

REVIEW

Current status and agronomic aspects of herbicide resistance in Korea

Aung Bo Bo^{1,†}, In Ho Jeong^{1,†}, Ok Jae Won¹, WeiQiang Jia¹, Hye Jin Yun¹, Botir Khaitov¹, Thi Hien Le¹, Mirjalol Umurzokov¹, Farrukh Ruziev¹, Min Ju Lim¹, Kwang Min Cho¹, Kee Woong Park^{1,*}, Jeung Joo Lee^{2,*}

¹Department of Crop Science, Chungnam National University, Daejeon 34134, Korea

²Department of Plant Medicine, IALS, Gyeongsang National University, Jinju 52828, Korea

*Corresponding authors: parkkw@cnu.ac.kr, jeunglee@gnu.ac.kr

[†]These authors contributed equally to this work

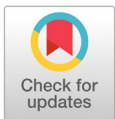
Abstract

Weeds are a serious problem in crop production. Use of synthetic herbicides is rapidly increasing in weed management worldwide including Korea. Herbicide application reduces the time spent on weed control. However, the evolution of resistance to herbicides in weeds has become widespread as a natural response to selection pressure imposed by agricultural management activities. If an herbicide with the same mechanisms of action is used repeatedly and intensively, it can rapidly select for a weed biotype that shifts toward difficult-to-control becoming a more tolerant weed and lead to the evolution of herbicide-resistant weeds. Moreover, agricultural and biological factors have an important role in the development of herbicide-resistant weed populations. Mitigating the evolution of herbicide resistance in weeds relies on reducing selection through the diversification of weed control techniques. The resistance management of weeds in the future will strongly depend on intensive cropping systems. The current situation of intensive cropping systems with their heavy reliance on the efficacy of chemical weed control will not lead to significant containment of this problem. Therefore, management strategies need to overcome the further spread of herbicide resistance in weeds in Korean crop production. This review presents the current information on herbicide resistance in Korea and factors controlling the development of herbicide resistant weeds.

Keywords: herbicide resistant factors, management, resistance

Introduction

Every year a major threat to agricultural production comes from the infestations with wild plant species (weeds). Since the dawn of agriculture, human beings have battled against weeds to improve crop survival and productivity. Weeds have an adverse impact on agricultural production and represent the most significant pest threat to crop yields. Weeds are unanimously considered one of the costliest and limiting factors in crop production. Crop yield reductions caused by weeds are mainly derived from direct competition with



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crop plants for available water, nutrients, light, and space, which causes great losses (Roskopf et al., 1999).

The physiological and biochemical processes of weeds can be disrupted by herbicides, especially through a specific interaction with a single target molecule in a plant. At the appropriate concentration, herbicide molecules are transmitted into the target cells of a plant, which inhibit vascular processes so that the plant can no longer continue to survive (Devine and Preston, 2000). Recently, modern herbicides have largely replaced human, animal, and mechanical weed controls. They have made a great contribution to the high productivity of worldwide agriculture (Powles and Yu, 2010).

Herbicide resistance in weeds is not a new phenomenon but is somewhat less known and experienced than insecticide or fungicide resistance. According to the definition given by the Weed Science Society of America (WSSA), herbicide resistance refers to a species or a plant surviving and reproducing by its intrinsic natural ability after herbicide treatment without any selection or genetic dominant. Selection of resistant biotypes may result in control failures. Therefore, selection pressure is an essential requirement for herbicide resistance.

The first report of herbicide resistance was around the 1960s with the finding of triazine resistant common groundsel and 2,4-D resistant bindweed. Since that time, a total of 216 weed biotypes around the world have evolved resistance to herbicides (Ryan, 1970; Vargas, 2001). In an agricultural situation, herbicide resistance is the evolved ability for an herbicide susceptible weed population to withstand and complete its life cycle after an herbicide has been applied at its normal rate.

History of herbicide resistance

Herbicides are applied to the soil to manage weeds. It is necessary to control weeds during the crop growing season, but it is not desirable for herbicides to persist and affect the following crop growth. Moreover, herbicides can provide impressive levels of weed control in many crop and non-crop situations. However, not all weedy species are equally controlled due to the varying levels of natural tolerance or evolution of herbicide-resistant weed biotypes which is a result of the repeated use of the same herbicides or herbicides with the same modes of action imposing a great degree of selection pressure on weed populations (Hanson et al., 2013).

