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Review Article

Evolution of Herbicide Resistant Weeds in Agro-ecological Systems

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Abstract: Weed management through herbicides continues to be the most efficient and cost-effective component of integrated weed management (IWM) in crop production systems. However, the current production systems are characterised by intensive, inappropriate use of herbicides along with misapplication which creates selection pressure and leads to the rapid evolution of herbicide resistance in weeds. Currently, there are 511 unique cases of herbicide-resistant weed species globally, involving 266 species and these comprise 153 and 113 dicots and monocots respectively. To date, herbicide resistance has been reported from 96 crops in more than 71 countries. Furthermore, weeds have evolved resistance to 21 of the 31 known sites of herbicide action in different crops. Understanding the mechanisms of herbicide resistance is therefore essential which when coupled with the ecological and management factors that affect herbicide resistance would lead to the development of appropriate, profitable, and sustainable weed management strategies. The review is aimed at the development of herbicide resistance, mechanisms of herbicide resistance, factors that influence the rate of resistance development and management of herbicide resistance by growers.

***Keywords*:** resistance, mode of action, target-site resistance, non-target-site resistance, cross-resistance, multiple-resistance

1. Introduction

Herbicide weed management is one of the most efficient and widely used technologies for improved crop yields in large-scale crop production [1]. Herbicides are chemical products that kill or retard the growth of unwanted plants. They work by targeting specific plant processes and this is called the mode of action (MOA) [2]. Herbicide MOA is the mechanism by which the chemical inhibits the key metabolic or physiological processes, causing cessation of growth and death of susceptible plants [3]. Some of the key metabolic processes influenced by herbicides include disruption of pigment, cell membrane, growth hormones and/or inhibition of photosynthesis, lipid biosynthesis and amino acid or protein synthesis [2].

The continuous and intensive herbicide use and misuse have resulted in some weed species that were once susceptible and easily managed by certain herbicides developing resistance [3]. Resistance is defined as the inherited ability of a plant/weed to survive and reproduce following exposure to a herbicide dose that used to be lethal to the same weed species. For example, *Senecio vulgaris* (L.) was the first weed that showed resistance to triazine herbicides but to date, 511 unique cases of herbicide-resistant weed species have been reported globally [4, 5]. These cases have

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increased by 14% (233 to 266) in the last 20 years. The current number of 153 herbicide-resistant weeds consists of 153 dicots and 113 monocots [6, 7]. Figure 1 gives an insight into the number of herbicide-resistant species for the top 10 weed families.

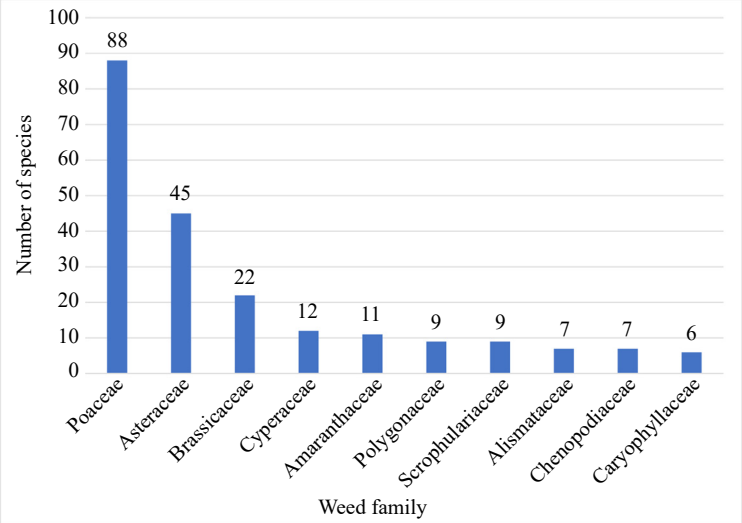

Figure 1. Number of herbicide-resistant species for the top 10 weed families (adapted from [8])

