Eco. Env. & Cons. 30 (January Suppl. Issue) : 2024; pp. (S359-S367)

ISSN 0971–765X

DOI No.: http://doi.org/10.53550/EEC.2024.v30i01s.073

Herbicide Resistant Crops and Weeds - A Review

Kanta Rani[1], Manisha Agrawal[2] and Puneet Kumar Chhokar[3*]

[1, 2] G.G.D.S.D.College, Palwal 121102, Haryana, India
[3]Department of Agronomy, Naini Agricultural Institute, Sam Higginbottom University of Agriculture Technology and Sciences, Prayagraj 211 007, U.P., India

(Received 14 June, 2023; Accepted 18 August, 2023)

ABSTRACT

Herbicide is an important tool for weed management in modern agriculture. However, due to evolution of herbicide resistance in weeds and no discovery of new mode of action has made the weed management a challenge. Herbicide resistant crops are an alternative for broadening the weed control options, as besides providing broad spectrum weed kill they also also helps in reducing the risk of herbicide carry over effect. Glyphosate resistant crops have made the weed control effective and economical but recently the excessive use have led to the evolution of glyphosate resistant weeds. The gene flow from the herbicide resistant crop is also an emerging challenge and many weeds are now becoming the constraints to the sustainable crop production. Herbicide resistant crops as well as weed management practice should be practiced in such a way that reduces the risk of evolution of herbicide resistant weeds and Integrated Weed Management practices should be followed for sustainable crop production.

Key words: *Herbicide resistant crops, Herbicide resistant weeds, Glyphosate, Glufosinate, Gene flow, Super weeds*

Introduction

Weeds have been regarded as the most detrimental biotic constraints to crop production causing around 38% of the total losses to the crop production (Das, 2015). The losses caused by weeds vary depending on weed flora and weed density. Globally, weeds decreases the production of the world's eight most important food and cash crops by 13.2% (Oerke, 2006). Weeds beside reducing the yield also reduces the quality of the produce. According to Chhokar *et al.,* 2012 the introduction of herbicides during 1940's made weed control less labor-intensive and more energy efficient, at the sametime its cost and time effectiveness has rapidly extended itsuseall over the world and has now become one of the most popular means to control weeds. Unfortunately, this useful tool has been challenged by the evolution of herbicide resistance in current scenario.

The evolution of Multipleh Herbicide Rresistance (MHR) in weeds have further adds to the already existing menace resulting in aggravated yield losses and inturn reduced profitability. Herbicide resistance has rendered several effective herbicides belonging to different MoAuseless, which were being used top control the weeds for quite some time

Worldwide, at present, there are 154 cases ofdicot and 113 cases of monot weeds that have become resistant to different herbicides belonginmg to various MOA's, which makes around 495518 unique cases (species x site of action) of herbicide resistant weeds (Heap, 2023). Moreover, it is note worthy that in just 5 years 23 unique cases of herbicide resistance are added in list of HR weeds, where in 2018 same were around 495 (Heap, 2018 and Heap, 2023).

Controlling weeds has a become a challenge for both growers as well as for the experts around the globe, this is mailny due to the lack of dissemination of proper spray technology i.e. distribution of proper set of instructions for herbicide application and at the same time under dosage and over dosage of the herbicides should be prevented as over dosage will increase the selection pressure which will inturn result in the development of herbicide resistance, while under dosage although will control the weed upto a certain but in this case some weeds might survive and in long runthey might develop resistance to not only that herbicide, there are chances that it might develop cross resistanceto herbicides belonging to same MOA group. Forinstance a biotype of *Rumex dentatus* which was resistant to metsulfuron, has now evolved cross resistance tomesosulfuron + iodosulfuron etc. (Chhokar *et al.,* 2013). The situation is further aggravated as for the last three decades no new a.i of herbicide has been discovered or developed (Duke, 2012) and the possible reasons for the same might be the huge cost of development (more than 250 million dollar), more fund diversion towards development of new molecules for insecticides and fungicides development perspectives, industry consolidation, hostile properties of new candidate as a herbicide coupled with very short market buzz due to accelerated development of herbicide resistance (Duke, 2012; Reddy and Nandula, 2012).

Moreover, just in eight years 60 unique cases are added in list of HR weeds, where in 2010 species are 195 (Heap 2010). Further, aggravation of the problem is that during last three decades no new herbicide site of action or innovative chemistry has been discovered or developed (Duke, 2012) and the reasons might be huge cost of development (more than 250 million dollar from discovery to development), more fund diversion towards development of new molecules for insecticides and fungicides development perspectives, industry consolidation, hostile properties of new candidate as a herbicide coupled with very short market buzz due to accelerated development of herbicide resistance (Duke, 2012; Reddy and Nandula, 2012).