Beginning in the 1980s, the number of reported resistant biotypes began rapidly increasing in the United State and worldwide. Since then, resistance to one or more of the 25 herbicide families has been observed in more than 65 weed species in the U.S (Shaner, 2014).

Some modes of action have been a greater problem in herbicide resistance than others (Bo et al., 2017). For instance, the greatest number of resistant biotypes worldwide has been observed with acetolactate synthase (ALS)-inhibitors (imidazolinones, pyrimidinylthiobenzoates, sulfonyleureas, and triazolopyrimidines). Over the past decade, the most important area of herbicide chemistry has been the discovery of herbicides that inhibit ALS. ALS catalyzes the formation of the essential amino acids valine, leucine, and isoleucine, all of which are necessary for protein formation and subsequent plant development (Heap, 1997). Nowadays, the evolved resistance of weeds to the mode of action of this herbicide has resulted in the selection for resistant biotypes in 160 weed species (98 dicots and 62 monocots) (Heap, 2018).

Over the last three decades, increasing resistant biotypes to other modes of action of herbicides have been

reported. In 1978, herbicides inhibiting the activity of Acetyl-CoA carboxylase (ACCase), a key enzyme that regulates the metabolism of fatty acids in monocotyledonous plants, made their first appearance on the market. Only four years later, in 1982, resistance to ACCase inhibitors was reported in Australia. Today, 48 weed species (monocots only) worldwide have evolved resistance to this group of herbicides (Heap, 2017).

The second most common herbicide with resistant biotypes is the photosystem II inhibitors (primarily triazines). Cases reporting resistance to PSII-inhibitors have been documented in several weed species including *Capsella bursa-pastoris* L., *Chenopodium album* L., *Setaria viridis* L., *Echinochloa crus-galli* L., and *Alopecurus myosuroides* Huds. (Grignac, 1978). Resistance to PSII-inhibitors occurred because of the repetitive use and high residual activity of these compounds which consequently resulted in selection pressure for resistant biotypes. Up till now, 74 weed species (51 dicots and 23 monocots) have been identified to have evolved resistance to PSII-inhibitors in the world (Heap, 2018).

Glyphosate is used as a board spectrum herbicide for crops after both the crop and weeds have emerged. There is no chemical that has had a greater positive impact on weed management than the herbicide glyphosate. In fact, glyphosate is widely used worldwide. Glyphosate inhibition of the 5-enolpyruvyl-shikimate synthase (EPSPS) activity disrupts the shikimate pathway and inhibits aromatic amino acid production which is vital for protein synthesis in plant growth (Dill, 2005). Therefore, glyphosate was less toxic than some of the other pesticides available and enabled more farmers to adopt a no-tillage approach, both of which were better for the environment. Glyphosate was introduced to the world by the Monsanto Company in 1974. Currently, 43 weed species (23 dicots and 20 monocots) worldwide have evolved resistance to this group of herbicides (Heap, 2018).

Scientists have said that ten specific weed species were confirmed to be especially hard to kill. Most farmers are raising awareness of the fact that they are finding the most important herbicide resistant species of weeds difficult to control as they become resistant to the most popular herbicides (Table 1).

Recently, the reliance on modern herbicides has been increasing which has led to a reduction in the need of traditional techniques for weed control. However, the application of herbicides to large weed communities induces a high rate of genetic diversity which causes a strong selection pressure promoting resistance evolution (Fig. 1 and 2).

Table 1. The most important herbicide resistant weed species worldwide (Source: Heap, 2016).