Herbicide resistance in weeds is due to an evolutionary process influenced by gene and environment (G × E) interactions [9]. The resistant weed biotypes survive herbicide application through target-site or non-target-site mechanisms. This review focuses on forms and mechanisms of herbicide resistance and management strategies farmers can use to manage weed resistance in cropping systems. Herbicide selectivity is one of the factors influencing effective herbicide use among farmers. Selectivity is defined as the differential effect of the herbicide dose on plant species while other plant species succumb or are killed with the same herbicide concentration but some weed species may survive the same dose [10]. In other words, when a herbicide is applied, the weeds respond differently where susceptible weeds will be killed while the resistance will survive [11]. The surviving weeds are tolerant to the herbicide and hence able to grow and reproduce after herbicide application. In this case, there is no selection or genetic manipulation but the plant is naturally not affected by the herbicide for example, grass plants are tolerant to 2,4-dichlorophenoxyacetic acid (2,4-D), Dicamba or 2-methyl-4-chlorophenoxyacetic acid (MCPA) [11]. Resistance may occur naturally or may be induced by selection pressure.

Over time especially in mono-cropping systems, intensive repeated herbicide application, and sometimes misuse (e.g. very high dosages) reduce the herbicide selectivity due to the development of herbicide resistance [11]. Weeds that previously were susceptible become resistant and dramatically affect the growth performance and yield of crops. In view of this challenge, we focused on reviewing research and developments on herbicide-resistant weeds in different agro-ecological systems. The objective is to demystify the complex processes and provide a better understanding of the mechanisms of herbicide resistance to growers and extension personnel on the ecological and management factors that affect herbicide resistance and weed management strategies that can be employed to reduce herbicide resistance in agro-ecological systems and increase agricultural crop productivity. The mechanisms of herbicide-resistance processes can be grouped into target-site, non-target-site, cross-resistance and multiple-resistance [2, 12].

2. Development of herbicide resistance

Generally, herbicide resistance in weed populations develops in three major ways namely: pre-existing resistance, importation of resistance and natural dispersal.

2.1 *Pre-existing resistance*

In a normal weed population, some weeds naturally contain rare genes or undergo gene modification/evolution that enables them to survive the lethal herbicide dose rate that would normally kill them [2]. This genetic variation may morphologically and/or physiologically change the herbicide penetration, translocation and activation at the site of action. Alternatively, the changes may cause the weeds' ability to detoxify herbicides or sequester the herbicide to a site within the plant where the herbicide is not lethal [13]. When a particular herbicide is applied to a weed population, susceptible weed plants are injured or die while resistant weed plants survive the same herbicide dose.c

2.2 *Importation of resistance*

Initially, resistance may be absent within a given weed population but it can be introduced through weed-contaminated seed, crop, fodder, or moved by machinery or in/on animals that are endo-zoochory or epi-zoochory respectively. This form of resistance is somehow uncommon but was once observed in glyphosate-resistant weeds [2, 14].

2.3 *Natural dispersal*

There are several methods of seed and weed dispersal and these methods can be mechanical. Other forms of weed seed dispersal (allochory) are through the wind (anemochory) and water (hydrochory) [14]. Pollen from weed plants can be dispersed over long distances although greater than 10 m. Besides floodwater has also been found to move a wide range of weed seeds over long distances [14]. Natural dispersal can aid the herbicide-resistant weeds to spread and colonise new agro-ecological systems.

3. Mechanisms of herbicide resistance

Mechanisms of herbicide resistance can be classified as target-site and non-target-site resistance categories. The efficacy of any herbicide is generally influenced by the quantity of herbicide that penetrates the plant cells and the duration of the active form in the plant and how it interacts with the site of action. The non-target-site resistance mechanisms involve the alteration of one or more physiological processes leading to reduced herbicide absorption and metabolise the herbicide into less toxic compounds [3, 13]. On the other hand, target-site resistant mechanisms alter the target enzyme and/or expression level thereby increasing herbicide concentration to achieve adequate inhibition or reduce herbicide binding affinity to the site of action. Under intense herbicide selection pressure and highly effective herbicides, more than one mechanism may be responsible for conferring resistance and/or a combination of target-site and non-target-site mechanisms.

