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Herbicide Resistance from First Reports to the Present Day: Global Trends and Integrated Weed Management Approaches

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Abstract: Herbicides are among the most widely used methods in modern agriculture for controlling weeds. However, the intensive use of herbicides over many years, mostly with active ingredients possessing the same mode of action, has led to the emergence and rapid spread of herbicide resistance in weed populations. Today, herbicide resistance is recognized as a major problem that negatively affects agricultural production and yield. In this review, cases of resistance recorded in the International Herbicide-Resistant Weed Database (www.weedscience.org) were examined based on global data on herbicide resistance in weeds. The study evaluated the change in herbicide resistance over the years based on countries, modes of action, active ingredients, weed species, and crop plants; it revealed in which production systems and herbicide groups resistance is concentrated. The data obtained show that resistance to commonly used modes of action, such as ALS (Acetolactate synthase), EPSP (5-enolpyruvylshikimate-3-phosphate), and PSII (Photosystem II) inhibitors, is frequently reported in many countries and that resistance to multiple modes of action has developed in some weed species. Consequently, it is evident that relying solely on chemical methods to manage herbicide resistance is insufficient. Therefore, it is important to adopt integrated weed management approaches that combine cultural, mechanical, biological, and chemical methods. This review aims to contribute to understanding the current situation regarding herbicide resistance and evaluating approaches to existing control methods.

Keywords: Resistance mechanisms, sustainable agriculture, monitoring, database, mode of action

1. Introduction

Weed control methods have evolved over the last century from cultural and mechanical control to mechanical and chemical control, and then to the widespread use of chemical control independently. The importance of herbicides in modern agriculture has continued to grow gradually, and today synthetic herbicides are used worldwide to control weeds not only in major crop groups (primarily wheat, corn, and rice) but also in minor crop groups (Charles, 2001; Gianessi, 2013). According to global estimates, weed-related yield losses in major crop groups are around 34%, which is significantly higher than the 18% yield loss caused by plant pests (insects, mite, nematodes etc.) and the 16% yield loss caused by plant diseases (fungi, bacteria, and, virus etc,) (Oerke, 2006).

To minimize this loss, herbicides are used intensively worldwide. In 2023, the total amount of pesticides used worldwide was 3.728.427 tons, of which 2.009.099 tons were herbicides, 778.387 tons were fungicides, and 759.403 tons were insecticides. In Türkiye, the total amount of pesticides used was 57.576 tons, of which 19.551 tons were fungicides, 18.619 tons were insecticides, and 15.509 tons were herbicides (Anonymous, 2026a).

Herbicides rank first among pesticides used in 41 agriculture worldwide, accounting for 53.89%. Along with the high cost of labor in agricultural fields, herbicides are heavily preferred due to their rapid effect and quick results, long duration of action, and relatively lower application costs (Menguc, 2018; Usta and Karaca, 2021). Therefore, it is known that the continuous use of herbicides leads to resistance (Baucom, 2016). Resistance to herbicides is defined as an acquired genetic trait that allows weeds to survive and reproduce under exposure to the herbicide used. The genetic diversity and reproductive biology of weeds are the most important driving forces behind the phenomenon of resistance (Gressel, 1984; Moss and Naylor, 2002; Neve, 2007; Neve et al., 2014; Güncan, 2016; Torra et al., 2021).

Herbicide resistance may occur either as cross-resistance or multiple resistance. Cross-resistance refers to the ability of a weed biotype to survive two or more herbicides because of a single resistance mechanism, whereas multiple resistance occurs when a weed population possesses two or more distinct resistance mechanisms conferring resistance to herbicides with different sites of action. Multiple resistance is considered one of the greatest challenges in modern weed management because it substantially reduces available chemical control options and increases dependence on integrated weed management strategies (Beckie and Tardif, 2012; Délye et al., 2013; Peterson et al., 2018).

With the continued increase in herbicide use since the 1940s, resistance became a major issue in the 1970s. From the 1970s to the present, 539 cases of resistance have developed in 273 weed species. Of these 273 weeds, 156 are dicots and 117 are monocots, and these cases have been recorded in 102 crop plants in 75 different countries (Heap, 2026).