The evolution of herbicide resistance in weeds as well as non-availability of selective weed control options or in efficiency or unability of available herbicide options to control weed population in some of the crops, restricted the chemical weed control option. This problem was resolved during the past 2-3 through the development of herbicide resistant crops against some of the broad spectrum herbicides like glyphosate, which can used to control broad spectrum of weed flora as they have negligent effect on the crop being grown and are non sleective in nature. This technology has given some of the advantages as follows:

1. Broad spectrum weed control i.e. control of grasses and broadleaved weeds in single go, thus providing economical weed control as herbicide mixture and herbicides in rotations as multiple applications are required for diverse weed flora control
2. Herbicide like glyphosate are non residual type and have no restriction of follow crops, which is not possible with use of some persistent herbicides like sulfosulfuron (Chhokar *et al.,* 2006)
3. Less environmental degradation or pollution i.e. less mammalian toxicity and less leaching
4. Time saving by avoiding the multiple application options
5. More crop productivity and profitability

Development of herbicide resistant crops

For developing herbicide resistant crops two methods can be adopted. One is classical breeding approach, in which the tolerant/resistant lines/ closely related species are used to transfer the resistance gene in agronomic superior cultivars, which are susceptible to herbicides. However, this classical breeding method takes a longer period to produce resistant lines. Whereas Aanother faster method is the use of biotechnology techniques carried out under controlled environmental conditions such as vitro cell culture, mutagenesis or genetic transformation etc.

Herbicide resistant crops can be developed 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 biotechnological interventions are widely used in various parts of the world for developing herbicide resistant crops. Such crops are commonly made resistant to post emergence non selective herbicides such as glyphosate and glufosinate. These herbicides allowsed farmers to adopt modern concept of tillage that is use of minimum tillage/ stubble mulch tillage or even the extreme form of minimum tillage which is zerno tillage practices, these practices have dual benefits; which is apart from reducing cost of cultivation they also help in reducing overall weed flora diversity, but the drawback is the dependence on herbicides andweed florashift in the favor of perennial weed

History of Herbicide resistant crops

The principle behind the development or evolution of herbicide resistant weed was applied to crop with the view to reduce crop injury due to herbicide application, broaden spectrum of weed control, increase weed control efficiency and induce herbicide selectivity even against non-selective herbicideby impacting resistance in crop against non selective herbicides.

According to Reddy and Nandula, 2012, First herbicide resistant crop was released in 1984 through a breeding programme which was a triazine resistant canola while first transgenic herbicide resistant crops development started during early 1990's, resulted in the development and release of bromoxynil-resistant cotton and glufosinate-resistant canola in 1995, Since then, number of commercial crops like (alfalfa, canola, cotton, maize, sugarbeet, wheat and soybeanetc) have been developed by genetic manipulation (Reddy and Boykin 2010) and companies have also sought regulatory approval for the comercial production of these crops (AGBIOS 2018).

According to Das, 2015 weeds and insects are the two factors responsible for causing maximum losses to the production of crop, thus combining two traits (herbicide tolerance and insect resistance) into a single crop like cotton or corn, which are greatly affected by both weeds and pests, have further given the added advantage of tackling two major problems easily that is insect and weed in asingle go at the same time also increases the efficiency of management and reduces the time and labour consumption.

During early 2000's this technology was further improved by imparting resistance against two or more non-selective herbicides (glyphosate and glufosinate etc.) to avoid weed emergence during late stages of crop or to avoid development of herbicide resistant weed population and to facilitate rotational use of herbicides which has been advocated to avoid or 'at least' to delay the development of resistance against herbicides by the weed species. Presently, transgenic herbicide-resistant crops and gene transferred for herbicide resistance are given in Table 1.

The area under herbicide resistant crops is increasing over the year and presently about 24 countries are adopting the technology, with USA being the leading adopter. Now focus is on to include several transgenes in a single variety or hybrid, which is commonly known as "stacked genes" or "stacked traits". Some maize and cotton hybrids have been genetically engineered to contain two transgenes, one for insect tolerance and another for herbicide tolerance (*e.g.* Bt/glyphosate, or Bt/glufosinate). Also, some maize hybrids have three traits, two for herbicide tolerance and one for insect tolerance (*e.g.* Liberty, Clearfield, and Bt).

Table 1. Transgenic herbicide resistant crops and gene responsible for resistance.