No.	Common name	Botanical name
1	Rigid ryegrass	<i>Lolium rigidum</i>
2	Wild oat	<i>Avena fatua</i>
3	Redroot pigweed	<i>Amaranthus retroflexus</i>
4	Common lambsquarters	<i>Chenopodium album</i>
5	Green foxtail	<i>Setaria viridis</i>
6	Barnyardgrass	<i>Echinochloa crus-galli</i>
7	Goosegrass	<i>Eleusine indica</i>
8	Kochia	<i>Kochia scoparia</i>
9	Horseweed	<i>Conyza canadensis</i>
10	Smooth pigweed	<i>Amaranthus hybridus</i>

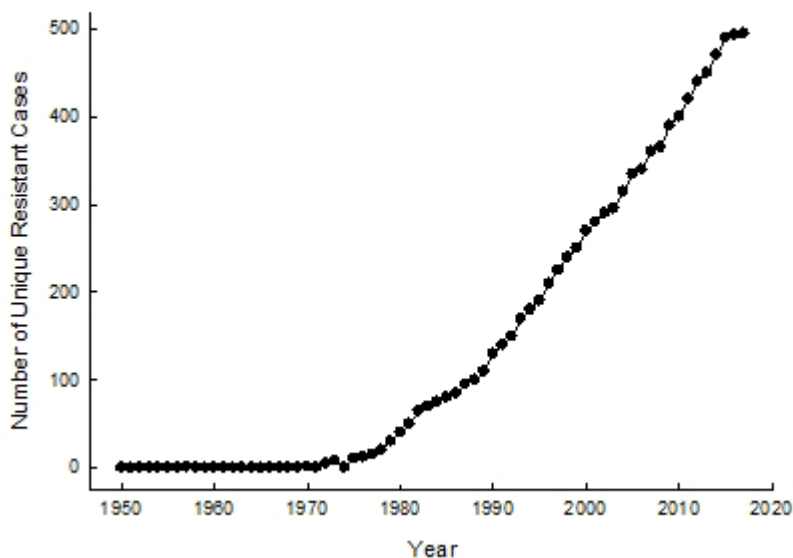


Fig. 1. Evolution of herbicide resistant cases in weed biotypes (Source: Heap, 2018).

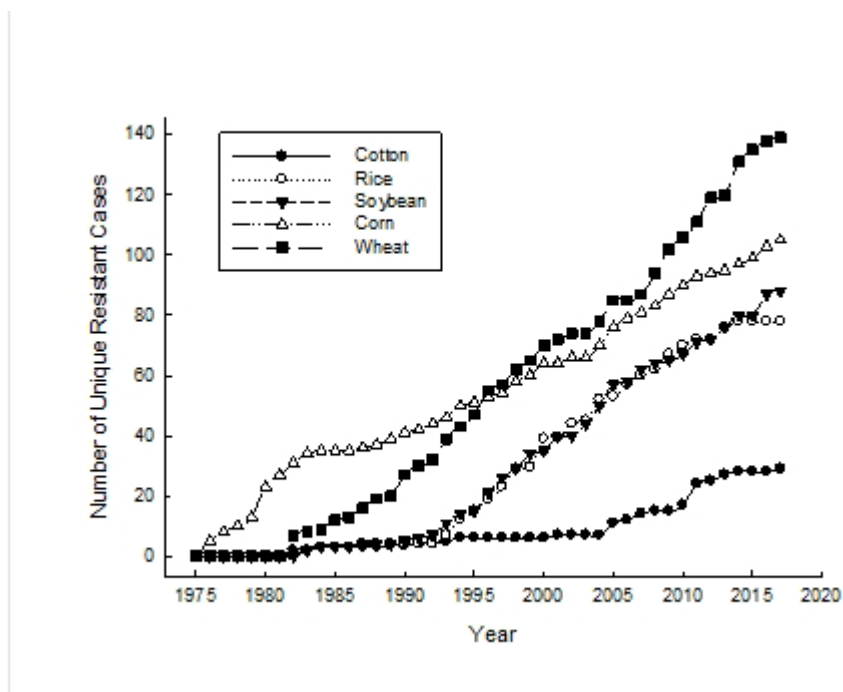


Fig. 2. Increasing herbicide resistant weed cases in selected crops (Source: Heap, 2018).

Today, globally, there are 255 herbicide-resistant weeds species (148 dicots and 107 monocots). Weeds have evolved resistance to 23 of the 26 known herbicide sites of action and to 163 different herbicides. Herbicide resistant weeds have been reported in 92 crops in 70 countries globally (Heap, 2018).