3.1 *Target-site resistance*

In order to cause plant injury or kill, the herbicide molecule should move from the position of application through apoplastic, symplastic or ambimobile routes to the site of action [15]. The herbicide lethal concentrations should reach a specific site of action so as to kill the weeds. The mechanism of resistance can involve single, double or triple mutations in the gene encoding the herbicide target enzyme [16]. For example, *Lolium* species, a glyphosate resistance species, uses one-codon change (Pro-106 to Ser, Ala, Thr, or Leu and Thr-102Ser) in the gene for 5 enol-pyruvate shikimate 3-phosphate synthases (EPSPS) target-site glyphosate resistance (Table 1) [17]. Some species use higher levels of target-site glyphosate resistance e.g. *Eleusine indica* via two- (Thr-102Ile and Pro-106Ser) and *Amaranthus hybridus* using three-codon mutations (Thr-102Ile, Ala-103Val, and Pro-106Ser) [18] (Table 1). In addition, gene deletion and/or gene over-expression is responsible for target-site resistance although the latter is uncommon.

Table 1. Mechanism of evolved resistance to glyphosate (adapted from [17])

Target-site mechanism mutated EPSPS	Glyphosate-resistant species	Reference
One-codon change Pro-106 to Ser, Ala, Thr, or Leu	Several e.g. *E. indica* and *Lolium* species	Sammons and Gaines, 2014
One-codon change Thr-102 Ile	*Tridax procumbens*	Li et al., 2018
Two-codon change (Thr-102Ile and Pro-106Ser	*E. indica*	Yu et al., 2015
Three-codon change (Thr-102Ile, Ala-103 Val, and Pro-106 Ser)	*A. hybridus*	Perotti et al., 2019
EPSPS gene duplication	*Lolium perrene, Bromus diandrus,* and *Chlorus truncata*	Patterson et al., 2018
On an extrachromosomal circular deoxyribonucleic acid (DNA)	*Amaranthus palmeri*	Koo et al., 2018
Tandem duplication at a single locus	*Kochia scoparia* and *Amaranthus tuberculatus*	Gaines et al., 2019

The alteration occurs on the herbicide site of action resulting in either structural or biochemical changes on the site of action within the plant [16, 19]. The structural or biochemical changes will prevent the herbicide molecule from binding or decreases the binding affinity of the herbicide molecule to the enzyme resulting in the plant surviving the herbicide treatments [15]. Besides, target-site resistance is also conferred via increased expression or gene overproduction, for example, EPSPS gene amplification was reported in glyphosate resistance *A. palmeri* [18] and *K. scoparia* [20]. Herbicide resistance was caused by increasing the production of the target enzyme, resulting in effective dilution of the herbicide on the target site. This entails that more herbicide is then required to achieve a lethal effect [2]. However, this mechanism of herbicide resistance is less common. [2] reported that 478 weed biotypes were found to be herbicide resistant in 67 countries. The majority of the weed biotypes are resistant to photo-system II (PS II) inhibitors, aceto-lactate synthase (ALS) inhibitors, EPSPS inhibitors and acetyl co-enzyme A carboxylase (ACCase) inhibitors. Most, but not all cases of resistance to herbicide are due to the modifications of the herbicide site of action, for example, ALS inhibitors, ACCase, triazine and dinitroaniline as shown in Table 2.

Table 2. Mechanism of evolved resistance to glyphosate (adapted from [17])

Target site	Representative herbicide	Year*	Author
D1 protein	Atrazine	1983	Hirschberg J. and Mcintosh L.
ALS	Chlorimuron	1992	Guttieri et al.
Tubulin	Trifluralin	1998	Anthony et al.
ACCase	Clethodim	2001	Zagnitko et al.
EPSPS	Glyphosate	2002	Baerson SR.
Phytoene desaturase	Fluridone	2004	Michel et al.
Protoporphyrinogen	Lactofen	2006	Patzoldt et al.
Glutamine synthetase	Glufosinate	2012	Avila-Garcia et al.
Auxin receptor	2,4-D	2018	LeClere et al.