In this review, cases of resistance were systematically examined using the International Herbicide-Resistant Weed Database (www.weedscience.org), which records weed resistance globally. The aim was to reveal the changes and trends in resistance from the past to the present 56 based on species, mechanisms of action, and production systems.

2. Assessment of Herbicide Resistance Reports

2.1. Changes over the years

The possibility of herbicide resistance in the world was first proposed by Harper in 1956 (Demirkan, 2009; Boylu and Kaya Altop, 2021). In 1957, a study by Switzer reported the first resistance to 2,4-D in *Daucus carota* L. (wild carrot) (Switzer, 1957; Heap, 2026). A total of 1.776 resistance reports have been made from the first record to the present day, and their distribution by year is given in Table 1. Table 1 shows that only 39 cases were reported between the first recorded case in 1957 and 1980. Between 1980 and 2000, 604 cases were recorded, and 1.133 cases have been reported from 2000 to the present. The number of cases reported from 1957, the first year of registration, to 2014, excluding the period between 2000 and 2004, increased rapidly, and the number of cases reported since 2015 has decreased.

Table 1. Distribution of reported resistance cases by year

Years	Number of reports	Percentage
1955-1959	2	0.11
1970-1974	5	0.28
1975-1979	32	1.80
1980-1984	106	5.97
1985-1989	109	6.14
1990-1994	171	9.63
1995-1999	218	12.27
2000-2004	176	9.91
2005-2009	277	15.60
2010-2014	327	18.41
2015-2019	225	12.67
2020-2025	128	7.21
Total	1776	

2.2. Changes by country

Since records of herbicide resistance began, cases of herbicide resistance have been recorded in 75 different countries. The United States has the highest number of recorded cases with 610 reports. The USA is followed by Australia (156), Canada (128), France (66), and Brazil (58). Türkiye ranks 26th among the countries reporting the most cases, with 15 reported cases (Table 2).

The high number of resistance reports in countries such as the United States, Australia, and Canada likely reflects a combination of intensive herbicide use, large-scale and highly mechanized agricultural production systems, and the existence of well-established resistance monitoring programs and strong research infrastructures. Moreover, the International Herbicide-Resistant Weed Database relies largely on voluntary reporting, and countries with active research communities and extensive resistance surveys tend to contribute a disproportionately high number of confirmed cases (Beckie, 2006; Peterson et al., 2018; Heap, 2026). In contrast, lower numbers of reported cases in some regions may partly reflect under-reporting and limited monitoring capacity rather than a genuinely lower occurrence of herbicide resistance.

Table 2. Distribution of herbicide resistance by mode of action in countries

Countries	Mode of actions*						Number of cases**
	ACCase	ALS	PSII	EPSP	Auxin	PPO	
United States	53	237	138	189	26	31	610
Australia	29	56	14	39	12	-	156
Canada	18	68	33	17	8	4	128
France	9	28	24	5	2	-	66
Brazil	10	32	6	20	6	5	58
China	12	23	3	2	6	3	53
Spain	5	14	22	12	2	1	47
Italy	12	20	7	5	2	-	40
Argentina	5	10	-	23	5	2	37
Japan	3	22	1	3	-	-	37
Israel	8	16	14	2	-	1	34
Germany	9	15	17	-	-	-	33
United Kingdom	4	11	10	-	1	-	28
New Zealand	3	6	3	5	6	-	25
Poland	6	11	9	1	1	-	25
Switzerland	3	5	17	3	-	-	22
Belgium	3	5	9	-	-	-	21
Malaysia	3	6	1	3	4	-	20
Türkiye	6	11	-	2	1	-	15

*: The number of cases reported for each mode of action is presented separately for each country. Since resistance to multiple modes of action may occur within the same population, row totals may not equal the total number of reported cases, **: The table includes only countries with ≥20 reported resistance cases, ACCase: Acetyl CoA Carboxylase enzyme inhibitors, ALS: Acetolactate Synthase enzyme inhibitors, PSII: Photosystem II inhibitors, EPSP: 5-enolpyruvylshikimate-3-phosphate synthase enzyme inhibitors, PPO: Protoporphyrinogen oxidase enzyme inhibitors