Herbicide resistance in Korea

Agriculture is also an important sector of the economy of South Korea. Natural resources for agriculture in South Korea are not abundant. The arable land occupies only 22 percent of the area of the country, and two-third of the country is occupied by mountains and hills. A total of 28 families and 90 species of weeds occurred in the rice fields of Korea (Lee et al., 2017a). The weeds occur in the descending order of *Echinochloa* spp, *Monochoria vaginalis* and *Schoenoplectus juncooides* although there are differences according to climate and area (Lee et al., 2017b).

The total area under rice cultivation in Korea has been found to be 746,614 ha, out of which 20.9% of that area is infested by herbicide-resistant weeds which is 167,081 ha (Park et al., 2011b). In a 2011 survey, the areas infested with herbicide-resistant weeds in Chungnam, Jeonbuk and Jeonnam provinces were 72,736 ha (47.6%), 35,194 ha (16.4%) and 21,410 ha (36.9%), respectively (Lee et al., 2012). In a 2017 survey, in the Chungnam province, the infested area with a herbicide-resistant weed was 64,782 ha (47.0%). However, these areas in the Jeonbuk and Jeonnam provinces increased to 81,494 ha (68.9%) and 91,543 ha (51.5%), respectively, and the incidence of herbicide-resistant weeds has increased in other provinces (Jeong et al., 2018, Lee et al., 2018a, Lee et al., 2018b, Won et al., 2018). Recently, the occurrence of resistant weeds has increased in new areas (Won et al., 2018). This shows that the increase rate of herbicide resistant weed areas was considerably, and if this pace continues, we expect many more infested areas in the coming future.

In Korea, rice cultivation areas have decreased by 16 percent from 1995 to 2010; however, herbicide use has increased. The percentage of herbicide use in rice cultivation areas increased by 116% in 1995 followed by an increase of 205% in 2010 (Park et al., 2011a). The rapid increase of herbicide use in rice cultivation areas is due to the development of resistant weeds to sulfonylurea (SU) herbicides which have been introduced since the late 1980s; furthermore, the continuous use of ACCase and ALS inhibitors has led to the selection of herbicide-resistant *Echinochloa* spp. in direct-seeded rice cultivation of Korea.

In the history of paddy herbicide use in Korea since 1989, SU herbicides have been widely used as a "One-shot" weed control. The applied areas of SU-containing herbicides have been increasing rapidly by 69 and 96%, respectively. This is because these herbicides have a broad control spectrum against sedges and broadleaved weeds (Park et al., 2014). Additionally, they are major components of many commercial herbicides used for rice production. The extensive and persistent use of these herbicides with a relatively long residual activity and high selection for the last ten years in Korea has resulted in the evolution of resistant weeds against SU mixtures (Lee et al., 2012) (Table 2).

Furthermore, the resistance of barnyard grass to ACCase and ALS inhibitors was confirmed in 2008. The repeated use of ACCase and ALS inhibitors for barnyard grass control in rice led to the evolution of herbicide-resistant barnyard grass. Moreover, SU herbicides like pyrazosulfuron-ethyl and imazosulfuron, which are effective against barnyardgrass, can be associated with the resistance of *Echinochloa oryzoides* (Park et al., 2015). As a result, ALS and ACCase resistant *E. oryzoides* have occurred nationwide. (Lee et al., 2017c)

Conyza canadensis is the most frequently developed resistance to glyphosate in many agricultural crops in Korea. In 2017, glyphosate resistance of horseweed to EPSPS synthase inhibitors was discovered in the

tangerine orchards of the Jeju province. Six glyphosate resistant horseweeds out of 18 biotypes were found at the recommended rate of 3.28 kg ha⁻¹ (Bo et al., 2016).

At the beginning of 1998, the number of reported herbicide-resistant weed species began to increase rapidly in Korea. Today, herbicide-resistant weeds have been reported in 15 weed species (Table 3). Despite the rapid expansion of herbicide resistance, there is no organization like WAHRI (Western Australian Herbicide Resistance Initiative) or HRAC (Herbicide Resistance Action Committee in the U.S.A) so far in Korea, and furthermore,

Table 2. Occurrence area of sulfonylurea herbicide resistant weeds in paddy fields. Adapted from Lee et al. (2012).

