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Herbicide resistance in weeds and its management strategies

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Abstract
Weeds are much older than crop cultivation for food, fuel, fibre and shelter. Weed management is a big task for production of various crops. At present time, herbicides are most popular and effective means for weed management due to their higher efficacy and time saving nature. But their continuous and indiscriminate use has created several problems like weed flora shift, herbicide resistance and environmental hazards. Out of these, herbicide resistance is most serious problem of present time. Currently there are 480 cases of herbicide resistance in 252 plant species. There are various types of herbicide resistance such as cross resistance, multiple resistance, partial resistance, full resistance etc. Herbicide resistance has become a major issue at world level, and number of resistant biotypes is increasing continuously at very rapid rate. Therefore, some alternate management practices such as cultural, mechanical and biological methods should be integrated in weed management program to combat this problem. A proper understanding of development and mechanism of resistance (altered target sites, rapid metabolism and sequestration) would help us for its management. With the help of various physiological and biochemical studies, some resistant screening techniques should be developed for yielding quick results. This paper provides information on status of herbicide resistance, development of resistance, factors affecting development of herbicide resistance in weeds, resistance mechanisms and its management.

Keywords: Herbicide, weed, biotypes, resistance and mechanism of resistance

Introduction

Biodiversity is simply a combination of evolution and natural selection. Plants are at a higher risk towards various stresses when they are being directly exposed to external environment. Majority of weeds are C_4 plants and contain enough genetic diversity that they can survive even under worst environmental conditions or various stresses. Among different factors responsible for reduction in agricultural productivity, weed is most important factor which affects the yield adversely. Beside huge yield reductions in crops, weeds also reduce input efficiency, decreases quality of crops, interfere with agricultural operations, act as collateral and alternate hosts for several pathogens and insect-pests, reduce aesthetic quality of the ecosystem, causes reduction in biodiversity, as well as detrimental impacts on human and animal health (Brown and Meagher, 1970) [5]. Yield reduction in various crops due to weed infestation is given in table no. 1.

Table 1: Reduction in yield of major crops in India due to weed infestation

Crop	Yield loss %	Crop	Yield loss %
Wheat	10-60	Rice	10-100
Cotton	40-60	Sugarcane	25-50
Maize	30-40	Sorghum	45-69
Pearl millet	16-65	Finger millet	50
Horsegram	30	Jute	30-70
Niger	20-30	Soyabean	10-100
Chickpea	10-50	Pea	10-50
Greengarm	10-45	Lentil	30-35
Groundnut	30-80	Pigeonpea	20-30
Vegetables	30-40	Potato	20-30

(Rao *et al.*, 2014) [46].

Although there are various weed management practices like cultural, mechanical and biological methods, but chemical method is most effective and time saving. Herbicides discovery has changed the scenario of weed management at world level. Discovery of new herbicides in last few decades provided a greater choice to famers for effective weed management (Duary and Mukhopadhyay, 2004) [21].

But some harmful impacts are also associated with these chemical herbicides like shift in weed flora, herbicide resistance and herbicide residue in food chain. Out of these, herbicide resistance is most prominent problem. Herbicide resistance develops mainly due to the repeated spray of same herbicide or a different herbicide with a same mechanism on the same piece of land year after year. *Phalaris minor* was the first weed in which herbicide resistance was reported against urea herbicides in the early 1990s in north-western India. A crop responding poor to herbicides does not mean that it has developed resistance against that herbicide. Conformation is necessary before calling it herbicide resistance weed and it is only done by sincerely evaluation. Areas where zero tillage or minimum tillage is practiced are at greater risk for development of herbicide resistance.

Definition

It is defined as the inherited ability of a weed biotype to survive and reproduce following exposure to rate of herbicide which would normally give effective control of wild type or to which the original population was susceptible. According to Holt and Le Baron (1990) [34], resistance development is directly related to the recommended dose of herbicides for field use. There can be evolution of resistance in asexually propagated (sterile *Cyperus spp.*) plants.

Herbicide tolerance

It means ability of a weed species to withstand or compensate the damaging effects of an applied herbicide naturally without involvement of any physiological mechanism (Menalled and Dyer, 2006) [43]. It is the inherent capacity of a weed species to survive and reproduce normally even after herbicide application at normal dose.

It is different from herbicide resistance as no genetic manipulation occurs in process of herbicide tolerance to make the plant tolerant; it is naturally tolerant. *e.g.* Tolerance of grasses against broadleaf herbicides and tolerance of broadleaf crops against AOPP herbicides.