Crop	Herbicide	Trait gene (s)	Year of release
Cotton	Bromoxynil	*bxn (*bromoxynil specific nitrilase)	1995
	Glyphosate	*EPSP synthase*	1996
		Two modified *EPSP synthase*	2006
		EPSP synthase	2009
	Glufosinate	*Phosphinothricin-N-acetyltransferase*(*pat*)	2004
Maize	Glyphosate	Three modified *EPSP synthase*	1998
		Two modified *EPSP synthase*	2001
	Glufosinate	*Phosphinothricin-N-acetyltransferase*(*pat*)	1997
	Glyphosate +glufosinate	*EPSP synthase* + *Phosphinothricin-Nacetyltransferase*(*pat*)	
Soybean	Glyphosate	*EPSP synthase*	1996 & 2009
	Glufosinate	*Phosphinothricin-N-acetyltransferase*(*pat*)	2009
Rice	Glufosinate	*Phosphinothricin-N-acetyltransferase*(*pat*)	2006
Sugarbeet	Glyphosate****	*EPSP synthase*	1999
Canola	Glyphosate	*EPSP synthase* and goxv 247	1996
	Glufosinate	*Phosphinothricin-N-acetyltransferase*(*pat*)	1995
	Bromoxynil	*bxn(*bromoxynil specific nitrilase)	2000
Alfalfa	Glyphosate*	*EPSP synthase*	2005

Source: (Duke and Cerdeira 2010, Green and Castle 2010, Reddy and Nandula 2012)

Problems with the adoption of herbicide tolerant crops

The HR crops allowed growers to rely heavily on glyphosate, which is less toxic than many other herbicides and kills a broad range of weeds without tillage, however WHO in 2015 reported that the most widely used non-selective herbicide that is Glyphosate not only implicates the aquatic life but may also probably be carcinogenic in nature, this is the reason why it has been banned in many countries around the globe.

At the same time Herbicide resistant crop cultivation and us of the herbicides belonging to same 'Mode of Action' (MOA) year after year leads to the increased selection pressure, which is one of the primary reasons for the weed flora shift in the modern cropping systems adopting genetically modified crops. This resulted in the development of glyphosate resistant weeds, ultimately rendering this broad spectrum herbicide useless in the long run.

As of now glyphosate-resistant weeds have now been found in 31 countries worldwide and most of such cases has been reported from USA. Fig. 1, shows the year wise reported herbicide resistant weeds according to the data base maintained by heap, 2021.

Globally 52 weed species have been found to be resistant to glyphosate resistance due to excessive dependence on this herbicide as shown in Figure 1. thus there is a need to find newactive ingredients with wide spectrum of control so as to effectively control weed population by reducing the selection pressure and in turn preventing the dissemination of herbicide resistance and weed flora shift.

Major concern associated with herbicide resistant crops is their potential to create new weeds through outcrossing with wild relatives resulting in the development of weeds containing the resistant trait

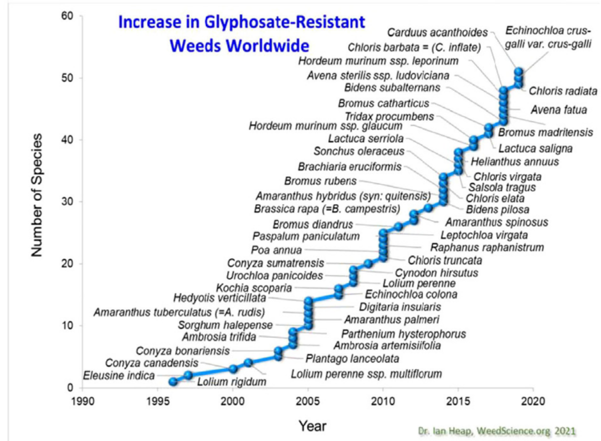

Fig. 1. Worldwide reported cases of glyphosate resistant weeds (Heap, 2021)

often known as the super weed. A possible countermeasure to avoid such scenariocan be the use of sustainable farming practices together with mixtures of herbicides or their rotation which will be discussed in the later part of the review. The adoption of alternative weed management strategies solves the problem of herbicide resistant weeds and is sustainable in the long run (Owen 2001). Carson (1962) suggested that the use of genetic engineered crops as an alternative for chemicals (pesticides, herbicides etc.). The agricultural crops are not only used for providing food, feed and fibers but are also used for the production of some chemicals, bio-products, like- biodegradable plastics, pharmaceuticals (Bloedon and Szapary, 2004). As the human beings are facing the problem of antibiotic resistance and Multi Drug resistance (MDR) for medicines similarly continuous use of herbicides also results in the evolution of weeds that demonstrate single herbicide resistant (Norsworthy *et al.,* 2012) and cross- resistance or multiple herbicide resistance (Yu, and Powles, 2014). The first case of herbicide resistance was re-

Table 2. Worldwide list of glyphosate resistant weeds (Source: Heap 2018)

