Herbicide Resistant *Phalaris minor* in Wheat – *A Sustainability Issue*

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Cover Pictures :
Top : *Phalaris minor* Retz. spikes at maturity
Bottom : Wheat crop at maturity

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FOREWORD

The history of detection of herbicide resistance in weeds began in Washington in 1960s with the discovery and report of triazine resistance in common groundsel (*Senecio vulgaris* L.) in 1964. Currently there are recorded 272 biotypes comprising 163 species (98 dicots and 65 monocots) which have evolved herbicide resistance worldwide. The first case of herbicide resistance in India and for the first time in the world in littleseed canary grass (*Phalaris minor* Retz.) against isoproturon was reported by the scientists of CCS Haryana Agricultural University, Hisar during 1992-93. This was the most serious case of herbicide resistance in the world, resulting in total failure of wheat crop under heavy infestation (2000-3000 plants m^{-2}) . *Phalaris minor* is the most common and predominant weed of wheat under rice-wheat cropping system in the North-Western Indo-Gangetic Plains of India. Rice-wheat cropping system comprises 13.5 m ha (10 m ha in India, 2.2 m ha in Pakistan, 0.8 m ha in Bangladesh and 0.5 m ha in Nepal) of land in South Asia.

Until the early 1990s, *Phalaris minor* could be effectively controlled by isoproturon, a substituted urea herbicide first recommended in 1977-78 and widely used since the early 1980s. But continuous use of this single herbicide for 10-15 years coupled with monocropping of rice-wheat led to evolution of resistance in this weed. By 1993, the resistance affected area ranged between 0.8 and 1.0 million hectares in N-W India and it also affected other tarai areas. Resistant biotypes from Haryana have been reported to require upto eleven times the pre-susceptible dose of isoproturon to achieve 50% growth reduction. The resistance was also found to be of metabolic in nature. Consequently, four alternate post-emergence herbicides (clodinafop, fenoxaprop, sulfosulfuron and tralkoxydim) were recommended in 1997-98 and the recommendation of isoproturon was withdrawn. The new herbicides brought the *Phalaris minor* infestation under control and restored yields to their previous levels. But red signals of resistance against these alternate herbicides have also been speculated in 2002 and thereafter. It warrants for integration of different weed control methods.

While managing herbicide resistance, the main focus of change that emerged in the rice-wheat cropping system is the evolution of zero tillage in wheat. After seeing this opportunity which emerged from the crisis of herbicide resistance, the ICAR and NATP project authorities sanctioned a special project on the acceleration of such technologies for the larger benefit of farmers. In order to further avoid or delay herbicide resistance, it is important to understand various causes and effects of resistance. Renewed concerns about the possibilities of cross-resistance have encouraged the project scientists to bring out this book. Factors that help countering such problems in future have also been discussed. Authors have brought together topics of major importance to help students, researchers and extension agencies understand the topic for designing future management strategies.

(Mrs. Asha Sharma, *IAS*)
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PREFACE

Rice-wheat cropping system is the most important regional base for providing staple diet to the population of South Asia. Due to development of herbicide resistance, the productivity of this cropping system especially in the high productivity zones of Haryana and Punjab was on an unsustainable trajectory from 1993-94 to 1997-98.It was a crisis like situation of that time. Since late 1980s, the rate of yield increase has slowed partly due to increasing incidence of weeds particularly *Phalaris minor*. Moderate infestation of *Phalaris minor* alone can cause 15-20% reduction in grain yield of wheat and it may cause total crop failure under heavy infestation (2000-3000 plants m^{-2}). The herbicide, isoproturon was widely used in north-western states of India to control this weed in wheat. With the use of this herbicide, it became possible to shield huge losses caused by this weed. However, continuous use of isoproturon has resulted in widespread development of resistance in *P. minor* which has wiped out some of the productivity gains achieved since 1982. The resistance affected area ranged from 0.8 to 1.0 million hectare in N-W India. After reporting resistance in 1992-93, many biotypes of *P. minor* have been found resistant to isoproturon. To achieve 50% growth reduction, resistant biotypes of this weed now require 8 to 11 times more isoproturon than susceptible biotypes. A considerable research effort is required to develop alternative weed management practices that can prevent or delay development of herbicide resistance. The most exciting outcome in the form of an integrated solution through alternate herbicides and zero-tillage has made the scientists of CCSHAU, Hisar more excited. Multi-disciplinary and multi-institutional efforts including that of Rice-wheat Consortium (RWC), Australian Centre for International Agricultural Research (ACIAR) and National Agricultural Technology Project (NATP) have changed the nature and scope of herbicide management strategy.

The publication is divided into 15 chapters. Research findings on resistance mechanism, antagonism, effect of alternate herbicides and herbicide mixtures, cross-resistance/multiple resistance, resistance reversibility, and integrated management of resistant *P. minor* have been compiled in this publication. Role of some of the RCTs including zero-tillage and furrow-irrigated-raised-bed-system has also been outlined.

The publication is in continuation with our earlier bulletins and the work done in other projects including the NATP project on Acceleration of RCTs. We sincerely hope that this book will help the researchers, extensionists and students in better understanding the herbicide resistance issue, and that the full utilization of the results will improve profitability and productivity of farmers in the entire rice-wheat cropping systems of South Asia.

Special thanks are due to all stakeholders who rendered their valuable help in pursuing the studies on herbicide resistance management. We also recognize the valuable contributions made by fellow scientists, extension agencies and policy makers in this endeavour.

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Chapter 1

Introduction

Rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.) are now grown in sequence on the same land in the same year over 26 million hectare of South and East Asia to meet the food demand of a rapidly expanding human population. These are the world's two most important cereal crops, contributing 45% of the digestible energy and 30% of total protein in the human diet as well as a substantial contribution to feeding livestock (Evans, 1993). Most rice-wheat (R-W) systems are located in South and East Asia within subtropical to warm-temperate climates characterized by cool, dry winters, and warm, wet summers. They extend across the Indo-Gangetic Plains (IGP) into the Himalayan foothills, spanning a vast area from Pakistan's Swat-Valley in the north to India's Maharashtra state in the south and from the mountainous Hind Kush of Afghanistan in the west, to the Brahmaputra floodplains of Bangladesh in the east. The IGP, where approximately 85% of R-W system is practised in South Asia is composed of the Indus Plains (area in Pakistan, and parts of Punjab and Haryana in India) and the Gangetic Plains (Uttar Pradesh, Uttaranchal, Bihar and West Bengal in India, Nepal and Bangladesh). The remaining 15% is in Himachal Pradesh, Madhya Pradesh and south-western India and in the hills of Nepal.

R-W is the most important cropping system in India comprising 10 million hectares out of 13.5 million hectares of land in South Asia under this cropping system (Woodhead *et al*., 1994). Modern technology contributed to an impressive increase in the productivity of this cropping system especially in North-West India. However, this cropping system has become more frazile and system productivity is showing the signs of fatigue (Hobbs and Morris, 1996).

The sustainability of the R-W rotation has been repeatedly questioned over the last decade. An exploratory survey conducted jointly by the Centro Internacional de Mejoramiento de Maizy Trigo (CIMMYT), Mexico; International Rice Research Institute (IRRI), Philippines; Indian Council of Agricultural Research (ICAR) and CCS Haryana Agricultural University in Karnal and Kurukshetra districts of Haryana (India), concluded that littleseed canary grass (*Phalaris minor*) and decline in soil productivity as two most important constraints for declining the total factor productivity of R-W cropping system (Harrington *et al*., 1992).

Isoproturon recommended against *P. minor* in late 1980s reduced huge losses in wheat but continuous use of this herbicide for more than 10-15 years resulted in the evolution of herbicide resistance in R-W cropping system (Walia *et al*., 1977; Malik and Singh, 1993, 1995). This was the most serious case of herbicide resistance in the world resulting in total crop failure under heavy infestation (2000-3000 plants m^{-2}) (Malik and Singh, 1995). Modern short-statured wheat varieties having high harvest index survived due to this herbicide but their high productivity endangered because of the development of herbicide resistance in this weed (Malik *et al.*, 1998). The resistance affected area ranged between 0.8 and 1.0 million hectares in N-W India mostly contained in the states of Punjab and Haryana. These two states account for around 3 million hectares of R-W cropping land out of India's 10 million hectares R-W cropping system and about 35% of India's wheat production.

After reporting resistance in 1992-93, many biotypes of *P. minor* have been found resistant to isoproturon (Malik and Singh 1993, 1994, 1995; Malik and Malik, 1994; Malik *et al*., 1995, 1996, 1997; Malik, 1996, Yadav *et al*., 1995, 1996, 1997; Balyan *et al.,* 1997). The resistant biotypes from Haryana required 2-8 times (Malik and Singh, 1995), 5-6.5 times (Yadav *et al*., 1996) and 6.3 to 11.2 times (Malik and Yadav, 1997) more dose of isoproturon compared to prestine/susceptible populations to cause 50% growth reduction. Resistance was also quantified and confirmed against this herbicide in various biotypes of *P. minor* from Punjab and N-W India (Yadav *et al*., 1996, Malik *et al*., 1998). The resistance was found to be of metabolic in nature (Malik *et al*., 1995, Singh *et al*., 1996, Kirkwood *et al*., 1997). Isoproturon resistance multiplies with the increasing number of years the *P. minor* biotypes receive the treatment of this herbicide (Yadav *et al*., 2002).

Based on intensive research in Haryana, Punjab and Uttar Pradesh in conjuction with chemical companies, four alternate herbicides (clodinafop, fenoxaprop, sulfosuefuron and tralkoxydim) all of which provide effective control of *P. minor* were recommended in 1997-98 wheat growing season and the recommendation of isoproturon was withdrawn with the following year. These alternate herbicides brought the *P. minor* infestation under control and restored wheat yields to their previous levels. The yield levels of wheat in Haryana which was reduced to 34.5 q ha^{-1} in 1994-95 in resistance affected areas was increased to 43.5 q ha^{-1} in 1999-2000 due to these new herbicides with a cost : benefit ratio of 1 : 6. But future use of alternate herbicides is not a sure one way bet. Due to possibilities of resistance or cross-resistance (Yadav *et al*., 2002) if these herbicides not used properly, a gulf exists between risk and benefits. Therefore, the package of herbicides need to be integrated with other weed management strategies like zero-tillage (Malik *et al*., 2000, 2002), competitive varieties (Chauhan *et al*., 2001), early sowing, crop rotation, and proper spray techniques (Miller and Bellinder, 2001). Status of herbicide resistance worldwide, resistance mechanisms, biology of *P. minor*, current status of herbicide resistance in *P. minor* and role of herbicide mixtures, alternate herbicides and herbicide resistant crops alongwith integrated management of herbicide resistance with special emphasis on *P. minor* has been described in this book.

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Chapter 2

Botanical Characteristics, Biology and Distribution

Based on numerous evidences it is now well established fact that littleseed canary grass (*Phalaris minor*) infestation is mainly confined in the rice-wheat growing areas. Introduction of high yielding dwarf wheat varieties, increased use of fertilizers and improved irrigation facilities, under rice-wheat cropping system have modified the environment, which seems to have changed the ecological conditions that are conducive and favourable for the growth and development of this weed. Knowledge regarding botanical characteristics, biology and distribution of *P. minor* will help manage this weed more efficiently.

Nomenclature

English name : Small canary grass, Littleseed canary grass, Mediterranean canary grass and Canary grass

French name : Alpiste mineur

German name : Pasto romano, alpistillo, alpiste, alfarin

Botanical name : *Phalaris minor* Retz. (Synonym : *Phalaris canariensis* L.)

Local name : Chirya bajra, kanki, gulidanda, genhun ka mama, sitti, dumbi sitti, bandri, biluri and khuni dandi

Botanical characteristics

Phalaris minor is a most serious winter annual grass weed of wheat widely distributed in the rice-wheat cropping systems of north-west India. During initial stages of growth, it is very difficult to differentiate *P. minor* from wheat plants. However, if we look carefully, the leaves of *P. minor* are light green in colour and basal portion of plant is pink compared to dark green leaves and basal portion of wheat plants. The light green colour of *P. minor* leaves and pink colour of basal part near ground surface is maintained throughout the life cycle of this weed except at maturity. *P. minor* has prominent white and pointed ligule and very short auricle. Contrary to this, wheat has prominent auricle and very poorly developed ligule. The sheath at the base of *P. minor* often exudes a red pigment when broken at the base.

It germinates from November to January and matures in March-April. Favourable temperature for germination is 10-20^{0}C. It has an erect stem with distinct nodes and internodes and at maturity the plants are taller than wheat. Leaves are linear with finally pointed tips, ligule exceptionally long (about 1 cm long) that clasps the stem. Each seedling gives three to four tillers under crop situation and profuse tillering in an open habitat. *P. minor* besides tillering also possesses unique characteristics of branching which is not found in wheat. The inflorescence is thick, oblong-shaped spike which is 2.5-7.5 cm long and composed of densely crowded overlapping spikelets. Spikelets are laterally compressed. *P. minor* produces 300-450 seeds per panicle. Seeds are small and shining with blackish colour at maturity. The seeds mature before harvest of wheat and seed maturity in *P. minor* is non-synchronous. Its propagation is only through seeds. Identification characteristics of *P. minor* and wheat have been given in Table 1.

Table 1. Identification characteristics of *P. minor* and wheat

S. No.	*Phalaris minor* Retz.	Wheat (*Triticum aestivum* L.)
1.	At early stage (seedling), there is dark green/bluish green colour of leaves.	At this stage, the leaves are light green in colour.
2.	Upto initial 50 days, the lower parts of leaf and sheath have pink colour.	It is yellowish green/ greenish-yellow.
3.	Three times longer ligules than wheat and no auricle.	Ligules and auricle are small but hairy.
4.	Initial growth is slow.	Initial growth better than *P. minor.*
5.	Length of internodes is more than wheat, therefore, it has increased height.	Internodes comparatively smaller than *Phalaris.*
6.	There is branching and tillering both, tillering is of rosette type.	Only tillering and no branching and plant grows erect.
7.	The root-shoot ratio is about 1 : 9.	The root-shoot ratio is 1 : 11.
8.	Pink colour sap exudes from stem, if the plant is removed/broken from near to soil surface.	Water coloured exudation from stem.
9.	About 8-9 cm long earhead with compact spikelets.	10-15 cm long earhead, having 18-22 spikelets and not so compact.
10.	One earhead having about 300-450 seeds.	About 30-50 seeds/earhead recorded.
11.	Upper part of ear matures earlier and usually shatters before harvest.	Whole spike matures almost at the same time.
12.	1000-grain weight is 1.5 to 2.0 g (each kilogram of *Phalaris* seed contains about one million seeds).	1000-grain weight varies between 40-45 g.
13.	Seed is generally black and oval shaped.	Seed is amber to red in colour.

The weed is known as small canary grass and has been described as "mainly self fertilizing" in nature (Whyte *et al.,* 1961). Two other species : short spiked canary grass (*Phalaris brachystachys* Link) and hood canary grass (*Phalaris paradoxa* L.) have been found to be serious weeds of wheat in Mexico (Malik, 1996). There are 8-10 species of *Phalaris*, but these three are so closely related that it is difficult to distinguish one from the other. *Phalaris brachystachys* has the smallest spikelets, while spikelets of *P. paradoxa* have short pedicels at the base with the outer four spikelets deformed. The panicle is dense and narrow at the base, often enclosed with an enlarged sheath. Seeds of *P. paradoxa* are grey and longer than those of *P. minor*.

Biology

The success of *P. minor* in the rice-wheat rotation appears to be related to high surface moisture for seedling emergence, high input levels, and a phenology which is ideally suited to the climatic conditions (Malik *et al.,* 1995). The weed is favoured by late sowings (December) due to faster seedling emergence and because wheat growth in late sowings is slower than in normal sowings (November) (Malik *et al.,* 1995). The weed also tends to be surface rooting (Okereke *et al.,* 1981), which may partly account for its preference for the rice-wheat system where adequate soil moisture is available for extended periods throughout the growing season.

Most common in rice-wheat rotation and other irrigated areas, *P. minor* is a vigorous competitor throughout its growing period. One reason for its continuous success is cropping pattern itself. With continuous growing of wheat, weed flora did not diversify as the use of alternate crops brings fundamental changes in the weed spectrum. This is because alternate crops will make other weeds to emerge and grow, thus easing out the competitive advantage to a single weed like *P. minor*.

P. minor has established itself in rice-wheat system because it finds a good choice of high surface moisture to emerge with the special advantage of high input base and set time table of emergence, growth and development.

Littleseed canary grass emerges earlier than wheat in December sowings but later than wheat in November sowings. The detailed information on growth period of this weed in relation to wheat and the effect of planting time have been given in Tables 2 and 3. In terms of relative growth advantage littleseed canary grass is favoured in end of November or end of December sowing because of its early emergence and because wheat growth in late sowing is less than in normal sowings. In addition to adequate soil moisture and relatively heavy soils, this weed became more problematic by its emergence and growth advantage and by its large population due to delayed sowings in rice-wheat sequence. In the present context of herbicide resistance, the emergence and growth of this weed is likely to be reduced not by continuous use of same herbicide but the evolution of systems which enables its seed bank to be exhausted and wheat growth to be encouraged.

Table 2. Physiological stages (DAS) of wheat and *P. minor* as influenced by different sowing dates (Av. of two years)

Physiological stages	Different sowing dates					
	2nd week of November		End of November		3rd week of December	
	Wheat	*P. minor*	Wheat	*P. minor*	Wheat	*P. minor*
Emergence	5-6	10	7-8	8-11	8-9	12
First leaf/pair	7-10	12-14	9-10	13-15	10-11	15-16
Second leaf/pair	12-14	19-20	13-17	20-25	12-14	21-28
Tillering/branching	23-25	32-40	26-28	38-41	29-31	35-38
Initiation of heading/anthesis	70-80	85-98	70-76	77-84	63-72	66-74
50% heading/anthesis	83-90	92-105	80-82	90-100	70-78	72-92
Maturity/harvest	153-156	130-136	133-138	116-118	117-118	98

Source : Annual Report, AICRP on Weed Control, 1990 (CCSHAU, Hisar, India).

Table 3. Dry weight (g m^{-2}) of wheat and *P. minor* as influenced by different sowing dates (Av. of two years)

Days of sowing	Different sowing dates					
	2nd week of November		End of November		3rd week of December	
	Wheat	*P. minor*	Wheat	*P. minor*	Wheat	*P. minor*
45	103	31	76	53	37	25
60	291	95	241	190	168	143
90	1048	555	899	792	763	934
120 (at harvest)	2463	1657	1943	1728	1605	1283

Source : Annual Report, AICRP on Weed Control, 1990 (CCSHAU, Hisar, India).

Optimum temperature for germination

Optimum temperature for seed germination of *P. minor* is in the range of 10-20^{0}C (Table 4.) Late sowings are quite common in the rice-wheat rotation (particularly after basmati rice) which has been found to favour competitiveness of this weed against wheat (Paul and Gill, 1979). It germinates over a range of ambient temperature from 10 to 25^{0}C, with optimum germination at 10 to 20^{0}C (Mehra and Gill, 1988; Chhokar and Malik, 1999).

Table 4. Effect of temperature on the germination (%) of little seed canary grass seeds after different periods of storage at different constant temperatures

Storage period (months)	Storage temperature (^{0}C)								
	0			10			30		
	10*	20*	30*	10*	20*	30*	10*	20*	30*
1.	–	–	–	–	–	–	–	–	–
2.	–	–	–	–	–	–	–	–	–
3.	–	–	–	–	–	–	7	7	–
4.	–	–	–	–	6	–	9	23	–
5.	–	16	–	–	28	–	13	4	–
6.	4	32	–	10	51	–	15	56	4
7.	7	38	–	13	68	7	15	72	12
8.	10	52	7	17	74	13	19	81	13
9.	14	68	13	22	78	18	30	89	21
10.	14	76	18	26	84	22	30	91	28
11.	15	89	23	34	86	23	36	91	30
12.	15	82	26	42	88	31	38	92	31

*Germination temperature (^{0}C)
Source : Singh and Dhawan (1976).

The rate and extent of germination decreases with increase in temperature upto 30^{0}C (Bhan and Chaudhary, 1976). They further added that germination was more between 10-20^{0}C and no germination above 30^{0}C and below 5^{0}C.

Optimum depth for emergence

Phalaris minor cannot emerge from depths greater than 4-5 cm, therefore, availability of moisture in the surface soil is necessary for seedling emergence and growth of this weed. Sowing at 10-15 cm depth can cause a considerable reduction in seedling establishment (Fig. 1). This may be due to increased seed mortality or extended dormancy.

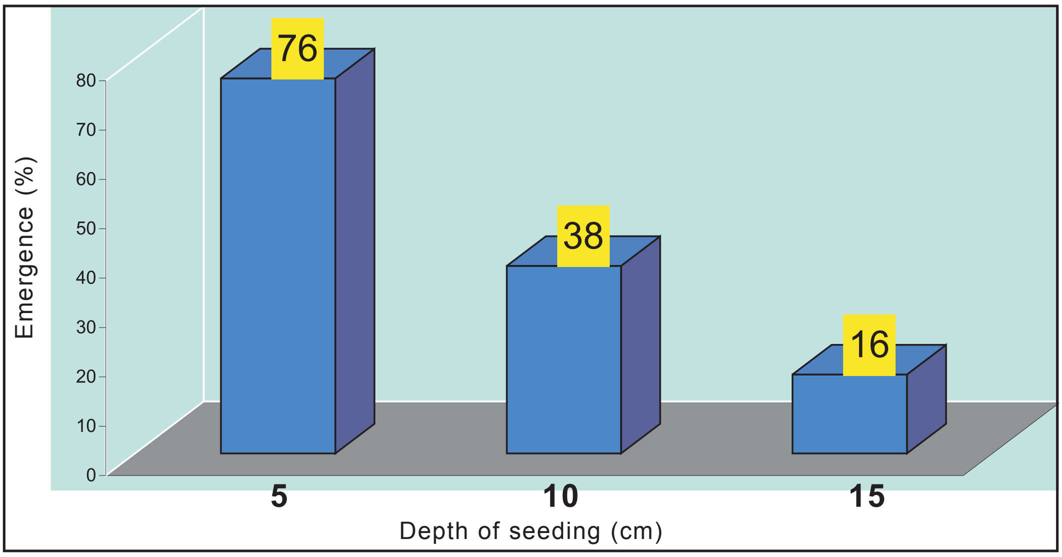

Fig 1. Effect of depth of seed placement on the emergence of littleseed canary grass.

Source : Shad and Siddique (1996).

The highest number of *Phalaris* seeds get accumulated in top 5.0 cm layer of soil and this decreases with the increase in depth (Singh and Ghosh, 1982; Om *et al.,* 2002; Yadav, 2002). However, Franke *et al.* (2002) observed that seeds of *P. minor* were relatively equally distributed over the upper 10 cm of the soil both under zero and conventional tillage system. This could be due to extensive tillage operations associated with the preceding rice cultivation under puddled conditions.

Phalaris is an excellent fodder for cattle and usually collected for this purpose after initiation of earheads. But it can be poisonous to livestock in the early vegetative stage (Whyte *et al.,* 1961).

Effect of soil pH on germination

Yadav (2002) observed highest germination of *P. minor* seeds (92.7%) at pH 6.0 and there was significant reduction in germination above and below this level of pH. No germination was observed at pH 3.0, 9.0 and 10.0. The pH of soil of rice-wheat cropping systems in Haryana, India usually varies between 7.5-8.5 but due to prolific seed production and already rich soil seed bank, the *Phalaris minor* germinates profusely, which can reduce the wheat production significantly, if not tackled effectively.

Dormancy and viability

Phalaris seeds have been shown to remain dormant for 3-4 months after maturity (Singh and Dhawan, 1976). Seeds of *Phalaris* are capable of tolerating anaerobic conditions by entering into secondary dormancy which perhaps is one of the reasons of its better adaptation in rice-wheat cropping systems (Parasher and Singh, 1985). The presence of chemical inhibitors in the seeds might be responsible for true dormancy in *P. minor* seeds (Rost, 1975). Singh (1998) reported that matured seeds of *P. minor* remained dormant for six months and germination increased from 88 to 96% after 12 months compared to only 4 to 24% after five months. But Jimenez-Hidalgo *et al*. (1993) did not find any difference in germination of *Phalaris* seeds aged 6 to 18 months. Om *et al.* (2002) observed that dormancy in *P. minor* was lesser than two months under natural field conditions as the seeds retrieved from soil of infested field in the last week of May exhibited 80 to 96% germination.

Half-life of seeds buried at Hisar (Sandy loam) was 10 months, while this was more than 15 months for seeds buried at Karnal (Clay soil) (Franke *et al.,* 2002). Heavy compacted soils with high soil moisture content, similar to Karnal soils, are usually poorly aerated, which may reduce *P. minor* seed decomposition. Seed half-life buried at 20 and 30 cm depth at Karnal was 11.3 and 15 months, respectively (Franke *et al.,* 2002).

Om *et al.* (2002) reported that there was complete loss of viability in 10 months of *P. minor* seed retrieved from the soils under wet rice conditions. However, under laboratory conditions (at room temperature), the viability of *P. minor* seeds of isoproturon resistant (R) and suceptible (S) biotypes after 3-4 years ranged between 75 to 99% (Table 5), and germination drastically reduced after 6th year.

Table 5. Seed germination of R and S biotypes of *P. minor* stored under laboratory conditions in November 1995

P. minor biotype	Year of collection	Number of seeds germinated at 15 DAS (out of 50 seeds kept in incubator at 10^0C for germination test) Av. of three replications	Germination (%) at 15 DAS
H2 (S)	April, 1991	45.3	90.6
H2 (S)	April, 1992	46.3	92.6
H3 (R)	April, 1991	37.6	75.2
H3 (R)	April, 1992	48.3	99.6
KR1 (R)	April, 1991	39.3	78.6
KR1 (R)	April, 1992	44.0	88.0

Source : Yadav A. and Malik R. K. (1995, Unpublished data).

Detailed studies on biology of *P. minor* in the rice-wheat cropping system are further required to understand the dynamics of soil seed banks, and impact of crop diversification, straw burning and zero-tillage in wheat.

Yadav (2002) at Pantnagar concluded that wheat residue burning helped in reducing the *Phalaris* seed density (69.6%) by destroying their viability, and if residue is not burnt there would be heavy increase in weed seed bank. However, the issue of environment pollution and use of wheat straw for livestock feed are two important issues. On the other hand, burning of rice straw before wheat sowing has been found to induce and encourage *P. minor* germination and also to reduce efficacy of isoproturon (Singh, 1996).

History and distribution

Phalaris is a native of the Mediterranean region but has been introduced into many other parts of the world. At present, 22 species of *Phalaris* are recognized in the world, of which 11 are native to the Mediterranean including *Phalaris minor* Retz. and four in South-Western USA. *Phalaris minor* is widely distributed in many countries of the world from Macronesia to Mediterranean, Irano-Turnic and Saharo-Sindic regions, Eastern and South Africa, North and South America, Australia and Far East. It is, however, not mentioned in the list of world's worst weeds by Holms *et al.* (1997). Its distribution is wide spread in India, Pakistan, Nepal, Myanmar, Sri Lanka, (Bor, 1960; Deshpande and Singh, 1986), and Saudi Arabia (Chaudhary *et al.,* 1981). In the plains of North India, the presence of *P. minor* has been mentioned at Hansi (Haryana) and Saharanpur (Uttar Pradesh). *Phalaris canariensis* (canary grass) is listed as a North-West Indian grass in old literature but Hooker (1961) has mentioned its close resemblance with *P. minor* differing mainly in the wings of glumules. *Phalaris paradoxa* is also stated as a North-East Indian weed but in the book, 'Fodder Grass of North India', this species was not mentioned. In his book, 'Flora of British India' initially published in 1837 and reprinted in 1961, Hooker has chronicled its presence in the plains of Western India and the Himalaya from Kashmir to Nepal. *Phalaris canariensis*, which resembles *P. minor*, is unquestionably endemic in the countries around the Western end of the Mediterranean; although there is a doubt about it being native to the Canary Islands, where from its name was derived (Piper, 1924). It was introduced to Mexico and probably to India from the Mediterranean region or east of the Mediterranean (Orient) which includes South Asia (Hitchcock, 1950). The English name, canary grass, was derived from canary birds, which were fed on seeds of *Phalaris canariensis* which resembles *Phalaris minor*. In USA, it is found in California and from Brunswick to New Jersey. It is widely distributed in Mexico (Hitchcock, 1950). The University of California, in its Agricultural

Extension Service Bulletin, has shown its distribution in North and South America, Africa, Europe, Asia and Oceana.

Many farmers believe that the seed of littleseed canary grass (*P. minor*) came to India with modern dwarf wheat varieties from Mexico and later became a serious weed pest of wheat. There was no attention for *P. minor* as a weed to be managed in wheat crop in India before 1968. In the past survey reports of Food and Agriculture Organization of the United Nations (FAO, Italy) sponsored survey reports of Parker (1968), the weed survey conducted by Adlakha *et al.* (1971) and weed surveys of Haryana (Malik *et al.,* 1984; Singh *et al.,* 1995) have also no mention of this weed in India upto 1968. It was reported to be a major weed in Latin America and probably reached India through the import of Mexican wheat (Lerma rojo and Sonora 64 through PL-480) which was observed to be a problem by the 1970s (Bhan and Chaudhary, 1976).

However, Narayanan and Dabadghao (1972) have paced its presence in association with field oats (*Avena* sp.) in New Delhi, India in 1948. At that time it was locally known as “Chidia bajra”. The association of *P. minor* with CIMMYT dwarf varieties may simply be due to their less competitiveness with the weed compared to old tall wheat varieties. Consequently, it was able to proliferate in these modern wheat varieites and became a much more significant weed of Indian agriculture. Changes in management practices subsequently led to sizeable population of this weed (2000 to 3000 plants m^{-2}), which later became increasingly common (Malik and Singh, 1995). After evolution of resistance against isoproturon, many wheat fields in Haryana, India were found to be infested with *P. minor* so badly (5000-8000 plants m^{-2}) during 1993-1996 that at many locations wheat crop used to appear as if it was a weed and *Phalaris minor* as a crop. Under such situations, many farmers harvested their immature wheat crop and used it as fodder for cattle because they did not expect any yield from such fields.

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Chapter 3

Spread of *Phalaris minor* in India–Possible Reasons

Littleseed canary grass (*Phalaris minor*) has become the most serious weed in the entire belt of north-western India, where rice-wheat cropping system is being followed. The presence of this weed has been noticed in other cropping sequences also but at lower intensities. The most affected states in India are Punjab and Haryana, however, *P. minor* infestation is one of the serious causes of concern in Uttar Pradesh, Uttaranchal, Madhya Pradesh and parts of Bihar, and Himachal Pradesh, where it reduces wheat production significantly. Area under isoproturon resistant *P. minor* varies between 0.8 to 1.0 million hectares in India mainly confined to Haryana (0.5-0.6 m ha) (Fig. 1) and Punjab (0.3 m ha).

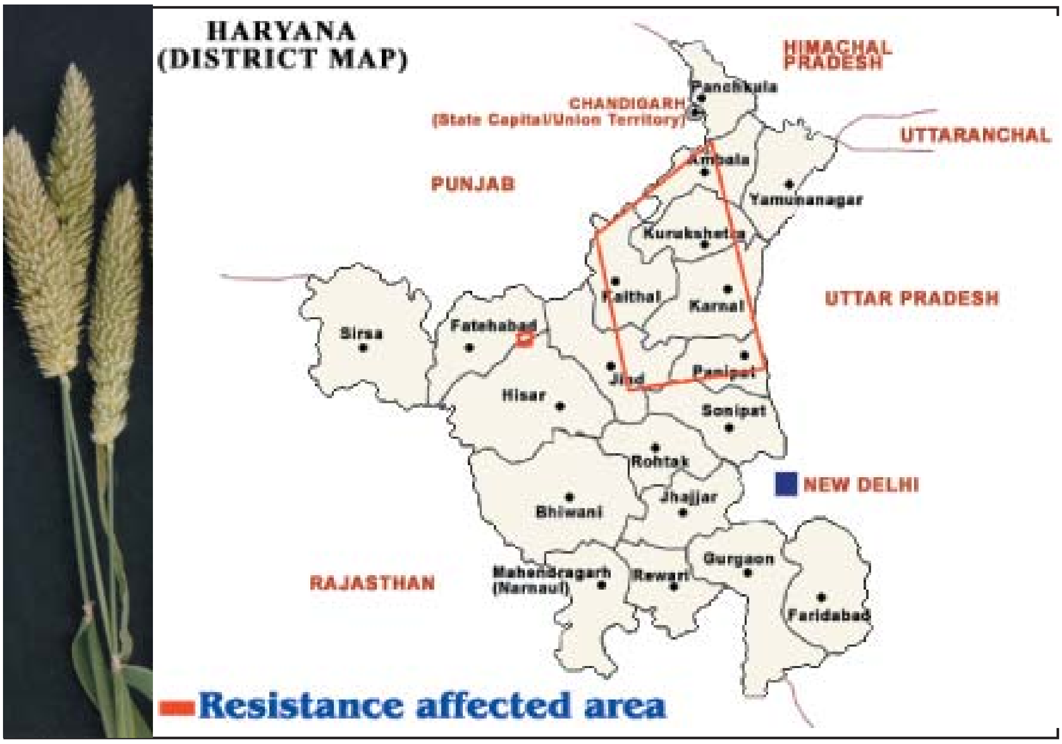

Fig. 1. Area under isoproturon resistant *Phalaris minor* in Haryana.

Dhiman *et al*. (2002) have outlined following possible reasons, which help *P. minor* to survive in rice-wheat cropping systems :

- It is suceptible to solarization. Presence of water in rice fields lowers the temperature of soil, and thus helps in its survival in rice-wheat system as compared to other cropping systems.

- Puddling helps in deep placement of seed in the soil and hence exposure to relatively lower temperature.
- The increased and prolonged activity of alcohol dehydrogenase in *P. minor* is known to play a detoxifying role in anaerobic respiration, hence retaining viability.
- Its tolerance to anoxia might be due to inherent ability of seed in using NO_3 as an alternate electron acceptor in Electron Transport System (ETS) with the help of nitrate reductase activity.

In past surveys by Parker (1968) and Adlakha *et al*. (1971), there was no mention of *P. minor* in India upto 1968, but later it became most serious weed in late 1970's and early 1980's. Malik *et al*. (1984) and Singh *et al.* (1995) have also shown *P. minor* at number one alongwith three other weeds which seriously infested wheat crop. Changes in the management practices subsequently led to sizeable population of this weed (2000-3000 plants m^{-2}) which later became increasingly common (Malik and Singh, 1995).

There are several reasons for the spread of this weed, before and after reports of herbicide resistance in rice-wheat areas and other zones. Malik *et al*. (1998) and Malik (2003) have outlined some of the following important causes responsible for spread of *P. minor* in different parts of the country; these possible reasons have also been supported by relevant data wherever it was possible :

1. Spread of littleseed canary grass from farm to farm in contaminated wheat seed and in irrigation water particularly under canal irrigation system. Occasional flooding of infested areas appears to have facilitated its spread to new areas. Farm machinary and equipments, combine harvesters, weed seed transport alongwith wheat straw, exchange of wheat-seed amongst farmers (which is quite common) are other possible causes for its spread.
2. Inadequate cleaning of wheat seed by mechanical threshers often results in contaminated seed with *Phalaris* and it is usually used for sowing. Frequent use of contaminated wheat seed with *Phalaris* seeds for sowing can help travel this weed to distant areas.

   Alarming contamination of wheat seed in grain samples collected largely from market (Table 1) may be a serious cause of concern because part of this wheat seed may be used by the growers for sowing purposes.

Table 1. Contamination of wheat seed with *P. minor* in different districts of Haryana (1999-2000)

District	No. of samples	No. of *P. minor* seeds/125 kg wheat		
		Mean	Minimum	Maximum
Kurukshetra	16	379,896	98,738	940,847
Karnal	39	330,687	48,350	1,700,003
Fatehabad	15	302,818	32,213	1,537,547
Kaithal	33	189,017	17,784	679,172
Barwala (Hisar)	11	128,437	46,578	214,891

Source : Yadav *et al.* (2002).

Mool Chand *et al*. (2002) have also reported 13 weed species, which were present in wheat imported from Australia during 1996 to 1998 to supplement the public distribution system. It really warrants for the strict implementation of seed laws and plant quarantine regulations. Contamination of wheat seed with *P. minor* was found in Nepal also (data not given).

It is quite often that most of the farmers use wheat seed for sowing purposes from their own stocks of previous years, because seed replacement with certified seed is hardly 10% each year.

The seed used from farmers' own stores for sowing purpose may also contain large number of *P. minor* seed due to carelessness or ignorance in cleaning before sowing. The seed samples collected from boxes of drills while in operation or from farmer's stores after winnowing and/or sieving i.e. even made ready for sowing by farmers were also found to be contaminated with large number of *Phalaris* seeds (Table 2).