Herbicide susceptibility: It is defined as the lack of ability of biotype to withstand herbicide treatment at recommended dose that the plant gets injured by herbicide application (Ashton and Crafts, 1981) [1].

Types of herbicide resistance

Simple resistance: It develops due to repeated application of single herbicide. It can be of partial or complete types.

Cross resistance: Rubin *et al*. (1991) [48] defined it as form of resistance in which a population becomes resistant to two or more than two herbicides by the action of same resistance mechanism. It works on mechanism which endows the capacity to withstand herbicides belonging from same or different chemical classes having same mode of action (Hall *et al.*, 1994) [30]. *Rumex dentatus* biotypes resistant to metsulfuron, have evolved cross resistance to mesosulfuron + iodosulfuron, halauxifen + florasulam. (Chhokar *et al.*, 2014) [12]. A biotype of *Avena fatua* in Australia became resistant to fenoxaprop also became resistant to several other ACCase inhibiting herbicides.

Multiple resistance: Multiple resistance is the phenomenon of resistance through which a weed species shows resistance to herbicides of chemical classes with different mode of action by two or more distinct mechanisms. It is also defined as resistance to herbicides from more than one chemical class to which a population has been exposed (Holt *et al.*, 1993) [35]. Multiple resistance was first reported in *Lolium rigidum* and *Alopecurus myosuroides* in Australia and Europe, respectively. Multiple-resistant plants have more than two resistance mechanisms (Gunsolus *et al.*, 1993) [29].

Reverse resistance: It occurs when a biotype resistant to some herbicide becomes susceptible to same herbicide if it is not used for a long period (say 7-10 years) during which some other herbicide is used.

Creeping Resistance: Normally there is a small increment of resistance due to action of several genes, so there is gradual but rapid creep (shift) in the mean level of resistance of a population.

Phoenix Resistance: There are number of weeds like *Conyza* spp. and *Sorghum halepense* with glyphosate, where leaves are withered and dead within week but misdiagnosed as death by herbicide. If the pots were watered, a regrowth can be seen from hidden buds in the resistant biotype.

Negative cross resistance: In this type of resistance, a resistant biotype shows higher susceptibility to other classes of herbicide as compare to susceptible biotypes (Gressel *et al*., 1991) [21]. It refers to the phenomenon by which an individual resistant to one herbicide or a chemical family of herbicides shows higher or increased sensitivity or susceptibility to other herbicides than its natural wild type susceptible population. For example, an biotype of *Echinochloa crusgalli*, resistant to triazines, found 53 times more resistant than susceptible one, shows 33 and 2 times higher sensitivity to fluazifop- butyl and sethoxydim, respectively (Gadamaski *et al.*, 2000) [25].

Co-resistance: It is also known as compound resistance. It is defined as a resistance mechanism in which weed develops resistance to both chemical components of a mixture herbicide. E.g. - *Lolium rigidum.*

Table 2: Year of reporting of herbicide resistance against widely used herbicides

Herbicide	Year of resistance reported	Herbicide	Year of resistance reported
2,4-D	1963	Picloram	1973
Dalapon	1962	Trifluralin	1982
Atrazine	1988	Diclofop	1982
Triallate	1987	Isoproturon	1995
Chlorsulfuron	1987	Gyphosate	2006

(Modified from: Duary and Yaduraju, 1999; Valverde and Gressel, 2006) [22, 61]

Table 3: Assessment of risk associated with herbicide resistance

Management options	Risk of resistance		
	Low	Moderate	High
Herbicide mix or rotation	>2 modes of action	2 modes of action	1 modes of action
Weed control in cropping system	Cultural, mechanical and chemical	Cultural and chemical	Chemical only
Use of same mode of action herbicide	1 year	More than one	>3 year
Cropping system	Full rotation	Limited rotation	No rotation
Weed infestation	Low	Moderate	High
Herbicide residual period	Short	Intermediate	Long

Table 4: Resistance factor for various herbicides reported in India

Herbicide	Resistance factor	References
Isoproturon	2.0-15.0	Malik *et al*., 1995, Rasool *et al*., 2016 [41, 19]
Sulfosulfuron	1.2-10.0	Yadav *et al*., 2002; Dhawan *et al*., 2009 [42, 16]
Tralkoxydim	1.2-1.7	Yadav *et al*., 2002 [42]
Clodinafop	1.2-4.0	Yadav *et al*., 2002; Dhawan *et al*., 2009; Rasool *et al*., 2016 [42, 16, 49]
Fenoxaprop	3.7-10.0	Dhawan *et al*., 2009; Rasool *et al*., 2016 [16, 49]