Glyphosate resistant weeds	Amaranthus hybridus (syn: quitensis); Amaranthus palmeri; Amaranthus spinosus; Amaranthus tuberculatus (=A. rudis); Ambrosia artemisiifolia; Ambrosia trifida; Bidens pilosa; Bidens subalternans; Brachiaria eruciformis; Brassica rapa (=B. campestris); Bromus catharticus; Bromus diandrus; Bromus rubens; Chloris elata; Chloris truncate; Chloris virgata; Conyza bonariensis Conyza Canadensis; Conyza sumatrensis; Cynodon hirsutus; Digitaria insularis; Echinochloa colona; Eleusine indica; Hedyotis verticillata; Helianthus annuus; Hordeum murinum ssp. Glaucum; Kochia scoparia; Lactuca saligna; Lactuca serriola; Leptochloa virgata; Lolium perenne; Lolium perenne ssp. Multiflorum; Lolium rigidum; Parthenium hysterophorus; Paspalum paniculatum; Plantago lanceolata; Poa annua; Raphanus raphanistrum; Salsola tragus; Sonchus oleraceus; Sorghum halepense; Tridax procu (mbens; Urochloa panicoides

ported in 1957 and since than many economically considerable weeds like- *Lolium rigidum* (rigid Ryegrass), *Avena fatua* (wild oats), *Amaranthus retroflexus* (redroot pigweed), *Amaranthus hybridus* (smooth pigweed), *Setaria viridis* (green foxtail) and *Conyza canadensis* (horseweed) etc. become herbicide resistant (Robin Bingham *et al.*, 2017).

"Resistance is a natural phenomenon which occurs spontaneously in weed populations, but is only noticed when a selection pressure is applied to the weeds via herbicide application". Moreover he also explained that the number of herbicide resistant plants are very rare, i.e. "1 in 100,000 to 1 in 1000,000", this resistant character can pass from one generation another generation (Gallegje, 2016).

Types of Herbicide Resistance

According to HRAC (2015) Herbicide resistance is defined as " naturally occurring inheritability of some weed biotype within given weed population to survive a herbicide treatment that should under normal use condition, effectively control that weed population" (Aung *et al.*, 2017). Resistance can be classified into two types on the basis of the mechanism of action of herbicides:

Multiple Resistance: When the weed is resistant to two or more herbicides having different mechanism of action are said to be multiple resistant and the phenomenon is known as multiple resistance. For example, A weed that is resistant to Sulfonylurea herbicide (due to ALS inhibitor) and Glycines herbicides (due to EPSP synthase inhibitors).

Cross Resistance: It is the phenomenon in which weed is resistant to two herbicides having same mechanism of action. For example, A weed resistant to imidazolinone (ALS inhibitor) and Sulfonylurea herbicide (ALS inhibitor) is said to be have cross resistance (Buhler, 2023).

History of Herbicide Resistance

The first ever case of herbicide resistance was reported by Hilton During mid 1950's against 2,4-D (Valverde, 2003). Although the first confirmed case of herbicide resistance is reported to be of *Senecio vulgaris* against Photosystem II inhibitor herbicides (Atrazine and Simazine) as reported by (Vrbnièanin *et al.*, 2017). Glyphosate being a non-selective herbicide is the most widely used herbicide, which was discovered by Monsanto during Mid 1970's (Valverde, 2003), upuntil today around 52 weed species have been reported to be resistant to glyphosate as aforementioned. According to Heap, 2023 data there are 522 unique cases of herbicide resistance globally, consisting of 154 Dicots and 115 monocots which adds to a total of 269 resistant species. Which included *Philaris minor* from India (first everweedin India to develop resistance) which has evolved resistance to multiple herbicides with different mode of action from isoproturon to clodinafop, sulfosulfuron etc. (Heap, 2023). Different herbicides have different mode of actions which depends on the chemical constitution of the herbicide and the plant or weed on which they are being used.

These were only of the cases which are the part of a long list of the herbicide resistance cases that evolved during earlier decades and have spread to other countries as well and are not localized in single region. This has happened because of the indiscriminate use of a particular herbicide on the single crop or in a same cropping pattern, for example resistance of little seed canarygrass to isoproturon as reported by Singh and Malik, 1995). According to Battel, 2018 and Reddy and Reddy, 2012, increased selection pressure allowed plants or more specifically weed to get acclimatized to that herbicide and as a result they got resistant and application of that herbicide doesn't render any advantage over the weed population and as they are able to produce very minute and numerous seeds so they are easily transmitted to different areas via air, water, other vectors and are very tedious to control. Figure 2 shows the number of herbicide resistant cases crop wise.

