*Plant Archives* Vol. 25, Supplement 2, 2025 pp. 2011-2021 e-ISSN:2581-6063 (online), ISSN:0972-5210

Plant Archives

Journal homepage: http://www.plantarchives.org
DOI Url : https://doi.org/10.51470/PLANTARCHIVES.2025.v25.supplement-2.254

# HERBICIDE RESISTANCE: EXPLORING MANAGEMENT TACTICS AND RECOMMENDATIONS FOR SUSTAINABLE AGRICULTURE

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(Date of Receiving : 25-04-2025; Date of Acceptance : 01-07-2025)

**ABSTRACT**

Managing weed resistance has become a critical challenge for agricultural producers globally. The rise in resistant weed species and increasing number of herbicides which these weeds are adapting underscore the urgency of this issue. The weed population susceptibility to herbicides is viewed as diminishing common-pool resource, influenced by local farming practices and environmental conditions. Recognizing that weed resistance is not merely a private property concern, it must be approached as a complex problem without a one-size-fits-all solution. A holistic perspective that incorporates socio-economic factors influencing weed management is essential. Innovative practices such as crop rotation, using multiple modes of action in herbicide applications, and integrating cultural practices are vital for enhancing resilience against resistance. Collaboration among farmers, researchers, policymakers, and extension services is crucial for developing adaptive management strategies that mitigate existing resistance and prevent future occurrences. By fostering collaboration and embracing diverse perspectives, stakeholders can create innovative solutions to effectively address the complexities of resistance of herbicide.

***Keywords*** **:** Herbicide resistance, weed species, weed management, adaptive strategies.

## Introduction

The ability of unwanted plants (weed) to withstand dose of herbicide that would normally kill it (Roma *et al.*, 2018). In this application, resistance refers to the progression of a population from vulnerable to resistant. Herbicides do not appear to alter a plant's genetic makeup rather, the proportion of resistant individuals within a population grows over time as a result of repetition choice for crops with the same amount of natural resistance gene to that herbicide (Colbach *et al.*, 2016, Hawkins *et al.*, 2019). It's crucial to understand that any hereditary process that gives some plants an edge in terms of survival will be used in such a selection procedure. As a result, multiple alternative processes may be selected at the same time in a big weed population, and there's no reason to think they'll happen at the same time in geographically disparate population (Jenkins *et al.*, 2017, Dentzman, 2018).

From an agronomic standpoint, the emergence of herbicide resistance becomes a significant issue when a farmer finds weed control to be "unacceptable." This situation generally arises when approximately 10 to 15% of weeds that are typically deemed susceptible survive after herbicide application (Moss, 2017; Cobb, 2022). However, there are numerous factors contributing to herbicide failures in agricultural settings, such as inadequate application methods, adverse weather or soil conditions, excessively large weeds, or severe infestations. Moreover, new instances of resistance are seldom confirmed solely through field observations (Peterson *et al*., 2018; Cobb, 2022). Resistance does not necessarily imply that weeds cannot be effectively managed in the field; often, a small fraction of the weed population may be resistant or certain species may exhibit partial resistance rather than complete insensitivity (Moss, 2017; Mendes *et al*., 2022). At the field level, resistance should be viewed as a continuum ranging from full susceptibility to total resistance. This variability complicates the detection and assessment of the extent and consequences of resistance (Corwin *et al*., 2017; Mancuso *et al*., 2021).

Recent advancements and trends in herbicide resistance weed control include revived attempts in herbicide development by the fertilizers in agricultural sector after a protracted break from 1980s to the present-day, during which no novel herbicide SOA has been put on the market (Montgomery, 2017; Gazziero *et al*., 2022). Since then, the industry has worked to expand the use of current chemicals by adding herbicide resistant characteristics, either alone or in combination, into our main crops, particularly cotton (Gossypium sativum L.), maize (*Zea mays* L.), and soybeans (*Glycine max* (L.) Merr.) (*Gossypium hirsutum* L.) (Anderson *et al*., 2019, Rahman *et al*., 2023). Although herbicide resistance trait stacking gives growers more options in managing herbicide resistance weeds, weed science scholars agree that given existing techniques, this solution is not long-term sustainable and will certainly lead to increase in occurrence of multiple-herbicide resistance populations (Owen *et al*., 2015, Peerzada *et al*., 2019).