Table 2. Contamination of wheat seed (collected just before sowing) with *P. minor* in Haryana (2001-02)

District	No. of samples	Per cent containing *P. minor*	Number of *P. minor* seeds per 125 kg wheat	
			Mean	Maximum
Kurukshetra	3	33	5,000	15,000
Karnal	8	50	4,766	25,000
Fatehabad	13	31	3,462	28,750
Kaithal	27	30	5,718	72,500
Barwala (Hisar)	9	67	6,250	46,875

Source : Yadav *et al.* (2002, Unpublished data).

3. After the evolution of herbicide resistance (1992-93), this weed has flourished in the absence of serious competition from other weeds. *P. minor* is highly competitive and in most of the instances it does not allow other weeds to pose serious threat in wheat. It hardly needs any evidence because we know that mostly broadleaf weeds appear in wheat when *Phalaris* is effectively controlled.

4. Burning of rice stubbles straw, especially after combine harvesting, appears to have reduced herbicide efficacy possibly due to increased adsorption of isoproturon on ash (Table 3 and 4).

   It is general opinion of the growers also that rice straw burning induces profused germination of *P. minor.*

Table 3. Effect of burning rice straw on the density (number m^{-2}) of *Phalaris minor* before sowing of wheat

Treatment	1992-93	1993-94	Mean
Straw removal	242	380	311
Straw burning at 6 t ha^{-1}	340	478	408
Straw burning at 12 t ha^{-1}	488	648	568

Source : Singh (1996).

Table 4. Interaction of rice straw burning and isoproturon (IPU) at 1 kg ha^{-1} on the density of *Phalaris minor* at 120 days after sowing wheat

Straw burning	Density of *Phalaris minor* (Number m^{-2})			
	1992-93		1993-94	
	IPU	Weedy check	IPU	Weedy check
Straw removal	5.72 (32)	11.13 (123)	5.08 (25)	9.32 (83)
Straw burning at 6 t ha^{-1}	7.99 (61)	12.25 (150)	6.03 (34)	10.14 (102)
Straw burning at 12 t ha^{-1}	9.43 (88)	13.03 (170)	6.32 (39)	11.16 (123)
C. D. (P=0.05)		1.04		0.66

Figures in parentheses are original values of *Phalaris* population.
Source : Singh (1996).

5. Continuous rotation of rice-wheat could have favoured this weed because of adequate moisture availability throughout the year. In a survey conducted in 1992-93 and 1993-94 in Haryana, 64% of the farmers practising the rice-wheat rotation for more than eight years reported heavy infestation of *P. minor* and no control of little seed canary grass with isoproturon (Malik, 1996). Bhan and Singh (1993) and Banga

et al. (1997) have also reported maximum infestation of *P. minor* in wheat crops under rice-wheat cropping sequences.

Moody and Drost (1983) also observed that there was change in weed flora of rice crop after three years depending on type of crop rotation.

6. Growing of short-statured high yielding varieties of wheat and increased fertilizer use will continue to favour this weed.

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Chapter 4

Chemical Weed Control in Wheat in India

India now ranks as the second largest wheat-producing nation in the world with a production of 76 million tonnes from an area of 27 million hectare. The present national average of 2.7 tonnes per hectare need to be raised to 3.5 tonnes per hectare to feed 1.25 billion population of the country by 2020 (Gautam, 2001). India's population growth has been shown in Table 1. It means we have to add within 20 years another 30 million tonnes of wheat, which is an opportunity as well as challenge. Irrespective of the area, it was evident that there exists a yield gap of 1.5-2.0 tonnes per hectare between what is being achieved and what can be achieved.

Table 1. India's population growth

Year	Population (Crores)
1901	27.01
1950	35.04
2001	102.70
2020 (Estimate)	130.42

Source : Agrolook 4(3) : 2003.

Introduction of high yielding dwarf wheat varieties coupled with improved facilities of fertilizers and irrigation have undoubtedly increased the grain yield of this crop in the past. But it has also triggered the problem of insect-pests and diseases, in general, and weeds in particular. It has been found that weeds reduce the grain yield of the wheat to the extent of 10 to 50% depending upon intensity and type of weed flora under different cropping systems. Grassy weeds have a potential to remove 40-50 kg N ha^{-1} in wheat. Weeds cause yield losses to the extent of 33%, which is more than losses caused by insects and pests (Kulshrestha and Parmar, 1992). Estimates show that weeds in India cause an annual loss of Rs.1980 crores. Ten most important weeds infesting wheat crop in rice-wheat and other cropping zones of Haryana have been given in Table 2. Area under rice-wheat cropping system in India is around 10 million hectares out of 13.5 million hectares in South Asia and the weed flora in N-W India under rice-wheat cropping system is more or less same as given in Table 2. *Poa annua* and *Lolium temulentum* among grassy weeds, and *Rumex retroflexus, Lathyrus indica* and *Malwa parviflora* among broadleaf weeds have also been noticed to increasingly infest wheat field in the recent years.

Introduction of high yielding dwarf wheat varieties alongwith intensive cultivation of cereals have increased the population of grassy weeds like *Phalaris minor* and *Avena ludoviciana* at much faster rate replacing broad leaf weeds in wheat fields (Malik and Singh, 1993; Singh *et al.,* 1995; Balyan and Malik, 2000). The shift of weed flora in favour of wild oat and some other broadleaf weeds has further been intensified due to changes in input availability and crop sequence in wheat. The problem of *P. minor* is serious under rice-wheat cropping systems (Malik *et al.,* 1995) while that of *A. ludoviciana* is more severe in irrigated, well drained and light-textured soils particularly in the areas other than rice-wheat sequence (Panwar *et al.*, 2000).

Weeds, not only cause significant losses in quantity, but the quality of the crop is also influenced. Depending upon the nature and intensity of weeds as well as duration of crop-weed competition, climate, agronomic practice and relative emergence pattern of weeds in relation to crop, the grain yield losses in wheat caused by weeds vary between 10 to 52 per cent (Gill and Brar, 1975; Bhan and Singh, 1979; Gupta, 1984; Walia *et al.,* 1990; Gogoi *et al*., 1993). Moderate infestation of *P. minor* alone can cause 15-20 per cent reduction in grain yield of wheat (Walia and Gill, 1985) and even total crop failure under heavy infestation of *P. minor* (2000-3000 plants m^{-2}) has already been reported in Haryana (Malik *et al.*, 1995). Whereas infestation of broadleaf weeds in wheat may lead to the reduction of grain yield to the tune of 7-50 per cent depending upon their intensity (Kurchania *et al*., 2000).

Table 2. Ten most important weeds in rice-wheat zone and other cropping zones in Haryana

Rice-wheat zone		Other cropping systems	
Weed species	% occurrence	Weed species	% occurrence
Phalaris minor	86	*Chenopodium album*	93
Avena ludoviciana	83	*Avena ludoviciana*	48
Chenopodium album	58	*Phalaris minor*	48
Melilotus indica	56	*Melilotus indica*	40
Medicago denticulata	51	*Anagallis arvensis*	33
Rumex maritimus	45	*Asphodelus tenuifolius*	30
Anagallis arvensis	42	*Trigonella polycerata*	26
Cirsium arvense	35	*Fumaria parviflora*	21
Convolvulus arvensis	24	*Vicia sativa*	19
Polypogon monspeliensis	18	*Spergula arvensis*	19

Source : Malik and Malik (1994).

P. minor and *A. ludoviciana* mentioned in Table 2 are two grassy weeds and rest of the others are broadleaf weeds. Four important weeds of wheat recorded during surveys conducted in India have been mentioned in Table 3.

Table 3. Four important weeds of wheat recorded during surveys conducted in India

1968	1971	1984	1995
Carthamus oxycantha	*Chenopodium album*	*Phalaris minor*	*Phalaris minor*
Asphodelus tenuifolius	*Anagallis arvensis*	*Avena ludoviciana*	*Avena ludoviciana*
Chenopodium album	*Asphodelus tenuifolius*	*Chenopodium album*	*Medicago denticulata*
Convolvulus arvensis	*Fumaria parviflora*	*Asphodelus tenuifolius*	*Chenopodium album*
(Parker, 1968)	(Adlakha *et al*., 1971)	(Malik *et al*., 1984)	(Singh *et al*., 1995)

The problem of herbicide resistance in *P. minor* against isoproturon (Malik and Singh, 1995) in rice-wheat cropping system has led to replacement of this herbicide with recommendation of alternate herbicides (clodinafop, fenoxaprop and sulfosulfuron) during 1997-98 in N-W India. These herbicides have been reported successful to control resistant *P. minor* (Malik and Yadav, 1997) but the problem of resistance against these herbicides cannot be excluded.

The exploratory surveys conducted by CIMMYT, IRRI, ICAR and CCSHAU, Hisar in 1992 have estimated that annual productivity losses in wheat yields are likely to be maximum due to the presence of weeds particularly *P. minor* (Table 4).

Table 4. Estimation of expected annual regional productivity loss (ARPL) for wheat related problems

Problem	Area loss (%)	Productivity (%)	Frequency (%)	ARPL (%)
Weeds	65	12	100	7.80
Declining soil health	64	10	100	6.40
Poor ground water quality	11	30	100	3.30
Low population	28	11	100	2.94
Late planting	14	19	100	2.66

Source : Harrington *et al*. (1992).

Annual loss of agricultural produce in India has been given in Table 5 and weeds cause maximum loss (33%) compared to other yield reducing factors.

Table 5. Annual loss of agricultural produce in India

Losses caused by	Annual monetary loss (Rs. crores)	% Losses
Weeds	1980	33
Diseases	1560	26
Insects	1200	20
Storage	420	7
Rats	360	6
Others	480	8
Total	6000	100

Source : Pesticide 27(1) : 2001.

Chemical Control of Weeds in Wheat

Due to industrialization, labour constraints at peak growth periods, small family size and under certain specific situations where weeds are very difficult to remove manually, the herbicidal use becomes inevitable. Chemical control of weeds, in general, has been realized to be more cost-effective and easy compared to manual weeding. Sales of different pesticides during 2000-01 have been depicted in Fig. 1.

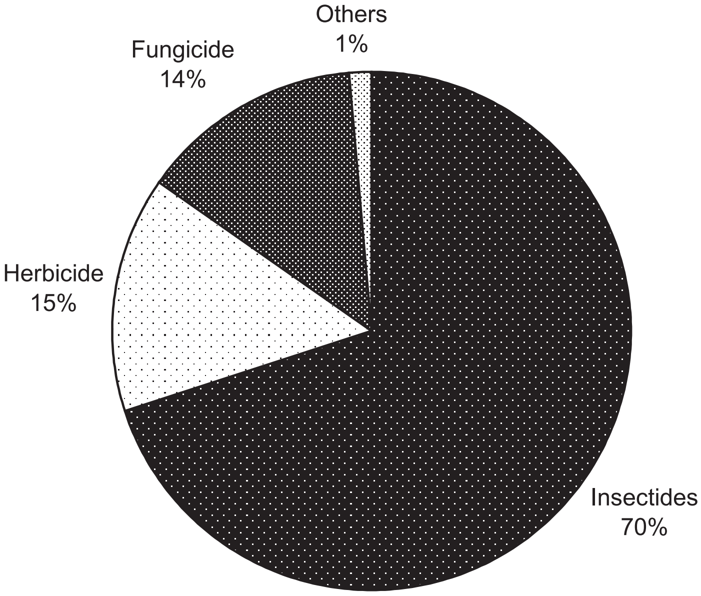

Fig. 1. Pesticide sales during 2000-01.

Sales of herbicides during 2000-01 and 2001-02 in India have been given in Table 6. The pesticide market size during 1998 through 2001 has been given in Table 7. Total sales include both technical and formulations (in terms of technical) of pesticides.

Isoproturon, sulfosulfuron, clodinafop, fenoxaprop and 2, 4-D (Table 6) are the main herbicides which are being used in wheat.

Table 6. Herbicide sale during 2000-01 and 2001-02

Product	Rs. crores	
	2000-01	2001-02
Isoproturon	67.00	61.38
Glyphosate	58.29	43.16
Sulfosulfuron	56.40	70.47
Clodinafop	50.00	59.93
Butachlor	48.00	39.60
Paraquat	30.80	26.77
Fenoxaprop	30.70	35.49
2,4-D	21.00	21.50
Atrazine	27.00	26.99
Pretilachlor	20.50	16.30

Source : Agrolook 2 (4) : 2002.

Table 7. Pesticide market size-2001 (Value in Rs. crores)

Pesticide	Change	2001	2000	1999	1998
Insecticide	584	2951	2367	2449	2741
Herbicide	17	517	500	455	461
Fungicide	32	497	465	430	411
Rodenticide	12	60	48	35	23
Total	645	4025	3380	3369	3636

Source : Agrolook 2 (4) : 2002.

Based on the recommendation and research, the chemical control of weeds in wheat has been given in Table 8 for areas other than rice-wheat cropping sequence of Haryana, India.

Table 8. Chemical control of weeds in wheat for areas other than resistant affected rice-wheat cropping sequence in Haryana, India

S. No.	Weeds	Herbicide	Dose (g ha^{-1})	Time of application (DAS)
1.	Broadleaf weeds	2,4-D Na (80% WP) or 2,4-D E (34.6% EC)	500 200	30-35 30-35
2.	Hardy broadleaf weeds (*R. retroflexus, C. arvenis, C. arvense* and *Lathyrus* spp.)	2,4-D Na (80% WP) or 2,4-D E (34.6% EC)	1000 500	30-35 30-35
3.	Broadleaf weeds and *Asphodelus tenuifolius. Fumaria parviflora* is not effectively controlled by metsulfuron	Metsulfuron-methyl (Ally/Algrip, 20% WP)	4	30-35
4.	Grassy weeds	Hiproturon, Nosilon-75, Isoproturon (Delson, Agron-75, Arelon, 75% WP)	1000	30-35
		or Metoxuron (Dosanex, 80% WP) or	1400	30-35
		Methabenzthiazuron (Tribunil, Ambinil, Yield, 70% WP) or	1600	30-35
		Pendimethalin (Stomp, 30% EC) or	1500	Pre-emergence
		Isoproturon (75% WP) with surfactant (Selvet, Teepol, Triton, Sendevit)	750	30-35

		Isoproturon (75% WP) particularly *Avena ludoviciana*	750	20 (before irrigation)
5.	*A. ludoviciana*	Diclofop-methyl (IIlaxon, 28% EC	700	30-35
		or Triallate (Avadex, 10% EC) Use 25% extra seed rate or	300	PPI
		Triallate fb Isoproturon	200 & 500	PPI & 30 - 35
6.	Weeds (*A. ludoviciana, P. minor* and *C. album*) in late sown wheat	Isoproturon (75% WP)	500	30-35
7.	*Pluchia lanceolata*	Glyphosate (Round up, Glycel 41% SL) or Glyphosate+surfactant	2.0-2.5% sol. (product) 1.0%+0.1% sol. (product)	Spray after wheat harvest at peak growth of weed
		or 2,4-D E (34.6% EC)	1000	–do– –do–
8.	Complex weed flora (grassy+ broadleaf weeds)	Isoproturon (75% WP)+ 2,4-D Na (80% WP)	750+500	30-35
		or Isoproturon+metsulfuron	1000+3	30-35
9.	Complex weed flora in late sown wheat	Isoproturon+2, 4-D Na	500+250	30-35

Metoxuron and isoproturon have been found to cause phytotoxicity in wheat cultivars WH 157 and DWL 5023, respectively. Similarly, 2, 4-D should not be used under mixed cropping where gram, raya or any other broadleaf crop has been grown in wheat. It should also not be used in wheat varieties like WH 283 and HD 2009, otherwise due to malformation of earheads; the grain yield will be adversely affected. 2, 4-D has been reported to show poor efficacy against some broadleaf weeds and many wheat cultivars like HD 2009, WH 283, WH 416 and Sonak produced malformed spikes leading to yield reductions (Balyan, 1999).

Medicago denticulata and *Melilotus* spp. not controlled by 2, 4-D were effectively controlled by metsulfuron-methyl at 4 g ha^{-1} (Singh *et al*., 2002) and similarly *Rumex retroflexus* (Balyan and Malik, 2000). Kurchania *et al*. (2000) also found satisfactory control of *C. album, C. arvensis, M. indica, Vicia sativa* and *Chicorium intybus* with metsulfuron at 4 g ha^{-1} but not of *P. minor*. Yaduraju and Das (2002) also reported metsulfuron at 4 g ha^{-1} as very effective against *C. arvense*. Metsulfuron at 4 g+isoproturon at 1000 g ha^{-1} was very effective against complex flora of weeds in wheat (Kaur *et al*., 1996; Singh and Singh, 2002). Besides being safe in almost all wheat varieties, metsulfuron takes care of wide variety of broadleaf weeds except *Fumaria parviflora*. Additionally, it controls *A. tenuifolius* also. Its action is slow compared to 2, 4-D; however, it arrests growth of weeds quickly and death occurs within a week or so.

In rice wheat growing areas, due to continuous use of isoproturon as single herbicide from last 10-15 years, resistance has evolved in *P. minor* (Malik and Singh, 1993; Malik and Singh, 1995; Walia *et al*., 1997).

After excluding all possible factors, which could be responsible for reduced efficacy of isoproturon (Malik and Singh, 1993, 1995) and further confirmation of resistance (Malik and Singh, 1993, 1995, Malik and Yadav, 1997), the recommendation of isoproturon was withdrawn from resistance-affected areas. Based on research in Haryana, Punjab and Uttar Pradesh, four alternate herbicides, *viz*. clodinafop (Topic, 15% WP) at 60 g ha^{-1}, fenoxaprop (Puma Super, 10% EC) at 120 g ha^{-1}, sulfosulfuron (Leader, 75% WP) at 25 g ha^{-1} and tralkoxydim (Grasp, 10% EC) at 350 g ha^{-1} were recommended in the winter season of 1997-98 for the control of resistant *P. minor* in rice-wheat growing areas. Clodinafop, fenoxaprop and sulfosulfuron when sprayed at 30-35 days after sowing (DAS) were found very effective against resistant *P. minor* (Malik and Yadav, 1997; Malik *et al*., 1997; Walia *et al*., 1998; Balyan, 1999; Brar *et al*., 1999; Brar *et al*., 2002).

These alternate herbicides have been found very effective against

A. ludoviciana even at 20% reduced dose compared to *P. minor* (data not given). Hence, either of these herbicides may be used against *A. ludoviciana* or to combat combined infestation of *P. minor* and *A. ludoviciana* in wheat. To control mixed population of *P. minor* and *A. ludoviciana* in wheat, the dose of any alternate herbicides will be the same as recommended against resistant *P. minor*.

These herbicides need to be sprayed at 2½ to 3 leaf stage of *P. minor*, which generally appears at 30-35 DAS. Sometimes due to lack of moisture or late application of first irrigation, *P. minor* either does not germinate or does not attain 2½ to 3 leaf stage at 30-35 DAS. So, under such situations, growers should be advised to wait and go for spraying of alternate herbicide only when they see *P. minor* in their field at 2½ to 3 leaf stage. For the control of complex weed flora in resistance affected areas, spray 2, 4-D Na at 500 g ha^{-1} or metsulfuron at 4 g ha^{-1} a week after application of any of the aforesaid alternate wheat herbicides. Never use 2, 4-D or metsulfuron as tank mixed with alternate herbicides; otherwise efficacy of alternate herbicides will be reduced against *P. minor* due to antagonism (Yadav *et al*., 2002).

Triasulfuron 20 g ha^{-1} alone against broadleaf weeds and in combination with clodinafop, fenoxaprop, sulfosulfuron or tralkoxydim against complex weed flora in wheat has also been reported effective (Yadav *et al*., 2004a). Whereas use of metribuzin in wheat caused detrimental effects on crop (Yadav *et al*., 2004; Singh *et al*., 2004). Recently carfentrazone-ethyl, another broadleaf weed killer has been found promising against many broadleaf weeds (Punia *et al*., 2005), and it may prove effective against *Malwa parviflora* (which is not effectively controlled by 2, 4-D and metsulfuron) in wheat. However, further research is required to study the compatability of triasulfuron and carfentrazone with other grass herbicides.

Herbicides should be sprayed with knapsack sprayer fitted with flat fan nozzles (80 or 110^0 angle) in a spray volume of 500-625 litre ha^{-1} and herbicides should be rotated every year. Sulfosulfuron has been found to cause residual toxicity to succeeding crops like sorghum and maize grown after wheat harvest. So, this chemical should be strictly used only in those areas where rice-wheat cropping sequence is followed. Herbicides should be used at recommended dose, with proper method and at appropriate stage with all other safety precautions. Moreover, use of herbicides as an integral component of integrated weed management will provide long-term benefits.

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Chapter 5

Herbicide Resistance Evolution – History

The consistent demand for increasing crop output has further increased the reliance on herbicides in modern agriculture leading to a reduction in the need for 'traditional' techniques of weed control. Whilst economically this shift has been rewarding to farmers, some negative consequences like 'herbicide resistant weeds' have also emerged which now need to be addressed in the interest of long-term sustainability.

How resistance evolves?

All natural weed populations regardless of the use of any weed killer probably contain individuals (biotypes), which are resistant to herbicides. Repeated use of herbicide will expose the weed population to a 'selection pressure' which will lead to an increase in the number of surviving resistant individuals in the population. As a consequence, the resistant weed population may increase to the point that adequate weed control can't be achieved by the application of that herbicide.

History of herbicide resistance evolution

The history of detection of herbicide resistance in weeds began in Washington in 1960s with the discovery and report of triazine resistance in common groundsel (*Senecio vulgaris* L.) in 1964. In 2003 there were recorded 272 biotypes comprising 163 species (98 dicots and 65 monocots), which have evolved herbicide resistance worldwide. Summary of worldwide occurrence of resistant weeds by herbicide group (Heap, 2000) has been given in Table 1. At that moment, there were 53 countries with 210,000 total number of fields infested with resistant weeds and most affected countries were USA, Australia, Canada and France. Australia ranks third behind USA and France in the number of cases of confirmed herbicide resistance (Heap, 1998). The problem of herbicide resistance initiated in 1960s was limited to only few weed species (<50) upto 1980s, but the number of resistant biotypes then increased abruptly to more than 250 in next 20 years. In 2003 the figure touched to 272 and the current status in April 2005 is 296 resistant biotypes comprising 178 species (107 dicots and 71 monocots) infesting over 270,000 fields.

The chronological increase in unique cases of herbicide resistant weeds worldwide has been depicted in Fig. 1. Obviously this increase was due to increased use of herbicides in this era. Inspite of this dramatic development, no herbicide has been lost to agriculture; they are today, and they will remain an integral part of food production through their effective use in combination with other weed control practices.

Trend of herbicide resistance evolution

From 1960 to 1980, the herbicide resistant weeds were more in case of triazines followed by synthetic auxins and ACCase inhibitors. From 1980 to 1990, the triazines were still at the top followed by ALS inhibitors and bypyridiliums. However, with the change and development of modern herbicides, the trend of herbicide resistance cases during 1990-2000 was triazines followed by ALS inhibitors, ACCase inhibitors, bypyridiliums, ureas and amides, synthetic auxins, dinitroanilines and glycines (Heap, 2000) in descending order (Fig. 2).

Table 1. Summary of world-wide occurrence of resistant weeds by herbicide group (Heap, 2000)

Herbicide group	WSSA Code	HRAC Code	Example	Dicots	Monocots	Total
ALS inhibitors	2	B	Chlorsulfuron	43	20	63
Triazines and others	5	C1	Atrazine	42	19	61
Bipyridiliums	22	D	Paraquat	18	7	25
ACCase inhibitors	1	A	Diclofop-methyl	0	21	21
Synthetic auxins	4	O	2, 4-D	15	4	19
Ureas and amides	7	C2	Chlorotoluron	6	11	17
Dinitroanilines and others	3	K1	Trifluralin	2	7	9
Triazoles	11	F3	Amitrole	1	3	4
Chloroacetamides and others	15	K3	Metalochlor	0	3	3
Thiocarbamates and others	8	N	Triallate	0	3	3
Glycines	9	G	Glyphosate	0	2	2
Benzoflurans	16	N	Ethofumesate	0	1	1
Chloro-carbonic acids	26	N	Dalapon	0	1	1
Nitriles and others	6	C3	Bromoxynil	1	0	1
Organoarsenicals	17	Z	MSMA	1	0	1
Pyrazoliums	8	Z	Difenzoquat	0	1	1
Unknown	25	Z	Flamprop-methyl	0	1	1
			Total	129	104	233

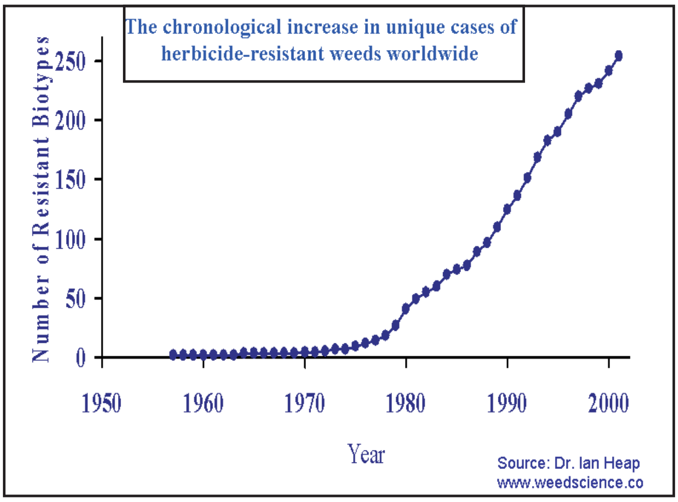

Fig. 1. The chronological increase in unique cases of herbicide-resistant weeds worldwide.

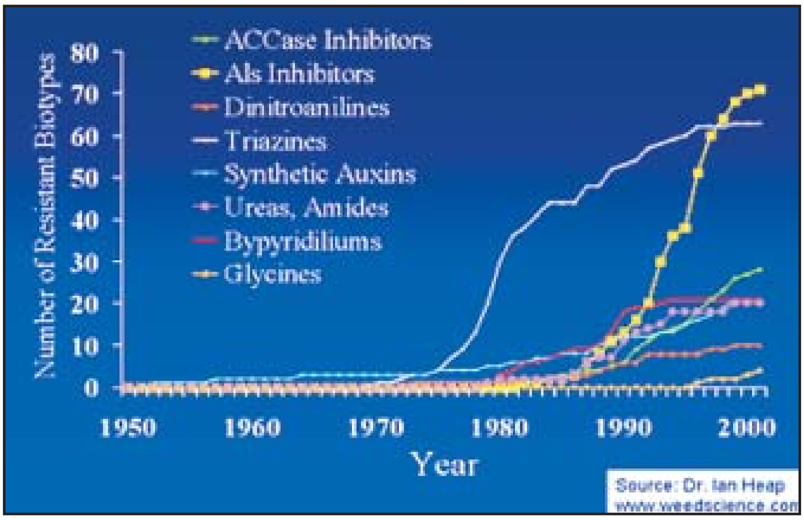

Fig. 2. Trend of resistant biotypes against different herbicides.

Herbicide resistance in other countries :

Herbicide-resistant populations of annual rye grass (*Lolium rigidum*) from Australia and black grass (*Alopecurus myosuroides*) from England are two most discussed cases of herbicide-resistance. Several biotypes of *Phalaris paradoxa* are resistant to triazines in Israel. Large areas of farming land are affected by herbicide resistant weeds in Australia, USA, Canada, England, France and Israel. Selection pressure exerted by herbicides instead of spreading through seeds appears to be major cause of proliferation of these resistant strains. The expansion of herbicide use in India and Mexico in the late 1970's closely mirrored the herbicide use pattern in developed countries in the early 1960s. However, implications of such intense herbicide use for resistance development have become more evident in India and Mexico than Europe probably due to lack of proper integrated management of weeds, limited choice for available herbicides, poor quarantine rules and inadequate technical expertise on herbicide resistance in developing countries.

The scientists of CCS Haryana Agricultural University, Hisar reported the first case of herbicide resistance in India and for the first time in the world in *Phalaris minor* Retz. against isoproturon during 1992-93 (Malik and Singh, 1993, 1995). This was the most serious case of herbicide resistance in the world (Malik and Singh, 1995), resulting in total crop failure under heavy infestation (2000-3000 plants m^{-2}).

Herbicide resistance by gene mutation theories

Two theories have been suggested to explain how gene mutations causing herbicide resistance develop in a population; the gene pool theory, and the selection theory (Franetovich, 1995).

Gene pool theory

It is based on the idea that at some point of time, the genetic make of a plant changes through directed mutagenesis *e.g.* plant mutates as a result of herbicide treatment. There is little evidence supporting this theory (Holt, 1992). However, in one case, S-triazine herbicides were shown to induce genetic mutations in some non-weedy species, but these mutations do not lead to resistance (Jasieniuk *et al*., 1996). Presence of 'unusual genotypes' of *Chenopodium album* gives rise to resistant mutants upon herbicide application.

Selection theory

Most widely accepted theory, which states that in any population of weeds, there will be some plants that can naturally tolerate a particular herbicide *i.e.* one or more individuals in a population will be resistant because of natural variation. The fact that natural mutation causes variable, genetically dissimilar genomes at a rate of 10^{-6} (Gressel and Segel, 1982; Maxwell *et al*., 1990) supports this theory. According to this theory, resistance cannot be avoided, but will occur by random chance. The rate of resistance development, relates to the intensity of the selection for resistance (Martinez-Ghersa *et al*., 1997). This is known as the selection pressure of an herbicide, and is defined as the effectiveness with which the herbicide selects resistant individuals within a population. Selection pressure is directly proportional to the efficacy of the herbicide (Wrubel and Gressel, 1994).

Herbicide resistance prediction models

Following two models have been put forward to explain the herbicide resistance evolution :

(a) Gressel and Segel model (1990)

It considers the relative population of resistant weeds to be an important characteristic of resistance development.

Predictions based on Gressel and Segel model (1990) suggest that three main variables determine the rate at which herbicide resistance develops :

1. Intensity of selection pressure,
2. Seed bank dynamics (where resistance is more likely to develop in those species that have a relatively short seed bank lifetime), and
3. The relative fitness of resistant plants *e.g*. according to their model, a decrease in herbicide efficacy from 99 to 95% significantly decreases the rate at which herbicide resistance develops and, therefore, predicts that resistance will first occur in weed species that are more easily killed by one herbicide.

(b) The Maxwell *et al.* model (1990)

It is based on the idea that weed gene flow may be an important factor for resistant development and assumes that herbicide resistance is conferred by a recessive allele in a highly outcrossing species. It has been used to determine that;

1. The relative fitness of the resistant (R) biotypes, compared both to susceptible (S) weeds as well as to crops, and
2. Gene flow, from susceptible to resistant, is the most important factor influencing the rate of resistance development. They suggested that a reduction in the efficacy of the herbicide by intentionally leaving skips in the herbicide application may allow for the survival of enough healthy susceptible individuals in the population to reduce the level of resistance development *i.e.* via gene flow from S to R plants as well as competition losses due to any fitness disparity. Gene flow from S to R may actually dilute the resistance traits causing the population to regress back to susceptibility. Initial frequencies of resistance, rates of random mutation, relative fitness of resistant plants and level, and importance of gene flow remain unknown.

Role of Herbicide Resistance Action Committee (HRAC)

It fosters co-operation among plant protection manufactures, governments, researchers, advisors, and farmers to facilitate the effective management of herbicide resistance (Anonymous, 2000). HRAC is regionally represented by the following Working Groups :

- European Herbicide Resistance Working Group (EHRWG).
- North American Herbicide Resistance Working Group (NAHRWG).
- National Resistance Working Groups in Australia, South Africa, and others including India.

Important Definitions Related to Herbicide Resistance

Weed resistance

Resistance is normally occurring inheritable ability of some weed biotypes within a given weed population to survive an herbicide treatment that would under normal use conditions, effectively control that weed population. Selection of resistant biotypes may result in control failures.

Herbicide resistance is the inherent ability of a plant to survive and reproduce following exposure to a dose of herbicide normally lethal to wild type (Heap, 2000). Therefore, for a population of plant species to become resistant, a population shift from predominantly susceptible to predominantly resistant takes place. This idea of a population shift is one of the fundamental tenets of resistance theory. However, before a population of a species becomes resistant, resistant individuals must first occur.

Partial resistance

It occurs when plant growth is severely inhibited but it still reproduces seeds. Previously it was called as tolerance but now it has been dropped because resistance and tolerance are two entirely different phenomena.

Herbicide tolerance

It is the inherited ability of a species to survive and reproduce after herbicidal treatment. This implies that there was no selection or genetic manipulation to make the plant tolerant; it is normally tolerant.

Cross-resistance

When resistance to two or more herbicides (with the same or different mode of action) resulting from the presence of single resistance mechanism (one genetic mutation) is termed as cross-resistance (Peever and Milgroom, 1995). Even new herbicides may offer no solution-there may be resistance to them from the first time they are used. The presence of such a mechanism can complicate the selection of alternate herbicides as tools to control a resistance situation. If evolution of resistance to one herbicide immediately endowed resistance to other herbicides, there is cross-resistance. It is **target-site cross-resistance** if all the herbicides affect the precise target. It is **metabolic cross-resistance**, if all the herbicides or their toxic products are degraded by the same mechanism. **Negative cross-resistance** occurs when the resistant plant is more susceptible to some other herbicide than the wild susceptible biotype. It is for this reason that management-strategies must incorporate more than simply a switch of product.

Multiple resistance

Resistance to several herbicides resulting from two or more distinct resistance mechanisms in the same plant (more than one mutation) is called multiple resistance. Multiple-resistance occurs due to sequential selection (one herbicide was used until resistant population evolved, then another was used and resistance was evolved to it). These are separate evolutionary events due to mutations in different genes.

Most cases of herbicide resistance so far studied are caused by single-gene mutation (Holt,1992; Jasienuik *et al.*, 1996). When resistance occurs to two or more target-site chemistries due to same genetic factor *i.e.* one genetic mutation, it is cross-resistance (Peever and Milgroom, 1995) and, conversely, if it is caused by more than one mutation, it is defined as being multiple-resistance.

Resistance mechanisms

The resistance mechanism refers to the method/way by which a resistant plant overcomes the effect of an herbicide. The mechanism present will influence the pattern of resistance, particularly to the cross-resistance profile and the dose response. The populations of *Lolium rigidum* display resistance to most of the modern herbicides with varying modes of action including ACCase inhibitors, ALS inhibitors, triazines, phenylureas and dinitroanilines (Powels *et al.,* 1997; Healy, 1999). The most common mechanisms of herbicide resistance are as follows :

1. An altered target site

An altered target site within a plant may mean that herbicide no longer binds to its normal site of action due to change in the structure of the target site, thereby allowing the plant to survive the herbicide treatment which relies on this site for its activity (ALS inhibitors, triazines and dinitroanilines). For example, an altered target site resistance was found in a biotype of *Eluesine indica*, which was highly resistant to dinitroaniline herbicides. Dinitroanilines interfere with the cell division, but in resistant plants it has been shown that an altered tubulin, the major constituent of the microtubules was insensitive to the herbicide (Vaughan and Vaughan, 1990). The site of herbicide activity is blocked/modified, it is less common but increasing; resistance only to 'fops' and 'dims' and resistance is absolute. There is increasing evidence that resistance development is more rapid to herbicides of the aryloxyphenoxy-propionate and cyclohexanedione groups ('fops' and 'dims') (Chauvel *et al.,* 1992). The foliage acting-nature and high intrinsic activity of such herbicides may impose a rapid selection pressure than that of soil acting herbicides.

2. Enhanced metabolism

It means that a resistant plant can degrade a herbicide to non-phytotoxic metabolites faster than a normal sensitive plant, thereby surviving a herbicide treatment in much the same manner as many crop plants *e.g.* 'fop' resistance in *Alopecurous myosuroides*, and urea herbicide isoproturon in *P. minor* (Malik *et al.,* 1995; Singh *et al.,* 1996). The selectivity of wheat against most herbicides including isoproturon is based on the degradation through membrane bound NADPH-dependent Cytochrome P-450 monooxygenases. Most wheat has one enzyme; weeds with lower level of such a system can overcome herbicides by evolving higher enzyme levels. Malik *et al.* (1995) observed marked decrease in photosynthetic activity upto 4th day in the resistant (R) as well as susceptible (S) biotypes of *P. minor* due to isoproturon; indicating that absorption and translocation could be similar in all biotypes but recovery in photosynthesis only in R-biotypes suggests some degradation of isoproturon at 4-5 days after treatment. The main mechanism of resistance at least in the case of substituted urea herbicides chlorotoluron and isoproturon is due to enhanced ability of resistant plants to metabolize and detoxify the herbicide (Caseley *et al.,* 1990; Kemp *et al.,* 1990; Jorrin *et al.,* 1992). The severity of resistance in these herbicides tends to increase quite slowly from one year to next (Moss and Clarke, 1992).Yadav *et al*. (2002) also reported multiplication of isoproturon resistance in *Phalaris minor* due to its repeated use year after year.