From the above figure it can be clarly deduced that wheat fields reported highest hebicide resistance cases this is mainly due to pooror faulty spray technology and lackof new active ingredients and

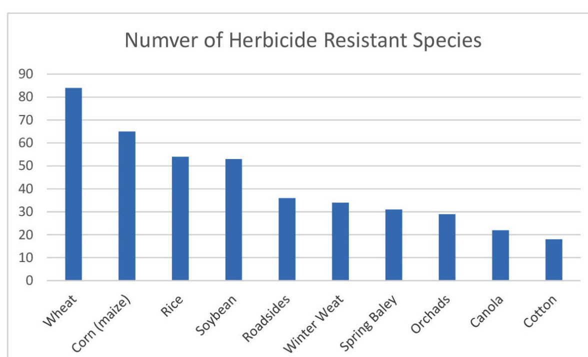

Fig. 2. Shows the number of Herbicidal-Resistant Species reported globally (Heap, 2023)

continous use of herbicides belonging to single MOA and not following rotations or using herbicide mixtures. Thus in order to prevent the development of new resistance and the control of herbicde resistant weed population the mechanism of development of resistance should be understood.

Mechanism of Herbicide Resistance: Resistance can be induced or conferred in a plant species in following ways-

1) **Target site resistance (TSR):** TSR is mainly inculcated due to the changes in the 3D structure of the target protein of the herbicide, and also by the replacement of amino acids at major position on the target protein. However many of the TSR are governed by dominant as well as semi-dominant alleles, while the cases of recessive are reported to be very less. And their frequency and rates of mutation also affect the TSR (Delye *et al*. 2013).
2) **Non target site resistance (NTSR)**: In this mechanism resistance is conferred due to enhanced herbicide metabolism or breakdown to inactive products, it has also conferred to the development of cross resistance (Delye *et al.* 2013). Now it is induced by a detoxification process including 4 phases. Phase I includes oxidation by mixed function oxidases or P450 monooxygenases. Phase II involves the aggregation of hydrophilic molecules to xenobiotics. Phase III involves the transportation of aggregated molecules into extracellular spaces or vacuole. And the phase IV includes the degradation of these transported molecules (Bo *et al.* 2017, Aung *et al*., 2017 and Im *et al*., 2016). This is the cause of the induction of the resistance, because the herbicide is not able to reach the target site and in turn is metabolized after its entry into the plant vascular system by various enzymes.

It is seen in few cases that a plant may be found resistant to more than one herbicide belonging to same group as they have same target site or MOA (Mode of Action) or Binding site Yu and Powles (2014). For example if a weed become resistant to triazine then there is a possibility that the plant might become resistant to uracil as they belong to same MOA family, i.e Photosystem I inhibiting herbicide. But an additional case of cross resistance is also seen in few types of weeds i.e. these weeds show resistance to more than one herbicides having unrelated Mode of action or the binding site, this is due to the modification or change in binding site or MOA which results in conferring resistance to more than one herbicide belonging to different MOA family Valverde (2003).

Evolution of Herbicide Resistance Weeds

Continuous use of single herbicide for a long time renders it ineffective against the target species. S surviving species gradually becomes resistant, suppose if a herbicide is sprayed on a population of freely living species of weed, after few days you will see that very few are left, i.e. only those having the resistance gene will survive. This happens because they could resist the herbicide and in turn got acclimatization (Adaptation) to the changing environment (herbicide action).

Now as you see not all plants survived, this is because the gene for resistance was in low frequency in large part of the population. Generally the gene for resistance is present naturally in wild variety at a very low frequency, and in the absence of the herbicide or in general in the presence of favourable climatic conditions these genes do not express themselves, but when opportunities present itself i.e. when climate changes or adverse conditions arises like, when herbicide is applied then these genes express themselves and their frequency also increases with applications. The frequency of these genes, will also tell how long will it take for the resistance to develop or get perceptible (Valverde, 2003).

Some weeds have evolved from sameancestor as that of crop example Johnsons grass and Sorghum both have same ancestors, thus are genetically related to eachother. So, they can interact with crop plants in field. There are also some crop plants which are domesticated from wild form, shows more compatibility with crops and can easily exchange genes (Jamal R. Qasem, 2013) and are known as weedy relatives. Transfer of genetic information (Gene flow) can be between different individuals, population, generation and across spatial dimensions (Jamal R. Qasem, 2013). The process of hybridization and introgression occurred continuously between crops and wild relatives (Loureiro *et al.*, 2006), Although the hybridization of crops and weeds play an important role in the evolution of many weed species, which are more aggressive (Ellstrand *et al.*, 1999). Gene flow can occur between sexual compatible individual (Vertical Gene Glow), between distant related species (Horizontal Gene Flow), between incompletely incompatible but related species (Diagonal Gene Flow) (Gressel, 2015).