**Table 1:** The world's most significant herbicide-resistant weed species (Bo *et al.,* 2017)

| Scientific Name | Common Name | Number of Site of Action |
|---|---|---|
| *Lolium rigidum* | Ryegrass | 11 |
| *Echinochloa crusgalli var crus galli* | Barnyard grass | 10 |
| *Poa annua* | Annual blue grass | 9 |
| *Alopecurus myosuroides* | Black grass or twitch grass | 7 |
| *Eleusine indica* | Goose grass | 7 |
| *Amaranthus palmeri* | Pig weed | 6 |
| *Lolium perenne ssp. Multiflorum* | Italian ryegrass | 6 |
| *Amaranthus hybridus* | Smooth pigweed | 6 |
| *Ambrosia artemisiifolia* | Annual ragweed | 5 |
| *Avena fatua* | Common wild oat | 5 |
| *Conzya Canadensis* | Fleabane or horse weed | 5 |
| *Kochia scoparia* | Ragweed | 5 |
| *Raphanus raphanistrum* | Wild radish or jointed charlock | 5 |

**Types of herbicides**

**Herbicide resistance comes in a variety of forms**

Herbicides target one or more parts of a weed's genome. Enzymes, non-enzyme proteins, cell division mechanisms, and other sites of action are examples of these locales (Bo *et al*., 2017). It is an evolutionary process that is heavily influenced by genetic factors, weed species, herbicide and herbicide, as well as herbicide (Bo *et al*., 2017, Powles, 2018). Weed populations can develop resistance to one or more active components in herbicides in general.

According to the mode of action, herbicide resistance are classified as given below:

**1. Herbicide Cross-resistance**

The term cross resistance used to describe a plant's resistance to one or more herbicide classes within a group. Herbicides targeting acetolactate synthase (ALS) have bred a resistant biotype that is immune to all herbicides and targets a specific spot (Menon, 2021). For both clinical and technical reasons, the phenomenon of cross resistance is significant. If weed management options are limited due to cross resistance to a variety of herbicides, growers and agrochemical manufacturers may face significant financial losses (Peterson *et al*., 2018, Alcantara *et al*., 2020). Cross resistance's biochemical and genetic foundation, as well as the implementation of long-term weed control operations, are significant scientific issues (Powle s and Preston, 2016).

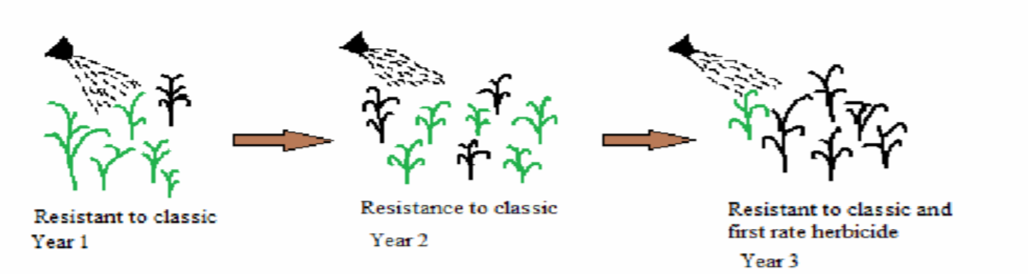


**Fig 1 :** Cross Resistance (Singh *et al.*, 2020)

## 2. Multiple resistance to herbicides

Multiple resistance occurs due to differences in the action sites of herbicides. It describes a weed biotype that developed resistance mechanisms against various herbicide modes or sites of action, with this resistance resulting from separate selection processes (Won *et al.*, 2015; Beffa *et al.*, 2019). An individual plant or population may possess two or more distinct mechanisms of resistance, each providing protection against a specific herbicide or group of herbicides (Gaines *et al.*, 2020). When both the non-target site and target site resistance processes are present in the same population or individual, it creates particularly challenging situations for weed management (Ghanizadeh and Harrington, 2017; Hu and Chen, 2021).