It should be noted that the number of cases presented in Table 2 is based exclusively on records available in the International Herbicide-Resistant Weed Database (Heap, 2026). Therefore, these values represent confirmed cases reported to the database rather than the total number of herbicide resistance studies conducted within each country. For example, several studies conducted in Türkiye have documented herbicide-resistant populations of *Sinapis arvensis*, *Alopecurus myosuroides*, *Conyza* spp., *Lolium multiflorum*, *Avena sterilis* subsp. *ludoviciana*, *Avena* spp., and *Amaranthus palmeri* (Boylu and Kaya Altop, 2021; Sin and Kadıoglu, 2021; Doğan et al., 2022; Kaya Altop et al., 2022; Türkseven et al., 2022; Çil Turgut, 2023; Ateş et al., 2024; Süer et al., 2024; Kaya-Altop et al., 2025), although many of these cases have not yet been incorporated into the international database. This observation further highlights that differences among countries may partly reflect variations in reporting and database submission practices rather than true differences in the occurrence of herbicide resistance.

2.3. Changes by mode of actions

Considering the current resistance status, resistance has been detected in 21 of the 26 different 78 modes of action, and these have been recorded with a total of 1.776 reports (Heap, 2026). The distribution of these recorded reports according to their modes of action is given in Table 3.

Table 3 shows that, the highest rate, 42.23%, belongs to the Acetolactate Synthase (ALS) inhibitor group. This shows that almost half of the herbicide resistance reported worldwide occurs in herbicides that inhibit the ALS enzyme.

Table 3. Distribution of cases recorded according to mode of action

Mode of action	Number of cases	Percentage of total reports (1776 total reports) (%)
ALS inhibitors	750	42.23
EPSP inhibitors	387	21.79
PSII inhibitors	386	21.73
ACCase inhibitors	285	16.05
Auxins	96	5.41
PPO inhibitors	50	2.82

The predominance of ALS inhibitor resistance worldwide is likely associated with their extensive and repeated use, broad-spectrum weed control, and the relatively simple genetic basis of resistance. In many weed species, single point mutations in the ALS gene can confer high levels of resistance, facilitating the rapid evolution and spread of resistant populations (Tranel and Wright, 2002; Yu and Powles, 2014; Peterson et al., 2018).

The ALS inhibitor group is followed by 5-enolpyruvylshikimate-3-phosphate (EPSP) synthesis inhibitors (21.79%) and Photosystem II (PSII) inhibitors (21.73%). Again, these two groups of modes of action are important mechanisms in which resistance development is common. Acetyl CoA Carboxylase (ACCase) inhibitors (16.05%) are another mechanism of action frequently reported, especially in monocots weeds. Resistance to auxin group herbicides and Protoporphyrinogen Oxidase (PPO) inhibitors occurs at lower rates. This highlights that resistance to ALS, EPSP, and PSII inhibitors has become a serious global problem.

2.4. Changes based on active ingredients

Currently, there are 361 different active ingredients belonging to 26 different mode of action (Anonymous, 2026b) (Figure 1). As can be seen from the Figure 1, the largest number of active ingredients belong to PSII inhibitors (73). This group is followed by ALS inhibitors (58) and VLCFA (Very Long Chain Fatty Acid Synthesis) inhibitors (46) (Figure 1). Additionally, resistance cases have been reported for 168 of the 361 different active ingredients (Heap, 2026). Of the 1.776 total reported cases, the 20 active ingredients with the highest resistance are listed in Table 4, which shows that glyphosate ranks first among all cases with 386 reports, followed by atrazine (246), imazethapyr (142), iodosulfuron-methyl-Na (129), and fenoxaprop- ethyl (123).