Table 5: Reports of herbicide resistance in *P. minor* in India

Herbicide	Incidence of resistance
Isoproturon	Malik and Singh, 1993; Malik *et al*., 1995; Walia *et al*., 1997; Brar *et al*., 2002; Chhokar and Malik, 2002; Yadav *et al*., 2002; Bhullar and Walia, 2004; Singh *et al*., 2007 [40, 42, 62, 4, 9, 58, 6, 53]
Sulfosulfuron	Yadav and Malik, 2005; Chhokar and Sharma, 2008; Bhullar *et al*., 2014; [59, 7, 14]
Clodinafop	Yadav and Malik, 2005; Chhokar and Sharma, 2008; Bullar *et al*., 2014; Das *et al*., 2014; [59, 7, 14, 15]
Fenoxaprop	Bhullar and Walia, 2002; Yadav and Malik, 2005; Chhokar and Sharma, 2008; Dhawan *et al*., 2010 [8, 62, 59, 17]
Pinoxaden	Kaur *et al*., 2015 [37]

Scenario of herbicide resistance in India

The issue of herbicide resistance was originated, over the last 40 years. With the discovery of atrazine resistance in *Senecio vulgaris* in 1968 (Ryan *et al*., 1970) [50], number of herbicide resistant weeds are continuously increasing at a higher rate equivalent to that of insecticides and fungicide resistance (Heap, 2007) [31]. Table no. 2. Represents the year of reporting of herbicide resistance against the widely used herbicides. At present time, weeds have evolved resistance to 23 of the 26 known target sites and to 167 different herbicides. Herbicide resistance has become major problem in 92 crops in 70 countries (http://www.weedscience.org.2007). This is most severe in U.S.A. followed by Australia, Canada, France, Spain and U.K. etc. Table no. 3. Represents the assessment of risk associated with herbicide resistance. Maximum resistance was found against triazine group of herbicides. Since last few years the resistance against ALS inhibitors has rapidly increased in number almost one and half time more than the number of triazine resistant weeds. This group of herbicide is extensively used in more than 12 major crops due to its higher efficiency and greater selectivity (Das *et al*., 2008) [14]. Table no. 4. Represents the resistance factor of various herbicides reported in India. In crops mainly in wheat, herbicide resistance has developed in both grassy and broadleaf weeds. In grassy weeds, *P. minor* and *A. fatua* have developed resistance against several herbicides like sufofulfuron, clodinafop. Repeated use of IPU over several years caused evolution of resistance in *P. minor* in 1990s (Malik and Singh, 1993; Walia *et al*., 1997) [40, 62]. IPU resistance in *P. minor* was the first case of herbicide resistance in India (Malik and Singh, 1993) [40]. Heap (2016) [33] reported that multiple resistance in *P. minor* has developed against photosystem II inhibitors, ACCase inhibitors and ALS inhibitors. Kaur *et al*., (2015) [37] also reported resistance in *P. minor* against pinoxaden. Table no. 5. Represents the reporting of herbicide resistance in *P. minor* by different scientists of India. Sole dependence on these groups of herbicides led to development of many cases of cross resistance or multiple-resistance were in wild oat worldwide (Kern *et al*., 1996; Bourgeois *et al*., 1997; Friesen *et al*., 2000; Uludag *et al*., 2008) [39, 3, 24, 57]. Singh *et al*. (2016) [51] reported herbicide resistance in wild oat against application of sulfosulfuron, clodinafop and fenoxaprop to a population from farmer's field. Herbicide resistance in wild oat has been reported in 50 countries to more than 24 herbicides (Heap, 2016) [33]. Herbicide resistance in toothed dock (*Rumex dentatus* L.) has been confirmed recently (Chhokar *et al.*, 2013a; Heap 2014; Singh *et al*., 2017) [11, 32, 52].