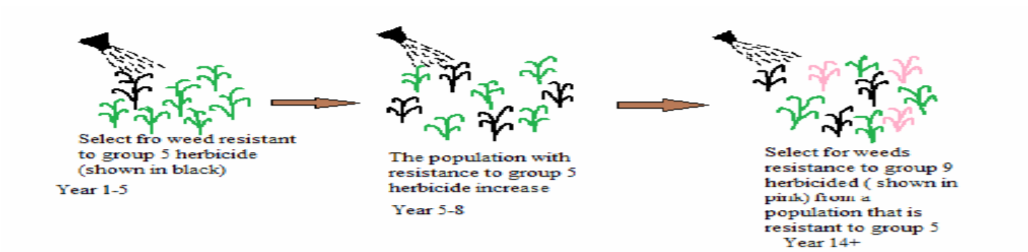


**Fig. 2 :** Multiple resistance (Singh *et al.*, 2020)

## Herbicide resistance in weeds

### Resistance mechanism

To categorize numerous herbicide resistance mechanisms, two types were identified: non-target site resistant and target site resistance (Singh *et al.*, 2020).

1. **Target site resistance**: It refers to the specific location or point where herbicide's active ingredient binds to that spot and subsequently disrupts its function by interfering with physiological processes (Koeller, 2018). The following are the main target site resistance mechanisms:

   - Target-site mutation
   - Number of copies of a gene has increased, as has number of copies .
   - Over expression of enzymes.

Most typical mechanism for developing target site resistance is mutation of the target site (Kwon *et al.*, 2015).

1. **Mutation of target site:** It is an enzyme providing a binding site for the herbicide molecule. The shape of the ligand binding of the targeted enzyme's active site is altered or transformed in this method (Liu *et al.*, 2023). Target enzyme activity is not impeded, and herbicide compounds have no effect on them, and these variations in binding site geometries are caused by gene mutations (Jia *et al.*, 2021).
2. **Expanded gene copy number:** This method produces a greater number of genes responsible for the synthesis of the enzyme system. Extra copies of a gene are created, resulting in copy number variations (CNV). This is known as gene amplification or gene duplication (Patterson *et al.*, 2018). An increase in CNV causes the synthesis of additional target enzymes. Plants of certain plants show resistance to glyphosate by enhanced expression the 5-enolpyruvylshikimate-3-phosphate synthase gene through increased gene copy numbers (Fernandez *et al.*, 2017).
3. **Increased expression of enzymes/ overproduction of action sites:** In this process, herbicide resistance is obtained by overproducing the targeted enzymes. When an enzyme is produced in excess, an increased rate of herbicide treatment is intended to pay for the higher enzyme concentration produced in order to block all of the

cytochrome p450 enzymes (Basso and Serban, 2019). If a herbicide is applied at a typical pace, its action is limited to a certain percentage of target enzymes, and the remainder enzymes continue to operate normally (Sammons and Gaines, 2014).

**2. Non-target site resistance**: In this, the herbicide molecules are blocked from reaching the target site by plant-developed mechanisms (I m *et al.*, 2016). The majority of non-target resistance mechanisms rely on the rapid breakdown of herbicide molecules caused by increased metabolic rate (Ghanizadeh and Harrington, 2017). Herbicides work in a various way, the most prevalent are:

1. **Herbicidal uptake in different ways:** This technique entails the alteration of anatomic or morphological traits in order to introduce obstacles to herbicide molecule absorption inside plant cells. Increases in the thickness/composition of the cuticle layer of the leaf, reduced leaf surface area, or oversupply of waxes are examples of these alterations. All of these structural or morphological changes diminish herbicide molecule retention, absorption, and penetration into plant cells. These morphologic changes are acquired by the resistant genotype (Mendes *et al.*, 2022).
2. **Impaired translocation:** The mode of action of systemic herbicides is to move herbicide molecules from the point of absorption to the site of action, which is aided by phloem tissue. The greater the herbicide's translocation, the greater its efficacy. If the translocation through phloem is adversely affected, the herbicide's phytotoxicity is lowered because the amount of herbicide necessary at the action site not met. (Goggin *et al.*, (2016) discovered that 2,4-D was poorly transported into the phloem tissue of two *Raphanus raphanistrum* biotypes, resulting in lower 2,4-D translocation and, eventually, resistance to it.
3. **Sequestration:** This process includes trapping herbicide molecules at dormant cell locations where they can't cause phytotoxicity. Vacuole or cell wall are the most common inactive locations. As a result, despite being absorbed by herbicide, plant cells continue to function normally (Heap, 2017).
4. **Enhanced Metabolism/Degradation**: Herbicide molecules are degraded before they reach action site in this mechanism. Herbicide metabolism is sped up, which helps to neutralize its effects. This method involves two phases: activation and conjugation. Poaceae weeds are extremely familiar with this method (Delye *et al.*, 2013). During the activation stage, the lyophilic component of the herbicide molecule is converted to lyophobic, followed by accumulation and oxidation by the P-450 enzyme (Setianingsih *et al.*, 2021).
5. **Phase of conjugation**: During this phase, the structure of the herbicide molecule is changed, and the final product loses its function and becomes nontoxic or less toxic (Lushchak *et al.*, 2018).

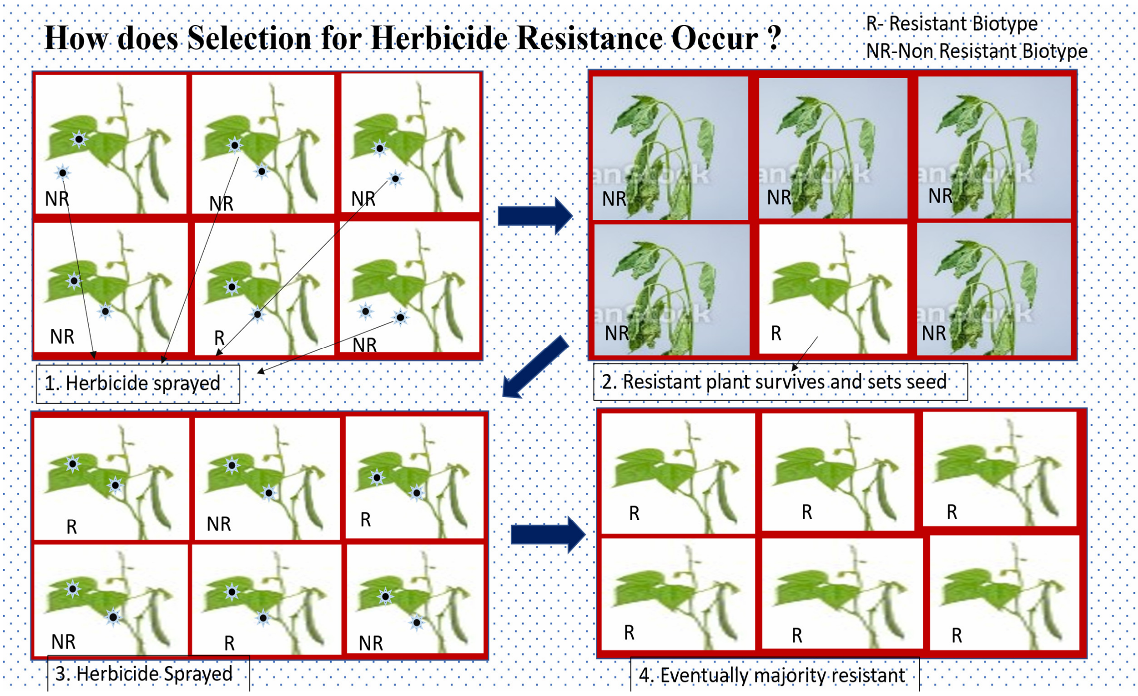


**Fig. 3:** This diagram is showing that the two types of biotypes. i.e R- Resistant biotype and NR-Non-resistant biotype (Source: Author)

In the 1st picture most of the biotype is susceptible and only a single biotype is resistant only. When the herbicide is sprayed all those sensitive plant are killed and only one plant/resistant one is living and that resistant plant will grow and will sets seed and after seed setting that the resistant one gained and that population will have the ability to survive and resists that particular herbicide and then if again the herbicide is sparyed due to which the eventually majority resists to that herbicide.