*Note: Indicates the first year of publication in peer-reviewed literature to a resistance-conferring mutation in the target site from a field-evolved weed population (adapted from [21])

3.2 *Non-target-site resistance*

Non-target-site resistance is also referred to as cellular, anatomical, physiological or metabolic process resistance. This is another mechanism of herbicide resistance that enable individual weed biotypes to survive the herbicide application [15, 22]. The mechanisms reduce herbicide absorption/penetration, alter herbicide translocation, reduce

herbicide activation, increase herbicide compartmentalisation/sequestration, and enhanced herbicide detoxification/metabolism [3, 13]. The mechanisms reduce the amount of herbicide active compound from reaching the target site in sufficient concentration to kill the plant. Understanding these mechanisms of herbicide resistance will help in the development of effective weed management strategies and reduce resistant weed biotypes [23]. The following sections describe the mechanisms of non-target-site herbicide resistance.

3.2.1 *Reduced herbicide uptake (absorption)*

Plant age and/or morphology affect herbicide molecule uptake, retention and translocation in the plant and determine the plant's susceptibility, tolerance or resistance to herbicide application [15]. The herbicide that fails to penetrate the plant may not cause toxicity or injury to the plant. In foliar-applied herbicides, plant leaf properties that are leaf surface, hairiness and angle present anatomical differences between plant species and as such confer the basis of herbicide selectivity [15]. Leaf structure that allows better herbicide spray retention, for example, hairy leaf surface results in more herbicide contact time and uptake by the plant which eventually causes injury or kills the plant. On the contrary, smooth leaf surfaces reduce herbicide retention and cause the plant to resist/tolerate herbicide spray [24]. Plant age often determines herbicide efficacy on weed spectra. Younger and actively growing annual, biannual or perennial weed plants are normally more susceptible to herbicide spray compared to old weed plants [24]. Mature and/or older weed plants have well-developed leaf cuticle layers which repel or reduce spray droplets penetration [25]. Moreover, the position and architecture of leaves, e.g. grass leaves are positioned at a narrow and acute angle to reduce penetration of some herbicides compared to legumes which have a horizontal or planophile architecture which increases herbicide-leaf contact and penetration time [15, 19]. Besides, the anatomical difference between grasses and legumes on the growing point makes grass plants tolerant to auxins mimicking herbicides as opposed to broad-leaf weeds [24].

3.2.2 *Altered translocation*

The herbicide molecule can only exert its toxic effect when it reaches the target site of action in enough concentration to kill the plant. The movement (translocation) of herbicide from the position of application to the site of action is key in herbicide resistance [15]. Resistant plants restrict herbicide molecule movement resulting in reduced herbicide dose reaching the target action site and the herbicide sub-lethal doses will not kill the plant [24]. In susceptible plants, fast herbicide movement in the plant occurs resulting in the accumulation of lethal herbicide concentration on the target site of action which eventually injures or kills the plant.

Some herbicides, for example, 2,4-D are found in two forms that are salt (amine) and ester forms and have to be transformed into free acid form for their translocation in plants. The enzymes responsible for the conversion from amine form through de-amination and ester form through de-esterification into free acid form are amidase and esterase respectively [24]. The free acid form of 2,4-D is readily translocated in the phloem to the meristematic regions where toxic effects are exerted [15, 26]. In resistant plant species, the process is very slow such that the herbicide does not reach the target site while tolerant grass species lack enzymes esterase and amidase and do not convert 2,4-D to free acid form for translocation.

3.2.3 *Reduced herbicide activation*

Pro-herbicides are formulated in such a way that when applied to plants, they are in non-toxic form and susceptible weed plants will convert it into the herbicidal active form which eventually injures or kills the plant [15]. However, resistant weed plants, lack the enzyme that converts the pro-herbicide into an active form or the conversion process of pro-herbicides is very slow such that the concentration of the herbicide's active form is in sub-lethal doses and does not kill the plant [24]. For example, susceptible target weed species will convert the pro-herbicide 4-(2,4-dichlorophenoxy) butyric acid (2,4-DB) and 4-(4-chloro-2-methylphenoxy)butanoic acid (MCPB) by beta-oxidation to the toxic form of 2,4-D and MCPA respectively which eventually kill susceptible broad-leaf weeds [15]. However, cereal and some legumes which either lack the enzyme for beta-oxidation to convert the non-toxic into toxic form are not affected by the herbicide.