Differential metabolism is a major and commoner mechanism of plant selectivity to herbicides. Several weed biotypes have evolved resistance to herbicides due to their capacity to degrade rapidly and/or conjugate the herbicide into less toxic compounds e.g. in Australia, some populations of diclofop-methyl resistant *L. rigidum* show cross-resistance to wide range of other herbicides including sulfonylureas like chlorsulfuron at least in some populations is due to increased metabolism in resistant plants (Christopher *et al.,* 1991). Enhanced metabolism leads to cross-resistance to many different herbicides and it is often partial rather than absolute.

3. Enhanced sequestration or compartmentalization

Herbicide is inactivated through binding or is removed from metabolically active region of the cell, often in vacuole ('fops' and paraquat). Compartmentalization may be achieved either by storage of the herbicides or its toxic metabolites in the cell vacuole or their sequestration in cells or tissues remote from the site of action (Coupland, 1991).

Herbicide resistance risk assessment

Biology of the weed species and farming practices need to be considered while evaluating herbicide resistance risk (Table 2).

Table 2. Assessment of the risk of resistance development per target species (Cropping system evaluation)

Management options	Risk of resistance		
	Low	Medium	High
Herbicide mix or rotation in cropping system	>2 modes of action	2 modes of action	1 mode of action
Weed control in cropping system	Cultural, mechanical and chemical	Cultural and chemical	Chemical only
Use of same mode of action per season	Once	More than once	Many times
Cropping system	Full rotation	Limited rotation	No rotation
Resistance status to mode of action	Unknown	Limited	Common
Weed infestation	Low	Moderate	High
Control in last 3 years	Good	Declining	Poor
Cultivation system	Annual ploughing	Reduced ploughing	Continuous non-ploughing
Resistance in vicinity	None	Frequent	Common

Source : HRAC guidelines for management of herbicide resistance.

Biology of weed species (a) and farming practices (b) may be helpful in evaluating risk of herbicide resistance evolution as follows :

(a) Biology and genetic make up of the weed species

Population of weeds, frequency of resistant plants and seed dormancy can influence the development of herbicide resistance.

1. **Number and density of weeds :** Higher the density of weeds, the higher the chances that some resistant individuals will be present in natural weed population. Annual growth, several generations per season, extreme susceptibility to a particular herbicide and high frequency of resistant gene(s), will evolve resistance.

2. **Natural frequency of resistant plants in the population :** Some weed species have a higher propensity towards resistance development; this relates to genetic diversity within the species, and in practical terms, refers to the frequency of resistant individual within the natural population.

3. **Seed soil dormancy potential :** Plant species with a longer soil seed dormancy will tend to exhibit a slower resistance development under a selection pressure as the germination of new, susceptible, plants will tend to dilute the resistant population.

(b) Crop improvement practices which may enhance resistance development

Following farming practices may influence the risk of herbicide resistance evolution :

1. **Frequent use of herbicides with a similar mode of action :** The combination of ‘frequent use’ and similar ‘mode of action’ is the single most important factor in the development of herbicide resistance. Long-term residual activity and broad-spectrum control will also enhance resistance.

2. **Crop rotations with reliance primarily on herbicides for weed control :** Crop rotations determine the frequency and type of herbicide to be used, selection of non-chemical weed control options and nature of weed flora. Shift from multi to mono crop rotation, little or no cultivation/tillage for weed control and continuous use of single herbicide(s) of same mode of action will enhance evolution of resistance.

3. **Lack of non-chemical weed control practices :** Faulty agronomic practices and lack of non-chemical weed control methods will lead to herbicide resistance. Integral approach is essential to the development of a sustainable crop management.

Recognizing resistance in the field/resistance confirmation

Before concluding that resistance has evolved, exclude the factors such as rate of use, weed type and stage of growth, climatic conditions, method of spray, quality of product and other agronomic practices that may lead to poor efficacy. Some indicators of resistance are :

1. If susceptible weed species have been controlled effectively at recommended dose, the resistance is a possibility in individuals, which were not controlled.
2. The presence of living plants next to dead plants of the same species.
3. Past experience : If a gradual decline in control has been noticed over a period of years, resistance may be responsible.
4. Herbicide history : Repeated annual use of the same herbicide or herbicides with the same mode of action, favours selection for resistance.
5. Cropping and cultural history : Many cases of resistance are associated with intensive winter cereals and non-inversion tillage.
6. Occurrence of resistance in the vicinity.

Depending upon mode of action, some herbicides are more prone to evolution of resistance compared to others (Table 3).

Table 3. Classification of herbicides based on risk of resistance development

Risk of resistance	Mode of action	Example
High	Acetolactate Synthase (ALS) inhibitors	Sulfonylureas, Imidazolinones
	Lipid synthesis inhibitors	Thiocarbamates, Benzofuran
	Cell membrance disrupters	Dinitrophenols
Medium	Contact photosynthesis inhibitors	Paraquat, Basagran
	Root growth inhibitors	Dinitroanilines
	Pigment inhibitors	Pyridazinones, Triazoles
	Systemic photosynthesis inhibitors	Triazines, Phenylureas and Amides
Low	Amino acid derivatives	Glyphosate, Touchdown
	Growth regulators	2,4-D, MCPA, Glufosinate
	Shoot growth inhibitors	Alachlor

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Chapter 6

Herbicide Resistant Crops–An Important Component of Integrated Weed Management

Integrated weed management (IWM) advocates the use of a combination of preventive, cultural, mechanical and chemical tools to keep weed pressure below threshold levels that reduce yields and profits. Herbicide tolerant crops (HTCs) represent a relatively new weed control technology that can be used in an IWM programme. Depending on the crop, herbicides may be applied prior to planting to reduce weed germination. Additional herbicides may be applied once the crop has germinated in order to kill weeds which escaped the first application. Although most herbicides are relatively non-toxic to human and other animals, there is need to reduce their impact on the environment. One way to do this is to use an herbicide that is less persistent in the environment but still provide good weed control. The rationale for biotech herbicide resistant crops (HRCs) is that the crop can be planted directly into the field, allowed to germinate with weeds already present, and then treated with an herbicide that kills only weeds. HRCs were first produced by methods of traditional breeding, whereas the majority of current HRCs have been produced by genetic engineering. Transgenic crops are those into which genes isolated from microbes, animals or other plants, have been inserted to make them resistant to insect herbivory or tolerant to herbicides.

Herbicide resistant crops have been grown commercially since 1984, when the first triazine-resistant oilseed rape cultivar (OAC Triton) was introduced in the Canadian market. Triazine resistance from *Brassica rapa* L. had been backcrossed using traditional breeding methods into a commercial variety of oilseed rape (Hall *et al*., 1996). On a world scale genetically modified (GM)-HRCs constituted 85 per cent (including stacked *Bt* and HR genes) of the total area of 52.5 million hectare grown with GM crops in 2001 (James, 2001). Out of total 52.6 million hectares under GM crops in 2001, USA, Argentina, Canada, China, S. Africa and Australia comprised 35.5, 11.8, 3.2, 1.5, 0.2 and 0.2 million hectares, respectively. Herbicide tolerant crops (HTCs) in USA covers 80% soybean, 57% cotton, 60% canola and 15% maize. Dominant GM crops during 2001 have been given in Table 1.

In total 70.3 million hectares were planted with biotechnology derived crops in 2003, reflecting an increase of 11.8% over the previous year. GM herbicide resistance accounted for 77% of total area of GM crops.These are often referred as ‘first generation crops’ and question have been raised as to their usefulness and putative risks to the environment and consumers.

Table 1. Dominant GM crops (2001)

Crop	Trait	Crop area (m ha)	% Total GM
Soybean	Herbicide resistance	33.3	63
Maize	Total all traits	9.8	18
	Insect resistance (Bt)	5.9	11
	Herbicide resistance	2.1	4
	Stacked Bt/herbicide resistance	1.8	3
Cotton	Total all traits	6.8	14
	Herbicide resistance	2.5	5
	Insect resistance (*Bt*)	1.9	4
	Stacked Bt/herbicide resistance	2.4	5
Oilseed rape	Herbicide resistance	2.7	5

Recent global status of transgenic crops

The first commercial transgenic crop was "Flavr Savr" tomato with delayed ripening characteristics introduced in USA in 1995. Crops alongwith the genetically improved trait and countries where they have been approved have been mentioned in Table 2. During 2004, herbicide tolerant maize, griwn in four countries USA, Canada, South Africa and Argentina on 4.3 million hectares (5%); herbicide tolerant canola grown in two countries, Canada and USA akso on 4.3 million hectares (5%); Bt/herbicide tolerant maize on 3.8 minnion hectares in the USA and Canada occuping 4% of the total global crop biotech area; Bt/herbicide tolerant cotton (4%) grown in 3 minnion hectares in the USA, Australia and Mexico and herbicide tolerant cotton grown in the USA, Australia and Sotyh Africa in 1.5 million hectares, equivalent to 2% of the global crop biotech hectares (James, 2004).

Four major transgenic crops, namely, maize or corn, cotton, soybean and canola out of 17 mentioned in Table 2 have come to market in various countries. Commercial production of papaya, squash and tobacco has been initiated in USA. Others such as chicory, tomatoes, rice, potatoes, flax, etc. have been approved for commercial use in one or more countries but have not yet been marketed.

Area under cultivation of transgenic crops

In the nine year period since the commercial cultivation of transgenic crops started, the global area under these crops increased by more than 47 fold from 1.7 million hectare in 1996 to 81.0 million hectare in 2004 (Fig. 1). There has been a 20% increase in 2004 in the area over the same in 2003 equivalent to 13.3 million hectare.

Table 2. Transgenic crops approved for commercial use

S.No.	Crop	Uses	Countries where approved
1.	Argentine Canola	Herbicide tolerance and improved protection against weeds	Canada, US, Japan Australia
2.	Carnation	Increased shelf life by delayed ripening, modified flower colour and herbicide tolerance	Australia, European Union
3.	Chicory	Herbicide tolerance, improved protection against weeds and higher yields	European Union
4.	Cotton	Improved insect protection, herbicide tolerance and improved protection against weeds	Japan, Australia, US, China, Mexico, South Africa, Argentina, India, Indonesia
5.	Flax, Linseed	Herbicide tolarance, antibiotic resistance and improved weed protection	Canada, US
6.	Green Pepper	Virus resistance	China
7.	Maize	Herbicide tolerance, improved weed protection, resistance against insects and restored fertility of seeds	Canada, Japan, US, Argentina, European Union, South Africa, Philippines
8.	Melon	Delayed ripening	
9.	Polish Canola	Herbicide tolerance and improved weed control	Canada
10.	Potato	Improved protection from insect and leaf roll virus	US, Canada
11.	Rice	Herbicide resistance	US
12.	Soybean	Improved weed control and herbicide tolerance, improved cooking quality	US, Argentina, Japan, Canada, Uruguay, Mexico, Brazil
13.	Squash	Resistance against watermelon, mosaic virus and zucchini yellow mosaic virus	US
14.	Sugarbeet	Herbicide tolerance	US, Canada
15.	Sunflower	Herbicide tolerance	Canada
16.	Tobacco	Herbicide tolerance	US
17.	Tomato	Improved shelf life, taste, colour and texture, improved insect resistance, virus resistance	US, Mexico, Japan, China

Source : http://www.agbios.com/

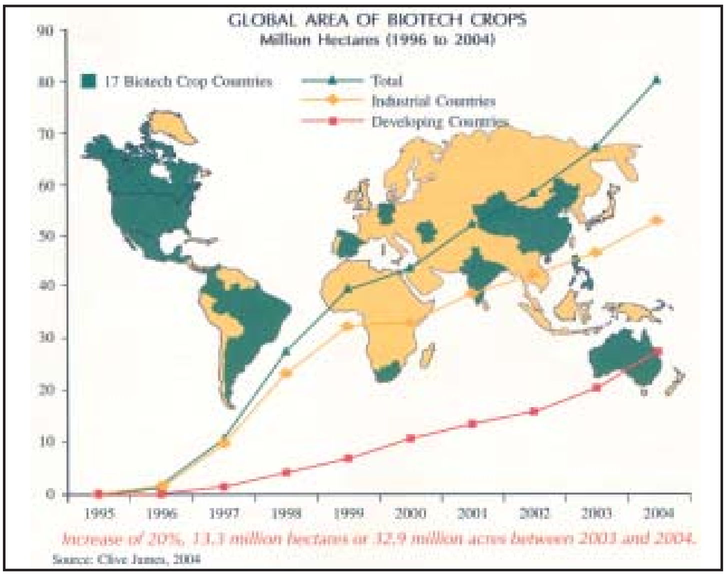

Fig. 1. Global area of trangenic crops from 1996 to 2004 (million hectare).

Source : James (2004) International Service for the Acquisition of Agri-biotech Applications (http://www.isaaa.org).

Seventeen countries have so for adopted biotech crops. More than one third (34%) of the global biotech crop area of 81 million hectare in 2004, which is equivalent to 27.6 million hectares was grown in developing countries. In 2004, there were 14 countries referred to as biotech mega countries which have 50,000 hectare or more under transgenic crops. These include nine developing countries and five industrial countries (Table 3).

Table 3. Area under biotech crops in differenct countries (2004)

S. No.	Country	Area (Million hectare)	S. No.	Country	Area (Million hectare)
1.	USA	47.6	10.	Australia	0.2
2.	Argentina	16.2	11.	Romania	0.1
3.	Canada	5.4	12.	Mexico	0.1
4.	Brazil	5.0	13.	Spain	0.1
5.	China	3.7	14.	Philippines	0.1
6.	Paraguay	1.2	15.	Columbia	<0.05
7.	India	0.5	16.	Honduras	<0.05
8.	South Africa	0.5	17.	Germany	<0.05
9.	Uruguay	0.3			

Source : James (2004) International Service for the Acquistion of Agri-biotech Applications (http://www.isaaa.org).

Biotech soybean occupied 48.4 million hectare (60%), corn 19.3 million hectare (23%), cotton 9 million hectare (11%) and canola 4.3 million hectare (6%) of the global transgenic area. The proportion of transgenic crops vis-a-vis global cultivation is also increasing rapidly. In 2004, 56% soybean, 28% cotton, 19% canola and 14% maize planted globally were transgenic (Fig 2).

Herbicide tolerance has consistently been the dominant trait introduced followed by insect-resistance. In 2004, herbicide tolerant soybean, maize, cotton and canola occupied 72% and *Bt* crops 19%. Stacked genes for herbicide tolerance and insect-resistance deployed in both cotton and corn covered 9% of the global transgenic crop area in 2004.

As on now, research and development programmes ranging from laboratory/greenhouse experiments, to field trials, to regulatory approval and commercial production are going on in 63 countries, and 57 plants (16 field crops, 14 vegetables, 16 fruits and 11 miscellaneous) have been identified for further research on this issue.

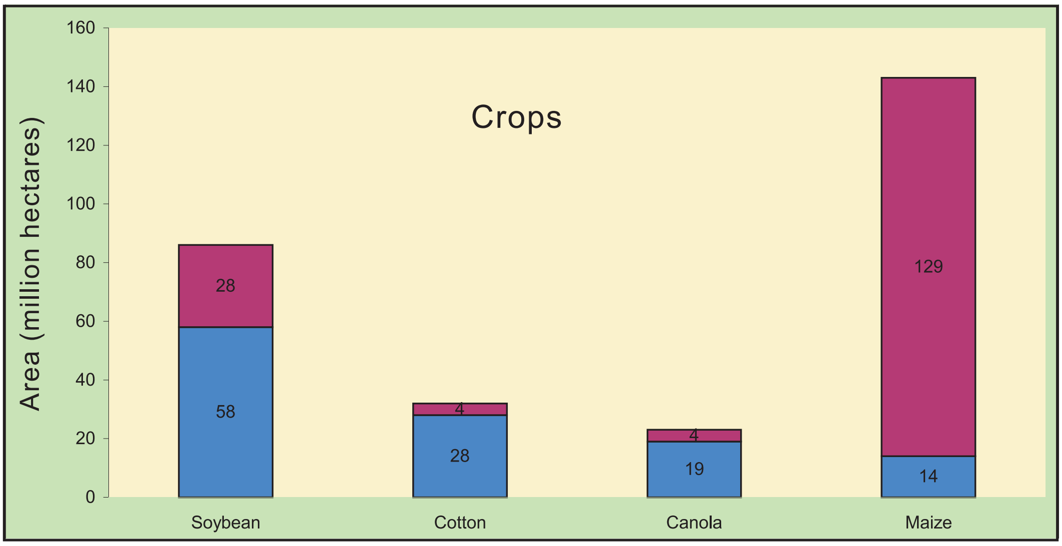

Fig. 2. Growth in transgenic crops in 2004.

Source : James (2004) International Service for the Acquision of Agri-biotech Applications (http://www.isaaa.org).

Important Definitions

Biotechnology

Biotechnology is the technique of modern biology that employs living organism (or part of organism) to make or modify products, improve plants and animals or develop microorganisms for specific uses. It can involve the use of genetic engineering as well as many other technologies commonly used for decades.

Genetic engineering

It is a form of biotechnology, which involves copying a gene from one living organism (bacteria, plant or animal) and adding it to other living organism.

Genetically modified organisms (GMOs)

Today's breeders define GMOs as an organism that has been modified using traditional plant breeding techniques or genetic engineering techniques in which only a small piece of one organisms genetic material (DNA) is inserted into another organism. In popular usage, the term GMO refers only to an organism produced by genetic engineering.

Herbicide tolerant crops can be produced by either insertion of a "foreign" gene (transgene) from another organism into a crop, or by regenerating herbicide-tolerant mutants from existing crop germplasm. The first type of HTC is also commonly known as GMO, while the second type is referred to as a non-GMO variety or hybrid. For example :

(a) GMO crops : Canola, wheat, rice and soybean varieties or corn hybrid tolerant to glyphosate and glufosinate herbicides.

(b) Non-GMO crops : STS-Soybean, Clearfield-Corn, Clearfield-Canola, Clearfield-Rice and Clearfield-Wheat (tolerant to imidazolinone herbicide). It is likely that glyphosate-tolerant spring wheat will be available in 2004 and 2005 for Canadian and US markets, respectively. Clearfield winter wheat tolerant to imazomox herbicide is likely to be released in South-Central US. Glyphosate tolerant alfalfa is currently being evaluated in variety testing trials.

Gene stacking

It is defined as inclusion of more than one gene in an organism. The inclusion of several transgenes in a single hybrid or variety, commonly referred as "stacked genes or stacked traits" is also under development e.g. some corn and cotton hybrids have been genetically engineered to contain two transgenes, one for insect-tolerance and another for herbicide-tolerance (e.g. *Bt* / glyphosate; *Bt*/glufosinate). Furthermore, some corn hybrids have three traits, two for herbicide-tolerance and one for insect-tolerance (e.g. Liberty, Clearfield and *Bt*).

Introgressive hybridization

The spread of genes from one species into the gene complex of another as a result of hybridization between the species.

Transgenic crops

Crops that contain a foreign gene(s) are called as trangenic crops. As genes continue to change, the characteristics they create in plant and animals are passed to subsequent generations. All living organisms have the same code for DNA and the synthesis of protein and other basic functions of life processes. At the molecular level, all living things are more alike than different. That is one of the reasons genes can be moved so successfully between such seemingly different organisms as plants, animals and bacteria (Fig. 3). Genes are not unique to the organisms from which they came.

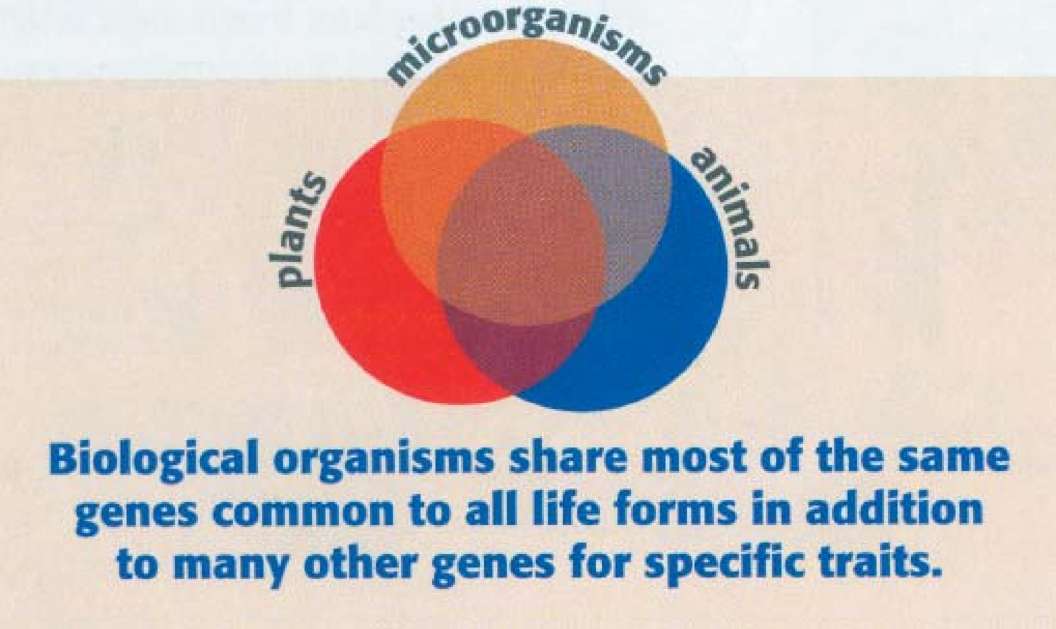

Fig. 3. Common gene pool among biological organisms.

Traditional plant breeding vs. genetic engineering

There are two major differences between "traditional plant breeding" (which also includes many techniques involving agricultural biotechnology) and "genetic engineering" (Fig. 4). The first is the amount of genetic material involved. When two parental plant lines are crossed using traditional breeding methods, the new plant ends up with half the genetic makeup of each parent. Thus, the desirable gene may be accompanied by many undesirable genes from that same parent.

To remove that undesirable genes continued breeding is required. In the case of genetic engineering, only the few specifically desired genes are moved into the new plant.

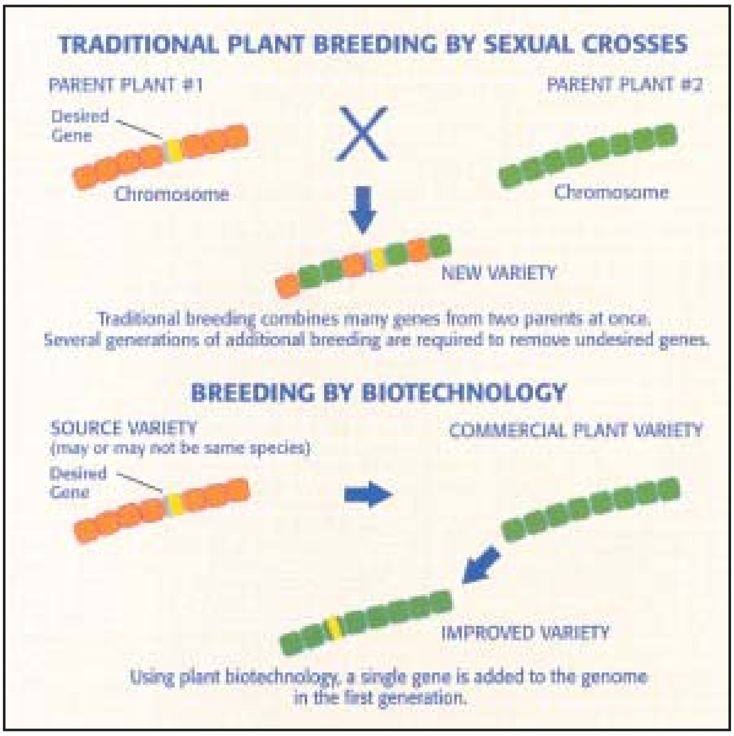

Fig. 4. Difference between traditional plant breeding and genetic engineering.

A second difference between traditional breeding and modern biotechnology is the source of genetic material. Traditional breeding largely relies on closely related plant species. In modern biotechnology, theoritically a gene from any living organism may be moved into other living organism. This permits to move the genes from a bacterium into plant. In fact, this was done to produce insect protected biotech plants using genes from a common soil bacterium, *Bacillus thuringiensis* (*Bt*). This bacterium has been used commercially by more than 50 years as an insecticide spray, but does not provide the same level of control as when *Bt* is transferred into a biotech plant, like Bt corn or Bt cotton.

Selection of herbicide resistant crops (Dekker and Duke, 1995)

It can be achieved by following techniques :

A. Traditional plant breeding techniques

B. Biotechnological techniques

  I. Cell and tissue culture selection (Table 4)

  II. Hybridization

  III. Microspore and seed mutagenesis

  IV. Plant transformtion (Table 5)

How are the genes put into crop plants?

Gene transfer using a common soil dwelling bacterium, *Agrobacterium tumefaciens*, is a powerful tool routinely used to transform plants using modern biotechnology methods such as genetic enginerring. Crown-galls of plants are caused by the transfer of a small piece of DNA from a plasmid in the pathogen *A. tumefaciens*, into the host plant where it becomes part of its genome. This bacterium naturally transfers its genetic material into their other plants and when a new gene is added to the bacterium, that new gene is also transferred.

Table 4. Herbicide resistant crops developed (Kandasamy *et al.,* 2002)

Herbicide group/herbicide	Resistant crops
ALS inhibitor sulfonylurea	Barley, cotton, maize, rapeseed, rice, soybean, tobacco
Imidazolinones ACCase inhibitor	Maize, rapeseed, wheat
Bypyridiliums	Potato, tobacco
DHPS inhibitors	Tobacco
Phenoxycarboxylic acids	Cotton, tobacco
Triazines	Foxtail millet, potato, rapeseed, tobacco
Bromaxynil	Cotton, tobacco
Cynamide, Dalapon	Tobacco
Glufosinate	Barley, sugarbeet, carrot, maize, oat, potato, rapeseed, sorghum, tobacco, tomato, wheat
Glyphosate	Maize, rapeseed, soybean

The “gene gun” developed in 1986 in Cornell University (USA) is another of the tools used worldwide for genetically engineered plant cells. A gene gun “shoots” DNA segments into cells at high speed and some of the DNA segments are incorporated into the plants genome.

Both transformation techniques require an additional step of tissue culture. In this process, newly transformed plant material is first tested to ensure that the gene transfer is successful. Then because the plant cells with the newly acquired genes require certain environmental conditions to flourish, they are first grown in tissue culture in the laboratory and then later in the greenhouse and field. Plants that carry a novel gene can be crossed with other plants possessing desirable characteristics and their off springs may then carry the novel gene. A plant carrying a novel gene can also be propagated by taking “cuttings” from the plant, as is done with many woody plant like apples and grapes. In either case, plants are further evaluated under greenhouse trials. Those that prove successful are then evaluated in small, regulated field trials before they are introduced into larger trials. The development of transgenic plants takes years together.

Table 5. Herbicide resistant crops developed by plant transformation (Kandasamy *et al*., 2002)

Herbicide	Source of resistant-gene	Mode of resistance	Transfer in plants
Glyphosate	*Escherichia coli* over expression *Agrobacterium tumefaciens*	Altered EPSPS Over expression of EPSPS	Tobacco
Glufosinate	*Streptomyces hygroscopiues*	Expression of PAT	Soybean, rapeseed
Chlorsulfuron	*Nicotiana tabacum*	ALS mutated gene	Tobacco, tomato potato, maize, soybean, wheat
Bromaxynil	*Klebsiella ozene*	Nitrilase	Tobacco, rice
Norflurazon	*Erwinia uredovora*	Enhanced carotenoid biosynthesis	Cotton, clover, rapeseed
Dalapon	*Pseudomonas putid*	Dehalogenase	Tobacco
2,4-D	*Alcaligene eutrophus*	Monoxygenase	Tobacco, cotton
Phenmediphem	*Arthrobactor oxidens*	Carbonate hydroxylase	Tobacco

Some of the herbicide resistant crops

- **IMP (IR/IT) or Clearfield (CL) corn**

  It was developed by tolerance selection to be resistant/tolerant to imidazolinone herbicides (e.g. Pursuit, Scepter). Some IMI varieties (IR) also are tolerent of some sulfonylureas (e.g. Accent, Exceed) and sulfonamide (Broad strike products) herbicide and are used to reduce injury potential from these products when they are applied alone or in combination with organophosphate (OP) insticides.

- **Liberty link/GR corn**

  It is genetically engineered to allow over-the-top application of liberty (glufosinate) herbicide. This programme should provide broad spectrum control of annual broadleaf weeds and grasses of low to moderate pressure.

- **SR (sethoxydim resistant) poast protected corn**

  It was developed using tolerance selection technique to allow over-the-top application of Poast (Sethoxydim). This can provide control of annual grasses in a planned post-emergence programme or help manage escaped grasses.

- **Roundup ready corn**

  It was developed using genetic engineering techniques. It allows post-emergence application of Roundup (glyphosate) and some other glyphosate-type products directly to corn. This system should provide broad spectrum annual and perennial weed control in corn.
- **The STS seed/herbicide system**

  It enhances crop safety from certain sulfonylurea herbicides such as Pinnacle and Classic (chlorimuron). The STS seed/herbicide system is designed to provide good weed control without crop injury.
- **Liberty link soybean**

  These are gentically engineered to allow over-the-top application of Liberty (glufosinate) herbicide. This programme should provide broad-spectrum control of annual broadleaf weeds and grasses of low to moderate pressure. Sequential application or tank mixtures may be required for new weed flushes and for perennials.
- **Roundup ready soybean**

  These were developed using genetic engineering techniques. This system allows over-the-top application of Roundup Ultra (glyphosate) and some other glyphosate containing products to soybean from cracking to flowering. The programme allows timely application and provides broad-spectrum control of many annual and perennial grasses and broadleaf weeds. Sequential applications may be required for harder-to-control perennials and wide row plantings.

Potential advantages/benefits of herbicides resistant crops

The most commonly cited benefits to the producers include :

- Broad spectrum of weed control
- Reduced crop injury
- Less herbicide carry-over
- Price reduction for conventional herbicides
- Use of herbicides that are more environment friendly
- New mode of action for resistance management
- Weed management flexibility and simplicity, especially in no-till system

These benefits of HTC have been described in brief as follows :

1. Broad spectrum of weed control

Non-selective herbicides such as glyphosate and glufosinate can provide effective control of wide spectrum of weeds, which is particularly important in no-till systems. Glyphosate being systemic helps control perennial weeds alongwith their stolons and rhizomes. Glyphosate can thus be an effective tool for control of many “Hard-to Control” weeds.

2. Reduced crop injury

Crop injury is reduced with the use of HTCs. Both glyphosate and glyfosinate cause almost no crop injury, compared to some traditional herbicides (e.g., lactofen, chlorimuron in soybean).

3. Less herbicide carry-over

Glyphosate and glufosinate have almost no soil residual activity because they are tightly bound to the organic particles in the soil. Hence, there are few restrictions for planting or replanting interval or injuries to the subsequent crops.

4. Price reduction for conventional herbicides

Price reduction due to market adjustment is an attempt by manufacturing companies to remain competitive with the pricing of herbicides used on non-HTCs. Introduction of HTCs in soybean brought down cost of conventional herbicides from US $ 40 to $ 60 per acre to $ 20 to $ 30 per acre.

5. Use of herbicides that are more environment friendly

Glyphosate and glufosinate have low toxicity to human and animals, because organic matter absorbs them and they decompose rapidly, they pose little danger for leaching and contamination of ground water or toxicity to wild life.

6. New mode of action for resistance management

Since the discovery and report of triazine resistance almost 40 years ago, weed resistance to herbicides has been well documented (Holt, 1992). For example, there are 40 dicot and 15 monocot species known to have biotypes resistant to triazine herbicides (Holt, 1992). Also atleast 44 weed species have been reported to have biotypes resistant to one or more of 15 other herbicides or herbicide families (Holt, 1992). At present, 296 weed species have developed herbicide resistance and the list of herbicides-resistance-weeds will continue to grow, especially with repeated use of herbicides with same mode of action. The number of worldwide cases of ALS and ACCase resistance is also increasing (Heap, 2000) and herbicides with alternate site of action are needed. Therefore, HTC (e.g. glyphosate and glufosinate) can provide a new mode of action when used in an IWM programme as an aid in resistance management.

7. Crop management flexibility and simplicity

The HTC technology is simple and flexible and requires neither skills nor training. It provides wide window of application time during the optimal period of weed control.

Besides aforesaid benefits, other advantages of HTCs may be reduced production costs (due to lower herbicides use and better weed management), increased yields, soil conservation (HRCs facilitate no-till and reduce-tillage agronomic system) and reduced herbicides use.

Disadvantages/concerns of adopting herbicide resistant crops

Some of the disadvantages of adopting HRC are listed below :

- Gene flow
- Shift in weed flora
- Single selection pressure and weed resistance
- Drift and non-target movement of herbicides
- World market and food labelling
- Effect of broad-spectrum herbicides on ecosystem
- Yield performance
- Socio-economic risks

These concerns regarding HTC have been described as under :

1. Gene flow

Transfer of gene from one population to another may lead to unwanted effects for weed management and the environment. Gene flow or gene escape may enable the resistance genes to move between HR and non-HR varieites or organic crops and thus pollute a crop which is considered GM-free. HR-genes may be stacked from years of cross-pollination of HRCs which may result in the problems for the farmers in controlling volunteer crops in the field.

The potential for the “escape” of gene conferring herbicide resistance via pollen from HTCs to other closely-related wild relatives is a major concern (Zemetra *et al*., 1998). Major concern is in a allogamous (maize, sugarbeet) and self-pollinated crops with high outcrossing (rapeseed) than autogamous crops (rice, wheat, soybean) and imidazolinone-tolerant-(IMI) wheat to jointed goatgrass (*Aegilops cylindrica*) in north-western U. S. (Seefeldt *et al*., 1998). Multiple resistance developed in volunteer canola (*Brassica napus)* due to pollen flow from relative species that were treated with three commonly used herbicides (glyphosate, glufosinate and imazethapyr) in Alberta, Canada

(Hall *et al.*, 2000). Glufosinate resistant gene from rice to red rice, Roundup ready corn to non-Roundup Ready corn and IMI-tolerant sunflower to common sunflower are few other examples. List of crops and weed species has been given in Table 6 where gene transfer of herbicide resistant may be important.

Table 6. Wild species and crops where introgression hybridization may be important for gene transfer of herbicide resistance

Crop	Weed species
Barley	Wild barley
Canola	Neumerous wild mustards
Carrot	Wild carrot
Corn	Teosinte
Foxtail	Green foxtail
Poplar	Cottonwood
Lettuce	Prickly lettuce
Oat	Wild oat
Radish	Wild radish
Rice	Red rice
Sorghum	Johnson grass
Sugarbeet	Wild cucurbits species
Sugarbeet	Wild beet
Sunflower	Wild sunflower species
Wheat	Jointed goatgrass

The so-called “high risk crops” and their weedy relatives include sorghum and its weedy relatives shattercane and johnsongrass; canola and mustards; wheat with jointed goatgrass and quackgrass; rice with red rice; sunflower with wild sunflower. Madsen (1994) showed pollen dispersal from *Beta vulgaris* var. conditiva to *B. maritima* where crossing frequency (%) reduced with the increasing distance from *B. vulgaris* var. conditiva towards east or east north-east.

2. Shift in weed species

Repeated use of glyphosate or glufosinate or imidazolinone can result in a shift in weed species from those easily controlled by these herbicides to those that become more tolerant to these herbicides. Under glyphosate system, chances of weeds which dominate are : Wild buckwheat (*Polygonum canvolvulus*), Pennysylvania smartweed (*P. pensilvanicum*), Ivy morning glory (*Ipomoea hederacea*), Horseweed (*Conyza canadensis*), Lady’s thumb

(*P. lapathifolium*), Field bindweed (*Convolvulus arvensis*), Venice mallow (*Hibiscus trionum*) and Yellow sweetclover (*Melilotus officinalis*) (Van Gressel, 2001). Such shift in weed population to more tolerant weeds increases weed control costs, even with the use of HTCs.

3. Single selection pressure and weed resistance

Widespread use of same HTCs results in repeated use of same herbicide, hence more selection pressure and hence resistance in weeds. Examples of herbicide resistance in weeds against glyphosate are : Rigid ryegrass (*Lolium rigidum*) in Australia (Poweles *et al*., 1998), Goosegrass (*Eleusine indica*) in Malaysia, Ryegrass in California and Horseweed (*Conyza canadensis*) in Delaware and Tennessee (Culpepper *et al*, 2001; Van Gressel, 2001). Waterhemp (*Amaranthus rubis* Sauer.) surviving label rates of glyphosate in glyphosate tolerant soybeans from Iowa, Illinois and Missouri, indicating the need for higher rates, repeated application, and ultimately higher cost of weed control programme.