However the transfer of genes from cultivated to wild form belonging to same species can be possible through Vertical and Diagonal Gene Flow. (Vrbnièanin *et al.,* 2017b) http://dx.doi.org/10.5772/67645)

Gene Flow can occur by any of these mechanism–

a) By Pollen : If pollen grain from a resistant plant happens to outcross with susceptible plant, results in the formation of resistant seeds. If the weed plants are self pollinating e.g. most grasses, the spreading of resistance would be less as compare to the plants without crossing species like- pigweeds (Sosnoskie *et al.,* 2012). The size of pollen, the dispersal agent, (water, wind, insect etc.), pollen viability period (affected by temperature and humidity) also affect the distance to which out crossing can occur. The height of the plant is directly related to rate of pollen dispersal by wind. Similarly transfer of herbicide resistance can also occur to longer distance in the plants pollinated by bees (Bagavathiannan *et al.,* 2023). Moreover if the distance between the pollen donor and recipient plant is 0 m, the average gene flow is maximum that keeps on decrease with increase in the distance.

b) By seeds: Herbicide resistant weeds can spread to longer distance through seeds. The agents for dispersal of seeds can be Human-mediated (Agricultural by-products, livestock transport, manure transport etc.), Animal - mediated (Birds, Grazing animals, Ants etc.) or Environmental (Wind, River flooding and Rain splash). The distance of seed dispersal depends on the type of dispersal agent (Bagavathiannan *et al.,* 2023.

c) By Vegetative Propagules : Gene Flow by vegetative propagules (stolon, roots and bulbs) can occur to short distance via natural means or field equipments and to long distance with the human activities. (Mallory and Zapiola, 2008).

Prevention and Management of Herbicide Resistance

If we study the resistance cases carefully, one will get to know that resistance is developed in cases where herbicides with same MOA are used as a main mode of controlfor eliminating the weeds. Few of the previous cases of herbicide resistance have already been discussed during the earlier section of the Review.

So efforts should be made to prevent resistance from developing in the new weeds by using integrated weed control measures and other measures, now factors like concentration, amount, interval of application of herbicide, MOA of the chemical used determines the expression of gene conferring for resistance in weeds. Now the continuous use of the same herbicide in the same cropping pattern increases the frequency of the gene causing resistance so it is advised that in order to prevent resistance, farmers should change cropping pattern and chemical being used.

Following are the methods for the prevention of herbicide resistance in weed population and also to control resistant weed population.

i. **Herbicide rotation**: It includes the substitution of presently used herbicide with a herbicide of another MOA group, Prevent the induction of resistance in weeds. This will not only prevent the development of resistant weed population but will also improve the weed control efficacy. Example: Using sulfosulfuron, clodinafop, atlantis, pinoxaden etc in place of Isoproturon to control Philaris minor, which has otherwise got resistant to isoproturon (Chhokar and Sharma, 2013).

ii. **Mixture application**: Appling a mixture or combination of two or more herbicides can effectively help in controlling diver seweed flora. Example metolachlor + atrazine and pendimethalin + atrazine at 1.0 + 2.0 kg a.i./ha was found to be efficient and economically viable to control weeds in maize (Imoloame, 2017).

iii. **Early maturing crop varieties**: These ae the cultivars orvarieties of a crop which will complete their vegetative growth early and will cover the ground faster than the weeds. And hence will smother their growth and will in turn reduce the need for the use of chemicals to control the weed population, which will inturn reduce the chances of development of herbicide resistance.

iv. **Cropping System:** Changing cropping system also reduces dominant weed population, for example use of an inter-cropping system includes use of an inter-crop which gives very less space for the growth of the weed and hence controlling the weed population.

v. **Use of integrated weed management:** Which is a holistic approach that integrated various methods like cultural, biological, chemical methods etc to control the weed population to a minimum level where it doesn't cause any economic loss in the yield of the farmer. Example atrazine @ 1.00 kg ha-1 + HW, 2 HW and paddy straw mulching, producing grain yield of (203.48 g, 188.34 g and 186.82 g) respectively, as compared to un-weeded plot (68.30 g) Rai *et al*. (2018).

vi. **Crop rotation**: Changing the cropping pattern, i.e the type of crops or crop grown on the same field is known as cropping pattern.

vii. **Flooding**: Some of the weeds like *Cyperus rotundus* can be controlled using flooding hence it is seen that there are less weeds in puddled rice than the direct seeded rice.