3.2.4 *Increased herbicide compartmentalisation/sequestration*

Compartmentalization involves processes or series of processes which physically separate xenobiotics (foreign substances) and their phytotoxic metabolites from entering the biochemical reaction of the cell [2]. This mechanism keeps the herbicide molecule away from the site of action so that it will not kill the plant. Vacuole compartmentalisation of phase II metabolism is the most common form in herbicide-resistant plants [27]. Resistant weed species have an active vacuole or cell wall that sequesters the herbicide and ensure the herbicide molecule is kept remote away from the active site of action. For example, vacuole herbicide compartmentalisation has been found in weeds that are resistant to paraquat and glyphosate. *Conyza canadensis*, and *Lolium* species express paraquat and glyphosate resistance through vacuole herbicide sequestration [27, 28].

3.2.5 *Enhanced herbicide detoxification (metabolism)*

One of the main mechanisms through which herbicide-resistant plants confer resistance is differential metabolism [29]. Susceptible weed species are less able to metabolise the herbicide. Herbicide metabolism is the conversion of herbicide-lethal molecules to fewer toxic compounds. The less toxic compounds are then stored where they would not affect plant cell survival, for example, in the vacuole [28]. Resistant plant species use such mechanisms to alter or degrade the herbicide molecule through biochemical reactions thereby producing non-toxic products [27]. Herbicide metabolism can be classified into four main phases: Phase (i) conversion; Phase (ii) conjugation; Phase (iii) secondary conversion and transport into vacuole; and Phase (iv) deposition of final metabolite [28]. In phase (i) of herbicide metabolism, the herbicide active ingredient molecule is modified through chemical reactions such as oxidation, reduction, hydrolysis, and hydroxylation [2]. The functional groups, OH, NH_2, and COOH are introduced to the herbicide molecule making it more hydrophilic, and less phytotoxic. The enzyme cytochrome P450 monooxygenases (P450), a membrane-bound catalyses oxy-reduction reaction of endogenous and xenobiotic substrates [30]. In phase (ii), the herbicide metabolite derived from phase (i) is conjugated with sugars, amino acids or with glutathione thereby increasing its solubility in water, while reducing herbicide phytotoxicity. In general, phase (ii) metabolites have low or no herbicidal activity and they can be stored in cell organelles [31]. The glutathione-S-transferases (GSTs) are the enzymes responsible for glutathione (GSH) conjugation with herbicide metabolites. GSTs catalyse the nucleophilic substitution of the sulphur atom from GSH or H-glutathione (hGSH) by the electrophilic centre of the herbicide. The herbicides conjugated by the GSTs include those from the group sulfonylureas, imidazolinones, aryloxy-phenoxy-propionates, triazines and chloraacetamilide. The enzymes responsible for conjugation with glucose are the glycosyl-transferases (GTs), that similarly to GSTs, can conjugate herbicides directly, by glycosylation of specific functional groups of lipophilic molecules, such as –OH, –COOH, $–NH_2$ and –SH [31].

In phase (iii), the metabolites derived from phase (ii) are actively transported to the vacuole mostly by adenosine triphosphate (ATP) binding cassette. Secondary conjugations might also occur during phase (iii), giving origin to non-phytotoxic compounds. In phase (iv), the metabolites of the detoxification process are compartmentalised in vacuoles and may be associated with components of the cell wall which are the pectin, lignin, polysaccharide and proteins. The importance of understanding the main stages of differential metabolism is that the plant uses cell energy to detoxify herbicides [31].

3.2.6 *Rapid necrosis (Phoenix phenomenon)*

This is an extreme non-target-site mechanism of herbicide resistance. [32] reported that *Ambrosia trifida*, evolved to glyphosate. The glyphosate-resistant weed responded rapidly to the slow-acting herbicide by rapid necrosis which occurs on foliage in direct contact with the herbicide spray, thereby preventing herbicide translocation to meristems. The plant will then re-establish from the unaffected meristems representing the “Phoenix phenomenon” when the tissue containing glyphosate dies (Table 3).