4. Drift and non-target movement of herbicides

Improper application of non-selective herbicides such as glyphosate and glufosinate, and misidentification of fields planted with non-HTCs can occur unless care is taken to identify such fields and to avoid drift onto nearby fields with crops that are not resistant to the herbicide applied.

5. World market and food labelling

Consumer rejection of transgenic crops in Japan, India and European countries may jeopardise the market. This may require labelling regulations for GMO crops and grain products. This becomes more important for farmers who are practising organic farming.

6. Effect of broad-spectrum herbicides on ecosystem

GM herbicide tolerant crops confer tolerance to broad spectrum herbicides such as glyphosate and glufosinate. Their extensive use may reduce the diversity of weeds in agricultural habitats and may reduce weeds and invertebrates populations, on which birds and other wild life depend.

7. Yield performance

HTCs must achieve yields comparable to conventional varieties to ensure economic return. But yield drag and yield lag are not uncommon due to use of HTCs (Elmore *et al*., 2001). Yield drag is yield reduction due to addition of foreign gene. Soybean varieites with glyphosate-tolerant-gene yielded 5% less than the sister lines without foreign gene (University of Nebraska study, Elmore *et al*., 2001). Yield lag is the yield depression due to the age of variety in which gene is inserted. Glyphosate tolerant varieties yielded 10% less than the best high yielding non-HTCs indicating yield lag (Univesity of Nebraska study as already indicated).

8. Socio-economic risks

Monopoly of seed companies and technical problem may arise for farmers. As such, IWM is not a “recipe” rather it needs to be changed and adjusted to a particular farming system.

Strategies for adopting herbicide resistant crops

Following strategies are needed to adopt HRCs for successful implications :

A. Selection of herbicide resistant crop
    1. Conventional breeding method
    2. Biotechnological approach
B. Reducing herbicide dependence
C. Development of enviromentally benign herbicides having following characteristics
    1. Optimum residual life
    2. Low volatility
    3. Toxic to broad spectrum of weeds
    4. Non-toxic to animal life
D. Reduce total herbicide usage
E. Development of suitable selective post-emergence herbicides
    1. Rely upon cultural and mechanical weed control
    2. Use of post-emergence selective herbicides, if needed
F. Herbicide rotations and mixtures
G. Concerns of herbicide resistant crops

CONCLUSIONS

Herbicide resistant crops have a great potential in the simplification of weed managment. Handled judiciously, these crops may be beneficial to the environment by enabling no-till systems, thus reducing erosion or allowing for later weed control, which may increase biodiversity in the field. However, it must be emphasised that the risk from HRCs should be carefully evaluated prior to releasing the HRC into a cropping system, especially when the HRCs possess weedy characters or may outcross to related weeds. If this is the case, and the HRC is grown commercially, then precautions need to be taken, similar to the management strategies adopted to prevent the development of naturally resistant weeds. Furthermore, precautions must, in particular, be taken before release into the genetic origin of the species. For long-term benefits of HRC, and avoiding concerns/risks, these must be used as component of IWM and not in isolation, and overuse, abuse or misuse should be avoided.

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Chapter 7

Resistance Evolution Against Isoproturon–Diagnostic Surveys

Farmers used to plough down their wheat crop in late seventies when heavy infestation of *Phalaris minor* (2000 to 3000 plants m^{-2}) was not uncommon. Isoproturon recommended in 1978 proved very useful to tackle this problem for a quite long period. But due to continuous use of this herbicide for 10-15 years in rice-wheat cropping system, resistance evolved in 1992-93. Due to development of resistance, farmers in some parts of Haryana, India again resorted to ploughing down of immature wheat in a population range of 2000-3000 plants m^{-2}. The average loss of 25 to 30% productivity became quite common due to this problem and the gains achieved due to use of this herbicide started reversing in resistance affected areas. Structure of isoproturon has been depicted in Fig. 1.

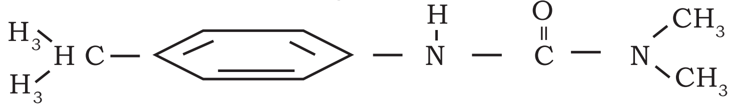

Fig. 1. Isoproturon structure.

Isoproturon [3-(4-isopropylphenyl)-1, 1-dimethylurea], is a phenylurea herbicide with molecular weight of 206.29. It is selective systemic herbicide, absorbed by the roots and leaves, with translocation through transpiration stream. Activity of this herbicide against plants is due to inhibition of photosynthetic electron transfer in PS II.

Soil moisture is the most important variable effecting the activity of this herbicide. Soil moisture in the upper surface is even more important than the moisture available in the deeper zones. When application is delayed or made in relatively dry surface, activity of isoproturon is reduced. Surface watering causes greater damage to this weed and that is why when herbicide applications are made immediately before first irrigation (20 days after sowing) at 0.75 kg ha^{-1}, it is as effective as at 1.0 kg ha^{-1} applied 30-35 days after sowing.

Isoproturon enters the plant largely from soil but there is some activity after its application to the foliage. Due to availability of low moisture in soil surface or on relatively dry surface, isoproturon available for transport in the transpiration stream is reduced.

For almost three decades after 1966 rice-wheat crop sequence in North-West India, symbolized the country's success in food production. In the early

1980s most of the rich farmers opted for isoproturon use but in the late 1980s, there was thin layer between farmers opting for isoproturon use as the family labour was no longer available for manual weeding. By the early 1990s things started looking different and at this time the sustainability of rice-wheat sequence was started being questioned. Due to serious problem of littleseed canary grass, isoproturon became favourite target for farmers as it provided excellent control of this weed with large scale yield advantage (Table 1). Herbicide sales in North-West India, in general, and in the eastern part of Haryana, in particular, increased sharply. During the first two decades of green revolution (1966-1975, 1976-1985), wheat yields increased more due to high yielding varieites and fertilizer use. Scientists, extension agencies and farmers saw the brighter prospects of herbicide use and most of direct subsidies for wheat were used for weed control. Isoproturon proved useful in cost cutting for manual weeding and thus breaking the old barriers of weed management through family or contractual labour.

Table 1. Effect of isoproturon on grain yield (kg ha^{-1}) of wheat in field demonstrations conducted during 1980-81, 1981-82,1982-83 and 1983-84

S.	1980-81		1981-82		1982-83		1983-84	
No.	Untreated	Treated	Untreated	Treated	Utreated	Treated	Untreated	Treated
1.	2930	4100	2300	3140	3075	3825	3660	4470
2.	1665	3150	2400	3180	2875	4075	3140	4300
3.	2265	3417	2510	3470	2986	4300	3400	4390
4.	2767	3917	2450	3470	3175	4570	3250	4800
5.	2004	2782	2470	3610	3300	4650	3570	4210
6.	2351	3226	2510	3580	2735	4005	2800	3910
7.	1880	3100	2390	3380	2475	3840	3900	4500
8.	1470	2825	2530	3480	3427	4220	3250	4950
9.	2020	4510	2550	3560	3400	4200	3700	4440
10.	3230	4620	2380	3660	2700	3400	3040	3600
Mean	2258	3545	2449	3453	3014	4108	3371	4356

Source : Seasonal Report, NARP Project, Weed Control Research (CCSHAU, Hisar, India).

But during 1992-93, the yield levels at five locations out of 10 ranged from 0-1500 kg ha^{-1} under isoproturon treated fields with an average of 2300 kg ha^{-1} as against expected yield of 4860 kg ha^{-1} under weed free situation in Haryana.

Harringaton *et al*. (1992) estimated that annual productivity losses in wheat are likely to be maximum due to presence of weeds particularly *P. minor*. The problem of littleseed canary grass in districts dominated by rice-wheat sequence has been given in Table 2.

The poor efficiency of isoproturon and subsequent evolution of resistance by this weed against isoproturon have allowed its complete dominance in rice-wheat zone.

Resistance in *P. minor* was reported for the first time in world and as first case of herbicide resistance in India in 1992-93 (Malik and Singh, 1993; Malik and Singh, 1995).

The quality of isoproturon which was suspected responsible for poor efficacy was also cross-checked (Malik and Singh, 1995). The results indicated that Ronak (a formulation of isoproturon) which the farmers at village Laloda, Haryana suspected to be of poor quality in 1991, provided good control of susceptible population (H2) but not of resistant population (H3). The recommended formulation of isoproturon (Arelon) also did not provide good control of resistant population (Table 3).

Table 2. Per cent occurrence and average intensity of *P. minor* in wheat in various districts of Haryana (1990-91)

District	Frequency (%)	Average intensity (0-10 scale)
Ambala	90	2.2
Karnal	100	3.9
Yamuna Nagar	90	2.4
Kurukshetra	100	3.0
Kaithal	100	2.7
Panipat	78	2.2
Sonepat	100	3.9
Jind	85	3.4
Rohtak	59	2.0
Hisar	62	2.5
Sirsa	62	2.4
Bhiwani	05	1.5
Gurgaon	18	0.8
Faridabad	47	3.8

Source : Annual Report, AICRP on Weed Control, CCSHAU, Hisar, India.

Table 3. Effect of isoproturon formulations on GR_{50} value of two biotypes of *P. minor* (Pot culture)

Formulations*	Biotypes	GR_{50} values (g ha^{-1}±SE)	Regression equation (Y=a+bx)**	Resistance factor
Arelon	H2	71±20	Y=3.70+1.52x	1.0
	H3	430±80	Y=0.90+2.52x	6.1
Ronak	H2	65±30	Y=3.75+1.54x	1.0
	H3	380±60	Y=2.13+1.81x	5.8

Source : Malik and Singh (1995).

* Arelon (75% WP), manufactured by Hoechst (India) Ltd. and Ronak (75% WP) by New (Chem. India) Ltd.

**In regression equation Y=a+bx; Y is the calculated (Probit) response of 'X' unit of herbicide (g ha^{-1}), 'a' is constant, and 'b' is the slope.

Following factors other than resistance were also outlined for poor efficency of this herbicide against this weed :

1. Late application : Application 35 days after sowing or when *P. minor* has passed 5-6 leaf stage provided poor control of *P. minor* as compared to early application at 20-25 days after sowing (Balyan *et al*., 1998).

2. Application method : Application of isoproturon by non-conventional methods including sand or urea mixing and broadcasting was less effective than application by spraying method (Malik *et al*., 1990).

3. Isoproturon resistance : Approximately 50% of added isoproturon was found to have disappeared in 15 days in sandy loam soil, while it took 18 to 21 days in the clay soil and the clay soil in which rice straw was burnt (Yadav and Malik, 1988).

4. Soil moisture : Presence of adequate moisture at spraying or immediately after spraying is necessary for maximum efficiency of isoproturon (Malik *et al*., 1989).

5. Under dosing : Application of isoproturon at less than the recommended dose (1.0 kg ha^{-1} applied 30 DAS) resulted in poor control and addition of surfactant to isoproturon at 25% less than its recommended dose improved the littleseed canary grass control (Malik *et al*., 1988; Malik *et al*., 1989).

6. Straw burning : Field experience and experimental evidence have suggested that the straw burning reduced the efficacy of isoproturon (Singh, 1996). Herbicidal performance has been reported to be affected by straw ash (Moss and Cotterill, 1985).

Resistance monitoring

Isoproturon was approved for use in 1980s. In the first few years, it provided acceptable control of *P. minor* at half of the recommended rate. Then farmers started increasing its dose and applied more than the recommended rates from late 1990s onward.

The excellent control of *P. minor* by isoproturon in 1980s seems to be on reverse path in 1990's. In 1978, 15% farmers who owned less than 10 acres and 37% farmers who owned more than 10 acres started using herbicides. *P. minor* occurred alongwith common lambsquarter (*Chenopodium album* L.) and wild onion/piazi (*Asphodelus tenuifolius*). By 1990, only *P. minor* remained the most dominant weed. After the development of resistant populations of this weed, all other weeds seem to have been eliminated as problems. In 1986-87, 16% farmers used the optimum dose of isoproturon, it was up by 60% in 1991 and by 1992-1993, 84% farmers used optimum dose (Fig. 2). Survey conducted after receiving complaints about its poor efficiency in 1991 in Eastern Zone of Haryana, has found that increase in dose in 1990s was associated with decreased efficiency of isoproturon.

The frequency of resistance in a population starts at a low value and increases by constant factor each year. There were few fields with isoproturon resistant population of *Phalaris minor* in Karnal, Kurukshetra districts and Tohana Tehsil of Fatehabad (then Hisar) district in 1991. Since then it has spread in almost geometrical progression. Immigration of resistant seeds can be a problem when introduced in other areas. Enrichment of fields with resistant population depends on selection pressure, seed bank dynanics, fitness and initial frequency. The use of same herbicide over years continuously exerts selection pressure in favour of resistant population.

In the problem zone, 45% of the farmers used a repeated spray of isoproturon at 20 days after sowing and 30-35 days after sowing each at recommended dose but without success. In 1989-90, 70% farmers got satisfactory control; by 1992-93 it was down to 21 per cent. Thirty-eight per cent farmers reported no control of *P. minor* by isoproturon (Fig 3).

A diagnostic survey of weed flora conducted in 1993-94 has shown that 99% farmers in rice-wheat zone reported the problem of a single weed *P. minor*. Out of 100 farmers, 23% reported that after treating with isoproturon there was no loss in wheat yield due to *P. minor* but 34, 14, 11 and 16% farmers

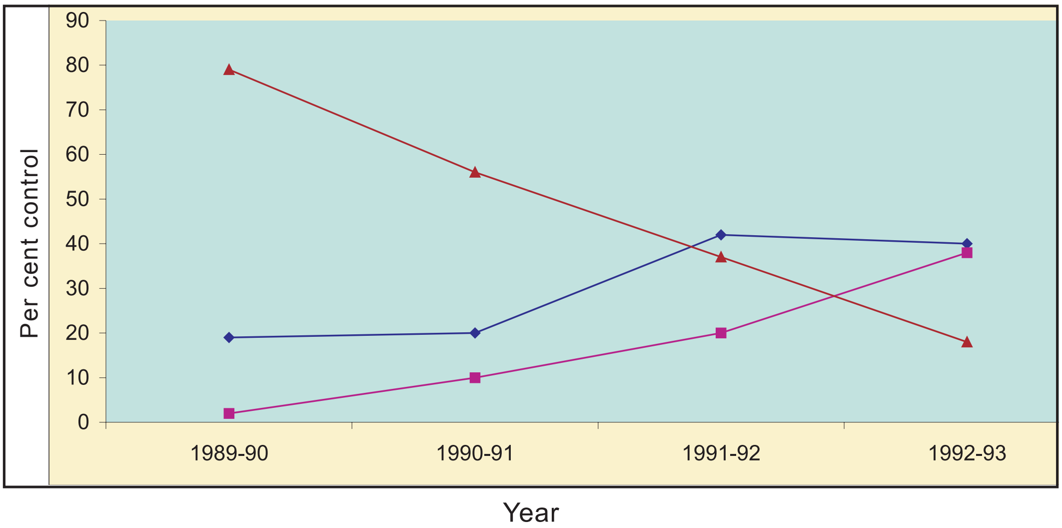

Fig 2. Percent control of collected canary grass by isoproturon applied at recommended dose at farmers field over a period of four years (1989-90 to 1992-93).

Source : Malik and Malik (1994).

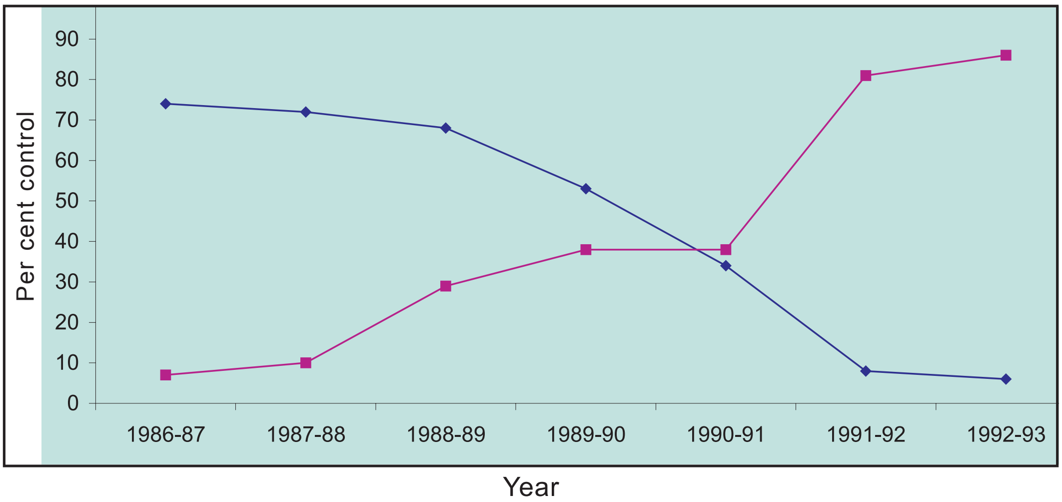

Fig 3. Percentage of farmers used less than the optimum dose and optimum dose of isoproturon over a period of seven years (1987-88 to 1992-93).

Source : Malik and Malik (1994).

reported a yield loss range of 10-25, 25-50, 50-75 and 75-100%, respectivley; even after treating *P. minor* with isoproturon at the recommended dose of 1.0 kg ha^{-1}. Most of the 16% farmers in a loss range of 75-100% ploughed down parts of their wheat in the mid season (Fig. 4) and planted sunflower (Malik *et al.*, 1995). The yield losses due to herbicide resistance in *P. minor* from 1981 to 1993 were significant (Fig. 4).

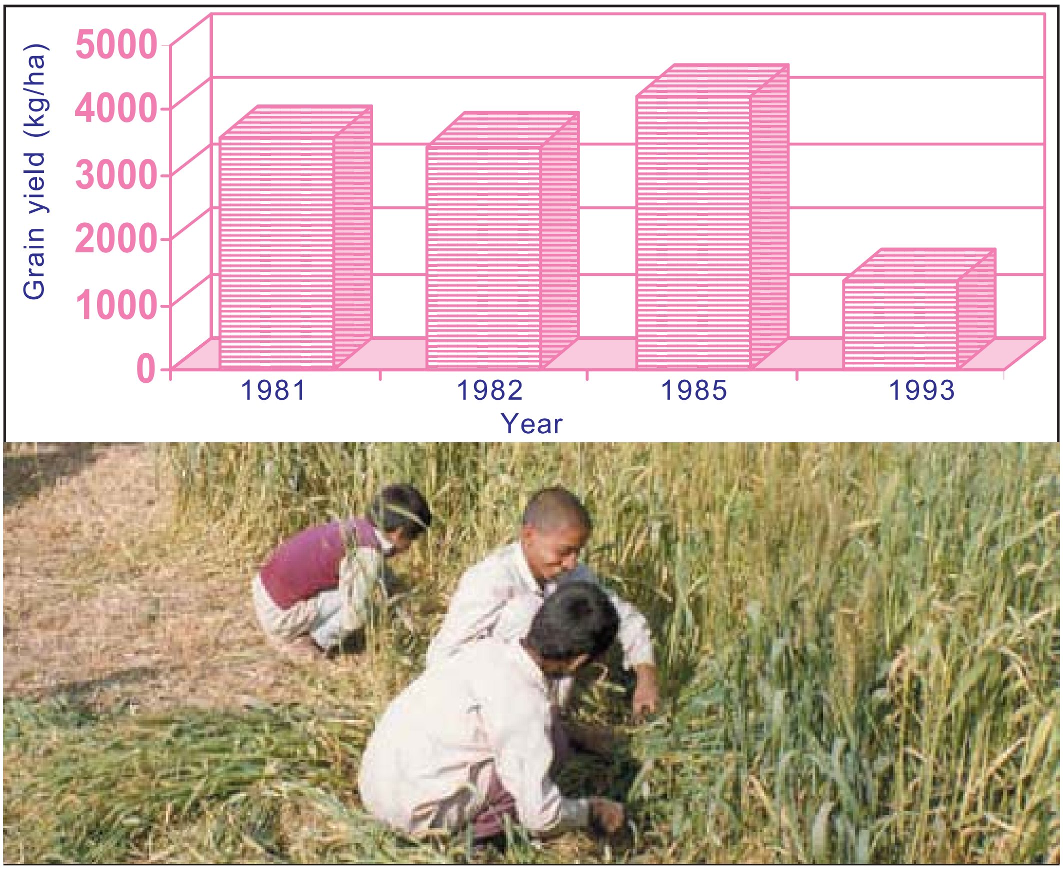

Fig. 4. Wheat yield reduction due to herbicide resistance in *P. minor* and farmers harvesting immature wheat.

The results of survey conducted for two years (1992-1993) suggested :

1. That the number of farmers with no *P. minor* control with isoproturon was increasing every year.
2. That the biggest problem of resistance was occuring in rice-wheat sequence.
3. That the requirement of isoproturon for acceptable control of *P. minor* was increasing every year.
4. That the farmers were not getting any control even by using 2-3 sequential sprays each at recommended rate.
5. That the farmers shifted to using spray pumps once the problem of resistance was encountered.
6. That almost total crop failure occurred in a population range of 2000-3000 plants of *P. minor* m^{-2}.

Small advantage given by isoproturon in very few cases was more than outweighed by the general economic loss incurred by farmers using isoproturon at much more than the recommended rate without any success. It was actually realized at this stage that why isoproturon should be used when resistance will render it ineffective. Therefore, in areas, where resistance had already occurred, switching over to alternate technology including alternate herbicides, herbicide rotations, crop rotation, etc. was realized important and also for other areas to delay or prevent resistance.

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Chapter 8

Resistance Against Isoproturon–Evidences

Grassy weeds are related to wheat in taxonomic, phenological, morphological and biochemical characteristics. Since the domestication of wheat 8,000 years ago, certain grassy weeds like *P. minor* have evolved morphological and phenological resemblances or mimicries to wheat.

About 40 years ago wheat yield in India was very low but the green revolution in late sixties helped India to avoid importing wheat from developed countries. However, with the introduction of high yielding dwarf wheat varieties, fertilizer use and assured irrigation facilities, the North-West Indian wheat was threatened by the presence of Littleseed canary grass (*Phalaris minor* Retz.) in 1976-77 and herbicide use became obligatory to maintain the productivity of wheat in rice-wheat cropping system. Three herbicides, isoproturon, metoxuron and methabenzthiazuron were recommended in 1978. However, isoproturon showed consistent superiority and farmers relied on a single herbicide since 1980's. Use of herbicides prevented a large scale yield reductions and stabilized the production of wheat by shielding at least a quarter of loss in potential yields of wheat due to this weed. But due to continuous use of isoproturon as single herbicide from last 10-15 years resistance evolved in *P. minor* in 1992-93 (Malik and Singh, 1995; Walia *et al*., 1997). The grain yields of wheat recorded in the isoproturon treated plots at farmer's fields during 1992-93 were exceedingly low (Table 1).

Table 1. Per cent mortality of *P. minor* at different locations by isoproturon at farmer's fields and the reduction in wheat yields in 1992-93

Location (Village/District)	Per cent mortality of *P. minor*	Grain yield of wheat (kg ha^{-1})
Amin (Kurukshetra)	0	Wheat ploughed in February
Laloda (Hisar)	0	Wheat ploughed in February
Asand (Karnal)	50	3500
Rampur (Jind)	0	500
Dharamgarh (Jind)	0	1500
Kutail (Karnal)	50	3000
Balana (Ambala)	0	1500

Source : Malik and Malik (1994).

Most of fields where early resistance was detected had almost similar frequency of herbicide use. Intensity of isoproturon use, cropping pattern and soil type were correlated with the evolution of resistance. However, during next three years (1992-1995), the spread of resistance was very quick and the factor of soil type was considered as poorly correlated. Experiments in the rice-wheat sequence zone, where rice straw is frequently burnt after harvesting indicated that burning straw was responsible for an increase in the density of *P. minor* (Singh, 1996). Growth in wheat productivity in N.W. India actually slowed down in 1990s and did not revive till 1998-99.

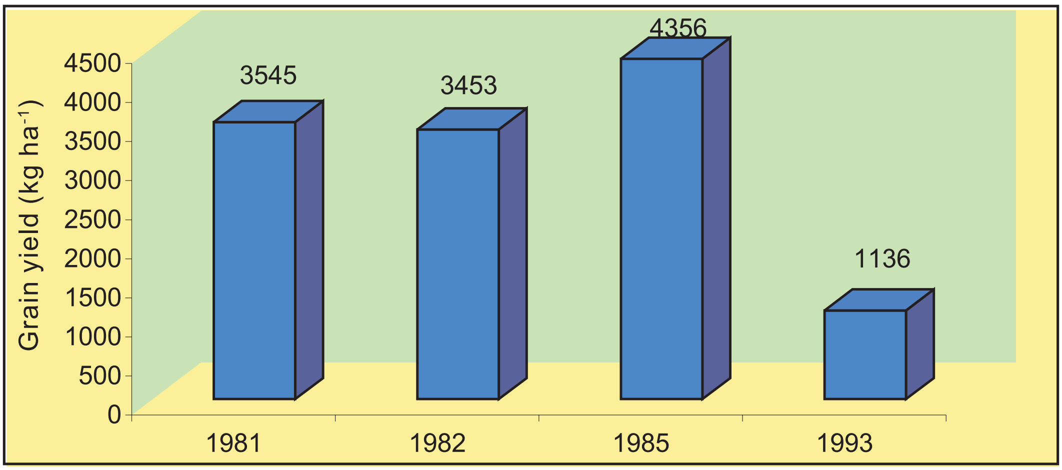

Fig 1. Grain yield of wheat in isoproturon treated demonstration plots against littleseed canary grass in rice-wheat zone of Haryana, India over a period of 12 years.

Source : Malik *et al.* (1995).

During the 1993 season, use of isoproturon alone did not prove effective against several populations of this weed and farmers had to resort to harvesting immature wheat as fodder because of imminent crop failure (Malik and Malik, 1994). Large yield reductions recorded on some farms in 1993 (Fig. 1) caused anxiety among the farming community. There was a clear trend for decline in wheat yield in the rice-wheat zone of Haryana as compared to areas where resistance was not a problem (Fig. 2).

After exploring some of the possibilities like late application, faulty application method, inadequate soil moisture, poor quality, underdosing and straw burning which could be responsible for poor efficacy of isoproturon, the possibilities of evolution of resistance by *P. minor* were explored. To further avoid the possible role of such unrelated factors, different populations collected from farmers' fields were subjected to bioassays during 1991-93 (Tables 2 and 3). These confirmed the evolution of resistance in some biotypes of *P. minor* (Singh *et al.*, 1993).

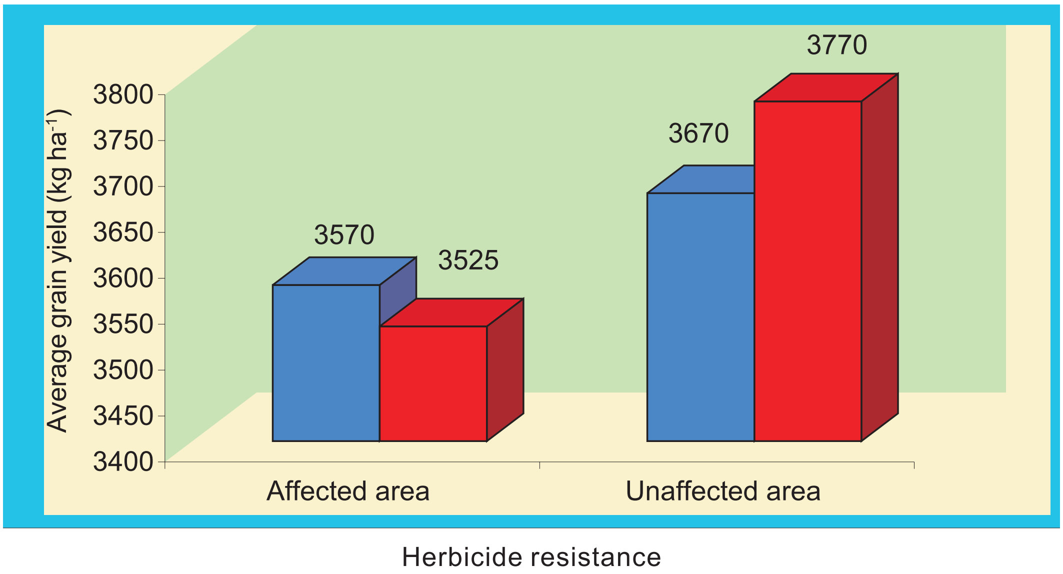

Fig. 2. Average grain yield of wheat in herbicide resistance affected and unaffected areas of wheat in Haryana, India during 1994-95 and 1995-96.

Source : Statistical Abstract of Haryana.

Table 2. Dose requirement of different biotypes of *P. minor* for 50% growth reduction by isoproturon

Biotypes	Regression equation (Y=a+b X)	GR_{50} values (g ha^{-1})	Resistance factor ($GR_{50}R/GR_{50}S$)
Garhi Gujran	2.43 + 2.16 X	236 ± 25	2.3
Balana	0.69 + 3.17 X	228 ± 23	2.2
Laloda	1.68 + 2.09 X	385 ± 59	3.7
HAU, Hisar	2.68 + 2.29 X	103 ± 15	1.0

Source : Singh *et al.* (1993).

Table 3. Dose requirement of isoproturon in resistant biotypes of *P. minor*

Biotypes	GR_{50} values (kg ha^{-1})		Resistance factor ($GR_{50}R/GR_{50}S$)	
	1991-92	1992-93	1991-92	1992-93
HAU, Hisar (S)	0.04±0.01	0.10±0.01	1.0	1.0
Garhi Gujran	0.18±0.05	0.24±0.03	4.5	2.4
Balana	0.21±0.04	0.23±0.06	4.5	2.3
Laloda	–	0.39±0.04	–	3.9
Amin	–	0.39±0.04	–	3.9

Source : Singh *et al.* (1993).

The resistance affected areas now range from 0.8 to 1.0 million hectare in N-W India comprising Haryana, Punjab, and parts of Delhi, Uttarachal and Uttar Pradesh, and it also affected other tarai areas. The resistant (R) biotypes of *P. minor* were reported to require 2-8 times more dose of isoproturon compared to susceptible (S) populations to cause 50% growth reduction (Malik and Singh, 1994; Malik and Singh, 1995).

Potency of various herbicides including isoproturon was tested against eight isoproturon resistant (H3, HR1, A2, KR3, KR4, KR5 KR6 and KJI) and two susceptible (R1 and H2) biotypes of *P. minor* in a field trial at CCSHAU, Hisar (India) during 1994-95 (Table 4). Isoproturon was found quite effective against both S-biotypes but its efficiency either alone or in combination with metribuzin or malathion (followed by isoproturon) was exceedingly low against all the resistant biotypes. Tralkoxydim and fenoxaprop were effective against R and S biotypes. Similar results were reported by Yadav *et al*. (1995).

Yadav *et al*., (1996) also reported resistance in various biotypes of *P. minor* collected from Haryana, Punjab and in areas around Delhi (seed provided by NRC-weed control, Jabalpur, M.P.) (Table 5). The dose requirement for 50% growth reduction of highly resistant populations from Haryana (H3) and Punjab (P4) were 5 to 6.5 times greater than the susceptible populations of Haryana (R1) and Jabalpur (J6). It indicated that the problem of isoproturon resistance in *P. minor* being widespread needs to be tackled immediately to restrict its spread in unaffected areas of India. Resistance in *P. minor* was also reported by Yadav *et al*. (1997).

Resistance factor ($GR_{50}R/GR_{50}S$) was further reported to increase and few R-biotypes of *P. minor* required 6.3 to 11.2 times more isoproturon to reduce 50% growth compared to S-biotypes (Table 6).

Data given in Table 6 clearly indicate that R-biotypes of *P. minor* KR1 and H3 required 8.8 to 11.2 and 6.3 to 8.0 times more of isoproturon to cause 50% reduction in their dry weights as compared to susceptible biotypes R1 and H2, respectively.

The R-biotypes given in Table 7 were collected from areas where isoproturon had been used continuously for more than 10 years in wheat in Haryana under a continuous rice-wheat cropping system. The resistance in biotypes from village Madha (Hisar) was mild because farmer started using isoproturon from last 4-5 years only. The isoproturon resistance was not detected where crops and herbicides were rotated. GR_{50} of isoproturon (Table 7) varied from 0.451 to 2.301 kg ha^{-1} for 33-R biotypes and from 0.133 to 0.393 kg ha^{-1} for 13-S-biotypes (Yadav *et al.*, 2002).

Table 4. Effect of different herbicides on the dry weight (g m^{-2}) of *P. minor* biotypes at 42 DAS under field conditions

Herbicides	Dose (kg ha^{-1})	R1	H2	H3	KR1	A2	KR3	KR	KR5	KR6	KJ1
Untreated check	–	277.0	293.6	333.3	262.3	272.6	307.6	371.3	294.5	276.3	375.0
Isoproturon	1.0	53.0	81.6	332.0	262.0	238.3	295.0	368.0	277.3	225.0	363.0
Isoproturon	2.0	23.3	51.6	328.6	251.3	222.6	224.3	281.6	154.0	121.6	305.6
Oxyfluorfen	0.05	143.0	275.6	224.0	220.0	240.0	289.0	270.6	215.0	205.3	333.3
Oxyfluorfen	0.10	142.0	181.6	164.0	150.3	172.6	252.6	259.6	168.0	183.0	292.6
Diclofop-methyl	0.70	66.0	110.6	133.3	111.3	128.0	143.0	153.0	85.6	79.3	61.3
Dicofop-methyl	1.40	42.0	69.3	106.0	61.6	90.0	39.3	92.3	47.3	41.6	54.0
Tralkoxydim	0.30	14.6	15.3	55.3	20.6	13.0	27.6	25.0	20.0	14.6	13.6
Tralkoxydim	0.60	5.4	0.1	11.0	9.0	5.3	8.3	6.0	0.7	2.7	2.7
Metoxuron	1.60	119.0	135.0	261.6	258.3	272.3	245.6	314.6	173.6	196.3	194.3
Metoxuron	3.20	96.0	109.0	253.3	246.3	233.0	210.3	296.6	147.3	176.3	159.0
Fenoxaprop	0.08	31.0	79.0	81.3	79.6	77.3	65.0	69.0	63.6	78.3	42.6
Fenoxaprop	0.16	0.1	11.6	5.7	3.4	8.3	11.3	7.0	6.6	16.6	16.6
Isoproturon+Metribuzin	1.00	52.6	75.6	304.6	213.6	231.3	265.0	358.3	253.3	183.3	274.6
Isoproturon+Metribuzin	2.00	36.0	47.0	292.3	210.3	203.3	241.0	280.0	255.0	138.0	241.6
Malathion (1%) fb Isoproturon	1.00	86.0	161.3	263.0	245.6	231.0	286.6	368.3	241.3	204.3	358.3
Malathion (1%) fb isoproturon	2.00	52.6	118.0	252.6	243.6	226.6	223.3	363.3	168.0	129.3	308.0
Metribuzin	0.04	194.6	228.6	289.0	229.3	241.6	256.3	352.0	212.0	271.0	372.0
Metribuzin	0.08	152.3	153.6	264.0	212.6	210.0	209.0	307.3	172.0	226.3	346.3

C. D. at 5% Herbicides = 13.6; Biotypes = 10.2; Herbicides x biotypes = 47.4

Source : Project Report on Herbicide Resistance Management in Wheat, November 17, 1997, Brighton, U.K.

Table 5. Dose response regression and dose of isoproturon (kg ha^{-1}) required for 50% growth reduction for biotypes of Littleseed canary grass

Biotypes	Regression equation (Y = a + bx)	GR$_{50}$ values (kg ha^{-1})
Haryana		
H3	4.683+4.186 (X – 2.182)	1.81±0.34
R1	5.093+8.100 (X – 1.481)	0.30±0.02
Punjab		
P1	5.083+2.853 (X – 2.146)	1.31±0.26
P2	4.949+1.408 (X – 2.000)	1.09±0.34
P3	5.033+3.790 (X – 2.147)	1.38±0.02
P4	4.593+1.517 (X – 1.915)	1.52±0.54
P5	5.017+2.497 (X – 1.688)	0.48±0.09
P6	5.124+2.747 (X – 1.698)	0.40±0.07
T7	4.886+4.077 (X – 1.716)	0.56±0.07
Jabalpur (Madhya Pradseh)		
J1	4.368+8.889 (X – 1.616)	0.49±0.07
J2	4.796+1.763 (X – 2.017)	1.36±0.39
J3	4.982+3.410 (X – 2.004)	1.02±0.15
J4	5.144+2.358 (X – 2.004)	0.88±0.17
J5	4.638+4.690 (X – 1.586)	0.46±0.07
J6	5.069+3.455 (X – 1.426)	0.26±0.04

Source : Yadav *et al.* (1996).