**Table 2 :** Most recent case studies of herbicide resistance in weeds (Singh *et al.*, 2020)

| S.No. | Species | Country | Year | Site of action |
|---|---|---|---|---|
| 1 | Amaranthuspalmeri | United States | 2019 | Multiple Resistance: 2 sites of action<br>ALS inhibitors (B/2) |
| 2 | *Aperaspica-venti* | Belgium | 2019 | ALS inhibitors (B/2) |
| 3 | *Avenafatua* | Ireland | 2019 | ACCase inhibitors (A/1) |
| 4 | *Conyzacanadensis* | France | 2019 | ESPS synthase inhibitors (G/9) |
| 5 | *Poaannua* | New Zealand | 2020 | ACCase inhibitors (A/1) |
| 6 | *Secalecereale* | United States | 2018 | ALS inhibitors (B/2) |
| 7 | *Echinochloa Crus-Galli Var. Crus-galli* | Agrentina | 2019 | ESPS synthase inhibitors (G/9) |
| 8 | *Capsella brusa-pastoris* | Norway | 2019 | ALS inhibitors (B/2) |
| 9 | *Eleusineindica* | United States | 2019 | PSI Electron Diverter (D/22) |
| 10 | *Sorghum halpense* | Australia | 2018 | Multiple resistance: 2 sites of action<br>ALS inhibitors (B/2)<br>EPSP synthase inhibitors (G/9) |
| 11 | *Loliumperenne ssp. Multiforum* | United States | 2018 | Long chain fatty acid inhibitors (K3/15) |
| 12 | *Amaranthuspalmeri* | United States | 2018 | Synthetic Auxins (O/4) |
| 13 | *Oryzasativa var. sylvatica* | Colombia | 2018 | ALS inhibitors (B/2) |
| 14 | *Conyzasumatrensis* | Turkey | 2019 | EPSP synthase inhibitors (G/9) |
| 15 | *Amaranthuspalmeri* | United States | 2018 | EPSP synthase inhibitors (G/9) |
| 16 | *Bidenssubalternanas* | Paraguay | 2018 | EPSP synthase inhibitors (G/9) |
| 17 | *Chlorisradiata* | Colombia | 2019 | EPSP synthase inhibitors (G/9) |
| 18 | *Rapistrumrugosum* | Spain | 2018 | ALS Inhibitors (B/2) |
| 19 | Lithospermumaevense | China | 2019 | ALS Inhibitors (B/2) |
| 20 | *Oryzasativa var. sylvatica* | Malaysia | 2018 | EPSP synthase inhibitors (G/9) |

## Herbicide Resistance - Management and Prevention

### (A) Detection of Resistance in the Field

Early detection of resistance is critical for implementing appropriate management methods across the farm to reduce the impact and spread of resistance (Sharma *et al.*, 2018). Herbicide resistance (HR) in the field can identified by:

- steady drop in the weed control over multiple years,
- healthy plants growing alongside dead plants of the same species.
- weed control issues resulting in isolated patches;
- When one sensitive species is poorly controlled, other, equally susceptible species are well controlled.

There are several factors contributing to ineffective weed management in agricultural fields beyond just resistance. Therefore, a steadfast diagnostic test that is quick, precise, cost-effective, and readily accessible is essential. Various diagnostic methods have been established, including glasshouse pot assays, Petri dish germination tests, molecular tests for specific mutations, and laboratory studies using radio-labeled herbicides assess metabolism (Sing *et al.*, 2020; Brown, 2022)

The most commonly utilized tests for assessing herbicide resistance are greenhouse pot assays. In these tests, plants are grownup from seeds collected from fields with questionable weed control, treated with the herbicide, and then their survival or biomass is measured (Cobb, 2022). However, the seeds or plants used for resistance testing often represent a biased sample, as they are typically sourced from herbicide survivors, which constitute only a small fraction of the overall population (Holmes *et al.*, 2022). Consequently, the results of these resistance tests may overestimate the actual level of resistance, potentially leading farmers to doubt the findings, especially if they successfully control weeds with the same herbicide in subsequent years. Despite this bias in resistance testing, it should be viewed as an advantage rather than a drawback. Confirming resistance can act as an early warning of more significant issues that may arise if current herbicide strategies are not adjusted (Ubel and Asch, 2015).