Table 3. Mechanism of glyphosate non-target-site resistance (adapted from [33])

Target-site mechanism mutated EPSPS	Glyphosate-resistant species	Reference
Reduced movement of glyphosate into the plant	Several e.g. *Sorghum halepense, Leptochloa vignata*	Heap and Duke, 2018
Reduced translocation of glyphosate	Several e.g. *Chloris elata, C. canadensis*	Heap and Duke, 2018
Phoenix phenomena (rapid necrosis followed and regeneration)	*A. trifida*	Van Horn et al., 2018
Vascuolar sequestration of glyphosate	*C. canadensis, Lolium* species	Gaines et al., 2019
Enhanced degradation to aminomethylphosphonic acid (AMPA) and glyoxylate by elevated aldo-keto reductase (AKR) activity	*Echinochloa colona*	Pan et al., 2019

3.2.7 *Exudation of the root system*

Some herbicides for example glyphosate can be easily exudated by the plant roots and released into the rhizosphere, through a diffusion process, together with sugars, amino acids and other low molecular weight compounds [34]. Exudation through the root is also considered one of the possible mechanisms involved in which resistant weed species can evade the herbicide effect.

4. Types of herbicide resistance

4.1 *Cross-resistance*

The term cross-resistance is the ability of a weed population to express a single-resistance mechanism and cause resistance across two or more herbicides in similar groups [2, 13]. This type of resistance is conferred by either a single gene or more than two genes that influence a single mechanism. Cross-resistance may occur even when the weed population has not been exposed to one of the herbicides [2]. There are two types of cross-resistance namely non-target-site cross-resistance and target-site cross-resistance.

4.1.1 *Target-site cross-resistance (across herbicide subgroups)*

This is the most common type of cross-resistance where an altered target site inhibits the same enzyme and confers resistance to many or all of the herbicides that use a similar MOA, for example, *Avena fatua* populations resistant to ACCase inhibitor 'fops' may also be resistant to 'dims', even when the weeds were not exposed to the 'dim' herbicide subgroup. This is because the herbicide sub-groups share the same MOA. Similarly, [31, 35] reported *Cyperus iria* resistance to bispyribac-sodium, imazamox, halosulfuron, and penoxsulam due to altered target site. In this study, Trp-574-Leu amino acid was substituted within the ALS gene [31, 35].

4.1.2 *Non-target-site cross-resistance (across herbicide MOA groups)*

On the other hand, the non-target-site cross-resistance is expressed when there are changes in the cellular, anatomical, physiological or metabolic process, for example, reduced absorption, translocation, and/or enhanced herbicide detoxification [13]. This type of herbicide resistance occurs when a weed population is resistant to more than one MOA group. For example, a population of annual *Lolium* species (ryegrass) selected only by group A herbicides may become resistant to both group A and group B herbicides. This is usually non-target-site resistance [13]. Another mechanism of resistance is negative cross-resistance and this occurs when a weed biotype resistant to a particular herbicide type is more susceptible to other classes of herbicides than the susceptible biotype. For example, atrazine-resistant *Amaranthus retroflexus* (redroot pigweed) may be more susceptible to fluometuron (cotoran/meturon) than the triazine-susceptible biotype [31].

4.2 *Multiple resistance*

Multiple resistance occurs when two or more resistance mechanisms are present within the same plant and confer resistance to chemically unrelated herbicides with different modes of action [27]. Weed populations that exhibit multiple resistance, result in plant species withstanding herbicides from different subgroups. For example, *Lolium* species populations developed resistance to ACCase inhibitors and glyphosate and were also found to be resistant to ALS inhibitors and glyphosate [36]. A study carried out in Australia showed ryegrass exhibiting resistance to five different herbicide MOA [27]. The resistant annual ryegrass population showed both target- and non-target-site resistance.

4.3 *Partial resistancee*

Partial resistance occurs in a population when a small proportion (less than 20%) develops resistance and survives the standard herbicide application dose rate. A weed population is normally classified as resistant when more than 20% of the population survives the standard herbicide application rate by the testing services [2].