Table 6. Probit transformed response of R and S biotypes of *P. minor*

Biotypes	Regression equation (Y = a+bx)	GR$_{50}$ (kg ha^{-1})
Resistant (H3)	4.584+2.432 (X–2.271)	2.767±0.414
Resistant (HR1)	4.827+2.535 (X–2.28)	1.978±0.243
Susceptible (R1)	5.043+2.541 (X–1.408)	0.246±0.028
Susceptible (H2)	4.910+2.480 (X–1.462)	0.315±0.037

Source : Malik and Yadav (1997).

Similar results were reported by Chhokar and Malik (2002), where 6 R-biotypes (H3, KRI, KR2, KNLI, KNL2 and KL-1) collected from rice-wheat areas, required 5 to 10 times greater GR$_{50}$ values of isoproturon than that of the most susceptible biotype from Mahendergarh (MH).

Bioassay studies conducted in 1996-97 indicated that once resistance has evolved, the resistance factor would increase (resistance multiplies) with continued use of isoproturon in the same field (Table 8). However, these studies would need further confirmation.

Table 7. Regression equation and GR_{50} values of isoproturon for different biotypes of *P. minor* during 1999-2000

P. minor biotype 1	Regression equation 2	GR_{50} (kg ha^{-1}) 3
Singhpura (Kurukshetra)	5.12+2.13 (X-1.88)	0.666±0.023
Pehwa-1 (Kurukshetra)	4.72+2.14 (X-2.16)	1.954±0.279
Thaneshwar (Kurukshetra)	4.43+2.17 (X-1.99)	1.789±0.355
Thol (Kurukshetra)	5.15+2.71 (X-1.79)	0.543±0.094
Landi (Kurukshetra)	4.55+0.95 (X-1.89)	2.310±1.100
Pehwa-II (Kurukshetra)	5.05+2.63 (X-1.84)	0.662±0.075
Amin (Kurukshetra)	4.47+2.17 (X-1.99)	1.715±0.329
Dholgarh (Karnal)	5.07+2.29 (X-1.95)	0.831±0.144
Phoolgarh (Karnal)	5.22+1.72 (X-1.93)	0.634±0.102
Gamli (Karnal)	4.44+3.22 (X-2.11)	1.923±0.290
Govindgarh (Karnal)	4.85+2.81 (X-2.01)	1.157±0.128
Bandrana (Kaithal)	4.92+2.64 (X-2.09)	1.319±0.144
Bhuna (Kaithal)	4.61+1.46 (X-1.91)	1.504±0.384
Bansa (Kaithal)	4.97+2.84 (X-2.04)	1.124±0.115
Dera-patti-kabrel (Kaithal)	4.58+1.28(X-1.90)	1.691±0.532
Sankhla (Kaithal)	4.78+2.17 (X-1.94)	1.099±0.163
Bharot (Kaithal)	4.47+2.25 (X-2.06)	1.975±0.425
Siwan-1 (Kaithal)	4.26+2.09 (X-1.99)	2.208±0.529
Siwan-II (Kaithal)	4.76+0.94 (X-1.87)	1.330±0.051
Noltha (Panipat)	4.78+2.41 (X-2.14)	1.703±0.209
Nalda (Panipat)	4.58+1.35 (X-1.91)	1.664±0.491
Sikhpari (Panipat)	4.92+5.19 (X-1.56)	0.397±0.033
Smain (Fatehabad)	4.90+2.90 (X-2.11)	1.395±0.145
Laloda-I (Fatehabad)	4.50+2.22 (X-1.97)	1.567±0.273
Laloda-II (Fatehabad)	4.34+1.75 (X-1.94)	2.076±0.553
Rampura-I (Jind)	4.43+5.82 (X-1.98)	1.196±0.074
Rampura-II (Jind)	4.52+1.74 (X-1.94)	1.644±0.033

Contd.

Table 7 contd.

1	2	3
Nangal (Ambala)	4.33+1.64 (X-1.97)	2.351±0.739
Mandi Serdi (Ambala)	4.53+1.37 (X-1.91)	1.791±0.550
Chikahnal Udham Singh Nagar, U. P.	4.63+1.37 (X-2.02)	1.950±0.667
P4 (Punjab)	4.31+2.25 (X-2.01)	2.073±0.442
J2 (M. P.)	4.56+1.33 (X-1.90)	1.702±0.517
Madha (Hisar)	5.15+4.20 (X-1.69)	0.415±0.036
Other than rice-wheat cropping area or university farms		
Karota (Rohtak)	5.44+3.87 (X-1.29)	0.150±0.016
Khera (Jhajjar)	5.52+2.85 (X-1.32)	0.137±0.004
Gudha (Jhajjar)	5.82+4.66 (X-1.65)	0.298±0.027
Chandanpur (Jhajjar)	5.21+3.94 (X-1.65)	0.393±0.001
Jita Kheri (Bhiwani)	5.51+5.62 (X-1.51)	0.263±0.024
Charkhi (Bhiwani)	5.23+6.95 (X-1.46)	0.216±0.021
Unani (Mahendergarh)	5.38+5.19 (X-1.48)	0.259±0.025
Bamolikhas Udham Singh Nagar (U. P.)	5.63+2.44 (X-1.60)	0.219±0.045
RRS, Uchani (Karnal)	5.23+2.50 (X-1.36)	0.185±0.027
RRS, Bawal-I (Rewari)	5.69+3.89 (X-1.30)	0.133±0.016
RRS, Bawal-II (Rewari)	5.29+1.44 (X-1.38)	0.151±0.043
Pantnagar Univ. Farm (U. P.)	5.38+2.73 (X-1.63)	0.309±0.046
CCSHAU, Farm (Hisar)	4.91+2.48 (X-1.462)	0.315±0.037

Source : Yadav *et al.* (2002).

Isoproturon at 1.0 kg ha^{-1} was very effective against S-biotype of *P. minor* (Fig. 3) and ineffective against R-biotype (Fig. 4).

Fig. 3. Isoproturon at 1.0 kg ha^{-1} was very effective against S-biotype of *P. minor*

Fig. 4. Isoproturon at 1.0 kg ha^{-1} was very ineffective against R-biotype of *P. minor*

Similarly, resistance factor was observed to increase in different biotypes of *P. minor* subjected to frequent use of diclofop-methyl during 1996-97 at CCSHAU, Hisar (data not given).

The behaviour of R and S biotypes against methabenzthiazuron and metoxuron was almost similar to that of isoproturon (Yadav *et al.*, 2002). *Trichoderma viridae*, Ecofit and neem oil cake alone or in combinations have been reported to be effective from National Research Centre on Weed Control, Jabalpur (India) against resistant *Phalaris minor*. However, these were found ineffective against isoproturon resistant population of *P. minor* tested under field conditions at CCSHAU, Hisar during 1996-97 (data not given).

During 2002-03, all 22 biotypes collected from Bihar (near Patna or Pilliganj) were susceptible to isoproturon and the control level was 90-100% at 1.0 kg ha^{-1}. Whereas out of 17 biotypes collected from Haryana, nine-biotypes belonging to rice-wheat areas were resistant to isoproturon and six-biotypes from areas other then rice-wheat sequence and two biotypes from research farms were sensitive to isoproturon. Resistance was also prevailing in two biotypes collected from Nepal (data not given). This study was conducted at Cornell University, Ithaca, U. S. A. during 2003.

Table 8. GR$_{50}$ of isoproturon against progeny of two resistant (R) and one susceptible (S) biotype of *P. minor* treated for different years starting from 1992-93

Biotype	No. of years treated with isoproturon starting from 1992-93	Regression equation (Y = a+bx)	GR$_{50}$(kg ha^{-1})
H3 (R)	1	5.007 + 2.603 (X – 1.681)	0.47 ± 0.052
	2	4.848 + 2.550 (X – 2.168)	1.760 ± 0.213
	3	4.787 + 5.572 (X – 2.490)	3.375 ± 0.272
KR1 (R)	1	5.21 + 3.20 (X – 1.76)	0.495 ± 0.051
	2	5.18 + 1.79 (X – 2.28)	1.510 ± 0.291
	3	5.08 + 2.25 (X – 2.29)	1.796 ± 0.261
	4	4.80 + 6.39 (X – 2.34)	2.351 ± 0.128
H2 (S)	1	4.869 + 2.695 (X – 1.586)	0.431 ± 0.068
	2	5.043 + 2.879 (X – 1.829)	0.645 ± 0.109
	3	4.958 + 2.956 (X - 2.009)	1.055 ± 0.119

Source : Yadav *et al.* (2002).

Note : Seeds of R-biotypes were collected from fields where isoproturon resistance was already detected in 1992-93 and then these were subjected to isoproturon treatment in subsequent years. Bioassay was conducted in a dose range of 0.063 to 2.0 kg ha^{-1}.

Table 9. Visual phytotoxicity due to isoproturon on R and S biotypes of *Phalaris minor* during 2003-04 in Haryana

Biotypes	Isoproturon (g ha^{-1})				
	0	250	500	1000	2000
HAU, Hisar (S)	0	13	77	80	99
RRS, Bawal (S)	0	13	68	92	99
Nangli Parsapur, Rewari (S)	0	12	33	82	98
Kamalpur, Rewari (S)	0	7	68	83	98
Khor Ateli (S)	0	10	47	93	99
Dalapur, Jhajjar (S)	0	3	45	77	92
Bhainsi, Rohtak (S)	0	7	27	86	97
Mundhal, Bhiwani (S)	0	5	57	77	90
Hansgabad, Palwal (S)	0	30	45	82	98
Faridabad (S)	0	0	53	88	99
Kharidwal, Fatehabad (R)	0	10	17	28	52
Siwan, Kaithal (R)	0	10	20	38	55

Source : Yadav, A., Malik, R. K. and Punia, S. S. (2003, unpublished data).

Data given in Table 9 indicate that out of 12 biotypes of *P. minor*, 10 biotypes collected from areas either other than rice-wheat cropping system or from the fields where isoproturon was being used from only 2-3 years were effectively controlled (77-93%) by the recommended dose of isoproturon (1.0 kg ha^{-1}). Whereas two resistance biotypes were not satisfactorily controlled by isoproturon even at 2.0 kg ha^{-1}. These results confirm the consistent findings since 1992-93 reported from Haryana.

Tables 1 to 9 and Figs. 1 and 4 are sufficient to provide ample evidences that *P. minor* has undoubtedly evolved resistance against isoproturon particularly in rice-wheat growing areas where this herbicide has been used for more than 10 years.

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Mechanism of Isoproturon-Resistance

For the effective management of herbicide resistant weeds, it is essential to understand the physiological and biochemical basis of resistance. Isoproturon, a phenylurea herbicide, has been commercially used in India since late 1980s for the control of *Phalaris minor* Retz. in wheat (Gill *et al*., 1978). Monocropping of rice-wheat and continuous use of isoproturon for 10-15 years have resulted in the evolution of resistance (Malik and Singh, 1993, 1995; Walia *et al*., 1997).

The resistant biotypes of this weed have been reported to require 2-12 times more isoproturon compared to pristine/susceptible populations to cause 50% growth reduction (Malik and Singh, 1993, 1994, 1995; Malik and Yadav, 1997; Singh *et al*., 1993, 1995; Yadav *et al*., 1995, 1996, 1997, 2002). Continuous application of chlorotoluron and isoproturon for two decades has also resulted in the evolution of resistance in *Alopecurous myosuroides* in Germany (Niemann and Pestemer, 1984), France (Chauvel, 1992) and Spain (Menendez *et al*., 1994).

Resistance to chlorotoluron and other phenylureas in *A. myosuroides* has been reported to be due to enhanced degradation by Cytochrome P-450 mono-oxygenases (Kemp and Caseley, 1987; Cabanne *et al*., 1987; Kemp *et al*., 1990; Hall *et al*., 1995).

The selectivity of wheat against most herbicides is also based on the degradation through mono-oxygenation. These degradations are performed by membrane-bound NADPH-dependent cytochrome P-450 mono-oxygenases. Most wheat has one enzyme, weeds with lower level of such a system can overcome herbicides by evolving higher enzyme levels. There is evidence that this has happened in annual ryegrass (*Lolium rigidum*) against chlorsulfuron (Christopher *et al*., 1991). The problem in wheat clearly stems from wheat's uniqueness among major crops in having but one basic mechanism to degrade herbicides, allowing weeds to evolve a mechanism similar to wheat.

A pot culture investigation was carried out at CCS Haryana Agricultural University, Hisar, India during 1994-95 to establish the possible role of metabolism in the development of resistance in *P. minor*. Seeds of isoproturon resistant biotypes H3 (Laloda), KR1 (Amin) and K4 (Taravari) were collected from three districts of Haryana (India). viz., Hisar, Kurukshetra and Karnal, respectively, and seeds of one susceptible biotype (H2) were collected from research farm of CCS Haryana Agricultural University, Hisar where alternate herbicides in crops were adopted in different years. Isoproturon (Arelon 75% WP Hoechst) was applied at 0, 0.063, 0.125, 0.25, 0.50 and 1.0 kg ha^{-1} at 2-3 leaf stage with knapsack sprayer using 700 litre water ha^{-1}. Photosynthetic rate (μ mol m^{-2} sec^{-1}) was measured at mid day (1200-1300 h) with CIRAS-1 Portable Photosynthesis System at 3, 4, 5, 7, 8, 9 and 25th day after herbicide application only in those pots which were treated with isoproturon at 0, 0.25 and 1.0 kg ha^{-1}. Data on dry weight of five randomly selected plants from each pot were also recorded at seven weeks after spray and GR_{50} values were calculated based on relative dry weight reductions using probit analysis (Finney, 1971). The dose of isoproturon required to reduce the growth by 50% in H3, KRI and K4 biotypes was 6.3 to 9.9 times higher than susceptible H2-biotype (Table 1), which confirms the development of resistance in these biotypes.

Table 1. GR_{50} values of isoproturon based on relative dry weight reduction for different biotypes of *P. minor*

Biotype	Regression equation Y=Y+b(X-X)	GR_{50} values of isoproturon (kg ha^{-1})	Resistance factor (GR_{50} of resistant biotype/GR_{50} of susceptible biotype)
H2	5.10+4.008 (X-1.217)	0.125±0.065	1.0
H3	4.232+1.593 (X-1.613)	1.246±0.688	9.9
KR1	4.183+3.458 (X-1.656)	0.786±0.126	6.3
K4	4.289+2.698 (X-1.677)	0.873±0.193	6.9

Source : Malik *et al*. (1995a).

Based on the average of isoproturon doses, the rate of photosynthesis increased with the corresponding increase in time from 5th to 25th day of isoproturon treatment. The photosynthesis reduced significantly with the increase in dose of isoproturon. In all biotypes, the rate of photosynthesis decreased upto 4th day following isoproturon treatment. From 5th day, there was a recovery in photosynthesis in the resistant biotypes H3, KR1 and K4 (Table 2). However, in the susceptible biotype (H2) there was a consistent decrease in photosynthesis with time with no photosynthesis activity from 7th day following isoproturon treatment. The magnitude of recovery in photosynthesis was almost similar in all the resistant biotypes. The recovery pattern in susceptible (H2) and resistant (H3) biotypes has also been given in Fig. 1.

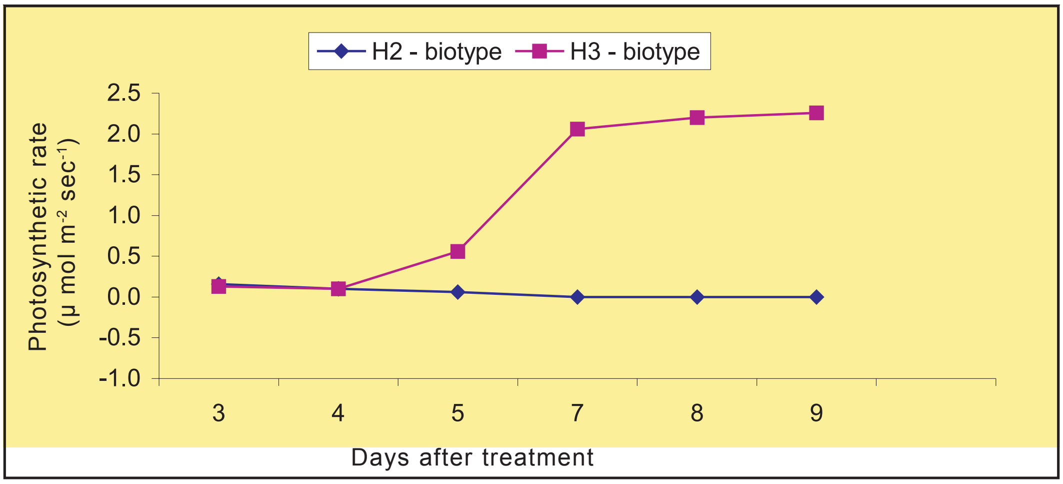

Fig. 1. Effect of isoproturon applied post-emergence at 1.0 kg ha^{-1} on the photosynthesis of R and S biotypes of *Phalaris minor* .

Source : Malik *et al*. (1995b).

Table 2. Effect of isoproturon on the photosynthesis of *P. minor* at different days after spray

Isoproturon (kg ha^{-1})	Biotypes of *P. minor*	Photosynthetic rate (µ mol m^{-2} sec^{-1}) Days after spray						
		3	4	5	7	8	9	25
0.00	H2	3.50	2.93	4.26	4.63	3.60	4.36	5.86
	H3	3.96	3.80	4.30	4.90	4.03	4.96	8.90
	KR1	2.96	3.20	3.10	5.26	4.93	4.73	7.33
	K4	3.93	4.00	3.73	2.66	4.16	4.20	6.70
0.25	H2	0.20	0.10	0.10	0.00	0.00	0.00	*
	H3	0.80	1.40	3.20	2.66	3.36	3.16	8.09
	KR1	2.83	2.83	2.46	2.50	2.50	3.23	6.23
	K4	1.13	1.43	2.50	2.33	3.36	3.16	6.33
1.00	H2	0.16	0.10	0.06	0.00	0.00	0.00	*
	H3	0.13	0.10	0.56	2.06	2.20	2.26	2.80
	KR1	0.23	0.10	0.16	1.90	2.06	1.93	3.23
	K4	0.46	0.10	1.23	1.46	1.70	2.20	3.20

C. D. at 5% for Conc.=0.32, biotype=0.37, days=0.49,
Conc. x biotype=0.064, biotype x days=0.98, *Complete mortality.
Source : Malik *et al.* (1995b).

Almost similar decrease in activity upto 4th day in resistant (R) and susceptible (S) biotypes indicates that absorption and translocation of isoproturon might be similar in all biotypes. Recovery in photosynthesis in R-biotypes suggests a significant reduction in the activity of isoproturon 4-5 days after treatment. It seems possible that in R-biotypes isoproturon might have been metabolised to an inactive compound and the recovery in photosynthesis might be of similar nature that exists in wheat.

Similar response in respect of photosynthetic activity of resistant (H3) and susceptible biotypes from Singhpura, Rohtak (R1) subjected to isoproturon were observed during 1997 (Table 3).

Table 3. Effect of isoproturon on the photosynthesis of *P. minor* at different days after spray

Isoproturon (kg ha^{-1})	*Phalaris minor* biotypes	1 day before spray	Photosynthetic rate (μ mol m^{-2} sec^{-1})						
			1	3	4	5	6	12	28
0.00	H3	5.52	6.66	6.80	7.70	7.93	10.48	10.96	11.94
0.00	H3	5.52	6.66	6.80	7.70	7.93	10.48	10.96	11.94
	R1	3.86	4.70	5.36	6.23	6.26	7.73	7.84	10.13
0.25	H3	5.56	4.56	4.23	6.23	7.25	10.46	10.96	11.95
	R1	3.88	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.00	H3	5.55	0.00	0.00	0.35	0.47	0.76	1.93	5.56
	R1	4.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.00	H3	5.52	0.00	0.00	0.01	0.20	0.36	0.65	2.11
	R1	3.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4.00	H3	5.58	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	R1	4.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Source : Yadav, A. and Malik, R. K. (1997, Unpublished data).

Studies to know the basis of resistance showed that there was no difference in target site protein as it was equally sensitive to photosynthesis inhibition by isoproturon in R and S biotypes under *in vitro* conditions (Singh *et al*., 1996a). *In vivo*, however, photosynthesis and chlorophyll fluorescence recovery was greater in the R-biotypes than S-biotypes and wheat (Singh *et al*., 1996a, b; Singh *et al*., 1997). Thus, the mechanism of resistance in resistant biotypes of *P. minor* appears to be of metabolic nature i.e. due to enhanced degradation and detoxification of isoproturon.

Degradation of ^{14}C isoproturon was greater in the R-biotype compared to S-biotype of *P. minor* and the amount of dealkylated and hydroxylated metabolites and conjugates was more in the R- biotype compared to the

S-biotype (Kirkwood *et al*., 1997). Chlorophyll fluorescence study is a sensitive tool with which the effect of herbicide can be detected within 30 minutes of application (Ireland *et al*., 1986) and it has been used to monitor chlorotoluron resistance in crop and weeds (Von Oorschot and Van Leeuwen, 1992; Ducruet *et al*., 1993). Chlorophyll fluorescence study also indicated that there was faster degradation of isoproturon in R-biotypes than the S-biotypes of *P. minor* and wheat (Singh *et al*., 1997). Temporary set back to wheat is often observed after application of isoproturon in many fields of growers in India, however, it recovers within 8-10 days. Most wheat herbicides compete with each other for P-450 enzyme binding site, suggesting relatedness (Frear *et al*., 1991).

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Chapter 10

Alternate Herbicides Against Isoproturon Resistant *Phalaris minor*

The research work on alternative herbicides to isoproturon was started immediately after the release of first report on resistance in *P. minor* against isoproturon. Until 1996-97, none of the herbicides evaluated was found as effective as isoproturon at the time of its approval in early 1980s. At farmer's field diclofop at 0.70 and 0.88 kg ha^{-1} outperformed against resistant populations but its relative potency was not as high as the potency of isoproturon against susceptible populations. Erratic performance of diclofop, pendimethalin and tralkoxydim against R and S biotypes of *P. minor* (Table 1) was reported by Malik *et al*. (1995).

Table 1. Effect of herbicides on the control of *P. minor* biotypes and injury to wheat

Herbicide	*P. minor*	Wheat		
	biotypes	H2 (S)	H3 (R)	KR 2 (R)
Untreated	2 (0)	2 (0)	2 (0)	2 (0)
Isoproturon	65 (82)	20 (12)	17 (12)	2 (0)
Diclofop	59 (72)	43 (47)	42 (45)	2 (0)
Pendimethalin	64 (80)	27 (20)	26 (20)	2 (0)
Tralkoxydim	56 (67)	45 (50)	44 (48)	2 (0)
Fluazifop	90 (100)	90 (100)	90 (100)	90 (100)
Trifluralin	59 (73)	53 (63)	58 (70)	30 (25)
C. D. at 5%	11	4	14	2

Source : Malik *et al*. (1995).

Some cross-resistance due to pendimethalin and diclofop-methyl was reported (Table 1 and 2). However, diclofop-methyl at 1.0 kg ha^{-1} applied at 2 to 3 leaf stage of *P. minor* in pot experiment and pre-emergence application of pendimethalin at 1.5 kg ha^{-1} in field trials effectively controlled resistant biotypes of *P. minor* (Malik and Singh, 1995).

Based on field trials (1994-95), tralkoxydim at 0.3 kg ha^{-1}, diclofop-methyl at 1.4 kg ha^{-1} but not at 0.7 kg ha^{-1} and fenoxaprop at 0.16 kg ha^{-1} proved to be promising herbicides for the control of one sensitive (R1 from Rohtak) and nine other resistant biotypes from Jind, Karnal and Kurukshetra (Yadav *et al*., 1995). However, isoproturon, oxyfluorfen, metoxuron, metribuzin, isoproturon + metribuzin and malathion spray one week before followed by isoproturon failed to provide satisfactory control of any resistant biotype (Yadav *et al*., 1995).

Table 2. Dose response of isoproturon, diclofop-methyl and their mixtures on two biotypes of *P. minor*

Herbicide	Biotype	GR_{50} values ($g\ ha^{-1}$)	Regression equation Y = a+bx
Isoproturon	H2 (S)	100±20	Y=1.57+3.46 X
	H3 (R)	840±230	Y=0.36+2.41 X
Diclofop-methyl	H2 (S)	180±30	Y=1.17+2.53 X
	H3 (R)	840±100	Y=1.41+2.53 X
Isoproturon+	H2 (S)	120±20	Y=1.23+2.53 X
Diclofop-methyl (1 : 1)	H3 (R)	380±80	Y=2.10+1.88 X

Source : Malik and Singh (1995).

Resistant biotypes of littleseed canary grass KR1 and H3 required 8.8 to 11.2 and 6.3 to 8.0 times more of isoproturon to cause 50% reduction in their dry weights as compared to susceptible biotypes R1 and H2, respectively (Malik and Yadav, 1997). But fenoxaprop (Table 3) and sulfosulfuron (Table 4) were found equally effective against susceptible as well as resistant biotypes.

Table 3. GR_{50} of fenoxaprop against R and S biotypes of *P. minor* on relative dry weight reduction basis during 1996-97

Biotype	Regression equationY = a + b x	GR_{50} values ($g\ ha^{-1}$)
H3 (R)	5.261+3.937 (X–1.428)	22.99±3.040
KRI (R)	5.305+2.791 (X–1.455)	22.17±2.416
R1 (S)	5.375+2.352 (X–1.457)	19.84±3.423
H2 (S)	5.377+2.097 (X–1.467)	19.34±2.842

Source : Malik and Yadav (1997).

Table 4. Effect of sulfosulfuron on dry weight of R and S biotypes of *P. minor* (1996-97)

Herbicide	Dose ($g\ ha^{-1}$)	Dry weight ($mg\ plant^{-1}$)	
		H3 (R)	R1 (S)
Untreated	–	644	521
Sulfosulfuron	10	289	205
Sulfosulfuron	20	130	108
Sulfosulfuron	40	125	87
Sulfosulfuron	80	117	64
Sulfosulfuron	160	102	56
C.D. at 5%	–	19	14

Source : Malik and Yadav (1997).

Clodinafop 60 g ha^{-1}, fenoxaprop 120 g ha^{-1}, sulfosulfuron 25 g ha^{-1} applied at 30-35 days after sowing of wheat or 2-3 leaf stage of *P. minor* provided excellent control ranging from 82-90% of resistant biotypes and yield levels were between 3916 to 4506 kg ha^{-1} in Laloda (Fatehabad) under zero tillage (Av. of four locations) and 4076 to 4648 kg ha^{-1} under conventional tillage (Av. of three locations) sowing (Malik and Yadav, 1997). Clodinafop, fenoxaprop and sulfosulfuron also proved very effective against isoproturon resistant *P. minor* in Karnal (Haryana) during 1996 (Table 5).

Table 5. Effect of new herbicides applied post-emergence on the grain yield of wheat (kg ha^{-1}) in the resistant *P. minor* areas of Karnal district in Haryana, India

Herbicide	Dose (g ha^{-1})	Location							
		1	2	3	4	5	6	7	Mean
Isoproturon	1000	2528	1820	2118	1640	2432	1914	2225	2097
Clodinafop	60	4345	5268	4054	5040	3886	4740	4870	4600
Fenoxaprop	120	4220	5115	4252	4946	4074	4856	4836	4614
Sulfosulfuron (+ 0.5% Adjuvant)	25	4105	4906	4528	4830	4184	4860	4960	4625
C. D. at 5%									369

Source : Project Report, AICRP on Weed Control, CCSHAU, Hisar (1996).

Looking into the fact of large scale failure of isoproturon, the recommendation of this herbicide was withdrawn during winter season of 1997-98 from resistance affected rice-wheat growing areas of Haryana and based on survey, monitoring and multi-locational research trials particularly at farmer’s field in Haryana, Punjab and Uttar Pradesh, four alternate herbicides (clodinafop 60 g ha^{-1}, fenoxaprop 120 g ha^{-1}, sulfosulfuron 25 g ha^{-1} and tralkoxydim 350 g ha^{-1}) were recommended in **rabi** season of 1998 for the control of resistant *P. minor*. Post-emergence application of clodinafop, fenoxaprop and sulfosulfuron was found very effective against resistant *P. minor* (Malik and Yadav, 1997; Malik *et al*., 1997, Walia *et al*., 1988; Balyan, 1999; Brar *et al*., 1999; Brar *et al*., 2002), and efficacy of these herbicides was clearly visible (Fig. 1).

The cost : benefit ratio in case of alternate herbicide was 1 : 6. The yield levels of wheat in Haryana which were recorded 34.5 q ha^{-1} in 1994-95 were increased to 43.5 q ha^{-1} in 1999-2000 and this was mainly due to effective management of resistant *P. minor* by the use of these alternate herbicides (Fig. 2, 3 and 4). The increase in yield levels pf wheat in resistance affected areas was much more than unaffected areas during this duration.

Fig. 1. Satisfactory control of isoproturon resistant *Phalaris minor* with alternate herbicides.

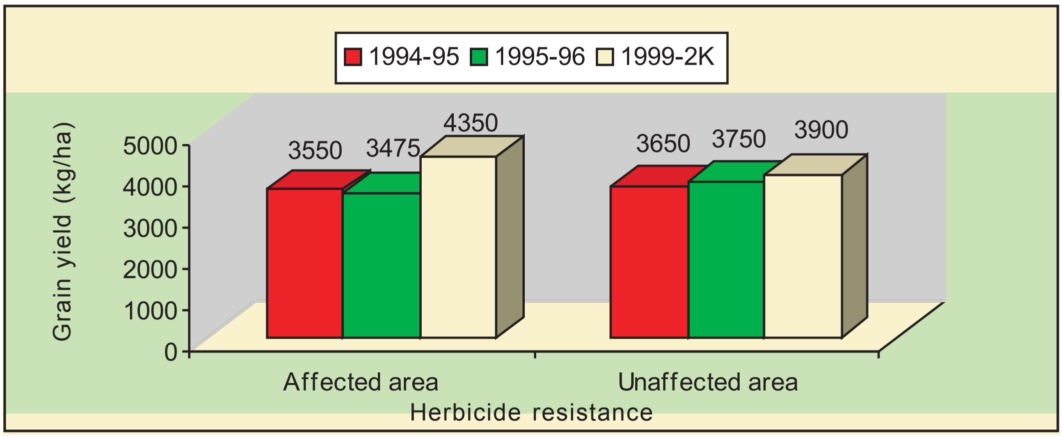

Fig. 2. Average wheat grain yield in herbicide resistance affected and unaffected areas of Haryana.

Source : Statistical Abstracts of Haryana.

Almost similar trend was observed during 1997-98, 1998-99 and 1999-2000 when average grain yield of wheat in resistance affected areas was 3497, 4075 and 4350 kg ha^{-1} as against 3704, 3685 and 3901 kg ha^{-1} in unaffected areas of Haryana, respectively.

These alternate herbicides are basically used against wild oat (*Avena ludoviciana* or *Avena fatua*) in western countries, and have been found very effective against this weed in India also even at 20% reduced dose compared

Fig. 3. Clodinafop at 60 g ha^{-1} was very effective against isoproturon resistant biotype of *P. minor.*

Fig. 4. Sulfosulfuron at 25 g ha^{-1} was very effective against isoproturon resistant biotype of *P. minor.*

to *P. minor* (data not given). However, to combat mixed population of *P. minor* and *Avena ludoviciana*, it is suggested to use these herbicides at their respective doses recommended against *P. minor*. Two biotypes of *P. minor i.e.* H3 (R) and R1 (S) were subjected to bioassay studies at CCSHAU, Hisar, India and GR_{50} values of different alternate herbicides were calculated during 1996-97 (Table 6) and 1998-99 (Table 7).

Table 6. Regression equation and GR_{50} of different herbicides for R and S biotypes of *P. minor*

Herbicide	*P. minor* biotype	Regression equation (Y=a+bX)	GR_{50} value (Y=a+bX)
Trifluralin	H3	4.69+1.44 (X–1.79)	1012±208
	R1	4.71+2.19 (X–1.84)	938±127
Chlorsulfuron	H3	4.92+0.88 (X–3.47)	36.38±9.40
	R1	5.10+0.99 (X–3.42)	20.80±4.85
Sulfosulfuron (Without Adjuvant)	H3	5.02+1.45 (X–2.84)	6.702±1.12
	R1	5.11+1.57 (X–2.81)	5.46±0.87
Metoxuron	H3	5.11+4.03 (X–1.95)	837±77
	R1	5.48+3.65 (X–1.28)	141±17
Clodinafop	H3	5.16+1.71 (X–3.25)	14.34±2.26
	R1	–	–

Source : Yadav, A. and Malik, R. K. (1996, Unpublished data).

Except clodinafop, fenoxaprop, sulfosulfuron and tralkoxydim (Tables 6 and 7), all other herbicides either could not control R-biotype of *P. minor* effectively or turned phytotoxic to wheat crop or both under field conditions.

Diflufenican was found ineffective against two R (H3 and KRI) and two S (R1 and H2) biotypes of *P. minor* during 1996-97 in pot culture experiments conducted at CCSHAU, Hisar. The relative dry weight reduction in these biotypes due to diflufenican at 12.5 to 400 g ha^{-1} was only 2.6 to 35.1 per cent.

Table 7. Regression equation and GR$_{50}$ values of herbicides against resistant and susceptible biotypes of *P. minor* during 1998-99

Herbicide	*P. minor* biotype	Regression equation (Y = a+bX)	GR$_{50}$ value (Y = a+bX)
Isoproturon	H3 (R)	4.64 + 2.60 (X – 2.25)	2446 ± 317
	R1 (S)	5.17 + 7.21 (X – 1.46)	273 ± 18
Metribuzin	H3	5.08 + 7.07 (X – 3.49)	30.11 ± 1.98
	R1	-	-
Sulfosulfuron	H3	5.40 + 1.71 (X – 2.65)	2.61 ± 0.45
	R1	5.51 + 2.12 (X – 2.55)	2.04 ± 0.02
Methabenzthiazuron	H3	4.91 + 4.82 (X – 2.02)	1093 ± 87
	R1	5.45 + 2.07 (X – 1.92)	504 ± 121
Fenoxaprop	H3	4.81 + 1.92 (X – 3.59)	48.86 ± 6.85
	R1	4.88 + 1.67 (X – 3.53)	39.98 ± 0.95
Fenoxaprop	Teek (R)	5.12 + 2.74 (X – 3.92)	75.19 ± 8.64
	Bawal (S)	5.40 + 1.37 (X – 3.89)	39.63 ± 11.82
Foe 5043	Teek	4.98 + 9.05 (X – 1.46)	289.9 ± 9.20
	Bawal	5.18 + 2.13 (X – 1.41)	211.6 ± 29.7
Isoproturon	UP biotype (R)	4.98 + 0.97 (X – 2.00)	1048 ± 330
Mon 48549	UP biotype (R)	4.68 + 3.52 (X – 2.93)	10.49 ± 105

Source : Yadav, A. and Malik, R. K. (1998, Unpublished data).

Based on separate set of pot culture studies conducted at CCSHAU, Hisar during 1998, Yadav *et al.*, (2002b) also found that clodinafop, sulfosulfuron, fenoxaprop and tralkoxydim were equally effective against R and S biotypes of *P. minor* (Table 8). These results are in conformity with earlier findings (Yadav *et al.*, 2002a).

Trifluralin, atrazine and metribuzin are other herbicides which were tested at various locations both under controlled and field conditions against

P. minor in wheat. Reduction in wheat germination due to trifluralin, foliage injury due to atrazine and setback in tillering due to metribuzin are some of the common features of these herbicides particularly at dose effective to control *P. minor*. Dose response equation and GR_{50} of atrazine for wheat and different biotypes of *P. minor* are given in Table 9.

Table 8. Dose response of alternate herbicides on *Phalaris minor* biotypes

Herbicide	*P. minor* biotype	Regression equation (Y = a+bX)	GR_{50} value (Y = a+bX)
Sulfosulfuron	H3 (R)	5.17+1.73 (X–2.75)	4.48±0.72
	R1 (S)	5.27+1.57 (X–2.73)	3.61±0.60
Clodinafop	H3	5.01+2.38 (X–3.48)	29.91±3.33
	R1	4.99+6.95 (X–3.25)	17.84±0.76
Fenoxaprop	H3	5.26+2.01 (X–3.32)	15.5±2.06
	R1	5.29+2.34 (X–3.26)	13.7±1.65
Tralkoxydim	H3	5.00+3.00 (X–1.21)	155±17
	R1	5.15+4.05 (X–1.12)	122±11
Isoproturon	H3	4.68+3.51 (X–2.23)	2095±209
	R1	5.54+4.18 (X–1.56)	273±30

Source : Yadav *et al.* (2002).