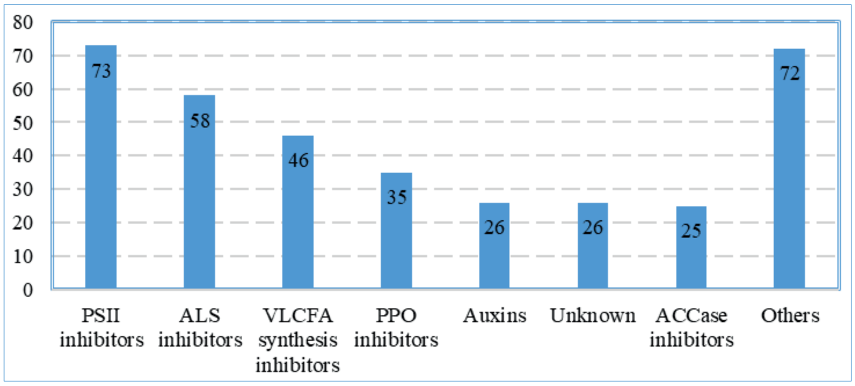

Figure 1. Number of active ingredients by mode of action

Table 4. Distribution of active ingredients in the total report

Active ingredients*	Number of cases	Percentage (%)
Glyphosate	386	21.73
Atrazine	246	13.85
İmazethapyr	142	8.00
İodosulfuron-methyl-na	129	7.26
Fenoxaprop-ethyl	123	6.93
Tribenuron-methyl	112	6.31
Mesosulfuron-methyl	98	5.52
Chlorsulfuron	98	5.52
Thifensulfuron-methyl	97	5.46
Diclofop-methyl	88	4.95
Metsulfuron-methyl	85	4.79
Clodinafop-propargyl	82	4.62
İmazamox	81	4.56
Paraquat	77	4.34
Simazine	72	4.05
Pinoxaden	65	3.66
Nicosulfuron	65	3.66
Chlorimuron-ethyl	64	3.60
Pyroxsulam	61	3.43
Bensulfuron-methyl	59	3.32

*: Since resistance to more than one active ingredient can be detected in the same population, row totals may not reflect the total number of reports.

The predominance of glyphosate resistance can largely be attributed to the widespread adoption of glyphosate-resistant (GR) crops and conservation agriculture systems since the mid-1990s. In many production regions, particularly in North and South America, glyphosate has been applied several times during a single growing season and often without sufficient herbicide rotation or diversification of weed management practices. This unprecedented dependence on a single herbicide has imposed exceptionally high selection pressure, leading to the rapid evolution and spread of glyphosate-resistant weed populations (Duke and Powles, 2008; Powles and Yu, 2010; Green, 2018; Peterson et al., 2018).

2.5. Changes based on weeds

As previously stated, the 1.776 reported cases were recorded across 273 weed species, comprising 156 broadleaf and 117 grass weed species (Heap, 2026). The weed species with the highest number of reported cases are listed in Table 5; these cases are particularly concentrated in dicots weeds of the

Table 5. Weed species with the highest number of resistance cases reported

Weed species	Number of cases
Amaranthus palmeri	86
Lolium perenne ssp. *multiflorum*	76
Conyza canadensis	70
Amaranthus tuberculatus (= A. rudis)	67
Kochia scoparia	59
Lolium rigidum	57
Avena fatua	56
Echinochloa crus-galli var. *crus-galli*	55
Chenopodium album	52
Amaranthus retroflexus	52

Amaranthus genus [*A. palmeri* (86), *A. tuberculatus* (67), *A. retroflexus* (52)] and annual monocots weed species (*Lolium* spp., *Avena* spp., *Echinochloa* spp.). *A. palmeri*, the most frequently reported species, is considered one of the most problematic weeds worldwide due to its rapid growth, high seed production capacity, and rapid development of resistance. Similarly, *Lolium* and *Conyza* species, as well as species such as *Kochia scoparia* and *E. crus-galli*, are also important in terms of weed management due to their tendency to develop resistance to multiple modes of action. Furthermore, as is well known, weeds can show resistance to multiple modes of action. *Lolium rigidum* and *Poa annua* rank first, developing resistance to 12 different modes of action. These weed species are followed by *E. crus-galli* (10) and *A. palmeri* (9), respectively (Figure 2).

2.6. Changes based on crops

Wheat, corn, and rice are among the most widely cultivated crops in the world. Consequently, cases of resistance associated with continuous herbicide use are most frequently encountered in these crops. Figure 3 shows that of the 1.776 cases reported, 482 occurred in wheat fields, 370 in soybean fields, 354 in corn fields, and 195 in rice fields. This distribution shows that resistance development occurs most frequently in production systems with intensive monoculture and large cultivation areas worldwide.