5. Factors affecting the rate of herbicide resistance development

5.1 *Selection pressure*

Selection pressure which is a measure of herbicide's ability to differentiate between susceptible and resistant plants is among the most important determinants of resistance development. Herbicide efficacy and the frequency of herbicide use are among the major factors contributing to selection pressure [14]. Herbicides with high efficacy in the control of a specific weed population exert high selection pressure on the resistant individuals within that weed population. Furthermore, soil and herbicide chemical properties, affect herbicide persistence and is also a major factor in herbicide resistance development [37]. Selection pressure is high on susceptible weeds from herbicides with long soil persistence or residual activities compared to herbicides with shorter persistence or no soil residual effect [38].

5.2 *The initial frequency of resistance mutations*

Detailed studies are still to be performed on the initial frequency of resistance mutations in weeds. It is, however, estimated that approximately one in a billion weed seeds could be resistant in any population [38, 39]. This form of mutation is rare, but large and prolific seed-producing weed populations increase the likelihood of resistant weed seeds.

5.3 *Gene flow*

Both pollen and seed are the major gene flow movement methods across and within plant populations [38, 40]. Moreover, resistance development occurs more rapidly in cross-pollinated plant species compared to self-pollinated plant species [37]. Resistant genes that arise within a weed population through mutation and gene flow are most likely responsible for resistance among individuals in that area [41].

5.4 *Fitness*

In herbicide-resistant biotypes, the term fitness is a measure of survival of the resistant biotypes and their ability to produce viable offspring that can compete with wild type for example herbicide-susceptible biotypes [39, 42]. Earlier studies have shown that the fitness of resistant weed populations varies. This has been attributed to the environmental conditions and resistance mechanism. However, herbicide-resistant biotypes are generally less fit than susceptible biotypes. For example, under field conditions, triazine-resistant biotypes have been shown to be less fit than susceptible biotypes [41]. However, under field conditions, fitness penalties can be exploited for the management of affected resistant biotypes.

6. Resistance weeds management strategies

There is no silver bullet in weed management. Weed management strategies for herbicide-resistance weeds should involve the integration of possible available options using an integrated weed management approach (IWM). The possible combinations should be cost-effective, environmentally safe and manage weed resistance [32]. IWM must be proactively adopted by growers in order to effectively embrace new technologies. This call for growers, academics, and industry scientists to work together to overcome the barriers to IWM adoption. The IWM encourages a multi-faceted approach to weed management which include a combination of strategies such as preventive, seed bank management, agronomic practices (i.e., diverse crop rotations, cover crops and cropping systems), robotics and remote sensing, biological, mechanical, physical and chemical measures [14].

6.1 *Identification of resistant weeds*

Early detection of resistant populations through frequent field inspections and surveys is vital. In most cases, resistant weed populations are not apparent to growers until when 10 to 30% of the weed population develops resistance [43]. Therefore, early detection of resistant weed populations using diligent field monitoring techniques is critical. This should be followed by rapid response to ensure that growers contain and manage the resistance problem at an early stage by employing preventative operational measures to manage the spread of resistance [32].

Knowledge and appreciation of how herbicide resistance weeds develop are vital for designing management strategies that prevent its manifestation. It is important that herbicide resistance biotypes be detected at an early stage. The most important factors to consider when designing herbicide resistance management programs are the characteristics of the weed spectra, the herbicide in use and common management practices [32]. Table 4 shows the identification of factors that enable the risk of resistance which requires assessment.

Table 4. Management/agronomic factors influencing the risk of herbicide resistance (adapted from [44])

Factor	Low risk	High risk
Tillage system	Conventional annual tillage	Continuous minimum tillage
Cropping system	Good crop rotation	Continuous monoculture
Weed management	IWM	Herbicide only
Herbicide use	Varying modes of action	Single MOA
Past-year weed control	Excellent	Poor
Field weed infestation	Low	High
Resistance in vicinity	Unknown	Common

Generally, herbicide resistance development is a result of repeated use of a single herbicide or herbicide with similar modes of action. An IWM approach is vital to reduce the incidence and/or manage herbicide resistance in agro-ecosystems.

6.2 *Preventative weed management*

Once weed resistance has been identified, the challenge can be confined by ensuring the limited movement of seed crops, livestock and equipment from the contaminated farm in a bid to reduce the transfer of resistant weeds biotypes [45]. The use of harvesting equipment such as combine harvesters has been found to be responsible for weed-resistant cases in fields where previous management practices should not have led to weed resistance. This calls for farm hygiene and biosanitary practices, such as cleaning farm equipment, and getting rid of and/or destroying resistant weed plants to avoid field re-infestation with resistant weed seeds or plant propagules.