Weed species	Occurrence area (ha)			
	2004	2006	2008	2012
<i>Monochoria vaginalis</i>	34,327	42,012	62,560	57,018
<i>Scirpus juncooides</i>	494	906	12,060	33,803
<i>Echinochloa oryzicola</i>	-	-	17	13,581
<i>Cyperus difformis</i>	12,800	13,171	14,230	13,085
<i>Lindernia dubia</i>	32	33	33	11,301
<i>Ludwigia prostrata</i>	-	-	-	10,719
<i>Rotala indica</i> var. <i>uliginosa</i>	5	5	5	2,047
<i>Sagittaria pygmaea</i>	-	17	17	701
<i>Eleocharis acicularis</i> for. <i>longiseta</i>	-	5	27	589
<i>Sagittaria trifolia</i>	-	-	-	191
<i>Scirpus maritimus</i>	4,000	6,000	8,000	111
<i>Monochoria korsakowii</i>	10,000	10,000	10,000	-
<i>Blyxa aubertii</i>	-	2	2	-
<i>Lindernia procumbens</i> (assumed)	-	-	-	33,135
<i>Diplachne fusca</i> (assumed)	-	-	-	353
<i>Dopatrium junceum</i> (assumed)	-	-	-	236
Total	61,658	72,241	106,951	176,870

Table 3. Reported herbicide resistant weeds of Korea (Source: Heap, 2017).

No.	Weed species	English name	Year	Herbicide
1	<i>Monochoria korsakowii</i>	Monochoria	1998	ALS inhibitors
2	<i>Monochoria vaginalis</i>	Arrowleafed monochoria	1999	ALS inhibitors
3	<i>Lindernia dubia</i>	Low false pimpernel	2000	ALS inhibitors
4	<i>Schoenoplectus juncooides</i>	Rock bulrush	2001	ALS inhibitors
5	<i>Cyperus difformis</i>	Smallflower umbrella sedge	2002	ALS inhibitors
6	<i>Sagittaria pygmaea</i>	Dwarf arrowhead	2004	ALS inhibitors
7	<i>Schoenoplectus fluviatilis</i>	River bulrush	2004	ALS inhibitors
8	<i>Echinochloa phyllopogon</i>	Late watergrass	2006	ACCase and ALS inhibitors
9	<i>Eleocharis acicularis</i>	Needle spikerush	2006	ALS inhibitors
10	<i>Blyxa aubertii</i>	Roundfruit blyxa	2006	ALS inhibitors
11	<i>Echinochloa crus-galli</i> var. <i>crus-galli</i>	Barnyardgrass	2008	ACCase and ALS inhibitors
12	<i>Sagittaria trifolia</i>	Threeleaf arrowhead	2011	ALS inhibitors
13	<i>Ludwigia prostrata</i>	False loosestrife	2011	ALS inhibitors
14	<i>Leptochloa chinensis</i>	Chinese sprangletop	2012	ACCase inhibitors
15	<i>Conyza canadensis</i>	Horseweed	2017	EPSPS synthase inhibitors

ALS, acetolactate synthase; ACC, Acetyl-CoA carboxylase; EPSPS, 5-enolpyruvyl-shikimate synthase.

research in this area has been decreasing rapidly.

Therefore, theoretical education and training of farmers are very important to control resistant weeds. The selection and application of herbicides with alternative modes of action would be much more effective to manage resistant weeds.

Factors inducing herbicide resistance in selection-biotype

Many weeds contain the modified genetic variation that enables them to survive under various environmental conditions. Most herbicides affect a specific site of action, the weed emergence period, or the seed bank duration; thus, there is potential for the utilization of alternative control measures (Greesel, 1978). Generally, weed species that lead to less resistance development have a slower generation time, an incomplete selection pressure for most herbicides, an ability to adapt to a changing environment, a lower fitness for their resistant biotypes, and an extended seed dormancy in the soil. These factors increase the number of susceptible biotypes in the population.

The following factors can stimulate the development of herbicide resistance in selection-biotypes.

