further extension of resistance. This has already happened in annual ryegrass (*Lolium* spp) in Australia (Burnet *et al*., 1991).

Herbicide group rotation is highly effective in preventing/delaying resistance evolution (Cavan *et al*., 2000). Besides herbicide rotation, Gardner *et al*., 1998 also suggested revolving herbicide doses, which can help in delaying the evolution of target site and quantitative resistance. However, for effective implementation of herbicide rotation, it is necessary that large number of herbicides with different modes and mechanisms of action should be available. Usually, if resistance evolves, then other herbicides of the same chemical group generally become ineffective. However, with *P. minor*, the isoproturon R populations are also R to metoxuron, methabenzthiazuron but sensitive to chlorotoluron (Singh *et al*., 1997), despite all belonging to the urea group. In contrast to it, *L. rigidum* (Burnet *et al*., 1993; Preston and Powles, 1997) and *A. myosuriods* (Kemp *et al*., 1990) populations R to chlorotoluron are R to isoproturon.

Attention will also have to be paid to ensure that timing, rates and method of application of herbicides are most effective and least likely to lead to the development of resistance. Further, resistance-infested fields increased/increasing due to exchange of *P. minor* contaminated wheat seeds from farmer to farmer. Measures should also be taken to check the spread of R biotypes to new areas by encouraging the use of certified crop seed and restricting the movement of crop seed and farmyard manure contaminated with resistant biotypes to new areas. Adopting these clean cultivation practices will be helpful in reducing the build up of soil seed bank of this weed. Additionally, the alternative herbicides, particularly those belonging to the fop, dim, den and sulfonyl urea groups are highly vulnerable to resistance evolution. Therefore, to manage /avoid the resistance an innovative approach involving integrating various control measures are needed.

Adjusting wheat sowing so that it would not coincide with peak period of germination (15 November to 15 December) of this weed also reduces its impact (Chhokar *et al*., 1999). The stale seed bed technique or wheat-seeding under zero tillage (ZT) can be used for management of isoproturon R *P. minor*. Zero-till wheat under rice-wheat system reduces the *P. minor* emergence due to increased soil strength (Chhokar *et al*., 2007b). The competitive effect of ZT wheat crop will be more, when sown immediately after harvest of rice crop due to lesser emergence of *P. minor*. If the time period between rice harvest and wheat sowing is more then the emerged *P. minor* can be controlled with pre-seeding non-selective herbicides like glyphosate/paraquat. The subsequent flush will be considerably reduced due to lesser soil disturbance. Further, adopting residue retention in ZT will be more beneficial. Replacement of wheat by an alternative crop, or substituting short duration crops, such as potato and pea in between rice and wheat sequence can also help in *P. minor* management (Chhokar *et al*., 2008a). The replacement of wheat crop by a dicotyledonous crop increases the choice for grass herbicides against *P. minor* that may not be selective to wheat and substitution of short duration crop will help in depletion of the seed bank of this weed. Rotating wheat with green fodder crops such as berseem, lucern and oat can also effectively reduce its seed bank. Thus, crop rotation has a strong effect on soil seed bank through its influence on seed germination and mortality, which can conserve R or S gene within a plant population (Maxwell *et al*., 1990). Malik and Singh, 1995 reported lesser problem of isoproturon resistance in *P. minor* in field where, rice-berseem-sunflower-wheat, sugarcane-vegetables-wheat and cotton-pigeonpea-wheat rotations were followed than under rice-wheat rotation. Although, crop rotation is quite effective practice but due to our food security issue we can not compromise with replacement of wheat crop. Therefore, feasible option is to integrate the alternative herbicides in rotation with other agronomic tactics (competitive variety, early sowing, higher seed rate, ZT, stale seed bed) for effective management of resistant *P. minor* in wheat. It is also necessary to follow sanitation practices (weed-free crop seeds, well-rotten manure and clean machinery). Where possible, consideration should also be given to applying manual weed control methods to remove weeds surviving the application of herbicide before seed-setting. The integration of all these approaches will likely to minimise the impact of herbicide resistance on wheat production and farmers income.

Curtailing the losses caused by herbicide resistance

As alternative herbicide is the central to the resistance management programme. There is need to evolve new herbicides with different mechanism of action. As the wheat herbicide market is decided by *P. minor*. Herbicide firms having more options will exist, which was experienced during late nineties with evolution of isoproturon resistance. Concerted efforts by farmers, researchers, extension personnel and herbicide development agencies are needed to guard some of the existing herbicides and to help in resistance management. Some of the strategies for curtailing the yield losses can be;

- Alternative herbicide and herbicide mixture
- Follow crop rotation
- Increase the herbicide application window (Pre–emergence, early post emergence and post emergence) and it will help in reducing the yield losses caused by delayed herbicide application and control failure.
- Efficient spray technology to use booms fitted with multiple-flat fan nozzles.
- Developing ecological based weed management strategies
- To manage or to delay the resistance is; to follow zero tillage sowing with integration of pre seeding herbicides and bringing at least some area under crops like sunflower.

Chemical weed control in wheat is preferred by farmers due to cost and time effectiveness compared to manual weeding. However, continuous use of same herbicide or herbicides of similar mode and mechanism of action is resulting in the build up of tolerant weed species as well as evolution of resistant populations of weeds. In India, *P. minor* has evolved multiple herbicide resistance and is a threat to wheat production. The evolution of multiple herbicide resistance is causing the crop failure in extreme cases and it is also making the weed control expensive. Long term strategies to manage or avoid the herbicide resistance should include integration of crop rotation, herbicide rotation, herbicide mixture along with various other agronomic practices like stale seed bed, zero tillage, early planting, competitive cultivars and increased seeding rate which will create the competition in favour of the crop over weeds. Thus integrated weed control in wheat requires an integrated system that relies on numerous management decisions related to maximizing crop growth and minimizing weed growth. The integration of multiple cultural practices along with chemical use for weed control provides greater benefits than the effects of using just one or two weed control practices in isolation.

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