Herbicide Resistance in Weeds: Mechanisms, Management Approaches and Emerging Technologies

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Introduction

Weeds are a major threat to global crop production, causing annual yield losses around 37%, with significant losses up to 50% in beans and corn, 48–60% in wheat, and 50–75% in sesame. While cultural, mechanical, and biological weed management strategies exist, they are often less effective, costly, and labour-intensive. Herbicides have become the most effective and economical method for weed control, offering broad-spectrum efficacy and lower costs compared to manual weeding. But their repeated use has led to the evolution of herbicide-resistant weed populations. Herbicide resistance was first documented in 1957 in Hawaii against 2,4-D. However, the earliest confirmed case of herbicide resistance was reported in 1968 in the United States, involving triazine resistance in common groundsel (*Senecio vulgaris*).

Table 1. Herbicide resistant weeds as on December 9, 2024

Sl. No.	Herbicide Group	Example herbicides	Dicots	Monocots	Total
1	Inhibition of Acetolactate Synthase	Chlorsulfuron	108	68	175
2	PSII inhibitors - Serine 264 Binders	Chlorotoluron	53	34	87
3	Inhibition of Enolpyruvyl Shikimate Phosphate Synthase	Glyphosate	28	32	60
4	Inhibition of Acetyl CoA Carboxylase	Sethoxydim	0	51	51
5	Auxin Mimics	2,4-D	35	9	44
6	PS I Electron Diversion	Paraquat	23	10	33
7	Inhibition of Protoporphyrinogen Oxidase	Oxyfluorfen	13	4	17
8	Inhibition of Microtubule Assembly	Trifluralin	2	10	12
9	Very Long-Chain Fatty Acid Synthesis inhibitors	Butachlor	2	8	10
10	Inhibition of Lycopene Cyclase	Amitrole	1	5	6
11	Inhibition of Glutamine Synthetase	Glufosinate-ammonium	1	5	6
12	PSII inhibitors - Histidine 215 Binders	Bromoxynil	3	2	5
13	Phytoene Desaturase inhibitors	Diflufenican	4	1	5
14	Inhibition of Hydroxyphenyl Pyruvate Dioxygenase	Isoxaflutole	4	1	5
15	Inhibition of Cellulose Synthesis	Dichlobenil	0	4	4
16	Unknown	Endothall	0	4	4
17	Inhibition of Deoxy-D-Xylulose Phosphate Synthase	Clomazone	0	3	3
18	Antimicrotubule mitotic disrupter	Flamprop-methyl	0	3	3
19	Inhibition of Microtubule Organization	Propham	0	1	1
20	Nucleic acid inhibitors	MSMA	1	0	1
21	Cell elongation inhibitors	Difenzoquat	0	1	1
			278	256	533

Modified from https://www.weedscience.org/summary/SOASummary.aspx December 15, 2024

Current scenario of Herbicide resistant weeds

Biotech crops resistant to glyphosate have led to increased reliance on this herbicide, contributing to the rise of glyphosate-resistant weeds. Herbicide resistance is driven by strong selection pressure, causing adaptive evolution in weeds across globe. Various weed species have developed resistance to herbicides like acetolactate synthase (ALS) inhibitors, acetyl-CoA carboxylase (ACCase) inhibitors, 5-enolpyruvylshikimate-3-phosphate (EPSP) synthase inhibitors, photosystem II (PS II) inhibitors, and fatty acid synthase inhibitors. Resistant species include *Conyza* species, which are resistant to herbicides used in vineyards and orchards, and *Lolium* species resistant to glyphosate. Other species, like *Digitaria sanguinalis, Panicum dichotomiflorum, and Echinochloa crus-galli* have developed resistance to ALS inhibitors in different regions. Certain herbicide active ingredients are linked to higher resistance incidences globally. These resistance cases are predominantly linked to monoculture farming practices, as summarized in Table 1.

Weed Characteristics favouring Herbicide Resistance

Initial frequency of the resistant individuals in natural populations

Although herbicides do not directly cause mutations, resistant biotypes can emerge in weed populations if selection pressure is not managed. Repeated use of herbicides with the same mode of action eliminates susceptible weeds, allowing resistant ones to dominate over time.

Ecological/Biological fitness

Fitness, defined as an individual's reproductive success and genetic contribution to a population, reflects relative evolutionary success. Studies show triazine-resistant plants are generally less fit than susceptible ones, considering factors like dormancy, germination, survival, and biomass.