Factors affecting resistance development

Characteristics of weed: The most favorable characteristics of weed that enhance resistance against specific herbicides are following:

- **Initial frequency of resistant biotype**: If there is more number of indivisuals having specific inherent resistance in a particular population then there will be more chances of resistance. Dormancy and Gasquez *et al.* (1990) [20] found an average frequency of 3´´ 10-3 triazine herbicide resistant individuals in a population of *Chenopodium album* and Powles *et al.* (1997) reported an average frequency of 1 ´´ 10-2 diclofop methyl-resistant individuals in a *Lolium rigidurm*.
- **Annual growth habit**: Annual plants produce tremendous amount of tiny seeds by completing their life cycle in a shorter time period as compare to perennials.
- **Selection pressure for evolution of resistant population**: It is relative proportion of resistant and susceptible plants left after herbicidal application (Gressel and Segel, 1990) [26]. Application of residual herbicides of single target site and specific mode of action when applied frequently without rotating with herbicides of different groups impose a high selection pressure (Holt and Lebaron, 1990) [34]. A highly effective herbicide also leaves some susceptible individuals to

contribute to the next generation as compare to less effective herbicide. This causes a remarkable difference in appearance of resistance. (Duary and Yaduraju, 1999; Das and Duary, 1999) [22, 13].

- **Extreme susceptibility to particular herbicide**: Also known as hyper sensitivity of weeds to a specific herbicide. As a result of this, most of population can be eradicated consequently, so that, high selection pressure will allow the resistant biotypes to prevail and thrive best to stand fit in the field.
- Some weeds have high frequency of resistant gene that develop higher and rapid rate of resistance e.g. *Lolium rigidum.*

Characteristics of herbicides: Properties of herbicide molecule that build the resistance in weeds to label them as different biotypes are discussed below-

- Herbicides that are subjected to enhanced metabolism in weeds have least chance to endure resistance in plants than weeds expressing resistance due to change in their target site. However, resistance to ACC-inhibiting herbicides (metabolism based) is much less known although seems to be spread at wider scale (Delye *et al.,* 2005) [19].
- An herbicide with single site of action is at greater risk for resistance development as compare to herbicide with several mode of actions.
- Herbicides having long residual activity in soil causes removal or suppression of susceptible biotypes for a long interval, so that resistant biotypes gets competition free environment to flourish and reproduce.

Cultural Characteristics: It includes various farm practices which have potential of shifting selection pressure on weeds. Some of these practices are discussed below:

- Practicing monoculture at a wider scale for a long period of time.
- Practicing conservation tillage such as zero tillage or minimum tillage.
- Using single herbicide or mixture having same chemistry continuously for a longer period.
- Improper or non-judicious use of herbicide.

Resistance mechanism

There are following two broad mechanisms given by Dekker and Duke (1995) [18] -

1. **Exclusionary resistance**: This mechanism excludes the herbicide molecule from the site in plants where they induce toxic response. This happens due to following four reasons –

a) **Differential herbicide uptake**: Herbicidal uptake become more difficult in resistant biotypes due to presence of some barrier like hairy epidermis, overproduction of waxes and reduced foliage area (low foliage number and size) etc.

b) **Differential translocation**: Translocation rate is reduced to a great extent in resistant biotypes due to reduction in apoplastic (cell wall, xylem) and symplastic (plasma lemma, phloem) activity (Ozair *et al.*, 1987) [44].

c) **Compartmentation (Sequestration)**: Sequestration of herbicides occurs in many sites before it reaches the site of action. E.g. Resistance in several biotypes of *Lolium rigidum* (Holtum *et al.*, 1991) [36]. Some lipophilic herbicides are immobilized due to partitioning into lipid rich glands or oil bodies (Stegink and Vaughn, 1988) [55].

d) **Metabolic detoxification:** Herbicide becomes detoxified at a faster rate before it reaches the site of action so that plants remain safe. Triazine resistance in *Abutilon theophrostii* is due to rapid metabolism of herbicide (Gronwaid *et al.*, 1989) [28]. Isoproturon resistance in *P. minor* was also due to rapid metabolism of isoproturon (Singh *et al.*, 1996) [54].

2. **Site of action of resistance:** This mechanism occurs by following two modifications -

a) **Target site alteration**: Target site is altered due to a mutation or other reasons in such a way that plant loses its susceptibility towards herbicide. E.g. In sulfonylurea herbicide resistant biotypes of *Lactuca sativa* target site is modified so that herbicide become unable to bind with the enzyme and inactivate it (Eberlein *et al.*, 1999) [23]. Ray *et al*. (1984) [47] reported that resistance to ALS inhibitors is due to target site alteration. Subramanian *et al*. (1990) [56] also reported that resistance to triazolopyrimidine is due to an altered site of action due to manipulation in the gene encoding of ALS accompanied by production of a form of ALS that is insensitive to inhibition. Resistance found in dinitroaniline resistant biotypes of *Eleusine indica* is due to alteration in the form of tubulin that cause microtubule to become insensitive towards dinitroaniline (Vaughn and Vaughan, 1990) [60].

b) **Overproduction of site of action**: It happens as enlarged or overproduced site of action which causes dilution of herbicide. The normal dose of applied herbicide is not enough to inactivate the entire amount of enzyme protein produced, so the additional amount of enzyme produced by the plant biotype can allow it carry on its normal metabolic activities.