### (B) Integrated Weed Management (IWM)

Farmers often depend heavily on pesticides for weed control, but this approach is unsustainable due to increasing resistance. Even with a variety of herbicides available, resistant biotypes with different resistance traits can still be selected (Powles, 2018). The limited availability of new herbicides means that overreliance on existing ones will likely lead to more cases and greater severity of resistance. To achieve effective long-term weed management, it is crucial to incorporate non-chemical control methods and reduce dependence on herbicides (Browne, 2020). An IWM strategy requires an application of multiple control approaches to effectively manage weeds (Moss, 2019).

### Non-Chemical Control Methods

Nonchemical weed management options such as primary and in crop cultivations, crop rotation, more competitive crops or cultivars, and fallowing are among (Mishra *et al.*, 2016). Within any particular agronomic system, individual circumstances will decide which are most appropriate to use. There must be no selection in favour of resistant plants if susceptible and herbicide-resistant plants behave identically. As a result, nonchemical means of control may be more long lasting than herbicides, even if they are less effective (Pannacci *et al.*, 2017, Davis and Frisvold, 2017).

### Herbicidal Control

Herbicides are unlikely to totally replace nonchemical weed management measures in the fight against herbicide resistant weeds. Herbicide resistance frequently results in reduced herbicide activity rather than none at all, especially at the field scale when just a portion of the weed population is resistant.

### Alternative Herbicides

The effectiveness of alternative herbicides is essential when resistance is confirmed. If resistance is limited to a single mode of action, switching to a different class can be an effective solution (Davis and Frisvold, 2017). For example, ALS-resistant *Papaver rhoeas* (common poppy) in the UK can be controlled with pendimethalin (K1), which has a different mechanism unaffected by ALS mutations. However, this approach depends on having viable alternatives available (Torra *et al.*, 2024). When resistance involves multiple herbicide classes, as seen with populations showing both target site and metabolic resistance, the challenge increases. It is prudent to assume that resistance affects all herbicides with similar modes of action unless proven otherwise. In summary, managing herbicide resistance effectively requires diverse strategies, including crop rotation and varied herbicide use (Moss, 2017, Beckie and Harker, 2017).

### Mixtures, Sequences and Rotations

Using two or more herbicides with different modes of action is considered a crucial strategy for reducing the selection of resistant weeds. This approach is particularly effective when resistance mechanisms are based on target sites and the weed species involved is self-pollinating. Herbicide mixtures, sequences, and rotations can significantly help delay the development of resistance (Vats, 2015). The likelihood of plants developing multiple target site resistance is extremely low, as it depends on the probability of mutations occurring at each action site (Bado *et al.*, 2015). Ideally, each component should:

- be active at multiple target sites
- have a high level of efficiency against the target weed
- be detoxified through various biochemical mechanisms
- If a residual herbicide is used, it will have a comparable persistence in the soil

**Table 3 :** Herbicide Action Resistance Committee (HRAC) Classification of herbicides (Beffa *et al.*, 2019)

| Mode of action | Chemical family | Active ingredient (a.i) |
|---|---|---|
| Inhibition of acetyl CoA carboxylase (ACCase) | Aryloxy phenoxy propionate<br>Cyclohexanedione | Fenoxaprop, Fluazifop, Quizalfop, Clethodim, Sethoxydim |
| Inhibition of Acetolactate synthase (ALS) | Sulfonylurea<br>Imidazolinone<br>Triazolopyrimidine | Chlorimuron, Chlorsulfuron, Foramsulfron, Halosulfron, Iodosulfron, Nicosulfuron, Primisulfuron, Prosulfron, Rimsulfron, Sulfometuron, Thifensufuron, Tribenuron<br>Imazamox, Imazapyr, Imazaquin, Imazethapyr, Flumetsulam, Cloransulam. |
| Inhibition of microtubule assembly | Dinitroaniline | Benefin, Ethafluralin, Pendimethalin, Trifluralin |