Table 9. Dose response equation and GR_{50} values of atrazine for wheat and *P. minor* biotypes

Biotypes	Regression equation (Y =a + bX)	GR_{50} (g ha^{-1})
H3	2.797+3.590 X	41±6
KR1	0.521+3.950 X	42±5
R1	1.132+5.643 X	48±4
Wheat	3.024+2.273 X	74±14

Source : Balyan *et al.* (1997).

Based on the studies conducted at CCSHAU, Hisar (Yadav and Malik, 1995-96, unpublished data), the GR_{50} value of metribuzin for resistant biotype of *P. minor* (H3) was found to be 59 g ha^{-1}, whereas it was 57 g ha^{-1} for susceptible biotype (R1). It was also evident from farmer's field demonstrations that when compared to isoproturon, metribuzin reduced the wheat yield in the presence of susceptible population of *P. minor* but increased the wheat yield in the presence of resistant-population (Tables 10 and 11).

Differences in GR_{50} values of pendimethalin, trifluralin, oryzalin and fenoxaprop against R and S biotypes of *P. minor* (Table 12) further warrant for cross-checking of these herbicides both under pot culture and field conditions.

Table 10. Effect of metribuzin on *P. minor* and wheat yield at farmer's field (Resistance population)

Herbicide	Dose (g ha^{-1})	Population of *P. minor* (No. m^{-2})		Grain yield of wheat (kg ha^{-1})	
		Gheer	Premkhera	Gheer	Premkhera
Isoproturon	1000	1077	460	987	2040
Metribuzin	90	988	400	960	2020
Metribuzin	125	583	267	1667	2560
Metribuzin	166	296	183	2133	2760
Metribuzin	200	195	57	2467	3040
Weedy check	-	1181	580	950	1875

Source : Project Report on Herbicide Resistance Management in Wheat, HRAC, Brighton, U. K. 17 Nov., 1997, 37 pp.

Table 11. Effect of metribuzin on weeds and growth yield of wheat at RRS, Karnal (susceptible population)

Herbicide	Dose (g ha^{-1})	Dry weight of weeds (g m^{-2})	Grain yield of wheat (kg ha^{-1})
Isoproturon	1000	55.3	5434
Metribuzin	100	101.9	4850
Metribuzin	200	73.5	4573
Metribuzin	300	28.0	4195
Isoproturon+metribuzin (10 : 1)	750	60.1	4789
C. D. at 5%	-	22.6	359

Source : Project report on " Herbicide Resistance Management in Wheat, HRAC, Brighton, U. K., 17 Nov., 1997, 37pp.

Other herbicides such as prometryn and oxyfluorfen were also not found suitable against *P. minor* in wheat. Three alternate herbicides (Clodinafop, fenoxaprop and sulfosulfuron) recommended for resistance affected area of rice-wheat cropping systems, to replace isoproturon, did play an important role to shield huge yield losses from 1998 to date. The population of *P. minor*, in general, has reduced significantly in majority of fields. However, future of alternate herbicides (clodinafop, fenoxaprop and sulfosulfuron) is also not a sure one way bet. Due to possibilities of resistance (cross-resistance) if not used properly, a gulf exists between risks and benefit of these herbicides. In order to have a useful long life, alternate herbicides with diferent modes of action need to be used as a component of an integrated weed management.

Table 12. GR_{50} values of some herbicides against resistant (Nangal, Ambala) and susceptible (Karota, Rohtak) biotypes of *P. minor* during 2000-01

Herbicide	Biotype	Regression equation (Y=a+bX)	GR_{50} value (Y=a+b x)
Pendimethalin	Nangal	4.272+1.500 (X–1.876)	2.294±0.720
	Rohtak	4.847+0.871 (X–1.716)	0.780±0.430
Trifluralin	Nangal	4.828+3.194 (X–1.848)	0.799±0.076
	Rohtak	4.981+1.544 (X–1.679)	0.492±0.082
Oryzalin	Nangal	5.155+1.355 (X–1.658)	0.350±0.067
	Rohtak	4.935+1.392 (X–1.708)	0.568±0.103
Fenoxaprop	Nangal	4.973+2.909 (X–3.905)	0.082±0.009
	Rohtak	5.201+3.105 (X–3.761)	0.049±0.005

Source : Yadav, A. and Malik, R. K. (2000-01, Unpublished data).

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Chapter 11

Herbicide Mixtures to Control Isoproturon-Resistant *Phalaris minor*

Mixtures of herbicides with different modes of action may be helpful to avert or delay the development of resistance. To survive such herbicide mixtures, many genes may be required and the probability of them occurring in one plant is extremely low. Therefore, such herbicide mixtures can reduce the rate of buildup of resistant population. Weeds resistant to more vulnerable herbicides will be destroyed by the mixing partner or at least be rendered relatively unfit compared to the wild types (Anonymous, 1990). The main disadvantage of herbicide mixtures is that they may be more expensive or cause unacceptable toxicity to the crop or have negative cross resistance.

Pot culture studies conducted in 1993 and 1994 indicated that resistant biotype of *P. minor* required 2.5 to 3.0 times more diclofop-methyl, isoproturon+diclofop-methyl and pendimethalin+isoproturon as compared to susceptible biotypes. Other studies indicated that trifluralin similarly inhibited the susceptible and resistant biotypes of *P. minor* (Malik *et al*., 1995).

A pot culture study was carried out during the winter seasons of 1994-95 at CCSHAU, Hisar to study the selectivity of atrazine and isoproturon mixtures as an alternate herbicide to wheat crop and resistant (H3, KR1 and K1) and susceptible (H2) biotypes of *P. minor*. The magnitude of decrease in the dry weight of resistant and susceptible biotypes following the treatment of atrazine or atrazine+isoproturon was similar (Table 1). Atrazine applied alone or as tank mixture caused considerable injury to wheat crop. However, the dose of atrazine+isoproturon required for 50% growth reduction in wheat was 0.089 kg ha^{-1} compared to 0.047 to 0.053 kg ha^{-1} in different biotypes of *P. minor* (Tables 1 and 2). These studies indicated that atrazine alone or as a tank mixture with isoproturon may partially help to control the resistant biotypes. However, its phytotoxicity to wheat warrants further studies both in pot and field conditions.

A series of attempted tank mixtures of isoproturon with atrazine, prometryn, metribuzin, diclofop and other alternate herbicides not only failed to provide acceptable weed control but also caused severe crop injury. There are very few examples, where the theoretical promise of delayed resistance from herbicide mixtures has been translated into successful farmer practice in the field.

Table 1. Effect of atrazine or atrazine+isoproturon on dry weight of wheat and different biotypes of *P. minor*

Herbicides	Dose kg ha^{-1}	Dry weight (g/5 plants)				
		H3	KR1	R1	Wheat	Mean
Untreated	–	3.01	2.24	1.89	4.37	2.88
Atrazine	0.031	2.21	1.75	1.69	3.67	1.95
Atrazine	0.063	0.43	0.26	0.44	2.13	0.82
Atrazine	0.125	0.26	0.16	0.01	1.18	0.40
Atrazine	0.250	0.01	0.01	0.01	0.67	0.17
Atrazine+isoproturon	0.031	2.36	1.86	1.73	3.87	2.45
Atrazine+isoproturon	0.063	0.74	0.28	0.52	2.46	1.00
Atrazine+isoproturon	0.125	0.28	0.22	0.12	1.52	0.54
Atrazine+isoproturon	0.250	0.19	0.08	0.01	0.78	0.27
Mean	–	1.05	0.76	0.71	2.13	–

C. D. (5%) for herbicide=0.27, for biotype=0.18 and for herbicide x biotype=0.55.
Source : Balyan *et al.* (1997).

Table 2. Dose response regression equation and dose of atrazine+isoproturon required for 50% growth reduction of wheat and different biotypes of *P. minor*

Biotype	Regression equation (Y=a+bX)	GR_{50} values (kg ha^{-1})
H3	3.155+2.746X	0.047±0.013
KR1	2.853+3.274X	0.045±0.007
R1	1.576+4.726X	0.053±0.012
Wheat	2.776+2.339X	0.89±0.016

Source : Balyan *et al.* (1997).

The use of isoproturon as tank mixture with metribuzin, fenoxaprop and diflufenican reflected response of isoproturon (Table 3) during 1995-96. Probit tranformated response was computed on the basis of relative dry weight reductions at 30 days after spray.

Table 3. Probit transformed response of R and S biotypes of *Phalaris minor* to different herbicides in pot culture bioassay

Herbicide	GR_{50} (g ha^{-1}) levels of different herbicides			
	H3 (R)	KR1 (R)	R1 (S)	H2 (S)
Isoproturon	2767±413	1978±243	246±28	315±37
Fenoxaprop	22.99±3.04	22.17±2.42	19.84±3.42	19.34±3.42
Isoproturon+Fenoxaprop (15 : 1)	429±28	643±61	221±15	350±53
Isoproturon+Metribuzin (10 : 1)	707±43	544±54	261±44	312±28
Isoproturon+diflufenican (10 : 1)	979±133	1054±123	212±32	274±24

Source : Balyan *et al.* (1997).

Compared to alone application of metribuzin, metribuzin when tank mixed with tralkoxydim did not result into any additional gain in controlling R and S biotypes of *P. minor* (Table 4).

Table 4. GR_{50} levels of metribuzin and tralkoxydim + metribuzin against R and S biotypes of *P. minor* during 1995-96

Herbicide	R-biotype		S-biotype	
	Regression equation (Y=a+bx)	GR_{50} (kg ha^{-1})	Regression equation (Y=a+bx)	GR_{50} (kg ha^{-1})
Metribuzin	5.409+2.318 (X-0.951)	0.059±0.015	5.439+3.284 (X-0.888)	0.057±0.008
Tralkoxydim	4.572+2.891 (X-1.526)	0.472±0.065	5.06+3.875 (X-1.43)	0.259±0.038
Tralkoxydim+ Metribuzin (1.5 : 1)	5.282+3.07 (X-0.954)	0.73±0.007	5.377+4.013 (X-0.871)	0.059±0.005

Source : Yadav, A. and Malik, R. K. (1996, Unpublished data).

Series of field studies were conducted during 1996-97 at RRS, Uchani (Karnal) to evaluate the performance of isoproturon or metribuzin tank mixed with alternate herbicides against *P. minor* in wheat. The results indicated that there was no additional gain of tank mixed use of metribuzin either with clodinafop (Table 5) or fenoxaprop (Table 6), and isoproturon with sulfosulfuron (Table 7) against *P. minor* in wheat.

Table 5. Effect of clodinafop alone and in combination with metribuzin on dry weight of *P. minor* and yield of wheat

Herbicide	Dose (g ha^{-1})	Dry weight of *P. minor* (g m^{-2})	Grain yield of wheat (kg ha^{-1})
Clodinafop	50	53.0	5102
Clodinafop	60	40.3	5556
Fenoxaprop	120	45.0	5307
Fenoxaprop	140	35.5	5606
Sulfosulfuron+S	20+0.5%	53.8	5045
Sulfosulfuron+S	25+0.5%	38.3	5635
Chlorsulfuron	20	173.3	3440
Chlorsulfuron	25	144.8	3657
Clodinafop+Metribuzin	50+100	49.6	5247
Clodinafop+Metribuzin	60+100	45.5	5190
Fenoxaprop+metribuzin	100+100	50.0	5107
Fenoxaprop+metribuzin	120+100	92.7	4448
Isoproturon	1000	66.8	4771
Weedy check		277.5	2981
Weed-free check		0.5	5685
C. D. at 5%		18.5	285

Source : Project Report on Herbicide Resistance Management in Wheat, HRAC Meeting, Nov. 17, 1997, Brighton, U. K.

Table 6. Effect of fenoxaprop applied alone or in combination with metribuzin on the dry weight of *P. minor* and grain yield of wheat

Herbicide	Dose (g ha^{-1})	Dry weight of *P. minor* (g m^{-2})	Grain yield of wheat (kg ha^{-1})
Fenoxaprop	80	81.3	4390
Fenoxaprop	100	62.1	4747
Fenoxaprop	120	43.5	5252
Fenoxaprop	140	34.4	5428
Fenoxaprop+metribuzin (1:1)	80	148.8	3510
Fenoxaprop+metribuzin (1:1)	100	126.5	3926
Fenoxaprop+metribuzin (1:1)	120	92.9	4281
Fenoxaprop+metribuzin 1:1)	140	68.3	4718
Metribuzin	100	137.6	3824
Metribuzin	200	70.5	4773
Metribuzin	300	37.6	5162
Isoproturon	1000	70.2	4754
Isoproturon+tralkoxydim	375+250	35.2	5373
Weedy	–	246.1	2784
Weed-free	–	–	5594
C.D. at 5%	–	31.6	251

Source : Project Report on Herbicide Resistance Management in Wheat, HRAC Meeting, Nov. 17, 1997 Brighton, U. K.

Table 7. Effect of time of application of sulfosulfuron on the dry weight of *P. minor* and grain yield of wheat

Herbicide	Dose (g ha^{-1})	Time of application (DAS)	Dry weight of *P. minor* at 90 DAS (g m^{-2})	Grain yield of wheat (kg ha^{-1})
Sulfosulfuron	20	20	71.0	4586
Sulfosulfuron	25	20	56.4	4938
Sulfosulfuron	30	20	47.4	5104
Sulfosulfuron	20	35	68.2	4728
Sulfosulfuron	25	35	45.0	5204
Sulfosulfuron	30	35	41.2	5328
Sulfosulfuron	20	45	93.6	4476
Sulfosulfuron	25	45	74.4	4699
Sulfosulfuron	30	45	57.0	5140
Isoproturon	1000	35	74.4	4638
Isoproturon+Sulfosulfuron	250+20	35	62.4	4738
Isoproturon+Sulfosulfuron	375+20	35	58.5	4930
Isoproturon+Sulfosulfuron	500+20	35	47.4	5021
Weedy	–	–	295.0	3081
Weed-free	–	–	0.5	5554
C. D. at 5%			21.2	319

Source : Project Report on Herbicide Resistance Management in Wheat, HRAC Meeting, Nov. 17, 1997, Brighton, U. K.

Pendimethalin has already been recommended for the control of *P. minor* in wheat. This herbicide was not accepted by the farmers because of its higher cost, erratic performance and requirement of high moisture and fine tilth at the time of spray. The bioassay studies conducted against R and S biotypes have shown that dinitroanilines applied alone provided almost similar control of R and S biotypes but when tank mixed with isoproturon in the ratio of 1 : 1, the response was different with poor control of R-biotypes (H3) compared to S-biotypes (R1) (Table 8).

Table 8. Dose response of isoproturon and tank mixture of herbicides based on isoproturon (1:1) on *Phalaris minor* biotypes

Herbicide	Biotype	GR_{50} values ($g\ ha^{-1}$)	Regression equation (Y=a+bX)
Isoproturon	H3	2095±209	4.68+3.51 (X-2.23)
	R1	273±30	5.54+4.18 (X-1.56)
Isoproturon+Pendimethalin	H3	1142±181	4.70+2.03 (X-1.91)
	R1	253±23	5.29+3.61 (X-1.48)
Isoproturon+Fluchloralin	H3	1632±646	4.57+0.95 (X-1.76)
	R1	255±23	5.14+3.86 (X-1.44)
Isoproturon+Trifluralin	H3	487±95	5.20+1.78 (X-1.80)
	R1	185±19	5.52+3.40 (X-1.42)
Isoproturon+Oryzalin	H3	864±176	4.76+1.36 (X-1.76)
	R1	185±29	5.51+2.20 (X-1.50)
Isoproturon+Diclofop-methyl	H3	836±127	4.79+1.59 (X-1.79)
	R1	423±49	5.05+2.10 (X-1.65)
Isoproturon+Fenoxaprop (10 : 1)	H3	283±39	5.27+2.10 (X-1.58)
	R1	77±16	5.58+1.83 (X-1.21)

Source : Yadav *et al.* (2002).

These studies indicate that dinitroanilines will not be successful when tank mixed with isoproturon because the resistance is reflected when isoproturon is the part of mixture. Similarly, trifluralin though provides acceptable control of *P. minor* but also proves phytotoxic to wheat crop particularly under light or medium textured soils.

Data given in Table 8 indicate that tank mixture of herbicides based on isoproturon reflects the effect of isoproturon only. These herbicide mixtures will not be successful against *P. minor* in resistance affected areas. Therefore, use of isoproturon either alone or as tank mixture with other herbicides including clodinafop, fenoxaprop and sulfosulfuron should be avoided.

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Chapter 12

Antagonism of Herbicides Against *Phalaris minor*

Littleseed canary grass *(Phalaris minor)* and Wild oat *(Avena ludoviciana)* are two most important weeds of wheat in N-W India. The problem of *P. minor* is more serious under rice-wheat cropping systems (Malik *et al*., 1995) while that of *A. ludoviciana* is more severe in irrigated, well drained and light-textured soils particularly in areas other than rice-wheat sequence (Panwar *et al*., 2000). Besides these two grassy weeds, wheat fields are also invariably infested with number of broadleaf weeds with varying intensities in different regions of the country. The important **rabi** season weeds infesting wheat crop are : Bathu *(Chenopodium album),* Senji *(Melilotus indica),* Maina *(Medicago denticulata),* Jungli Palak *(Rumex maritimus),* Krishanneel *(Anagallis arvensis),* Hirankhuri *(Convolvulus arvensis),* Kandai *(Cirsium arvense),* Gajri *(Fumaria parviflora),* Chatri *(Vicia sativa),* Jungli Dhania *(Spergula arvensis),* Pithpapra *(Coronopus didymus),* etc. *Poa annua* and *Lolium temulentum* among grassy weeds, and *Rumex retroflexus*, *Lathyrus indica* and *Malwa parviflora* among braodleaf weeds have also been noticed to increasingly infest wheat fields in the recent years particularly under rice-wheat cropping systems.

The herbicide resistance evolution in *P. minor* against isoproturon in rice-wheat cropping system (Malik and Singh, 1995) has led to the replacement of isoproturon with alternate herbicides in winter season of 1997-98. The alternate herbicides (clodinafop, fenoxaprop, sulfosulfuron and tralkoxydim) were reported very effective against resistant *P. minor* (Malik and Yadav, 1997). But for the control of complex weed flora, we need to use some broadleaf weed killer alongwith grass-killing herbicides. But before making use of such combinations, there is a need to study their compatibility. Some herbicides like 2, 4-D and metsulfuron are very effective against most of the broadleaf weeds in wheat and both these have excellent compatibility when used with isoproturon against complex weed flora. But based on survey, farmer’s field trials and pot culture studies, it has been noticed that 2, 4-D and metsulfuron have antagonism with fenoxaprop and clodinafop when used against *P. minor* (Yadav *et al*., 2002). Efficacy of alternate herbicides (fenoxaprop and clodinafop) is reduced against *P. minor* when any of these is used as tank mixed with 2, 4-D or metsulfuron with the purpose of controlling broad-spectrum weeds in wheat. However, efficacy of 2, 4-D or metsulfuron against broadleaf weeds is generally not affected due to tank mixed use with grass herbicides.

When two or more chemicals accumulate in the plant, they may interact and bring out response different from those obtained when they were used alone. These interactions/responses are generally classified as additive, synergistic, antagonistic and enhancement effects (Akobundu *et al*., 1975) which have been described as below :

Additive effect : It is the total effect of a combination which is equal to the sum of the effects of the components taken independently. It can be expressed as that response which is the same as obtained when one chemical is substituted for the other at rates based on the activity of each herbicide used singly.

Synergistic effect : When the total effect of a combination is greater or more prolonged than the sum of the effects of the two taken independently.

Antagonistic effect : When the total effect of a combination is smaller than the effect of the most active component applied alone.

Independent effect : In this, the total effect of a combination is equal to the effect of the most active component applied alone.

Enhancement effect : The effect of a herbicide and non-toxic adjuvant applied in combination on a plant is an enhancement effect if the response is greater than that obtained when the herbicide is used at the same rates without the adjuvant.

There are numerous reports on the antagonistic responses between herbicides. O'sullivan *et al*. (1977) found that ester formulations of 2, 4-D caused less reduction in the activity of diclofop-methyl than did amine formulations. Several foliage-applied herbicides used for wild oat control lose part of their activity when applied as tank mixture with auxin herbicides such as 2, 4-D, MCPA and dicamba (O'sullivan *et al.*, 1977; Shirtliffe and Kaleta, 1977). Appleby and Somabhi (1978) reported that when simazine or atrazine was added to glyphosate solutions and sprayed, there was a reduction in glyphosate activity. Yadav *et al*. (2002) reported antagonistic effects between fenoxaprop or clodinafop and 2, 4-D or metsulfuron when used against complex weed flora in wheat.

However, to confirm the antagonistic effects between alternate herbicides (clodinafop and fenoxaprop) and broadleaf weed killing herbicides (2, 4-D, metsulfuron and chlorsulfuron), a detailed study was conducted at CCS Haryana Agricultural University, Hisar during 2000-01. In this study, two biotypes of *P. minor* including isoproturon resistant (R) from Noltha (Panipat) and other susceptible (S) from Karota (Rohtak), Haryana were subjected to pot culture studies. The herbicides included in these studies were clodinafop (0.0, 7.5, 15, 30, 60 and 120 g ha^{-1}) and fenoxaprop (0.0, 10, 20, 40, 80 and 160 g ha^{-1}) alone and in combination each at respective doses with metsulfuron (0, 1, 2, 3 and 4 g ha^{-1}) or 2, 4-D Na (0, 250, 500 and 1000 g ha^{-1}). Fenoxaprop at 0.0, 10, 20, 40, 80 and 160 g ha^{-1} at each respective dose tank mixed with chlorsulfuron at, 0, 2.5, 5, 10, 20 or 40 g ha^{-1} were also tested in a separate pot-experiment against the R and S biotypes. Dose response curves and GR$_{50}$ values were calculated to know the interaction effect of various herbicides (Tables 1, 2 and 3). GR$_{50}$ values were calculated based on visual toxicity recorded at 30 days after spray using probit analysis.

Table 1. Dose response regression equation and GR$_{50}$ values of clodinafop and fenoxaprop alone and in combination with metsulfuron against R and S biotypes of *P. minor*

Herbicide	Biotype	Regression equation (Y=a+bx)	GR$_{50}$ value (g ha^{-1})
Isoproturon	Noltha (R)	4.650+1.14 (X-2.069)	2417±698
	Karota (S)	6.620+3.569 (X-1.013)	144±65
Clodinafop	Noltha	4.943+3.159 (X-3.398)	26.11±2.61
	Karota	5.031+2.472 (X-3.343)	21.43±2.59
Fenoxaprop	Noltha	5.017+3.451 (X-3.637)	42.83±3.97
	Karota	4.979+2.893 (X-3.567)	37.51±4.43
Clodinafop+1 g ha^{-1} metsulfuron	Noltha	4.719+3.187 (X-3.543)	42.73±5.37
	Karota	5.067+2.963 (X-3512)	30.89±3.48
Clodinafop+2 g ha^{-1} metsulfuron	Noltha	4.819+4.686 (X-3.641)	47.80±3.86
	Karota	4.862+2.836 (X-3.503)	35.62±4.71
Clodinafop+3 g ha^{-1} metsulfuron	Noltha	4.809+4.195 (X-3.635)	47.88±4.26
	Karota	5.033+2.780 (X-3.597)	38.51±4.32
Clodinafop+4 g ha^{-1} metsulfuron	Noltha	4.742+4.799 (X-3.666)	52.47±4.23
	Karota	4.947+2.667 (X-3.594)	41.14±4.95
Fenoxaprop+1 g ha^{-1} metsulfuron	Noltha	4.821+1.743 (X-3.798)	79.56±13.84
	Karota	4.838+2.419 (X-3.804)	74.22±9.34
Fenoxaprop+2 g ha^{-1} metsulfuron	Noltha	4.694+1.179 (X-3.786)	110.97±33.11
	Karota	4.704+1.488 (X-3.801)	99.96±22.13
Fenoxaprop+3 g ha^{-1} metsulfuron	Noltha	4.571+1.556 (X-3.857)	135.93±35.70
	Karota	4.552+1.419 (X-3.817)	135.58±38.46
Fenoxaprop+4 g ha^{-1} metsulfuron	Noltha	4.456+1.743 (X-3.872)	152.96±39.19
	Karota	4.493+1.433 (X-3.825)	150.92±45.76

Source : Yadav, A. and Malik, R. K. (2001, Unpublished data).

The perusal of data given in Tables 1 and 2 clearly indicates that dose requirement to cause 50% growth reduction of clodinafop as well as fenoxaprop increased with the corresponding increase in the dose of metsulfuron and 2,4-D Na in the tank mixture. The dose requirement of clodinafop, and fenoxaprop for R and S biotypes when used tank mixed with metsulfuron or 2,4-D Na were higher compared to their respective alone applications. Resistance factor of isoproturon in R-biotype was 16.8 times compared to S-biotypes.

Table 2. GR_{50} values and regression equations of clodinafop and fenoxaprop alone and in combination with 2, 4-D Na against R and S-biotypes of *P. minor*

Herbicide	Biotype	Regression equation (Y=a+bx)	GR_{50} value (g ha^{-1})
Clodinafop	Noltha (R)	4.943+3.159 (X-3.398)	26.11±2.61
	Karota (S)	5.031+2.472 (X-3.343)	21.43±2.59
Fenoxaprop	Noltha	5.017+3.451 (X-3.637)	42.83±3.97
	Karota	4.979+2.893 (X-3.567)	37.51±4.43
Clodinafop+250 g ha^{-1} 2,4-D Na	Noltha	4.995+3.517 (X-3.771)	59.26±5.81
	Karota	5.006+4.176 (X-3.762)	57.66±5.07
Clodinafop+500 g ha^{-1} 2,4-D Na	Noltha	4.968+5.036 (X-3.786)	62.04±4.85
	Karota	4.994+4.193 (X-3.801)	63.46±5.49
Clodinafop+1000 g ha^{-1} 2,4-D Na	Noltha	4.820+1.742 (X-3.795)	78.15±12.12
	Karota	4.832+2.425 (X-3.808)	73.80±8.72
Fenoxaprop+250 g ha^{-1} 2,4-D Na	Noltha	4.587+2.885 (X-4.006)	140.89±21.45
	Karota	4.803+1.601 (X-3.917)	109±24.30
Fenoxaprop+500 g ha^{-1} 2,4-D Na	Noltha	4.607+1.542 (X-3.928)	152.58±46.77
	Karota	4.561+2.778 (X-3.969)	133.94±20.15
Fenoxaprop+1000 g ha^{-1} 2,4-D Na	Noltha	4.414+3.135 (X-4.018)	160.29±25.63
	Karota	4.557+4.255 (X-4.100)	160.00±19.79

Source : Yadav, A. and Malik, R. K. (2001, Unpublished data).

Antagonistic effect of 2, 4 D Na on activity of clodinafop and fenoxaprop against *P. minor* biotypes was even more than metsulfuron (Tables 1 and 2).

Table 3. GR_{50} values and regression equations of fenoxaprop alone and in combination with chlorsulfuron against R and S biotypes of *P. minor*

Herbicide	Biotype	Regression equation (Y=a+bX)	GR_{50} value (g ha^{-1})
Fenoxaprop	Noltha (R)	5.857+3.737 (X-3.911)	48.04±8.62
	Karota (S)	5.924+1.811 (X-3.995)	30.49±15.51
Chlorsulfuron	Noltha	4.923+0.881 (X-3.445)	37.40±9.38
	Karota	5.101+0.990 (X-3.430)	20.84±4.87
Fenoxaprop+2.5 g ha^{-1}	Noltha	4.358+2.508 (X-3.925)	151.53±27.23
Chlorsulfuron	Karota	4.879+2.870 (X-3.927)	93.23±11.07
Fenoxaprop+5 g ha^{-1}	Noltha	4.418+2.202 (X-3.963)	168.67±39.78
chlorsulfuron	Karota	4.424+1.881 (X-3.863)	147.68±26.98
Fenoxaprop+ 10 g ha^{-1}	Noltha	4.399+2.010 (X-3.962)	182.29±50.14
chlorsulfuron	Karota	4.401+2.267 (X-3.910)	149.34±29.24
Fenoxaprop+20 g ha^{-1}	Noltha	4.308+1.480 (X-3.838)	201.99±72.83
chlorsulfuron	Karota	4.432+1.865 (X-3.881)	153.50±36.67
Fenoxaprop+40 g ha^{-1}	Noltha	4.066+1.811 (X-3.828)	220.68±68.22
chlorsulfuron	Karota	4.342+2.228 (X-3.910)	160.38±33.84

Source : Yadav, A. and Malik, R. K. (2001, Unpublished data).

Response of tank mixture spray of fenoxaprop and chlorsulfuron also followed the similar trend as that of fenoxaprop used tank mixed either with metsulfuron or 2, 4-D Na. Chlorsulfuron reduced that potency of fenoxaprop even more than 2, 4-D Na or metsulfuron. However, these studies would need further research for confirmation under field conditions.

The results of these studies warrant for careful use of alternate herbicides (clodinafop and fenoxaprop) against resistant *P. minor* particularly under complex flora in wheat when these herbicides are required to be used in combination with other herbicides like 2, 4-D and metsulfuron.

At present, 2, 4-D Na at 500 g ha^{-1} or metsulfuron at 4 g ha^{-1} has been recommended as sequential application i.e. after a week of application of fenoxaprop or clodinafop for the control of complex weed flora in wheat in resistance affected areas.

Under certain situations, the wheat crop is also infested with *A. ludoviciana* as prominent weed with some infestation of *P. minor* alongwith broadleaf weeds. In such wheat fields, clodinafop at 60 g ha^{-1} or fenoxaprop at 120 g ha^{-1} each tank mixed with 2, 4-D at 500 g ha^{-1} or metsulfuron at 4 g ha^{-1} may provide excellent control of mixed weed flora. This is because clodinafop and fenoxaprop are basically wild oat targeted herbicides and the dose requirement of these herbicides is 20-25% less for *A. ludoviciana* than *P. minor*. So even if, there is some antagonistic effect between these grass and broadleaf weed killing herbicides, it will not be reflected in the wheat fields dominated with *A. ludoviciana*. But it does not mean that we should advocate their tank mixed application, because otherwise left over *P. minor* population will go on increasing year after year. Therefore, sequential application of these herbicides is expected to extend satisfactory results on long-term basis.

Triasulfuron and carfentrazone each at 20 g ha^{-1} as post-emergence (30-35 DAS) herbicides provides excellent control of most of the broadleaf weeds (Brar *et al*., 2005). Carfentrazone has been found to have an edge over other herbicides tested against broadleaf weeds (Punia *et al*., 2005; Patel *et al*., 2005) and it may be useful particularly against *Malwa parviflora,* as it is not effectively controlled by 2, 4-D and metsulfuron. However, these herbicides would also require further research from point view of crop safety and compatability with alternate herbicides in wheat especially infested with isoproturon resistant *P. minor*.

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Chapter 13

Cross-Resistance Against Alternate Herbicides

Littleseed canary grass *(Phalaris minor)* and Wild oat *(Avena fatua* and *A. ludoviciana)* are important grassy weeds of wheat in Asian countries. Short statured varieties coupled with increased fertilizer use and assured irrigation facilities under continuous rice-wheat cropping system possibly resulted in epidemic outbreak and survival of *P. minor* in India (Malik *et al*., 1995). *P. minor, P. paradoxa* and *P. brachystachys* are found in Mexico with dominance of *P. minor*. Monoculture of rice-wheat along with dwarf wheat varieties that are less competitive with weeds made use of herbicides obligatory (Gressel, 1995). Isoproturon was continuously used (10-15 years since 1980s) in the absence of alternate herbicides in India, while in Mexico diclofop was frequently used upto 1990 which was replaced by fenoxaprop for four years. The resistance in *P. minor* against isoproturon in wheat (Malik and Malik, 1994) became epidemic in 1992-93 (Malik *et al*., 1995) and isoproturon was replaced by four alternate herbicides (clodinafop, fenoxaprop, sulfosulfuron and tralkoxydim) during winter season of 1997-98. Continuous use of diclofop in Mexico from 1980 has turned into resistance both in *P. minor* and *P. paradoxa*. Few biotypes of *P. minor* and *P. paradoxa* were not controlled satisfactorily even by fenoxaprop, clodinafop and tralkoxydim (Sayre, 1998). Resistance in *P. minor* and *P. paradoxa* biotypes against fenoxaprop in Mexico (Table 1) was also detected by Yadav *et al*. (2001).

Table 1. Regression equation and GR_{50} values of fenoxaprop for different *Phalaris* species

Phalaris spp.	Regression equation (Y=a+bx)	GR_{50} value (g ha^{-1})	Resistance factor (GR_{50} R/GR_{50} S)
P. minor (S)	3.917+1.828X	87.35±11.73	1.0
P. minor (R)	1.593+1.491X	133.10±0.76	1.5
P. paradoxa (R)	0.819+1.705X	195.34±2.27	2.2

Source : Yadav *et al.* (2001).

Sayre (1998) cautioned that one must not feel safe with any one herbicide out of fenoxaprop, clodinafop or tralkoxydim for use as a routine control practice to be used crop cycle after crop cycle in Mexico.

Mahajan and Brar (2001) reported signs of cross-resistance in *P. minor* against fenoxaprop in India (Table 2), and according to them the order of occurence of cross-resistance to the alternate wheat herbicides may be fenoxaprop> clodinafop>sulfosulfuron.

Table 2. Dose response of different herbicides against resistant biotypes of *Phalaris minor*

Herbicides	GR_{50} value on dry weight basis (g ha^{-1})	
	1998-99	1999-2000
Isoproturon	1650.00	1640.00
Clodinafop	6.60	18.76
Sulfosulfuron	4.22	5.54
Fenoxaprop-p-ethyl	17.27	48.55

Isoproturon resistant biotypes of *P. minor* have shown cross- resistance to diclofop-methyl (Yaduraju and Ahuja, 1995; Kirkwood *et al*., 1997). Malik (1996) and Malik *et al*. (1998) speculated and warranted well in advance that if newly introduced herbicides (fenoxaprop, clodinafop, sulfosulfuron or tralkoxydim) against *P. minor* in wheat are not used properly, they are prone to evolve resistance more rapidly than isoproturon. Vincent and Quirke (2002) have also assumed that if integrated weed management approach is not adopted properly, the herbicide resistance story of the early 1990s would repeat itself by 2007 and by then 50,000 hectares (Haryana plus Punjab) would have a serious *P. minor* infestation in India.

GR_{50} of fenoxaprop in six biotypes during 1999-2000 in Haryana, India was much higher than that observed in 1997-98 (Table 3) and it not only increased in case of isoproturon resistant H3 (Laloda) and Teek (Kaithal) biotypes during 1998-99 but also in the sensitive fenoxaprop progenies (Yadav *et al*., 2002). GR_{50} of clodinafop and sulfosulfuron in few progenies was also found to increase though very marginally (Tables 4 and 5) (Yadav *et al*., 2002).

Similarly, the GR_{50} values of tralkoxydim for H3 and R1 biotypes recorded in 1997-98 were also found to increase in 1999-2000 (Table 6).

During 2000-01, there were large scale failures in respect of fenoxaprop against *P. minor* in Haryana, India. Complaints were also raised by growers and extension agencies regarding poor efficacy of clodinafop and sulfosulfuron during the same period. Few farmers also reported that spurious quality products (duplicate) particularly clodinafop and sulfosulfuron were sold in the market.

Table 3. Regression equation and GR_{50} values of fenoxaprop against progenies of fenoxaprop

Biotype	Regression equation(Y=a+bx)	GR_{50} value (g ha^{-1})
1997-98		
H3 (Laloda, Fatehabad)	5.261+3.937 (X-1.428)	22.99±3.04
KR1 (Amin, Kurukshetra)	5.305+2.791 (X-1.455)	22.17±2.42
R1 (Rohtak)	5.375+2.352 (X-1.457)	19.84±3.42
H2 (HAU, Farm)	5.377+2.097 (X-1.467)	19.34±2.84
1998-99		
H3	4.81+1.92 (X-3.59)	48.86±6.85
Teek (Kaithal)	5.12+2.74 (X-3.92)	75.19±8.64
R1	4.80+1.67 (X-3.53)	39.98±0.95
1999-2000		
Thaneshwar (Kurukshetra)	5.06+3.55 (X-1.386)	69.68±6.42
Teek (Kaithal)	5.04+3.42 (X-3.95)	86.76±8.34
Deora (Kaithal)	5.01+4.07 (X-3.92)	82.71±8.02
Laloda (Fatehabad)	5.17+2.72 (X-3.86)	62.73±7.23
Saga (Karnal)	5.04+5.15 (X-3.96)	90.65±2.03
Uchana (Karnal)	5.08+3.29 (X-3.91)	76.86±7.56

Table 4. Regression equation and GR_{50} values of clodinafop against progenies of clodinafop

Biotype	Regression equation(Y=a+bx)	GR_{50} value (g ha^{-1})
1998-99		
H3	5.01+2.38 (X-3.48)	29.97±3.33
R1	4.99+6.95 (X-3.25)	17.84±0.78
1999-2000		
Bandrana (Kaithal)	5.11+3.29 (X-3.52)	30.66±3.07
Bhakli (Kurukshetra)	5.04+3.71 (X-3.53)	33.05±3.09
Dubkheri (Kurukshetra)	5.06+3.54 (X-3.55)	34.12±3.12
Uchana (Karnal)	5.02+4.10 (X-3.62)	41.22±3.78

Other main reason regarding poor efficacy of these alternative herbicides probably was use of lower than their recommended doses obviously due to four times higher cost of these herbicides compared to isoproturon. This was the basic reason due to which some farmers though unsuccessfully tried to control resistant *P. minor* with metribuzin and atrazine either alone or as tank mixture with isoproturon. Tank mixture of isoproturon with these alternate herbicides (clodinafop, fenoxaprop, sulfosulfuron or tralkoxydim) also did not provide any additional advantage over their alone applications. Inadequate spray application techniques could be the other possible reason for the poor efficacy of these herbicides against *P. minor.* To quantify resistance, the seeds of *P. minor* were collected on large scale during April, 2000 from the fields in rice-wheat growing areas of Haryana, India, where these herbicides were used for once to thrice in the past (1998-2001). Some growers might have also used isoproturon in these three years. And pot culture studies were undertaken druing **rabi** season of 2000-01 at CCS Haryana Agricultural University, Hisar, India by subjecting the progenies of respective herbicides to their graded doses. Dry weight and visual phytotoxicity were recorded at 30 days after treatment, and GR_{50} values based on visual phytotoxicity were calculated using Probit Analysis (Finney, 1971).