Selection pressure by herbicides

In a species, the evolution of a resistant population appears in response to selection pressure imposed by herbicides sharing the same site of action. It is the selection pressure imposed by the herbicide that determines the enrichment of a weed population with resistant individuals.

Persistence of herbicides in the soil

Curran (2001) stated that soil persistence or soil residual life is the length of time of an active herbicide remains in the soil. Herbicides with a long residual effect exert selection pressure on weed populations longer than the herbicides that easily dissipate in the soil. Herbicides change their potential to persist in the soil. If the herbicide is not very persistent, the seed bank present in the soil may decrease the probability of proliferation of the resistant biotypes by keeping an elevated population of susceptible individuals that germinate and reproduce once the herbicide has lost its biological effect. Some herbicide families that are persistent in the soil include triazines, sulfonylureas, isoxazolidiones, imidazolinones, and pyridine which are plant growth regulators.

Soil factors

Soil factors that induce herbicide resistance in selection-biotypes include soil composition (texture), soil chemistry (pH), and microbial activity. *Soil composition* affects the herbicidal activity and persistence through soil-herbicide binding (adsorption), leaching, and vapour loss (volatilization). Naturally, high clay soils and organic matter have a greater potential to bind the herbicide to soil particles, with the result of a decrease in the leaching and loss of volatilization (De Prado et al., 1997).

Soil pH can influence the persistence of some herbicides, especially the triazines and sulfonylureas. In higher-pH soils (above 7.0), lesser amounts of these herbicides are bound to soil particles making them more available

for plant uptake. Thus, in higher-pH soils, triazine and sulfonylurea herbicides persist longer, and a greater amount is available for plant uptake. Low pH also can affect the persistence of both the triazine and sulfonylurea herbicides. In acid soils, herbicides like atrazine become bound to soil particles, making them unavailable for weed control, but at the same time, they are chemically degraded more quickly.

Degradation processes by soil microorganisms are the most important pathways responsible for the breakdown of herbicides. The types of microorganisms (fungi, bacteria, protozoans, etc.) and their relative numbers determine how quickly decomposition occurs.

Climatic factors

Climatic variables influencing herbicide resistance in selection-biotypes include *moisture*, *temperature*, and *sunlight*. Herbicide degradation rates generally increase when the temperature and soil moisture increase. Sunlight is also an important factor in herbicide degradation. Photodecomposition or degradation catalyzed by sunlight (photolysis) occurs especially in a liquid solution (i.e., water) or on plant leaf surfaces. Sensitivity to sunlight and losses through volatilization are the primary reasons for incorporating dinitroanilines at the application time of herbicides.

Biological factors

Although the herbicide resistance problem has become worse in recent years, the new herbicide resistance genes are found at a very low frequency within the population. Therefore, it is logical to conclude that if the resistant individuals were more fit in the absence of selective pressure (herbicide), they would be the dominant type within the population, and the herbicide would never have effectively controlled the weed species in the first place. Therefore, fitness could be described as reproductive success or the gene proportion left from the genetic pool of a population. Its two main components are survival and reproduction (Holt, 1992).

Herbicide properties

The chemical properties of herbicides include water solubility, vapour pressure, and the susceptibility of the molecule to chemical or microbial alteration or degradation.

When an herbicide is dissolved in water, leaching is induced and moves down through the soil profile. A leaching herbicide may readily be carried away from the crop and weed germination zones.

The vapour pressure of an herbicide determines its volatility. Volatilization is the process, whereby an herbicide changes to a gas from a liquid or solid. Volatile herbicides with higher vapour pressures dissipate more rapidly than herbicides with lower vapour pressures.

The chemical structure of an herbicide dictates how the herbicide will degrade in the soil. Some herbicides are rapidly decomposed by microorganisms if the right kind and number are present and the soil conditions are favourable for their growth. However, some herbicides are prone to chemical reactions. For example, members of the sulfonylurea herbicides are degraded through chemical hydrolysis and microbial processes.

Herbicide resistance management

Early detection of resistance makes management easier. Unfortunately, the features of resistant and susceptible plants are similar, and resistance is often not detected until the resistant biotype has spread to 30% of the field. Therefore, using proactive approaches toward diverse weed control tactics is the most effective way to manage herbicide-resistant biotypes (Powles and Yu, 2010).