6.3 *Agronomic weed management practices*

Crops and crop varieties differ in their competitiveness against weeds. Mono-cropping systems tend to promote close weed-crop association through routine crop management practices which could result in weed-resistant biotypes [45]. Crop rotations and the inclusion of competitive cover crops can be used to suppress some weed populations over period. Crops require different growing seasons, and different herbicides are registered for different crops. Rotating different crops will ensure alternate weed management methods and allows rotation of herbicides with different modes of action and this reduces the incidence of herbicide-resistant weeds. Crop rotation breaks down weed population synchrony with the crop cycle and prevents the build-up of herbicide resistance [15]. Moreover, good agricultural practices such as mulching, soil solarization, prevention methods of weed dispersal, fertilizer management and the use of varying tillage systems will suppress weed development and benefit the soil and future crops [46].

6.4 *Mechanical weed management*

Mechanical tillage systems and manual hoeing are among the weed management options that reduce over-reliance on herbicide weed management. However, mechanical and/or manual weed management increases the exposure of soil to a high risk of soil erosion [15]. Besides, the use of mechanical weed management is limited to certain crop stages and may not be possible in perennial cropping systems. For example, in alfalfa, later stages of sugar cane and banana plantations [46]. On the other hand, manual hoe weed management is associated with inefficiency, labour and time consumption. Moreover, soil disturbance using these weed management options can potentially encourage weed seed germination.

6.5 *Herbicide weed management*

Herbicide rotation and spray mixtures are vital in preventing and managing weed resistance. Recent studies demonstrated that herbicide mixtures were more effective in managing herbicide-resistant weeds compared to herbicide rotations [15]. The use of herbicide mixtures and/or rotations reduces selection pressure on resistant weed populations. It is important to note that any rotations or herbicide tank mix should include herbicides with different modes of action which control similar weed spectra [45]. The herbicides should also possess the same persistence in the agro-ecosystem. The use of two or more herbicides with different modes of action reduces the selection pressure of resistant weed biotypes. Ideally, each component of the herbicide in a mixture; targets different active/(target-sites) MOA; possesses a high efficacy level; should be detoxified in different biochemical pathways and have similar soil residual effects (similar persistent period); have a synergistic effect with the other herbicide and employ negative cross-resistance [46].

7. Conclusion

Herbicide weed management remains one of the most efficient and cost-effective methods of weeds. However, intensive herbicide use and misuse have been confirmed by many studies and reports to be the primary cause of the rapid evolution of herbicide-resistant weed populations. In agro-ecological systems, weed species either disappear, adapt, tolerate or resist unfavourable ecological conditions that affect their normal growth. Herbicide resistance is among the survival strategies that enable weed species to counteract or escape herbicide control. The mechanism involves target-site (altered binding site) resistance and non-target resistance. Non-target resistance includes cellular, anatomical, physiological or metabolic process resistance. Non-target resistance reduces herbicide absorption/penetration, reduces herbicide activation, alters herbicide translocation, and, increases herbicide compartmentalisation/sequestration, and enhanced herbicide detoxification or metabolism.

Weed resistance development is mainly due to mutation and natural selection. Weed species with high seed productive capacity and polymorphic characteristics, have rapid responses to ecological environments and express herbicide-resistant across wider ecological conditions. The presentation in this paper therefore clearly demonstrated that herbicide resistance weeds remain one of the most important problems in intensive crop production. Integration of available weed management options through IWM encourages a multi-faceted approach to weed management and

involves a combination of strategies. These include among others preventive, good agronomic practices, mechanical, biological, physical and chemical. The challenges of herbicide resistance management in agro-ecological systems require a proactive approach from interested parties. The involvement of government, industry, research institutes universities, technology development and transfer centres and farmers to develop cost-effective, weed resistance-management strategies and address emerging challenges associated with weed resistance is vital.

Conflict of interest

The authors declare no conflict of interest.

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