Table 5. Regression equation and GR_{50} values of sulfosulfuron against progeny of sulfosulfuron

Biotype	Regression equation (Y=a+bX)	GR_{50} value (g ha^{-1})
1996-97		
H3	5.17+1.73 (X-2.75)	4.48±0.72
R1	5.27+1.57 (X-2.73)	3.61±0.60
1999-2000		
H3	5.44+1.72 (X-3.14)	7.66±1.71
Uchana (Karnal)	5.24+3.39 (X-3.15)	12.00±1.18
Peond (Karnal)	5.30+2.77 (X-3.13)	10.51±1.28
Thaneshwar (Kurukshetra)	5.27+3.07 (X-3.14)	11.27±1.23
Dachaon (Karnal)	5.45+2.49 (X-3.11)	8.49±1.27

Table 6. Regression equation and GR_{50} values of tralkoxydim against progeny of tralkoxydim

Biotype	Regression equation (Y=a+bX)	GR_{50} value (g ha^{-1})
1997-98		
H3	5.06+3.00 (X-1.21)	155±17
R1	5.15+4.05 (X-1.12)	122±11
1999-2000		
H3	4.80+2.09 (X-4.44)	307.5±44.6
H3*	5.16+0.61 (X-1.17)*	808±376*

*This is regression equation and GR_{50} for isoproturon+tralkoxydim (1.5 : 1) for H3 biotypes indicating that this combination will also not work against R-biotype.

Source : Yadav, A. and Malik, R. K. (2000, Unpublished data).

The dose response regression equations and GR$_{50}$ values of fenoxaprop, clodinafop and sulfosulfuron obtained against their respective progenies during 2000-01 have been given in Tables 7, 8 and 9, respectively. It is evident from Table 7, that some biotypes particularly from Karnal have attained high resistance factor (3.0-9.3) inspite of the fact that these biotypes might have also been treated at least once with other alternate herbicides in

Table 7. Regression equation and GR$_{50}$ values of fenoxaprop during 2000-2001.

Biotype	Regression equation (y =a+bX)	GR$_{50}$ value (g ha^{-1})	Resistance factor (GR$_{50}$ R/GR$_{50}$ S)
HAU, Hisar Farm	5.3.24+3.805 (X – 3.472)	24.37±2.26	1.0
Bhaini, Hisar	4.964+2.278 (X – 3.778)	62.25±7.65	2.5
Karota, Rohtak	5.201+3.105 (X – 3.761)	49.72±4.68	2.0
Ram Rahe Batan, Jind	5.346+2.098 (X – 3.863)	48.74±7.85	2.0
Alewa, Jind	5.859+3.012 (X – 3.890)	72.70±7.46	2.9
Hasanpur–1, Jind	5.124+1.953 (X – 3.743)	47.80±6.65	1.9
Hasanpur–2, Jind	5.235+1.578 (X – 3.685)	34.38±6.19	1.4
Rajpura, Jind	5.304+2.247 (X – 3.848)	51.56±7.48	2.1
Jandda–1, Kaithal	5.238+2.705 (X – 3.898)	64.61±7.78	2.6
Jandda –2, Kaithal	4.845+3.435 (X – 3.649)	49.54±0.49	2.0
Teek, Kaithal	5.032+2.841 (X – 3.809)	62.81±6.43	2.6
Khanoda, Kaithal	5.169+3.487 (X – 3.616)	36.93±3.38	1.5
Mundri, Kaithal	5.094+2.835 (X – 3.686)	44.92±4.71	1.8
Faral, Kaithal	4.813+3.447 (X – 3.608)	46.05±4.65	1.8
Thaneshwar, Kurukshetra	5.489+2.536 (X – 4.012)	65.95±11.68	2.7
Beri, Kurukshetra	4.982+2.710 (X – 3.699)	50.79±5.62	2.1
Kheri, Kurukshetra	4.939+3.144 (X – 3.665)	48.39±4.89	1.9
Kheri Nagar, Kurukshetra	4.654+3.565 (X – 3.809)	50.28±5.53	2.1
Bhagthala, Kurukshetra	4.892+2.832 (X – 3.663)	50.24±5.57	2.1
Nangal, Ambala	4.973+2.909 (X – 3.905)	82.16±9.33	3.4
Saga–1, Karnal	4.447+1.528 (X – 3.911)	187.58±45.43	7.7
Uchana, Karnal	4.415+1.734 (X – 4.017)	226.10±56.80	9.3
Bhainikhurd, Karnal	4.701+2.210 (X – 3.914)	112.11±15.12	4.6
Kurak, Karnal	4.907+2.273 (X – 3.985)	105.05±14.32	4.3
Saga–2, Karnal	5.344+2.035 (X – 4.038)	73.97±14.68	3.0

Source : Yadav, A. and Malik, R. K. (2000, Unpublished data).

rotation with fenoxaprop. We usually advise to use herbicides in rotation year after year to prevent or delay herbicide resistance. In general, it is true also, but with aforesaid evidence it appears that herbicide rotation may not totally preclude the development of resistance as has happend in case of wild oat which developed multiple resistance inspite of herbicides used in rotation (Morrison and Bourgeois, 1995). GR_{50} values of clodinafop (Table 8) and sulfosulfuron (Table 9) have also increased in many biotypes compared to their respective GR_{50} values obtained during 1996-97 (Tables 4 and 5).

Table 8. Regression equation and GR_{50} values of clodinafop during 2000-01

Biotype	Regression equation (y = a + bx)	GR_{50} value (g ha^{-1})	Resistance factor (GR_{50} R/GR_{50} S)
Sohimajra, Kaithal	5.083+2.434 (x – 3.403)	23.38±2.72	1.1
Faral, Kaithal	4.811+2.459 (x – 3.360)	27.37±3.68	1.2
Murtazapur-1, Kurukshetra	4.991+2.969 (x – 3.352)	22.65±2.35	1.0
Murtazapur-2, Kurukshetra	4.997+3.418 (x – 3.348)	22.32±2.08	1.0
Dabhkheri, Kurukshetra	5.197+1.955 (x – 3.741)	43.62±6.21	1.9
Karota, Rohtak	4.834+3.759 (x – 3.452)	31.33±2.77	1.4
Nangal, Ambala	4.897+3.160 (x – 3.311)	22.05±2.39	1.0
Karak, Karnal	4.979+4.657 (x – 3.437)	27.64±2.07	1.2

Source : Yadav, A. and Malik, R. K. (2000, Unpublished data).

Table 9. Regression equation and GR_{50} values of sulfosulfuron against its progenies during 2000-01

Biotype	Regression equation (y=a+bX)	GR_{50} value (g ha^{-1})	Resistance factor (GR_{50} R/GR_{50} S)
Kaliheri, Karnal	5.268+1.694 (x – 3.023)	7.32±1.23	1.0
Kurak, Karnal	5.408+2.327 (x – 3.088)	8.19±1.37	1.1
Sultanpur, Karnal	5.324+2.799 (x – 3.085)	9.32±1.19	1.3
Bhainikhurd, Karnal	5.266+3.145 (x – 3.088)	10.08±1.13	1.4
Budhakhera, Karnal	5.348+2.614 (x – 3.082)	8.88±1.51	1.2
Budhthal, Karnal	5.066+2.172 (x – 3.048)	10.41±1.32	1.4
Dabhkheri, Kurukshetra	5.038+1.683 (x – 3.077)	11.333±1.73	1.5
Bhakli, Kurukshetra	5.105+2.419 (x – 3.000)	9.054±1.07	1.2
Pehwa, Kurukshetra	4.984+2.659 (x – 2.948)	8.991±1.09	1.2
Khanoda, Kaithal	5.096+2.302 (x – 2.916)	7.48±0.98	1.0

Source : Yadav, A. and Malik, R. K. (2000, Unpublished data).

Farmers and extension agencies invariably suspected that lower control levels of this weed due to sulfosulfuron and clodinafop could be due to spurious products. Whereas researchers were of the view that in most cases, the possible reason for poor control of *P. minor* was due to use of lower than recommended doses of these alternate herbicides. This was not merely a guess/speculation made by the scientists but it was true also as many farmers were doing this practice because of high cost of herbicides. Cases of fenoxaprop failure increased abruptly. In order to know the true reasons of poor efficacy of these herbicides, the seeds of *P. minor* biotypes were collected randomly in April, 2001 from the fields where alternate herbicides were used consistently at least twice or where control was poor. It is very important to make it clear here that *Phalaris* progenies of alternate herbicides collected during April 2001, might have received other alternate herbicides (s) during previous years i.e. before 2000-01. The *Phalaris* progenies of alternate herbicides were subjected to pot culture/bioassay against graded doses of clodinafop, fenoxaprop and sulfosulfuron. The sowing of *Phalaris* seeds was done on 11 January, 2002 and 10 plants/pot in three replications were retained after thinning. Spray of alternate herbicides each at respective doses *viz*., clodinafop (0, 15, 30, 60 and 120 g ha^{-1}), fenoxaprop (0, 30, 60, 120 and 240 g ha^{-1}) and sulfosulfuron with 0.5% adjuvant (0, 6.25, 12.5, 25 and 50 g ha^{-1}) was done with knapsack sprayer fitted with flatfan nozzle on 16 February, 2002 in a spray volume of 500 l ha^{-1}. Visual phytotoxicity using 0-100 scale (where, 0 = no mortality and 100 = complete mortality) and dry weight of 10 plants/pot was recorded at 40 days after treatment. Since the data on visual toxicity and relative dry weight reduction followed almost identical trend, the GR_{50} values based on visual toxicity were calculated by Probit Analysis (Table 10).

These studies also indicated that there was abrupt increase in the GR_{50} values of fenoxaprop in majority of the *P. minor* biotypes (Table 10). Failure of fenoxaprop even at 2X (240 g ha^{-1}) against many biotypes of *P. minor* (Fig. 1.) has become cause of concern.

There was also mild increase in GR_{50} values of sulfosulfuron in few biotypes compared to that of previous years but most of the biotypes were by and large effectively controlled by sulfosufuron as well as clodinafop at their recommended use rates. Based on the results obtained during the period of 1996-97 to 2001-02, it was evident that GR_{50} of fenoxaprop was found to increase very fast, and it also increased though very mildly in case of clodinafop and sulfosulfuron. It indicates that *P. minor* could be very strong candidate for evolution of cross-resistance or even multiple-resistance (however, this will require further confirmation before reaching to a final conclusion).

Fig. 1. Failure of fenoxaprop even at X and 2X doses against *P. minor*.

Brief description of resistance quantification studies with regard to alternate herbicides at CCSHAU, Hisar during 2002-05

Year 2002-03 (A)

Quantification of herbicide resistance at CCSHAU, Hisar (India) during 2002-03 and seeds of *Phalaris* collected during April 2002 were used in these studies. Out of 10 biotypes, eight belonged to rice-wheat resistance affected areas and two belonged to research farms where crop and herbicide rotations were followed. Isoproturon at 1.0 kg ha^{-1} provided 95-100% control of two sensitive biotypes but control level was less than 50% in case of resistant biotypes. Out of 10 biotypes, clodinafop and fenoxaprop failed to provide satisfactory control of four biotypes (50% or less), whereas sulfosulfuron also provided 50-60% control of five biotypes (data not given). These results require further research for verification.

Year 2002-03 (B)

Another lot of 33 biotypes of *P. minor* which received the treatment of alternate herbicides in previous years was collected randomly from resistance affected areas of Haryana by the scientists of CCSHAU, Hisar during April-May, 2002. These *Phalaris* biotypes/progenies of alternate herbicides were

Table 10. GR$_{50}$ values of clodinafop, fenoxaprop and sulfosulfuron against the *Phalaris* progenies of these alternate herbicides (2001-02)

Phalaris minor	GR$_{50}$ value (g ha^{-1})		
Biotype/progeny	Clodinafop	Fenoxaprop	Sulfosulfuron
Progenies of Fenoxaprop			
HAU farm (Hisar)	18.60 ± 1.77	64.27 ± 9.09	7.71 ± 1.36
Pirthala–1 (Fatehabad)	18.84 ± 1.24	88.92 ± 12.68	8.02 ± 1.16
Pirthala–2 (Fatehabad)	24.58 ± 1.82	86.29 ± 16.25	10.16 ± 1.04
Uchana (Karnal)	21.70 ± 2.07	229.03 ± 58.15	10.02 ± 1.00
Ferozpur–1 (Kaithal)	24.76 ± 1.78	109.52 ± 20.69	9.86 ± 1.06
Ferozpur–2 (Kaithal)	14.95 ± 2.26	94.10 ± 10.85	9.78 ± 0.99
Alewa (Jind)	17.85 ± 1.39	198.54 ± 38.57	10.66 ± 0.93
Laloda (Fatehabad)	18.04 ± 2.02	110.92 ± 19.79	12.25 ± 1.45
Khod (Mahendargarh)	19.99 ± 1.80	77.86 ± 6.15	6.26 ± 0.94
Progenies of Clodinafop			
Nangla–1 (Fatehabad)	21.27 ± 2.34	81.23 ± 10.06	7.08 ± 0.93
Pirthala–1 (Fatehabad)	17.38 ± 2.19	75.31 ± 1.75	7.65 ± 0.93
Asandh (Jind)	24.13 ± 1.67	93.45 ± 23.09	7.57 ± 1.10
Ferozpur–1 (Kaithal)	22.06 ± 1.75	108.28 ± 31.78	10.21 ± 1.22
Ferozpur–2 (Kaithal)	15.02 ± 1.89	95.17 ± 13.93	9.97 ± 0.95
Nangla–2 (Fatehabad)	16.23 ± 2.22	112.36 ± 20.83	10.02 ± 0.87
Uchana (Karnal)	25.63 ± 1.74	218.63 ± 65.66	10.96 ± 0.89
Progenies of Sulfosulfuron			
Nangla–1 (Fatehabad)	23.76 ± 2.02	110.28 ± 17.71	7.85 ± 1.05
Nangla–2 (Fatehabad)	31.78 ± 2.38	206.16 ± 43.46	8.43 ± 0.84
Laloda (Fatehabad)	30.17 ± 2.52	185.95 ± 59.85	10.05 ± 0.97
Pirthala–3 (Fatehabad)	25.83 ± 2.28	199.98 ± 48.35	7.64 ± 1.02
Ferozpur–1 (Kaithal)	26.15 ± 2.19	104.08 ± 16.48	10.35 ± 1.36
Bhaini Khurd (Karnal)	28.51 ± 3.15	128.56 ± 86.06	9.04 ± 0.94
Badagom (Karnal)	21.93 ± 2.13	192.31 ± 57.29	10.59 ± 1.07
Pirthala–4 (Fatehabad)	24.00 ± 1.88	143.55 ± 26.44	8.05 ± 0.95
Teek (Kaithal)	15.27 ± 2.44	66.64 ± 12.17	9.29 ± 1.31
Pirthala–5 (Fatehabad)	16.73 ± 2.55	159.69 ± 91.87	9.16 ± 0.96
Khanoda (Kaithal)	18.28 ± 2.77	177.01 ± 46.64	10.86 ± 0.95
Ferozpur–2 (Kaithal)	17.46 ± 1.97	98.32 ± 15.95	10.26 ± 1.15
Pirthala–6 (Fatehabad)	20.91 ± 2.71	233.35 ± 56.75	9.14 ± 1.11
Uchana (Karnal)	22.38 ± 2.19	192.31 ± 19.67	10.05 ± 1.36

Source : Yadav, A. and Malik, R. K. (2000, Unpublished data).

subjected to pot bioassay in Cornell University, Ithaca, U.S.A. during 2003. The herbicidal treatments included graded doses of clodinafop (0, 15, 30, 60 and 120 g ha^{-1}), fenoxaprop (0, 30, 60, 120 and 240 g ha^{-1}), sulfosulfuron (0, 6.25, 12.5, 25 and 50 g ha^{-1}) and isoproturon at 1.0 kg ha^{-1}. Among herbicides, fenoxaprop at 120 g ha^{-1} and isoproturon at 1.0 kg ha^{-1} did not provide satisfactory control of any biotype except two in case of fenoxaprop and one in case of isoproturon (data not given). Clodinafop at 60 g ha^{-1} and sulfosulfuron at 25 g ha^{-1} provided effective control of all 33 biotypes except that clodinafop and sulfosulfuron showed mild resistance (control level achieved was 67-71%) in one and two biotypes, respectively.

Year 2003-04

Sixteen biotypes were again subjected to pot bioassay using graded doses of isoproturon, clodinafop, fenoxaprop and sulfosulfuron (as described earlier) during 2003-04 at CCS HAU, Hisar. Two biotypes belonging to university's Regional Research Stations (RRS, Bawal and RRS, Uchani), and one from Lakhan Majra (Rohtak) were very effectively controlled (82-98%) by isoproturon at 1.0 kg ha^{-1} but rest 13 biotypes belonging to resistance affected areas of Haryana were not controlled (3-53%) satisfactorily (data not given). Clodinafop at 60 g ha^{-1} and sulfosulfuron at 25 g ha^{-1} provided acceptable control of all biotypes. However, fenoxaprop failed to provide satisfactory control of five biotypes in which the control level ranged between 50-65% only.

Year 2004-05

Fresh seeds of nine biotypes of *P. minor* were collected during April, 2004 in Haryana. Out of these, only two belonged to areas near Kaithal (Gamdi and Khard Pandwa) where rice wheat cropping system is followed from many years and isoproturon is used to control this weed. Rest six biotypes belonged to either Regional Research Stations (RRS, Bawal, RRS, Uchani, KVK, Kaithal) of CCS HAU, Hisar or areas adjacent to Hisar (Dabra and Sorkhi) and Rohtak (Bainsi) where rice-wheat cropping system was practised only recently and use of isoproturon is not so common. The biotypes were subjected to pot-culture bioassay during **rabi** season of 2004-05 using graded doses of isoproturon, clodinafop, fenoxaprop and sulfosulfuron as described earlier. All the herbicides at their recommended doses were found effective against all the biotypes except that isoproturon failed to provide satisfactory control of two biotypes collected from resistance affected rice-wheat areas (data not given). Compared to 1997-98, the dose requirement for 50% growth reduction due to fenoxaprop and sulfosulfuron was reported to increase 10 times while 2-3 times in case of clodinafop against progenies of *P. minor* subjected to rotational use of alternate herbicides for 4-5 years continuously (Dhawan *et al*., 2005). However, these studies need further research for verification. Yadav *et al*. (2005) have also reported frequent control failures due to fenoxaprop, and mild increase in GR_{50} values of sulfosulfuron and clodinafop though only in few cases. Resistance in *P. minor* against herbicides with different modes of action worldwide has been illustrated in Table 11.

Table 11. Herbicide resistant littleseed canary grass (*Phalaris minor*) globally

Country	Year	Sites	Acres	Mode of action
India	1991	10001-100000	1000001-2000000	Ureas and amides (C2/7)
Israel	1993	1	11-50	ACCase inhibitors (A/1)
Mexico	1996	501-1000	1001-10000	ACCase inhibitors (A/1)
South Africa (Multiple resistance)	1999	6-10	Unknown	ALS inhibitors (B/2)
USA (California)	2001	2-5	11-50	ACCase inhibitors (A/1)

Based on these intensive and consistent studies undertaken by the scietists of CCS Haryana Agricultural University, Hisar during last 15 years, it is clearly evident that isoproturon resistance multiplies due to its continuous use and once such resistance is evolved, it becomes irreversible. Alternate herbicides which replaced isoproturon in resistance affected areas are rendering a great service in combating the problem of *Phalaris minor* in wheat. But frequent cases of their failure warrants us to be more careful for future implications, as cross-resistance in *P. minor* against these herbicides has already appeared in some regions or it is at door steps in other areas. *P. minor* can be a strong candidate even for multiple-resistance, which needs further research to know resistance mechanism against alternate herbicides.

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Chapter 14

Isoproturon Use in Resistance Affected Areas–A Futile Exercise

It is now well known fact that resistance in *Phalaris minor* against isoproturon is very wide spread in rice-wheat growing areas of N-W India. It is also well established fact that the resistance has evolved due to continuous use of isoproturon against *P. minor* in wheat under monocropping of rice-wheat. To combat this problem more effectively, isoproturon was replaced by alternate herbicides (clodinafop, fenoxaprop and sulfosulfuron) in Haryana, India during 1997-98. Consequently, the average grain yield of wheat in resistance affected areas which dropped to the level of 34.9 q ha^{-1} during 1997-98 was increased sharply to attain a level of 43.5 q ha^{-1} in 1999-2000. The population of *P. minor* in resistance affected areas also reduced significantly. At this point of time, some growers sparkingly started thinking that at such a reduced level of *P. minor*, there should be no harm to use isoproturon again in place of alternate herbicides in those areas where resistance has become a history. Higher cost of alternate herbicides has also forced the farmers to opt for reuse of isoproturon either alone or mixed with unrecommended herbicides like metribuzin or atrazine. Many farmers unsuccessfully experimented at their fields to control resistant *P. minor* even with isoproturon tank mixed with reduced doses of alternate herbicides. However, based on scientific research as described in earlier chapters, it is now well proven fact that use of isoproturon alone or tank mixed with other herbicides will make the problem of resistance more complex. It has also been well documented by Yadav *et al*. (2002) that isoproturon resistance in *P. minor* once evolved is irreversible (Table 1).

Table 1. GR_{50} values of isoproturon against *Phalaris* progenies of alternate herbicides during 2000-01

Phalaris progenies	GR_{50} value (kg ha^{-1})	Resistance factor (GR_{50} R/GR_{50} S)
Progeny of Fenoxaprop		
Bhagthala (Kurukshetra)	2.940	9.3
Khanoda (Kaithal)	2.782	8.8
Bhakli (Kurukshetra)	2.747	8.7
Mundri (Kaithal)	0.942	2.9
Progeny of Clodinafop		
Dubkheri (Kurukshetra)	2.557	8.1
Murtazapur (Kurukshetra)	1.836	5.8
Progeny of Sulfosulfuron		
Pehwa (Kurukshetra)	3.905	12.4
Khanoda (Kaithal)	3.105	9.8
Susceptible to Isoproturon		
HAU, Hisar farm	0.315	1.0

In addition to the biotypes given in Table 1, considerably higher GR_{50} values of isoproturon in some more biotypes during 2000-01 also made it more clear that even after successful use of alternate herbicides for 3-4 years, the *P. minor* once evolved resistance against isoproturon in the past cannot be effectively controlled by reuse of isoproturon (Table 2).

Table 2. GR_{50} values of isoproturon against progenies of alternate herbicides and resistant (R) and susceptible (S) biotypes of isoproturon (2000-01)

Phalaris progenies	GR_{50} value of isoproturon ($kg\ ha^{-1}$)	Resistance factor
Progenies of Isoproturon		
Unani (M. Garh) – S	0.342 ± 0.058	1.0
Karota (Rohtak) – S	0.397 ± 0.064	1.2
Bawani Khera (Bhiwani) – S	0.339 ± 0.051	1.0
Charkhi (Bhiwani) – S	0.339 ± 0.064	1.0
Khera (Jhajjar) – S	0.330 ± 0.049	1.0
Chanderpur (Jhajjar) – S	0.325 ± 0.055	1.0
Bhaini (Hisar) – S	0.470 ± 0.040	1.4
Alewa (Jind) – R	2.219 ± 0.145	6.8
Hasanpur (Jind) – R	0.759 ± 0.090	2.3
Uchana (Karnal) – R	1.416 ± 0.125	4.3
Kulheri (Karnal) – R	0.977 ± 0.086	3.0
Jandola (Kaithal) – R	3.481 ± 0.767	10.7
Noltha (Panipat) – R	2.417 ± 0.698	7.4
Progenies of Fenoxaprop		
Hasanpur (Jind)	0.839 ± 0.138	2.6
Kheri (Kurukshetra)	2.782 ± 0.870	8.6
Kheri Nagar (Kurukshetra)	2.276 ± 0519	7.0
Beri (Kurukshetra)	0.906 ± 0.103	2.8
Progenies of Clodinafop		
Faral (Kurukshetra)	3.376 ± 0.892	10.4
Beri (Kurukshetra)	0.906 ± 0.103	2.8
Progenies of Sulfosulfuron		
Sultanpur (Karnal)	0.963 ± 0115	2.9
Budhthal (Karnal)	3.571 ± 1.536	10.9
Teek (Kaithal)	3.493 ± 1.215	10.7

Source : Yadav, A. and Malik, R. K. (2001, Unpublished data).

The perusal of data given in Table 2 clearly indicates that resistance factor of isoproturon in progenies of alternate herbicides varies between 2.8 to 10.9 times compared to the most susceptible population. The dose requirement of isoproturon in resistant biotypes was also found between 2.3 to 10.7 more than susceptible biotypes.

Pot culture studies conducted at CCS HAU, Hisar during the year 2001-02 also revealed that out of 35 biotypes, only three biotypes which belonged to areas not affected by isoproturon-resistance were effectively controlled by isoproturon at 1.0 kg ha^{-1}. Rest 32 biotypes which belonged to resistance affected areas and were subjected to the application of alternate herbicides by the growers for 3-4 years during past, were not controlled by X and 2X doses of isoproturon under pot culture. The control of these 32 biotypes with isoproturon at 1.0 kg ha^{-1} was only between 3 to 55% except that one or two biotypes were controlled at the maximum upto 65-73 per cent (data not given).

It means the dose requirement of isoproturon against biotypes which have already evolved resistance will not come down even after 3-4 years use of alternate herbicides before isoproturon is used again. Similar results were obtained against 10 biotypes at CCS HAU, Hisar and 33 biotypes at Cornell University, USA during 2002-03 as already discussed in previous chapter.

Poor control due to isoproturon at 1.0 kg ha^{-1} of 13 biotypes out of 16 belonging to resistance affected areas of Haryana was also observed in 2003-04. This is again important to point out here that these 13 biotypes had been the progenies of one or other of the three alternate herbicides during last 4-5 years period.

Christopher *et al.* (1994) reported that malathion antagonises metabolism based chlorsulfuron resistance in *Lolium rigidum*. Malathion has been found to inhibit cytochrome P-450 dependent primisulfuron metabolism in maize (Kranz and Pfister, 1992). Pipernylbuzoxide and aminobenzotriazol (ABA) have been used as inhibitors to study isoproturon metabolism in *Phalaris minor* (Singh *et al*., 1998a,b).

However, it was also evident from earlier studies that malathion spray one week before isoproturon treatment did not enhance the potency of isoproturon against resistant as well as susceptible biotypes under field conditions (Yadav *et al*., 1997). Malathion used before isoproturon spray or as tank mixed with isoproturon was not found to affect the activity of isoproturon against weeds and wheat under field conditions at research farm of CCSHAU, Hisar earlier also (data not given). Contrary to this, Dhawan (2004) based on pot culture studies at Karnal, India reported that malathion at 1.0 l ha^{-1} sprayed as tank mixed with isoproturon at 1.0 kg ha^{-1} controlled R-biotypes of *P. minor* to the extent of 50%, and 2.0 kg ha^{-1}, the control was 80-90% but with 50% phytotoxicity to wheat, and therefore, of no practical use.

To further verify the findings of Dhawan (2004), pot culture studies were conducted at CCSHAU, Hisar during **rabi** season of 2004-05. Nine biotypes comprising two resistant (R) and seven susceptible (S) were subjected to the graded doses of isoproturon (0, 250, 500, 1000 and 2000 g ha^{-1}) in a replicated trial arranged in completely randomised design. Additional pots with mixed sowing of respective biotypes alone and alongwith wheat were also arranged to accomodate the treatments of malathion at 1.0 and 2.0 l ha^{-1} tank mixed with isoproturon at 1.0 kg ha^{-1}. The spray was done at 3-leaf stage of *P. minor* with knapsack sprayer fitted with flat fan nozzle using spray volume of 500 l ha^{-1}. Visual toxicity (Table 3) and dry weight (data not given) of 10 plants per pot were recorded at 35 days after treatment.

It is evident from the data given in Table 3 that malathion did not enhance the activity of isoproturon. The toxicity levels of isoproturon at 1.0 and 2.0 kg ha^{-1} with and without malathion were identical against R and S biotypes. There was no toxicity on wheat crop. Based on the present findings (Table 3) and earlier reports by Yadav *et al*. (1997) and Project Report on herbicide resistant management in wheat (HRAC, Group meeting 17 November, 1997 in Brighton, U. K.), it can be argued that malathion sprayed earlier to isoproturon or as tank mixed with isoproturon would not provide any enhanced control of *P. minor*.

Walia and Manpreet Singh (2005) interestingly reported that sensitivity of isoproturon-resistant biotypes increased year after year, while it decreased in case of alternate herbicides (Table 4).

Walia and Manpreet Singh (2005) have further explained that the GR$_{50}$ values for isoproturon which was 1403 g ha^{-1} during 2000-01 (Brar *et al*., 2002) came down to 1380 and 1040 g ha^{-1} during crop seasons of 2001-02 and 2002-03 (Walia *et al*., 2004) and it was further decreased to 980 and 530 g ha^{-1} during 2003-04 and 2004-05, respectively. It seems unbelievable and needs thorough investigations because phenomenon of resistance can not be taken so lightly. It should not be treated as a simple ball of naphthalene which sublimes when left in open air. How it can be possible that isoproturon resistance gets reversed on its own in such a short time of 4-5 years (Table 4).

Table 4. GR$_{50}$ values for different herbicides on fresh weight basis

Treatment	Recommended dose	GR$_{50}$ (g ha^{-1}) 2000-01	2001-02	2002-03	2003-04	2004-05
Isoproturon	940	1403	1380	1040	980	530
Clodinafop	60	1.84	2.45	2.50	2.99	3.15
Sulfosulfuron	25	2.50	1.89	2.27	2.49	2.76
Fenoxaprop	100	4.90	6.62	8.55	9.08	12.34

Table 3. Visual toxicity due to isoproturon on different biotypes of *Phalaris minor* (2004-05)

Treatment	Dose (kg ha^{-1})	Visual toxicity (%) on various biotypes								
		RRS Bawal	Dadri Bhiwani	RRS Uchani	Gamdi Kaithal	KVK Kaithal	Khard Pandwa Kaithal	Dabra Hisar	Sorkhi Hisar	Bhainsi Rohtak
Untreated	-	0	0	0	0	0	0	0	0	0
Isoproturon	0.25	42	4	42	7	46	10	33	47	45
Isoproturon	0.5	88	88	88	10	60	27	56	96	82
Isoproturon	1.0	99	99	97	37	86	43	88	99	95
Isoproturon	2.0	99	99	99	63	89	65	90	99	99
Isoproturon+ Malathion*	1.0+1.0 l ha^{-1}	99 (0)	99 (0)	99 (0)	40 (0)	85 (0)	46 (0)	85 (0)	99 (0)	98 (0)
Isoproturon+Malathion	1.0+2.0 l ha^{-1}	99	99	99	40	87	45	86	99	98

**Phalaris* sown mixed with wheat (var. PBW 343). The phytotoxicity on wheat has been given in parentheses.

Source : Yadav A, Malik, R. K. and Punia, S. S. (2005, Unpublished data).

Evolution of resistance in *P. minor* against isoproturon took couple of years (10-15 years) and in resistance-affected fields, dominance of resistant population is well expected. Hence, it will require several years for the sensitive population of *P. minor*, that too if enough seeds are available in soil, to dominate once again over resistant population. This also requires effective elimination of seed multiplication of resistant population by any means except making further use of isoproturon. In the given situation, it seems a case of remote possibilites. Probably, Walia and Manpreet (2005) have collected seeds of *P. minor* from different fields in different years (Table 4) and obviously biotypes used in different years had different GR_{50} values. It is not surprising because still there may be many fields where isoproturon is found effective against *P. minor* in wheat even under rice-wheat cropping system. If this is not the case, then again comparing earlier and independent findings of Brar *et al*. (2002) and Walia *et al*. (2004) with the present findings of Walia and Manpreet (2005) in the form of Table 4 may give wrong message and confuse not only the growers but researchers also. Yadav *et al.* (2005) also reported that once resistance appeared in *P. minor* against isoproturon can not be reversed even after using alternate herbicides and then revising it in resistance affected areas.

Earlier during 1997 at CCSHAU, Hisar, it was also found that phenyl-hydrazine (PH) @ 0.1% sprayed one week prior to isoproturon application did not enhance activity of this herbicide against R and S biotypes of *P. minor* (Table 5).

Table 5. Effect of isoproturon alone and phenyl hydrazine (PH) 0.1% sprayed one week before isoproturon on R and S biotypes of *P. minor*

Treatment	Dose (kg ha^{-1})	Dry weight (g/10 plants) at 50 days after spray	
		H3 (R)	R1 (S)
Untreated	–	3.984	3.661
Isoproturon	0.063	3.989	3.665
Isoproturon	0.125	4.323	3.657
Isoproturon	0.250	4.024	2.357
Isoproturon	0.50	3.968	1.999
Isoproturon	1.00	3.844	0.461
Isoproturon	2.0	1.992	0.112
PH 0.1% *fb* Isoproturon	0.063	4.755	3.803
PH 0.1% *fb* Isoproturon	0.125	4.937	3.708
PH 0.1% *fb* Isoproturon	0.25	4.829	2.451
PH 0.1% *fb* Isoproturon	0.5	4.388	1.555
PH 0.1% *fb* Isoproturon	1.0	4.417	0.531
PH 0.1% *fb* Isoproturon	2.0	2.451	0.140
PH 0.1%	–	4.726	3.801
PH 0.2%	–	4.730	3.810
PH 0.1%	–	4.735	3.816

Source : Yadav, A. and Malik, R. K. (1997, unpublished data)

Based on these studies, it appears that isoproturon resistance in *P. minor* is an irreversible phenomenon under field conditions and it will be wise for the growers not to use isoproturon in resistance affected areas.

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Chapter 15

Management of Herbicide Resistance

In this chapter, strategies for the management of herbicide resistance, in general, and *Phalaris minor* in rice-wheat cropping sytem of N-W India in particular have been discussed.

Agricultural soils contain many weed seeds. Some seeds are non-dormant and germinate quickly while other seeds may persist for many months or years before germinating. Conventional herbicide and cultural procedures control weeds after germination but normally have little or no effect on dormant and other non-germinated seeds, which pose potential weed problems. Even if 100% weed control is achieved, the soil reservoir (Weed seed bank) of non-germinated, dormant seeds may persist to intermittently germinate and cause problems.

A proper combination of improved tillage, crop diversification, herbicide rotation, improved spray techniques, and training of users will be the key ingredients of a sustainable weed management system. Integration of mechanical methods with herbicides and cultural methods requires urgent and immediate attention for herbicide resistance management. Use of such a balanced approach will reduce the frequency of herbicide use, which in turn will delay the onset of herbicide resistance (Malik *et al.,* 1998).

Prevention is always easier than tackling confirmed resistance. Integrated management of weeds needs to be developed and the key objective should be the reduction in selection pressure for resistance development (Anonymous, 2000). Integrated weed management is defined as the use of a range of control techniques embracing physical, chemical and biological methods in a integrated fashion without excessive reliance on any one method. Shane Friesen *et al*. (2000) have concluded that adopting the currently promoted herbicide resistance management strategies may not always be effective in delaying the onset of herbicide resistance. Some mention of resistance management approaches reviewed by Rubin (1991) has also been made in the following text regarding important strategies which may be helpful to provide relevant solutions for this problem.