Cultivation practices associated with high selection pressure like the following must be avoided: use of very persistent herbicides, use of elevated concentrations, regular applications of only one herbicide and finally, mono-cultures that depend solely on chemical methods for the elimination of weeds.

Selection and use of herbicides

Herbicides with different mechanisms of action should be rotated. More than two consecutive uses of herbicides which have the same site of action should be avoided in the same place (Powles and Shaner, 2001). Two consecutive uses of an herbicide mean a single herbicide application for two years or two split applications during one year. The herbicides and alternative methods used must be active against the target weed.

Minimize the use of long-soil residual life herbicides. Susceptible plants emerging later in the season following the use of a long-residual herbicide are exposed to the herbicide, thereby increasing selection pressure. To manage glyphosate-resistant weeds in cropping systems, it is recommended to use a combination of short-term residual herbicides with post-emergence herbicides.

Apply herbicides evenly and accurately, and use of the labeled application rates is recommended. The conditions of metabolic resistance can increase when the application rates are lower than the labeled rates. Using rates that are higher than the labeled rates is illegal and can also enhance selection pressure for resistance. Herbicide preparation in tank-mixed, prepackaged or sequential mixtures can cause multiple sites of action which are recommended. Both herbicides must have a substantial activity against potentially resistant weeds to be effective.

Management of fields or sites

Farmers must capitalize correctly on cultural practices to reduce reliance on herbicides. When fewer non-chemical control methods (hand-weeding) are used, resistance will develop more rapidly. Sometimes, hand-weeding with a weed removal rate of 90% or greater can reduce the chances that resistant plants will produce seed. The use of correct row spacing, proper fertility, optimum planting dates, and management of pests will maximize the ability of the crop to compete with weeds (Thrall et al., 2011).

Mulching should be done with both synthetic and organic materials. After harvesting the crops, soil solarization is best for weed killing. Mechanical weed control methods should be combined with herbicide treatments.

Crops should be managed by having a different season of growth with different life cycles. At the same time, herbicides with the same site of action should be avoided on different crops against the same weed unless alternative weed control methods are also included in the management system.

Fields should be scouted regularly, and weeds should be identified using good record-keeping for herbicide

use. This will help in the planning of weed control in the following years. These measures quickly bring changes in weed control to protect against the spread of herbicide-resistant weeds. It is recommended to clean tillage and harvest equipment before moving to the fields infested with resistant weeds. The use of a power washer or compressed air can help to remove seeds. Farmers should be aware that resistant weeds can spread from highways, railroads, and other areas near their farm or treated sites.

It is important to use herbicides when necessary. Herbicide applications should be used based on economic threshold levels in the regions.

Conclusion

Herbicide resistance in weeds is related to many factors. However, herbicides are chemical resources of great utility aiding in crop production, and they should be used wisely to minimize the spread of resistance. To delay, avoid, or combat widespread herbicide resistance, it is recommended to use herbicides with restraint within IWM (Integrated Weed Management) strategies which minimize the selection pressures for herbicide resistance. Biological and evolutionary realities dictate that this is the only sensible way forward.

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Authors Information

Kee Woong Park, <https://orcid.org/0000-0003-0053-9543>

Aung Bo Bo, <https://orcid.org/0000-0001-7579-3429>

Ok Jae Won, Chungnam National Univeristy, Doctor of Philosophy

WeiQiang Jia, Chungnam National Univeristy, Ph.D. student

Hye Jin Yun, Chungnam National Univeristy, Researcher

Botir Khaitov, Chungnam National Univeristy, Senior researcher

Thi Hien Le, Chungnam National Univeristy, Ph.D. student

Mirjalol Umurzokov, Chungnam National Univeristy, Master student

Farrukh Ruziev, Chungnam National Univeristy, Master student

Min Ju Lim, Chungnam National Univeristy, Researcher

Kwang Min Cho, <https://orcid.org/0000-0003-0537-2164>

In Ho Jeong, Chungnam National Univeristy, Ph.D. student

Jeung Joo Lee, Gyeongsang National University, Professor

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