Weed reproduction, seed production, seed dormancy and germination and seed bank in the soil: The soil seed bank can delay herbicide resistance by continuously supplying susceptible weed seeds, slowing the dominance of resistant individuals. Species with dormant seeds in the soil take longer to develop resistance compared to those with rapid germination. High herbicide efficacy, which eliminates most susceptible weeds in a single application, increases selection pressure, accelerating resistance evolution in species with fast germination rates.

Nature of inheritance of resistant gene

Herbicide resistance is often influenced by factors like inheritance mode, gene flow, and genetic variation, with most cases linked to a single dominant gene.

Mechanisms of Herbicide Resistance: Resistance mechanisms can be majorly grouped into Target-Site Resistance (TSR) and Non-Target-Site Resistance (NTSR).

Target-Site Resistance (TSR)

Target site resistance (TSR) occurs when amino acid substitutions prevent herbicides from effectively binding to essential plant enzymes. Herbicides targeting enzymes like ACCase, ALS, PDS or PPO often bind to less conserved amino acids, which can mutate to form functional enzyme variants resistant to the herbicide. Additionally, weak herbicide binding due to poor substrate fit and reliance on amino acid radicals contributes to TSR evolution. TSR evolves rapidly under high selection pressure from herbicides with a single mode of action.

Non-Target-Site Resistance (NTSR)

Non-target site resistance (NTSR) involves various gene families and is less understood compared to target site resistance. Factors like cuticle thickness, trichome structure, and altered transport processes reduce herbicide absorption and translocation to the site of action. Mechanisms such as rapid vacuolar sequestration and metabolic detoxification by enzyme families like cytochrome P450 monooxygenases and glutathione S-transferases (GST) play critical roles in NTSR. Cytochrome P450 enzymes metabolize herbicides within the endoplasmic reticulum, while GST enzymes detoxify herbicides by conjugating them with glutathione. These mechanisms collectively contribute to reduced herbicide efficacy in resistant weeds.

Strategies for Managing Herbicide Resistance

Non-chemical management

Cultural methods

Effective weed management strategies should consider factors like tillage, irrigation, planting times, sowing techniques, and crop diversity. Cultural practices such as crop rotation, cover cropping, and intercropping enhance crop competition, suppressing weeds without herbicides and reducing resistance development. Growing crop cultivars with traits like rapid germination and high biomass can also improve weed competitiveness. Diversified cultivation systems, reducing reliance on monoculture and chemical controls, are crucial for managing herbicide resistance.

Allelopathy, the chemical interaction between plants, can be used in practices like crop rotation, intercropping, cover cropping, and mulching to manage weeds sustainably. It serves as an effective alternative to synthetic herbicides in both conventional and organic farming. For example, sorghum-wheat rotations reduce weed biomass due to allelochemicals like sorgoleone, and crops like alfalfa, sunflower, corn, and wheat also help lower weed densities. However, careful crop selection is crucial, as allelochemicals may negatively affect subsequent crops in the rotation.

Reduced tillage systems often rely more on herbicides to manage annual grasses and perennial weeds, with zero tillage keeping weed seeds near the surface and increasing herbicide efficacy. In contrast, deep tillage or inversion tillage reduces herbicide use by burying weed seeds and lowering selection pressure, delaying resistance buildup.

Physical methods: Physical weed control methods, such as hand weeding and hoeing, have been employed for centuries to manage weeds during cultivation and are still utilized in certain regions. However, their labour-intensive nature, time demands, and high costs make them impractical for weed management on a commercial scale.

Mechanical methods: Mechanical weed control has been effective in managing weeds by using implements capable of clearing large areas of infested land. However, its efficiency is limited by factors such as weather conditions, cropping patterns, operational costs, weed types, and potential threats to biodiversity, making it less effective compared to chemical weed control methods.

Biological weed control: Bioherbicide methods rely on allelochemicals, natural byproducts, plant extracts, microorganisms, and insects to manage weeds. Recent advancements in biological weed control have focused on using these agents effectively, with ongoing research exploring potential evolutionary adaptations following their application. Bioherbicides work by interfering with essential processes such as photosynthesis, nutrient absorption, and other vital functions required for plant growth and survival.

Chemical management

Discontinue the use of herbicides that have led to resistance development

Use of alternative herbicides: Employing alternative herbicides with different chemical compositions and modes of action is suggested as a short-term solution, provided cost-effective options are accessible.