A. Mechanical and Cultural Practices

Cultural weed control is promoted for resistance management mainly to take advantage of any fitness differential between resistant and susceptible plants which refers to their ability to survive and reproduce within a mixed weed population (Jasieniuk *et al*., 1996).

It is often assumed that mutations conferring herbicide resistance will be associated with decreased plant fitness (Holt, 1990), thereby implying that resistant population may be controlled via crop competition. However, fitness of resistant biotypes is not always reduced. In cases where resistant biotypes do not show substantial fitness, differential cultural control measures may not preferentially control resistant weeds any more than their susceptible counterparts.

Techniques such as little change in the sowing time *i.e*. delayed drilling or early sowing (depending upon situation), fallow, strategic fertilizer placement, growing of competitive crops either through sowing at higher seed rate or close spacing or choosing competitive varieties, biologiclal control, straw/stubble burning, stale seed bed technique, roughing, use of clean and certified seed, and minimizing the dissemination of seeds and plants in combine harvesters, cultivation equipments, straw or manure, and encouraging post-harvest grazing are some of the non-chemical methods of weed control. The mechanical and cultural practices for herbicide resistance management are as under :

1. Improved variety and certified seed : Pure and certified seed of improved and competitive varieties should be used for wheat sowing, so that every year contamination of problematic weed seeds (*A. ludoviciana, P. minor, C. arvensis, R. retroflexus, Lathyrus indica* and *Vicia sativa*) may be reduced. Yadav *et al*. (2002a) have also cautioned to avoid alarming contamination of wheat seed with resistant *P. minor*, which is generally not given proper attention by growers. According to general seed certification standards and quarantine rules, only 10 and 20 weed seeds kg^{-1} of foundation and certified seeds are allowed in wheat, respectively. Whereas in the case of objectionable weeds like *P. minor* only 2 and 5 seeds kg^{-1} of wheat are permitted.

Competitive genotypes of wheat may also play a vital role in the management of weeds. The varieties with quick initial growth and canopy cover can better compete with weeds compared to other varieties with slow initial growth and upright leaves. Chauhan *et al*. (2001) (Fig. 1) and Malik *et al*. (2002) have identified varieties of wheat such as HD 2687, PBW 343 and WH 542, which are competitive against grassy weeds in wheat.

2. Close spacing and higher seed rate : Higher seed rates and close row spacing may allow less weeds to grow and competing ability in favour of crop.

3. Proper time of sowing : Early sowing of wheat favours initial growth and crop competitiveness against weeds (Malik *et al*., 1998). This is more important under rice-wheat cropping system because *P. minor* germinates more profusely during last week of November to December and even January.

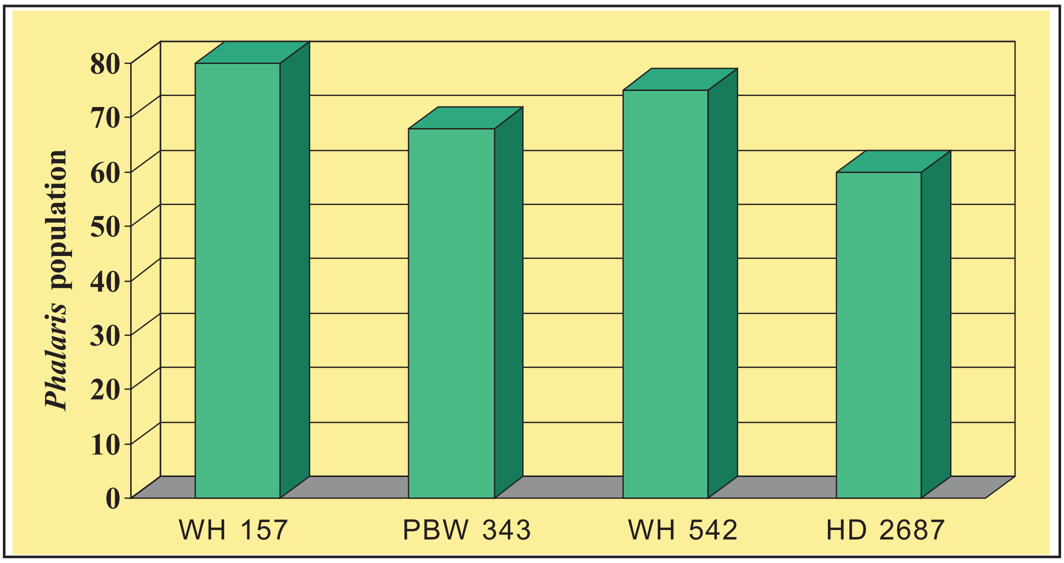


Fig. 1. Competitive varieties of wheat against resistant *P. minor.*

Therefore, sowing of wheat in the last week of October to second week of November will be of enormous help in combating the emergence and early growth of *P. minor* in particular and other weeds, in general. Early sowing of wheat can easily be possible under zero-tillage (Fig. 2).

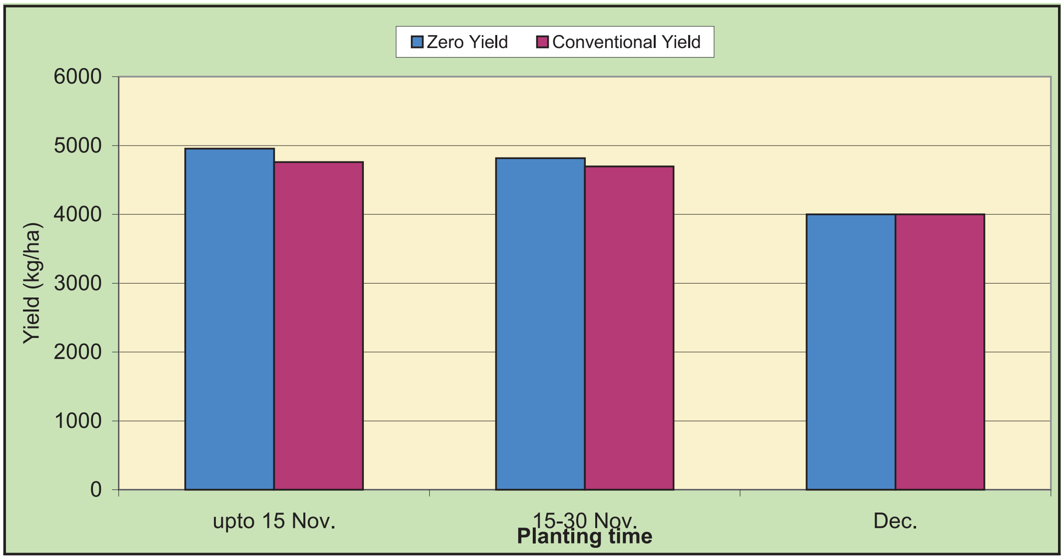


Fig. 2. Grain yield of wheat under different dates of sowing.

Source : Malik *et al.* (2002).

4. Crop rotation : Many serious weeds are strongly associated with specific crops; so crop rotations can reduce the intrinsic success of such weeds and, in many situations, permit the use of alternate herbicides. The inclusion of a grass lay in an arable rotation can also be an effective means of reducing populations of many arable weeds. Crop rotation changes ecology/environment of cropping system, inclusion of more competitive crops helps suppress weed flora, allows use of herbicide having different modes of action, fodder crops reduce seed production of resistant biotypes, and crops with different sowing times and seed bed preparation/field operations can lead to variety of cultural techniques being employed to manage a particular weed problem.

Continuous change in the cropping system is very important and beneficial. Besides maintaining soil fertility, change in the crop rotation helps to interrupt the life cycle of specific weeds. Therefore, instead of growing the same crop every year, efforts should be made to grow some other crops after every two or three years. Under rice-wheat cropping, efforts should be made to replace some of the possible area under wheat with other crops like sunflower, berseem, sugarcane, maize and vegetables. However, these alternate crops should be economically viable. Repalcement of wheat with sunflower in rice-wheat cropping areas may be helpful to reduce seed bank of resistant *P. minor* (Fig. 3).

Fig. 3. Replacement of wheat with sunflower reduces *P. minor* infestation.

Bhan and Singh (1993) reported the importance of including sugarcane in place of wheat to reduce the population of *P. minor* (Table 1). In order to reduce *Phalaris* infestation, the replacement of wheat by some other crops will be more useful than replacing rice from the rice-wheat cropping system. Banga *et al*. (1997) have reported 2350 plants m^{-2} of *P. minor* under continuous rice-wheat system for 10 years (Table 2) as against 255 plants m^{-2} under rice-berseem-rice-wheat and 19 plants under rice-winter maize-sorghum-raya-maize-wheat.

5. Stale seed bed technique : The promise behind the stale seed bed technique is that by delaying seeding after crop seed bed preparation, flushes of weeds can be induced to sprout and then be killed. If the weeds are killed with minimal disturbances, the weed seed bank in the upper few centimeters of soil will be depleted resulting in less weed pressure against subsequent crops. One or two irrigations given one or two months prior to wheat sowing may enhance germination of weed seeds sitting in the upper layers of soil surface (Fig. 4). After germination, these weeds may be killed by ploughings or by using pre-seeding herbicides (glyphosate @ 0.5% or paraquat @ 0.3% each on product basis). Stale seed bed technique helps reduce weed seed bank present in the soil (Malik *et al*., 1995; Hobbs *et al*., 1998).

Fig. 4. Pre-sowing irrigation encourages germination of *P. minor.*

Table 1. Effects of cropping sequence on the population of *P. minor* in wheat

Cropping sequence	*P. minor* (No. m^{-2})
Rice-wheat-rice-wheat-rice-wheat	54
Rice-potato-rice-berseem-rice-winter maize	16
Rice-sugarcane-sugarcane-ratoon-ratoon-wheat	4
Maize-wheat-rice-wheat-maize-wheat	18
Sorghum-wheat-maize-wheat-sorghum-wheat	22
Rice-potato-rice-wheat-rice-potato	253

Table 2. Effects of crop rotation on population of *P. minor* in wheat

Cropping sequence	*P. minor* (No. m^{-2})
Rice-wheat (continuously for 10 years)	2350
Rice-wheat-rice-wheat-cotton-wheat	2125
Rice-berseem-sorghum-wheat	190
Rice-potato-rice-wheat	255
Cotton-wheat (continuously for 4-5 years)	39
Rice-berseem-rice-berseem-rice-wheat	29
Rice-winter maize-sorghum-raya-maize-wheat	19
Maize-sunflower-rice-berseem-rice-wheat	35
Rice-potato-chilli-potato-rice-wheat	24
Rice-wheat- (continuously for 5 years)-chilli-wheat	2421

6. **Avoid sowing in moist soil :** Sowing of wheat should not be done in soil with high moisture rather it should be done when upper soil profile (1-2 cm) gets dried. It will reduce weed seed germination and thereby crop-weed competition at the initial stages of crop growth.

7. **Bar harrow/tooth harrow :** Mechanical weeding bar harrow (tooth harrow) at early growth stage of wheat preferably before first irrigation or a week after first irrigation coupled with post-emergence herbicides may be another alternative to manage resistant *P. minor.* It is practised by many farmers of Haryana and Punjab in India.

8. **Interculture :** One hand weeding or hoeing with hand-hoe (*Kasola*) or

wheel-hoe after first and second irrigation may be helpful in controlling weeds in wheat. However, manual weeding may not be successful under certain specific circumstances. Control measures should be integrated in such a way that weeds do not produce seeds. General problems associated with interculture are as follows :

(i) Many farmers opt wheat sowing by broadcasting and thus it becomes very difficult to work with implements (*Khurpa, Kasola* and Wheel hand-hoe, etc.).

(ii) It is difficult to control weeds germinating within rows or near plants particularly in those fields where crop is sown by broadcasting.

(iii) It is difficult to control grassy weeds because they resemble wheat plants.

(iv) Labour scarcity, re-emergence/regeneration of weeds, high cost and tediousness associated with manual weeding generally put a question mark on the success of this practice.

9. Straw burning : Stubble/straw burning of crops destroys weed seeds infesting those crops in the growing season. But situation may be different for the crop to be grown in the subsequent season. As in case of rice-wheat system, rice straw burning provokes more germination of *Phalaris minor* seeds in wheat. Moreover, straw burning has been reported to reduce the efficacy of post-emergence herbicides due to adsorption with ash (Singh, 1996). On the contrary, retention of rice crop residues particularly under zero-tillage in wheat will reduce germination of *P. minor* by acting as a mulch. Therefore, avoid residue burning as usually done by farmers (Fig. 5) and encourage residue retention on soil surface or its incorporation (Fig. 6). Some farmers also go for partial burning of wheat straw before rice transplantation. This practice may damage the *Phalaris minor* seeds in left over crop residues or even on soil surface but it will not be a healthy practice from soil health and environmental pollution point of view.

10. Roughing : Usually weeds remain uncontrolled inspite of implementing all possible methods of weed management. They produce ample number of seeds and add to the soil seed bank or crop produce. In case of *Phalaris minor* also, growers generally ignore left-over plants in wheat, which produce enough seeds for future infestation. This upsets the already made efforts for management of this weed. Care must be taken to break this cycle by removing the left-over weed plants before they set seeds. Avoid use of *P. minor* at maturity as fodder for animals because seeds of this weed do not loose viability even after passing through animals' digestive tract. Also avoid use of unfermented farm yard manure.

Fig. 5. Avoid residue burning.

Fig. 6. Retain crop residues on soil surface.

B. Cultivation/Tillage

Minimum tillage favours weeds especially annual grasses and perennial weeds, and consequently there is often an increased requirement for herbicides. Non-inversion tillage minimizes the proportion of weed population derived from seeds shed in the previous crop (because seeds are retained close to the soil surface), and minimizes the probability of back crossing with earlier, unselected generations derived from older, buried seeds. Inversion tillage such as mouldboard ploughing can reduce the requirement for herbicides and thus reduce the selection pressure. Zero-tillage in wheat has been found to curtail the germination of *P. minor* by 30-40% due to comparatively less soil disturbances (Malik *et al*., 2002).

Under certain situations where weeds have emerged before wheat sowing under zero-tillage, pre-seeding herbicides (glyphosate @ 0.5% or paraquat @ 0.3% each on product basis) are applied to knock down these weeds, thus reducing their seed bank in the soil.

In the first week of November, *Phalaris* can be encouraged to emerge by providing one or two pre-sowing irrigations. The first flush of weeds can be controlled by pre-seeding herbicides followed by direct-drilling by a zero-tillage planter. The second flush may be controlled by post-emergence herbicides, however, it will not be highly competitive because of less emergence due to fewer disturbances.

Based on the average of 10 farmer's field trials (each one acre size) under conventional tillage during 1997-98 under rice-wheat cropping system of Haryana, the population of *P. minor* (before spray) and grain yield of wheat were 1499 plants m^{-2} and 4173.3 kg ha^{-1}, respectively. Whereas, under zero-tillage (average of 32 field trials), these figures were 734 plants m^{-2} and 4405 kg ha^{-1} (Malik *et al*., 2002).

The vertical distribution of weed seeds also differs with type of tillage (Yenish *et al*., 1992). Unlike mouldboard plough and chisel plough systems, more weed seeds are distributed near the soil surface in no-tillage system (Yenish *et al*., 1992). When seeds remain near the soil surface rather than buried in soil, weed seedling emergence and seed bank depletion are greater (Roberts and Feast, 1992).

Adoption of zero-tillage in wheat on long-term basis in Haryana has also been realized helpful in reducing *P. minor* population and sustaining grain yield of wheat (Fig. 7). After realising benefits of zero-tillage in wheat farmers adopted this technology in a big way (Fig. 8). ZT initiated in 1996-97 only on 10 acres but then area under this technology increased in geometrical progression covering 1.0 m ha during 2003-04 in India. Zero-tillage may help in skipping off spray of costly alternate herbicides once or twice after every three or four years (Fig. 9) (Malik *et al*., 2002).

Inter-row cultivation or mechanical weed control under (Fig. 10) **furrow irrigated raised beds system (FIRBS)** can be another effective method of

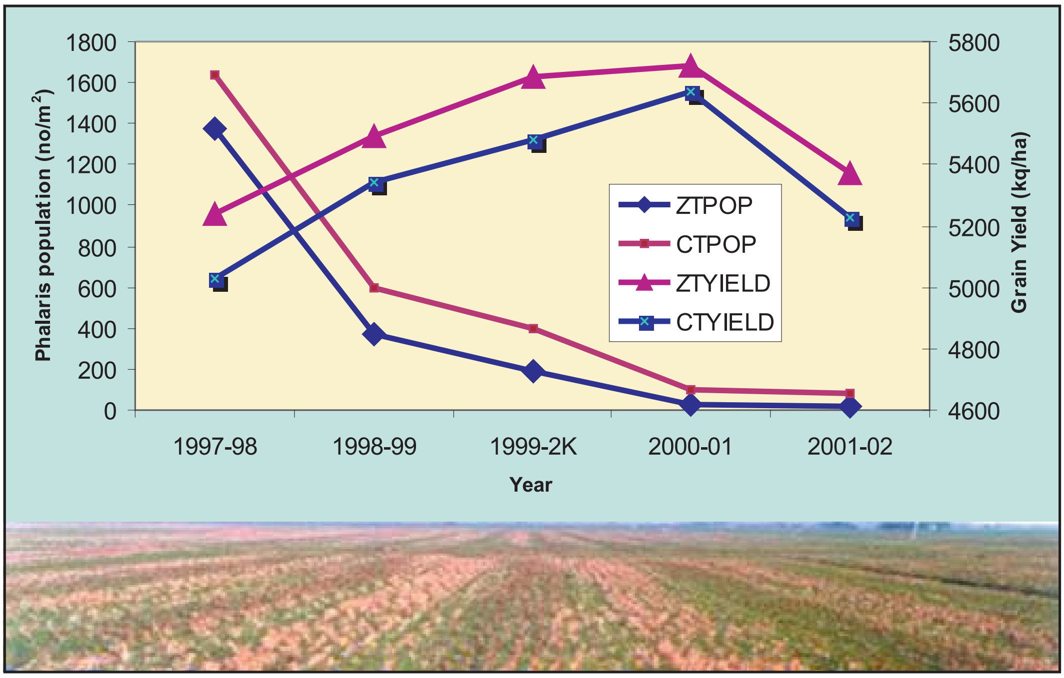


Fig. 7. Long-term zero-tillage reduces population of *P. minor* and sustains grain yield of wheat.
Source : Malik *et al.* (2002).

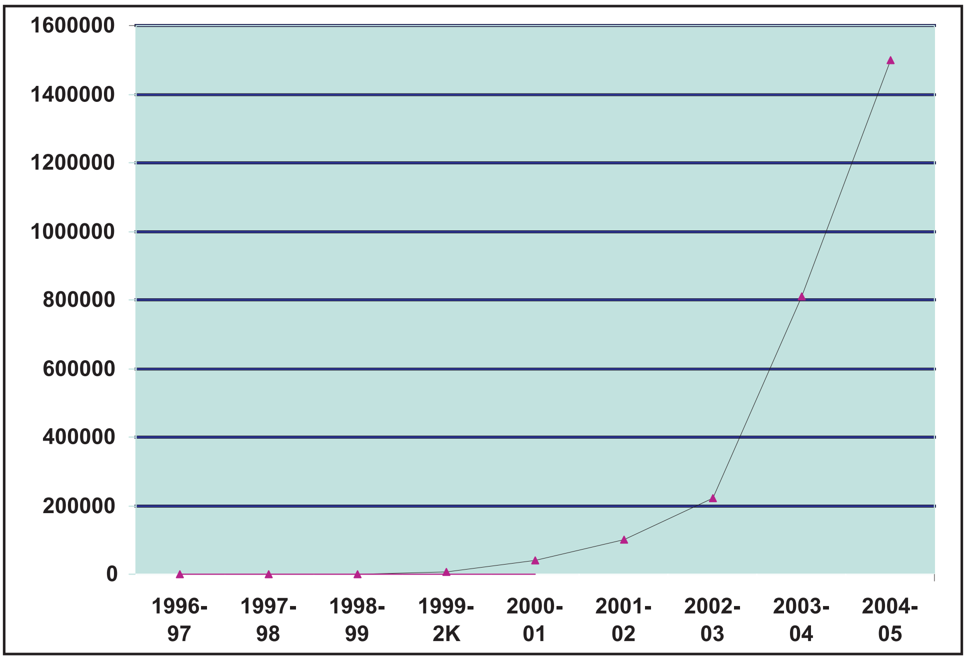


Fig. 8. Geometrical increase in area (ha) under zero-tillage in India.
Source : Malik *et al.* (2002).

Fig. 9. Skipping off alternate herbicides under zero-tillage once after 3-4 years is possible.

Fig. 10. Mechanical weed control is possible under FIRBS.

non-chemical weed control, which should impose no selection pressure if the same degree of control of S and R biotypes is achieved. The feasibility and effectiveness of such techniques depends on soil and environmental conditions under which the crop is being grown.

Under FIRBS, the inter-row space may be used to control weeds including *P. minor* by mechanical weeding during the early vegetative growth of weeds (Fig. 10). The technology, if made successful after fine tuning and refinement, has the potential to significantly reduce farmers' reliance on selective herbicides. Permanent beds or zero-tillage on raised beds, without disturbance and with drier soil at top, will allow only few weeds to germinate or establish. Crop diversification on raised beds may also play an important role in weed management.

C. Herbicides and their Proper Use

It is not only important to select most suitable herbicide but it is also equally important to use it at proper time and with correct methodology. Some of the issues related to chemical control of *P. minor* and methods to avert or delay herbicide resistance have been described as under :

1. Alternate herbicides : The use of alternate herbicides, already reported very effective against resistant populations of *P. minor*, can be a successful strategy, at least for short-term. In some instances, control level of resistant plant is more than susceptible plant (negative cross-resistant). However, if used repeatedly, there is a high risk of resistance developing against alternate herbicide, e.g. few biotypes of *P. minor* which were resistant to isoproturon have shown resistance to alternate herbicide fenoxaprop in recent years (Yadav *et al*., 2002) and mild resistance has also been observed in few biotypes against clodinafop and sulfosulfuron. Continuous use of non-selective herbicides (glyphosate, paraquat) may also result into herbicide resistance or shift in weed species that are harder to control.

2. Herbicides mixtures or sequences : Herbicides grouped according to biochemical mode of action (Table 3) and HRAC mode of action (Table 4) will help to select herbicides for proper rotation or mixtures. Use two or more than two herbicides with different mode of action (acting on the same weed at different sites of action i.e. heterologous mixtures) to reduce the selection pressure for resistant biotypes. The value of such a strategy depends upon the relative efficacy of each of the herbicide on the target weed and the specificity of the resistance mechanism. In case of *P. minor*, once resistance has evolved never use isoproturon alone or mixed with other herbicides. Also do not make tank mix spray of 2, 4-D or metsulfuron with alternate herbicides rather follow sequential applications, if needed.

Characteristics of some good herbicide mixtures (Gressel, 1992; Wrubel and Gressel, 1994) are : (i) Affect different target sites, (ii) Are not degraded by the same pathway, (iii) Have similar persistence and (iv) Control the same spectrum of weeds.

For the mixing partners to be effective each herbicide should be applied at normal field doses. However, from a producers' perspective, the cost of herbicide treatment may increase, and the crop may be damaged more than if one herbicide was applied at the field dose. If many herbicides are degraded by the same pathway, their mixture may not be effective. Herbicide mixtures also do not preclude the development of multiple resistance as in case of *Lolium rigidum* (one example so far) which became resistant to concomitant application of amitrole and atrazine (Gressel, 1992).

Table 3. Herbicides grouped according to biochemical mode of action

Biochemical action	Group	Common name
Inhibitors of photosynthesis at photosystem-II	Ureas	Chlorotoluron, Isoproturon, Methabenzthiazuron, Metoxuron
	Triazines	
	Triazinones	Atrazine, Cyanazine, Simazine, Terbutryn, Metribuzin
Inhibitors of lipid biosynthesis	Aryloxyphenoxypropionates ('fops')	Diclofop-methyl, Fenoxaprop-ethyl, Fluazifop-p-butyl, Quizalofop-ethyl
	Cyclohexanediones ('dims')	Alloxydim-sodium, Cycloxydim, Sethoxydim, Tralkoxydim
Inhibitors of tubulin formation	Dinitroanilines	Pendimethalin, Trifluralin
Inhibitors of branched-chain amino acid biosynthesis	Imidazolinones	Imazamethabenz-methyl
Inhibitors of photosynthesis at photosystem-1	Bipyridiliums	Diquat, Paraquat
Inhibitors of aromatic amino acid biosynthesis	Glycines	Glyphosate
Inhibitors of glutamine synthase	Phosphinates	Glufosinate-ammonium
Herbicide with multiple site of action	Amides	Napromide, Propazamide, Tabutam
	Aminopropionates	Flamprop-m-isopropyl
	Carbamates	Carbetamide
	Chloroacetamides	Metazachlor
	Halogenated alkanoic acid derivatieve	TCA
	Heterocyclic compounds	Ethofumesate
	Thiocarbamates	Trallate

Source : Moss and Clarke (1994).

Table 4. HRAC mode of action classification

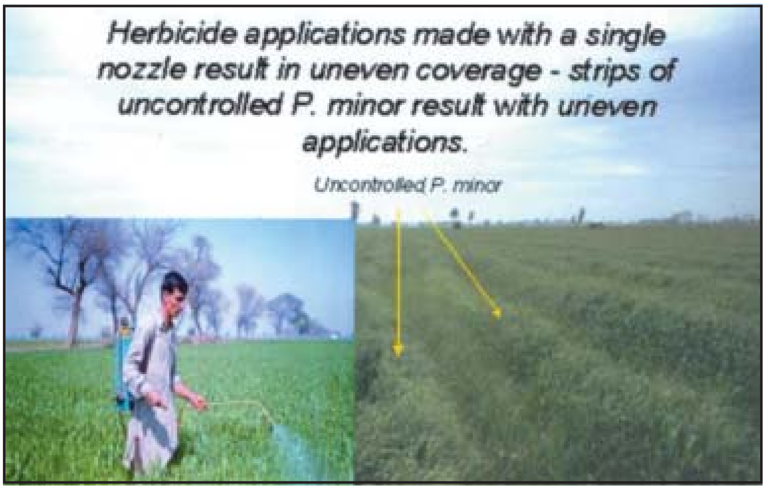
Group A	Inhibition of acetyl CoA carboxylase (ACCase) : Aryloxyphenoxy-propionates, cyclohexanediones
Group B	Inhibition of acetolactate synthase ALS (acetohydroxy acidsynthase, AHAS) : sulphonylureas, imidazolinones, traizolopyrimidines, pyrimidinylthiobenzoates.
Group C1	Inhibition of photosynthesis at photosystem II : Triazines, triazinones, uracils, pyridazinone, phenylcarbamates
Group C2	Inhibition of photosynthesis at photosystem II : Ureas, amides
Group C3	Inhibition of photosynthesis at photsystem II : Nitriles, benzothiadiazole, phenyl-pyridazines
Group D	Photosystem-I-electron diversion Bipyridyliums
Group E	Inhibition of protoporphyrinogen oxidase (PPO) Diphenylethers, n-phenylphthalimdes, thiadiazoles, oxadiazoles, traizolinones
Group F1	Bleaching : Inhibition of carotenoid biosynthesis at the phytoene desaturase step (PDS) Pyridazinones, nicotinanilides, others
Group F2	Bleaching : Inhibition of 4-hydroxyphenyl-pyruvate dioxygenase (4-HPPD) Triketones, isoxazoles pyrazoles
Group F3	Bleaching : Inhibition of carotenoid biosynthesis (unknown target) Triazole, isooxyzolidinones, ureas
Group G	Inhibition of EPSP synthesis Glycines
Group H	Inhibition of glutamine synthetase Phosphinic acids
Group I	Inhibition of DHP (dihydropteroate) synthase Carbamates
Group K1	Microtubule assembly inhibition Dinitroanilines, phosphoroamidates, pyridazines, benzoicacids
Group K2	Inhibition of mitosis/microtubule organisation carbamates
Group K3	Inhibition of cell division Chloroacetamides, carbamates, acetamides, benzamides, oxyacetamides
Group L	Inhibition of cell wall (cellulose) synthesis Nitriles, benzamides
Group M	Uncoupling (membrane disruption) Dinitrophenols
Group N	Inhibition of liquid synthesis-not ACCase inhibition Thiocarbamates, phosphorodithioates, benzofurans, chloro-carbonic-acids
Group O	Action like indoleacetic acid (synthetic auxins) Phenyl-carboxylic-acids, benzoic acids, pyridine carboxylyic acids, quinoline carboxylic acids
Group P	Inhibition of indoleacetic acid action Phthalamate, semicarbazones
Group/R/S/T	—
Group Z	Unknown Arylaminopropionic acids, organoarsenicals, others, benzylethers

3. Proper use of herbicides and herbicide rotation : Selection pressure should be reduced by using herbicides with no, or with limited residual activity in the soil. Ideally, the lowest possible rate of herbicide and the minimum number of applications per season should be used, and the same herbicide should not be applied more than once every 2-3 years. Follow label use instructions carefully *i.e*. optimum dose, method and time of application. Herbicide rotation is advocated in a way that the herbicide with same target site chemistry is not used on the same field for more than once every three years. But it may be impractical because alternate herbicides may not be as efficient (in cost and efficacy) and may not be similar with respect to crop safety and/or weed control spectrum. They may not be compatible with other spray tank additives or the planned crop rotation. Furthermore, herbicide rotation may not preclude the development of some type of resistance e.g. cross-resistance or, development of multiple resistance in wild oat in Canada inspite of herbicide rotation (Morrison and Bourgeois, 1995). In case of *P. minor* spray of alternate herbicide should be done at 2½ to 3 –leaf stage of the weed. Spray of herbicides should preferably be done with knapsack sprayer (or any sprayer) fitted with flat fan nozzle (Figs. 11, 12 and 13) with all precautions (Miller and Bellinder, 2001). Avoid using the herbicide to which resistance has been confirmed. Otherwise, it will further complicate the problem and resistance factor will increase with the time it will be used as in case of isoproturon against *P. minor* (Yadav *et al*., 2002).

4. Synergists and safeners : Although practical implementaiton of synergists in weed management programme is very limited at present, this approach may be particularly appropriate in case where resistance is due to enhanced metabolism. Take care, not to compromise with herbicide selectivity to crop.

5. Economic thresholds : An economic threshold is the pest density at which the value of crop loss equals treatment cost (Maxwell, 1992). Thus, at weed density lower than the economic threshold, the cost of applying a herbicide would, presumably, be more than the value of the damage the weeds cause. The number of herbicide application may be reduced by using economic threshold, which is good for producer and environment.

Optimizing herbicide input to the economic threshold level should avoid the unnecessary use of herbicides and reduce selection pressure. In addition, the survival of susceptible plants will encourage cross-pollination between R and S-individuals in allogamous species, which may arrest or reverse the selection process. However, because the rate of resistance is proportional to the number of weeds; higher density of weeds that may occur by using an economic threshold strategy may increase the probability of resistance development.



Herbicide applications made with a single nozzle result in uneven coverage - strips of uncontrolled P. minor result with uneven applications.

Fig. 11. Avoid spray of herbicides with single nozzle boom.

Fig. 12. Use multi-nozzle booms for uniform spray of herbicides.

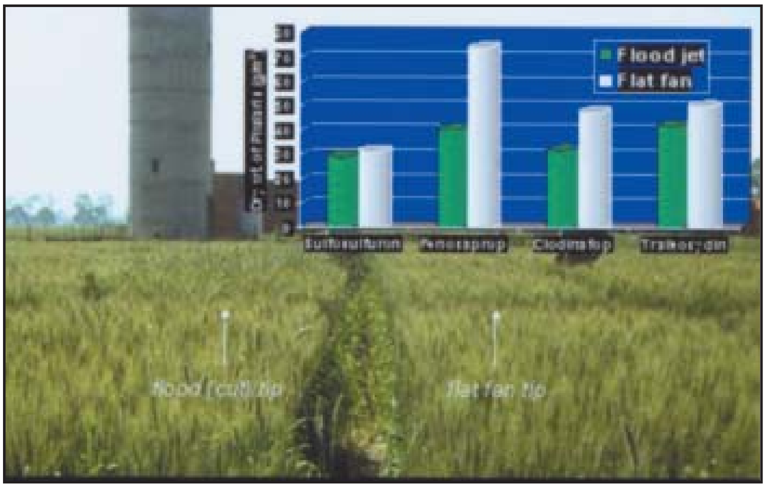


Fig. 13. Always use flat-fan nozzles for spray of herbicides.

6. Availability of new herbicides : Isoproturon resistance in *Phalris minor* has been well documented. Alternate herbicides introduced in 1998 to replace isoproturon in rice-wheat cropping sequences have also started showing red signals of resistance in *P. minor*. Due to further use of these herbicides, the severity of resistance in affected fields is likely to increase and spread further. Continuous research on the efficacy of existing herbicides alongwith new molecules against resistant *P. minor* will be required in the times to come. Industries should also intensify their efforts to ensure availability of new molecules from time to time for this purpose. It is the hightime for the Indian herbicide manufacturing industry to be more pro-active and work with public sector agencies in developing resistance monitoring and management programmes. Extension agencies should also accept the fact that resistance evolution against alternate herbicides in *P. minor* is just at the door-steps in wheat and extension programmes must be tailored accordingly.

D. Monitoring Trends or Change in Weed Population

Monitoring is the way of observing early symptoms of resistance development. The assumption is that weed patches represent herbicide resistant biotypes that have survived herbicide treatment. However, many weed patches could be susceptible. Based on epidemiological survey, the resistance may not be noticed until a large proportion of the population is affected e.g. 30% or more (Gressel and Segal, 1978).

The diagnostic survey conducted in early 1990's helped to detect isoproturon resistance in *P. minor* in India. Similarly, these surveys have indicated that frequent cases of poor herbicidal efficacy or failure are once again appearing in rice-wheat system of the country against alternate herbicides in *P. minor*. One farmer of district Kaithal (Haryana) reported in ***rabi*** 2004-05, that all the three herbicides (clodinafop, fenoxaprop and sulfosulfuron) each sprayed one after other (sequential application) even at double the recommended rate in the same wheat fields failed to provide satisfactory control of *P. minor*. Further investigations revealed that first fenoxaprop at 2X was sprayed at 40 days after sowing (DAS), there was poor or no control of *P. minor* at this farm. Then the farmer sprayed clodinafop at 2X dose at 55 DAS with no control and ultimately he sprayed sulfosulfuron at 2X dose at 75 DAS with some control of *P. minor* and satisfactory crop harvest. This information triggers many questions regarding growth stage, dose, spray methods, etc. used by the farmer, which need further answers. Anyway, such cases may provide sound background for generating valuable data on herbicide resistance, and all this can be possible only through feed back received in such type of surveys.

E. Herbicide Resistant Crops (HRCs)

Genetically modified (GM) crops may serve as a new tool in the integrated management of herbicide resistance as these can be used to combat herbicide resistant weeds with non-selective herbicides such as glyphosate. GM crops such as Roundup Ready or glufosinate tolerant corn, canola, soybean, wheat and rice are available in developed countries. Non-GM crops e. g. clearfield corn, clearfield canola, clearfield rice, clearfield wheat (tolerant to imidaxolinone herbicide) also have enough potential to be used as an important component of integrated weed management. There could be long-term benefits of such crops but potential long-term adverse effects of such technological innovations need to be carefully assessed before recommending their use. Gene flow into wild types and development of resistance against non-selective herbicides are the main causes of concern. For more details, refer Chapter-6 entitled “Herbicide resistant crops-An important component of integrated weed management”.

F. Farmers Participatory Approach

Resistance monitoring and management options should be framed by the scientists and planners in consultation and active participation of the growers (Fig. 14). This will help in restricting the physical spread of resistance to unaffected areas and developing appropriate management practices for resistance affected areas within short span of time and at lower cost. Interaction with farmers through diagnostic surveys can also help to prevent or delay resistance through early detection.

Fig. 14. Scientists interacting with farmers of village Teek, Kaithal (Haryana)

G. Training

Training programmes on resistance modeling, appropriate management strategies and basic research on resistance mechanisms are needed to improve the expertise of scientists of developing countries. Besides this, emphasis on training of growers (Fig. 15), extension workers and private sector should also be given top priority. Joint research projects among international institutes and upgrading weed science laboratories are other key issues which need attention of the planners and policy makers.

Fig. 15. Train growers to manage herbicide resistance.

Before recommending any management strategy, its consequences on weed dynamics, economics and sustainability of the cropping systems must always be kept in mind.

Herbicides resistance management strategies need to be customized to each situation so that the most relevant management strategy may be feasible for the producer and cropping system.

Any of the weed control methods, if employed in isolation, will not be successful to manage weeds and herbicide resistance as well. Therefore, looking into the situation and case-by-case, we should follow integrated approach to achieve sustainable weed management, to avert or delay or manage herbicide resistance and finally to get higher yields without much disturbance to agro-ecosystem.

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