| | | |
|---|---|---|
| Inhibition of indoleacetic acid transport | Phenoxy<br>Benzoic acid<br>Carboxylic acid<br>Semi carbazone | 2,4-D,MCPA,MCPP<br>Dicamba<br>Clopyralid, Fluoroxpyr, Picloram, Triclopyr<br>Diflufezopyr |
| Inhibition of photosynthesis at photosystem II site A | Triazine<br>Triazinone<br>Uracil | Atrazine, Ametryn, Prometon, Simazine<br>Hexazinone, Metribuzin<br>Bromoacil, Terabacil |
| Inhibition of photosynthesis at photosystem II site B | Nitrile<br>Benzothiadiazole | Bromoxynil<br>Bentazon |
| Inhibition of photosynthesis at Photosystem II site A different binding behaviour | Urea | Diuron, Linuron, Tebuthiuron |
| Photosystem I electron diversion | Bipyridilium | Paraquat, Diquat |
| Inhibition of EPSP synthase | None accepted | Glyphosate |
| Inhibition of glutamine synthease | None accepted | Glufosinate |
| Inhibition of lipid biosynthesis not ACCase inhibitors | Thiocarbamate | Butylate, EPTC |
| Bleaching: Inhibition of 4-HPPD | Isoxazole<br>Triketone<br>Pyrazolone | Isoxaflutole<br>Mesotrione, Sulcotrione<br>Topramezone |
| Inhibition of protoporphyrinogen oxidase(Protox or PPO) | Diphenyl ether<br>N-Phenyl phthalimide<br>Aryl triazinone | Acifluorfen, Fomesafon,<br>Lactofen<br>Flumiclorac, Flumioxazin<br>Sulfentrazone, Carfentrazone |
| Inhibition of synthesis of very-chain fatty acids (VLCFA) | Chloroacetamide<br><br>Oxyacetamide | Acetochlor, Metolachlor,<br>s-Metolachlor, Dimethenamid<br>Flufenacet |

**Agronomic implications of herbicide resistance**

Although herbicide resistance is a global problem, no special control methods were usually required for resistant biotypes, as alternative herbicides were usually sufficient (Powles, 2018). Weed resistance, on the other hand, rose at a similar rate to pesticide and fungicide resistance over the last decade. As a result, cropping practises and weed management have changed in some areas, particularly the selection and use of herbicides (Peterson *et al*., 2018). In addition, switching herbicides will not be sufficient to control multi-resistant weed populations, as any new herbicide that is used repeatedly is likely to develop resistance and thus become ineffective. Managing herbicide resistance in weeds requires reduced selection pressure for resistance development, which requires a reduction in the frequency and volume of herbicide application and an increased reliance on approaches of integrated management (Bagavathiannan and Davis, 2018).

The dynamics of susceptible and resistant weed populations are becoming increasingly useful in determining the factors influencing resistance development rates in the field, particularly fitness and low gene, and in developing effective management interventions (Holmes *et al*., 2022). Introducing herbicide-resistant crops could complicate resistance management, especially if modified genes can escape. While using herbicide-resistant crops has some benefits, if proper resistance management is not implemented, problems with resistant weeds may be exacerbated (Bagavathiannan and Davis, 2018).