Herbicide rotation: Herbicide rotation is crucial for preventing the emergence of resistant weeds. Alternating herbicide groups with different modes and sites of action, either within a growing season or over several years, can delay resistance development and reduce the risk of multiple resistance. Combining or rotating herbicides with different mechanisms of action lowers selection pressure and slows evolution compared to using a single herbicide.

Use of herbicides with short residual life: Herbicides with long residual life increase selection pressure, so using short-residual herbicides at recommended doses is preferable, as higher doses prolong residual effects.

Selecting suitable herbicide: Few weeds have developed resistance to chloracetamides, diphenyl ethers, and glyphosate, making them low-risk herbicides. In contrast, resistance has quickly emerged against ALS inhibitors, triazines, bipyridyliums, phenylureas, and ACCase inhibitors.

Integrated Weed Management and Precision Weed Management: Integrated weed management (IWM) combines cultural, mechanical, biological, genetic, and chemical methods to reduce herbicide reliance and prioritize environmentally safer options. However, factors like higher costs, weather dependency, and reduced efficacy limit farmers' adoption of non-chemical methods. While chemical control remains essential in commercial farming, site-specific weed management using geospatial tools (e.g., GIS, GPS, and remote sensing), robotics, artificial intelligence, machine learning offers a sustainable strategy. This approach manages inputs to field variability, enhancing profitability and environmental protection.

Remote sensing with UAVs (Unmanned Aerial Vehicles) and satellites: Remote sensing provides precise, site-specific data that can be utilized in decision support systems. Research shows that vegetation indices derived from spectral reflectance captured by remote sensors can assess herbicide effectiveness and detect herbicide-resistant weeds. This helps farmers choose appropriate herbicides and determine the optimal timing for their application.

Robotics: Robotics can combine mechanical, cultural, and herbicidal approaches for efficient and timely weed management, while improving time, labour, and cost effectiveness. Techniques like flame weeding, radio waves, microwave energy, animal use, and AI for real-time image processing and decision-making enhance its potential.

Artificial Intelligence and Machine Learning applied for herbicide resistance weed management: AI-based tools like Robocrop, Removeed, and Robovotor use machine learning to differentiate weeds from crops with high accuracy, up to 97%. The Autonomous Weeder utilizes carbon dioxide lasers to eliminate up to 100,000 weeds per hour, while electrocution technique is being researched as a solution for herbicide-resistant weeds. AI-based detection systems could be enhanced with weed removal technologies such as lasers or mechanical arms. Machine learning methods, like Convolutional Neural Networks (CNN), Deep convolutional neural network (DCNN), Support vector machine (SVM), Artificial neural networks (ANNs), Random Forest (RF) classifier, k-nearest neighbours (KNN), ShuffleNet-v2 and VGGNet etc. are employed in precision weed management for detecting and localizing weeds, distinguishing resistant and susceptible species, and integrating spectral properties for efficient control.

Future research needs

Herbicide resistance in weeds requires urgent research in weed biology, ecology, genetics, and the mechanisms of resistance. Studies on pollination behaviour, gene flow, and the biochemistry and physiology of resistance are essential for understanding its causes and development. Research should also include DNA fingerprinting for identifying resistant and susceptible biotypes, as well as investigations into genetic resistance mechanisms, whether due to a single gene or additive gene effects. Also, herbicides with novel mode of action urgently needed to be developed.

Conclusion

Effective weed management is essential for achieving optimal crop yields and requires an integrated approach combining cultural, mechanical, biological, and chemical methods. Herbicide resistance is a global challenge, driven by the repeated use of herbicides with the same mode of action, especially in monoculture systems and minimal tillage practices. Resistance develops through selection pressure on existing resistant biotypes within weed populations, with mechanisms such as altered sites of action, enhanced metabolism, and compartmentation. To combat this, herbicide rotation and mixtures, along with alternative practices, must be prioritized. Sustainable weed management should integrate herbicides with manual, cultural, and biological control methods to reduce over-reliance on chemical solutions. Proper herbicide application, including timing and dosage, is crucial to minimize resistance development. Capacity building and knowledge dissemination for growers on herbicide use and resistance management are vital. Additionally, interdisciplinary research and active participation from stakeholders, including ecologists, agronomists, plant breeders, and policymakers, are needed. With a balanced approach that respects biodiversity and employs all available tools, it is possible to maintain effective weed control and protect crop productivity.

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