Herbicide resistance management

First step of herbicide resistance management is to diagnose various herbicide resistant weeds and then monitoring of their nature, distribution and abundance (Beckie *et al*., 2000) [2]. Herbicide resistance can be managed efficiently by focusing on the ways of reducing selection pressure for evolution of resistance. So the factors responsible for evolution of resistance should be modified. At present time, herbicide resistance in *P. minor* is the most serious issue of Indian agriculture. So its management is very necessary for sustaining wheat productivity. Table no. 6 represents the effective herbicides for management of resistant *P. minor.*

Table 6: Herbicidal mixtures for management of resistant *P. minor*

Herbicide	Time of application	Dose (g/ha)
Pendimethalin + metribuzin	Pre-emergence	1500 + 150
Mesosulfuron + iodosulfuron,	Post-emergence	14.4
Sulfosulfuron + metsulfuron-methyl,	Post-emergence	32
Pinoxaden + metsulfuron-methyl	Post-emergence	64
Pendimethalin *fb* mesosulfuron + iodosulfuron	Pre-emergence *fb* post-emergence	1500/14.4

Pendimethalin *fb* sulfosulfuron + metsulfuron-methyl	Pre-emergence *fb* post-emergence	1500/32
Pendimethalin *fb* pinoxaden + metsulfuron-methyl	Pre-emergence *fb* post-emergence	1500/64

Kaur *et al.*, 2019 [38]

Some of the important strategies regarding herbicide use are described below –

a) **Stop use of herbicide to which resistance has developed:** Use of particular herbicide should be stopped if it is detected with problem of herbicide resistance.
b) **Use of alternative herbicides**: Alternative herbicides with different mode of action having higher efficacy for weed management should be recommended for use.
c) **Herbicide mixture and rotation**: An herbicide mixture is a best option for reducing the selection pressure for resistance biotype and delaying the evolution rate. Mixing two or more herbicides with different mode of action is also helpful in reducing the risk of weed flora shift. Herbicide rotation is defined as application of different herbicides with different mode of action in subsequent seasons. Problem of target site resistance is reduced to a great extent with the help of herbicidal mixtures.
d) **Herbicide selection and application:** There are several herbicides groups such as chloracetamides, diphenyl ether and glyphosate, against which very few weeds have developed resistance despite extensive use of these herbicides. On the other hand weeds have readily evolved resistance to ALS inhibitors, triazine, bipyridyliums, phenylures, and ACCase inhibitors. Non residual herbicides are best option for reducing selection pressure for resistant biotypes. Use of soil persistent herbicide should be minimized. Indiscriminate use of herbicides should be avoided. Growing of herbicide resistant crops is also beneficial.
e) **Use of herbicides with short residual life**: There is direct relation between selection pressure and residual nature of herbicides. Higher the residual life of herbicide, more will be selection pressure.

Additional cultural practices for herbicide resistance management

- Use of efficient sprayers fitted with multiple-flat fan nozzles.
- Growing of competitive crop varieties with closer row spacing.
- Use of clean seed and certified seed
- Optimization of water and nutrient management
- Follow up efficient crop rotation

Conclusion

Worldwide herbicide resistance becomes a serious issue and its severity is continuously increasing at a rapid rate. Main reason behind this problem is excess use of highly efficient herbicides with single site of action. Through the use of herbicide molecules is not good for our environment due to its harmful impacts on biodiversity, yet herbicides are used at a rapid rate with higher doses which is the key reason for resistance development. Proper knowledge of level, nature and mechanism of herbicide resistance will strengthen our efforts for herbicide resistant weed management. Herbicide mixtures and sequence, herbicide rotations are best management measure to tackle the problem of resistance. Several other practices like alternate cultivation and fallows, use molecular biology and biochemistry are also helpful in avoiding herbicide resistance. Field demonstration programs should be conducted to provide information to farmers about improved spraying technologies.

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