**Recommendations for Sustainable Agriculture**

Based on the insights from the review of herbicide resistance and sustainable agricultural practices, the following strategies are recommended to foster sustainable farming systems:

1. Crop Rotation and Diversity: Encourage the practice of rotating different crops to disrupt pest and weed cycles and enhance soil health. For example, alternating high-nutrient-demand crops with nitrogen-fixing legumes can enhance the fertility of soil and decline the need for chemical fertilizers (Valenzuela, 2023).
2. Integrated Pest Management (IPM): Implementation of IPM strategies that minimize reliance on synthetic pesticides. This approach includes regular monitoring of pest populations, utilizing natural predators, and applying chemical controls only when necessary. Such practices promote ecological balance and biodiversity (Baker *et al*., 2020).
3. Conservation Tillage: Use conservation tillage practises, such as no-till or reduced tillage, to limit

soil disturbance. This helps to maintain soil structure, reduce erosion and increase organic matter content, which contributes to better soil health and moisture retention (Bekele, 2020).

4. Cover Cropping: To protect the soil and enrich them, use the cover crops during fallow periods. These crops help prevent erosion, suppress weeds, and improve nutrient cycling, leading to healthier soils (Quintarelli *et al*., 2022).

5. Organic Fertilization: Switch to organic fertilizers such as compost or manure to improve soil fertility while minimizing the environmental impact associated with synthetic fertilizers. This switch supports ecosystem health and promotes long-term soil productivity (Verma *et al*., 2020).

6. Water Management Practices: Employ efficient water management techniques like drip irrigation and rainwater harvesting to optimize water use in agriculture. Monitoring soil moisture levels can help prevent overwatering and reduce runoff (Sun *et al*., 2022).

7. Soil Testing and Nutrient Management: Carry out regular soil tests to determine the nutrient content and adjust fertilization practices accordingly. This will ensure that plants are optimally supplied with nutrients while minimizing the environmental impact of over-application (Singh and Ryan, 2015).

**Future directions**

In response to the persistent challenges posed by herbicide resistance (HR) in agricultural practices, several strategic avenues should be explored to enhance management techniques and foster sustainable agriculture.

1. **Prioritization of Integrated Weed Management (IWM) :** Future initiatives should place a strong emphasis on Integrated Weed Management, which amalgamates mechanical, biological, and chemical control strategies. This multifaceted approach not only broadens the spectrum of weed management practices but also diminishes dependence on individual herbicide modes of action, which have historically facilitated emergence of resistance (Moond *et al*., 2023, Gonzalez *et al*., 2024).

2. **Innovation in Herbicide Development and Modes of Action :** Given stagnation in discovery of original herbicide modes of action over recent decades, there is an urgent need for innovation in herbicide formulation. Research efforts should concentrate on developing new herbicides that target distinct biochemical pathways in weeds, thereby lowering the likelihood of resistance development (Werner *et al*., 2022, He *et al*. 2022).

3. **Genetic Strategies for Crop Enhancement :** Advancements in *gene editing* technologies and genetically modified (GM) crops can yield varieties with improved resistance to weeds or enhanced tolerance to existing herbicides. This could lead to a decline in the overall application rates of herbicide, thereby minimizing environmental repercussions while sustaining agricultural productivity (Petit *et al*., 2015, Hussain *et al*., 2021).

4. **Education and Capacity Building for Farmers :** Enhancing awareness and education among farmers regarding optimal management practices is crucial. This encompasses understanding the significance of crop rotation, monitoring for resistant weed populations, and applying diverse weed control methods. Agricultural extension services should play a pivotal role in disseminating this information (Nemade *et al*., 2023).

5. **Implementation of Monitoring and Early Detection Systems :** Establishing systematic surveys and monitoring frameworks for the early identification of HR can enable prompt interventions. These systems should be tailored to provide site-specific recommendations based on local weed ecology and resistance dynamics, facilitating targeted management approaches (WHO, 2016, Gerhards *et al*., 2022).

## Conclusions

Synthetic herbicides are widely employed globally to manage weed populations. The development of herbicide resistance in weeds, results from evolutionary processes influenced by selection pressure exerted by these chemicals. The range of herbicide resistance mechanisms is evolving rapidly. Investigating herbicide resistance can provide insights into how plants activate their biological defense systems. Additionally, fundamental research into the mechanisms and genetic foundations of resistance is essential for understanding the development of herbicide-resistant weeds and for effectively managing current herbicides and resistant crop technologies. Progress in technology and a deeper understanding of resistance will be crucial in addressing challenges posed by herbicide resistance.

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