Conclusion

Herbicide resistant crops in general provide broad spectrum of weed control, reduced crop injury and phyto-toxicity, less herbicide carry-over on the succeeding crops due to feasibility of usage of non selective broad-spectrum herbicides like glyphosate and glufosinate. This powerful tool if used judiciously can prove a boon for the growers to provide the effective weed management solutions. However, the indiscriminate use of the chemicals always have bad or detrimental effect on human health as well as on the environmental health. And these chemicals should be applied according to the recommended dose as prescribed or suggested by the experts, use of these chemicals should be limited to the minimum required level and other methods of weed control i.e. non-chemical method of weed control should be used in combination with chemical methods (this constitute the integrated weed management practices). Now as the potential yields of the crops have stabilized and cannot be increased any further, and the land resources are also limited so there is a need for better resource management strategies (like weed control, use of modern tillage etc.) to further improve the profitability of the farmers. Hence developing a better weed control method will help in eliminating the competition proposed by the weeds to the crops and will ultimately help in increasing the production of the crops. These practices are the need of this Computer era to quench the needs of the increasing population, now it is estimated that the population of the earth will become twice by the year 2050. Hence improved agronomic measures/practices are the prerequisite to deal with the needs of the increasing population. But with the development of the herbicide resistance it seems to be an herculean task, as large amount of losses are caused by the weeds. Hence better weed management practices will help in increasing the yield of the crop even further and will also reduce the uncertainty in the yield of the crop, as this will also reduce pest and disease incidence, as these weeds are the home for many pests and diseases, during both off-season as well as on-season. It will be better if integrated weed management practices are adopted in these herbicide resistant crops for long term sustainability.

References

AGBIOS, 2018. Agbios GM Database. Available at http://www.agbios.com/ dbase.php. Accessed: January 9, 2018.

Aung Bo Bo, Ok Jae Won, Hun Tak Sin, Jeung Joo Lee and Kee Woong Park, 2017. Mechanisms of herbicide resistance in weeds. *Korean Journal of Agricultural Science.* 44 (1): 1-15.

Bagavathiannan, M.V., Norsworthy, J.K., Scott, R.C. and Barber, T.L. 2023. The Spread of Herbicide-Resistant Weeds: What Should Growers Know?. Agriculture and Natural Resources. University of Arkansas. Assessed on 24-07-2023.

Battel, R. 2018. *How does herbicide resistance occur?* Retrieved October 19, 2020, from Michigan State University: https://www.canr.msu.edu/news/how-does-herbicide-resistance-occur

Bloedon, L.T. and Szapary, P.O. 2004. Flax seed and cardiovascular risk. *Nutr. Rev*. 62: 18-27.

Bo, A. B., Jae, W. O., Tak, S. H., Joo, L. J. and Woong, P. K. 2017. Mechanisms of herbicide resistance in weeds. *Korean Journal of Agricultural Science*.

Buhler, W. 2023. Herbicide Resistance Terms to Know. Pesticide Environment Stewardship, Assessed on 09-08-2023.

Carson, R. 1962. Silent Spring. Houghton Miffin Company. New York, USA.

Chhokar, R.S., Sharma, R.K., Chauhan, D.S. and Mongia, A.D. 2006. Evaluation of herbicides against *Phalaris minor* in wheat in north-western Indian plains. *Weed Res*. 46 : 40-49.

Chhokar, R.S., Sharma, R.K., Garg, R. and Sharma, I. 2013. Metsulfuron resistance in Rumex dentatus. *Wheat Barley Newsletter*. 7(2): 11.

Das, T. 2015. *Weed Science Basics and Applications.* Jain Brothers

Delye, C., Jasieniuk, M. and Corre, V.L. 2013. Deciphering the evolution of herbicide resistance in weeds. *Trends in Genetics.* 29: 649-658.

Duke, S.O. and Cerdeira, A.L. 2010. Transgenic crops for herbicide resistance. In: *Transgenic Crop Plants Utilization and Biosafety*. (Eds. Kole C, Michler CH, Abbot AG and Hall TC), Springer: Heidelberg, Germany. 133–165.

Duke, S.O. 2012. Why have no new herbicide mode of action appeared in recent years? *Pest Management Science.* 68: 505-512.

Ellstrand, N.C., Prentice, H.C. and Hancock, J.F. 1999. Gene flow and introgression from domesticated plants into their wild relatives. *Annual Review of Ecology and Systematics.* 30: 539-563.

FAO, 2009. World agriculture 2030. *Main findings. Food and Agriculture Organization, Rome, Italy*.

Gallegje, 2016. Do GMOs cause "superweeds"?. Escaping the Bench - Science-Based Media by Jenna E Gallegos. Assessed on 09 - 08 - 2023

Green, J.M. and Castle, L.A. 2010. Transitioning from single to multiple herbicide-resistant crops. In: *Glyphosate Resistance in Crops and Weeds: History, Development, and Management* (Ed. Nandula VK). John Wiley & Sons, Inc., Hoboken, New Jersey, USA. 67–92.

Gressel, J. 2015. Dealing with transgene flow of crop protection traits from crops to their relatives. *Pest Management Science.* 71: 658-667.

Heap, I. 2018. The International Survey of Herbicide Resistant Weeds.

Heap, I. 2023. The International Survey of Herbicide Resistant Weeds

Im, S.B., Lee, S.H., Kim, Y.Y., Kim, J.S. and Kim, D.S. 2016. Construction of a full-length cDNA library from Cardamine manshurica Nakai and characterization of EST dataset. *Korean Journal of Agricultural Science.* 43 : 33-39.

Imoloame, E. 2017. Evaluation of herbicide mixtures and manual weed control method in maize (*Zea mays* L.) production in the Southern Guinea agro-ecology of Nigeria. *Cogent Food & Agriculture.* 1-17.

Jamal, R. Q. 2013. *Herbicide Resistant Weeds: The Technology and Weed Management, Herbicides*, Andrew J. Price and Jessica A. Kelton, IntechOpen, DOI: 10.5772/56036.

Loureiro, I., Escorial, M. C. and Chueca, M. C. 2016. Pollen-Mediated Movement of Herbicide Resistance Genes in *Lolium rigidum*. *PLoS ONE.* 11(6): e0157892. https://doi.org/10.1371/journal.pone.0157892

Loureiro, I., Escorial, M.C., García-Baudín, J.M., Chueca M.C. 2006. Evidence of natural hybridization between *Aegilops geniculata* and wheat under field conditions in Central Spain. *Environmental Biosafety Research.* **5:** 105-109.

Mallory, S. C. and Zapiola, M. 2008. Gene flow from glyphosate-resistant crops. *Pest Management Science.* 64: 428- 440.

Norsworthy, J.K., Ward, S.M., Shaw, D.R., Llewellyn, R.S. and Nichols, R.L. 2012. Reducing the risks of herbicide resistance: Best management practices and recommendations. *Weed Sci.* 60: 31-62.

Oerke, E.C. 2006. Crop losses to pests. *Journal of Agricultural Science.* 144: 31-43.

Padgette, S., Kolacz, K.H., Delannay, X. and Re, D.B. 1995. Development, identification and characterization of a glyphosate-tolerant soybean line. *Crop Science.* 35(5): 1451–1461.

Rai, A., Mahata, D., Lepcha, E., Nandi, K. and Mukherjee, P. K. 2019. A Review on Management of Weeds in Maize (*Zea mays* L.). *International Journal of Current Microbiology and Applied Sciences.* 7: 2906-2922

Reddy, K.N. and Nandula, V.K. 2012. Herbicide resistant crops: History, development and current technologies. *Indian Journal of Agronomy.* 57(1): 1–7.

Robin Bingham, Pamela King and Andrew G. Keck 2017. An Investigation of Tradeoffs in Herbicide Resistant Brassica rapa: Effects on Pollen and Ovule Production, Biomass and Development. *American Journal of Environmental Sciences.* 13 (1): 22-29

Rowland, G.G. 1991. An EMS-induced low-linolenic acid mutant in McGregor flax (*Linum usitatissimum* L.). *Can J. Plant Sci.* 71: 393-396

Singh, S. and Malik, R. 1995. Littleseed Canarygrass (Phalaris minor) Resistance to Isoproturon in India. *Weed Technology.* 9: 419-425.

Sosnoskie, L.M., Webster, T.M., Kichler, J. M., MacRae A.W., Grey, T.L. and Culpepper, A.S. 2012. Pollen-mediated dispersal of glyphosate-resistance in Palmer amaranth under field conditions. *Weed Sci.* 60: 366-373

Valverde, B.E. 2003. Herbicide-resistance management in developing countries: In Labrada R. (ed.) *Weed management for developing Countries Appendium 1*. Food and Agricultural Organisation of United Nations, Rome, Assesed on 18-July-2023.

Vrbnièanin, S., Bo•iæ, D. and Pavloviæ, D. 2017a. Gene Flow from Herbicide-Resistant Crops to Wild Relatives. InTech. doi: 10.5772/67645

Vrbnièanin, S., Pavloviæ, D. and Bo•iæ, D. 2017b. *Weed Resistance to Herbicides.* IntechOpen

Won, O.J., Park, K.W., Park, S.H., Eom, M.Y. and Kang, K.S. 2015. Weed control as affected by herbicide in winter cereal crops. *Korean Journal of Agricultural Science*. 42: 93-98.

Yu, Q. and Powles, S. 2014. Metabolism-Based Herbicide Resistance and Cross-Resistance in Crop Weeds: A Threat to Herbicide Sustainability and Global Crop Production. *Plant Physiology.* 166: 1106-1118.