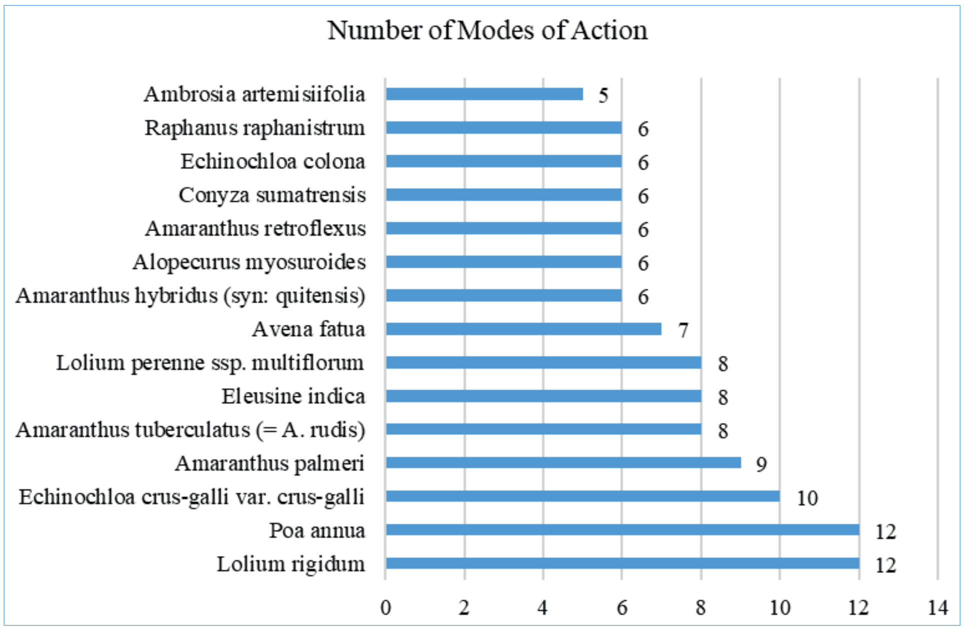

Figure 2. The 15 weed species showing the highest resistance to the most modes of action (Heap, 2026)

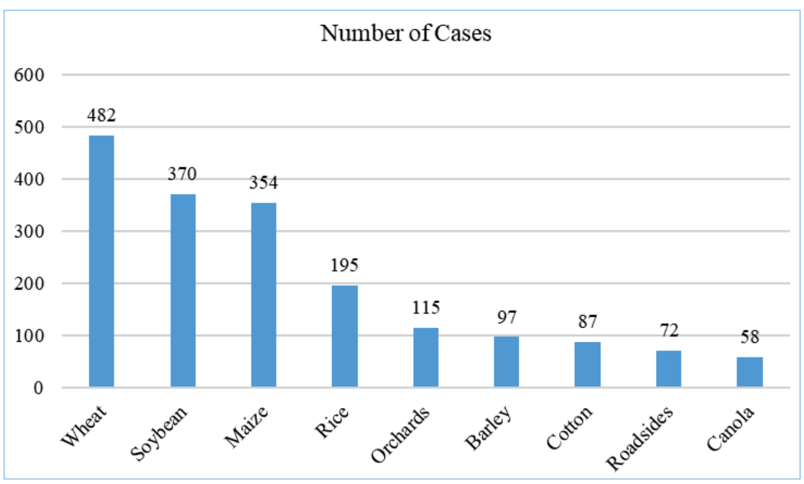

Figure 3. Number of cases by crops

3. Strategies for the Management of Herbicide-Resistant Weeds

The continuous growth of the world population has made food security a major issue, especially in developing countries. Sustainable increases in production have become essential to meet this growing demand. However, stress factors associated with climate change, such as drought, floods, fires, and unpredictable climate variations, significantly constrain efforts toward this goal (Ziska et al., 2004; Mia et al., 2020). Furthermore, the rapidly spreading herbicide resistance in weed species is also emerging as one of the most important factors threatening production potential.

The decline in the effectiveness of herbicides over time and the emergence of multiple resistances in many common weed species have led to the questioning of current control strategies in modern agriculture (Peerzada et al., 2019; Riemens et al., 2022). Therefore, it is clear that systems relying solely on chemical control are not sustainable in 21st-century agriculture. Therefore, more innovative, diversified, and holistic strategies, and consequently integrated weed management, are needed to slow down the development of resistance and make production systems sustainable (Hicks et al., 2018; Scavo and Mauromicale, 2020; Radicetti and Mancinelli, 2021). Integrated weed management involves the combined application of monitoring, prevention, and control methods and the selection of strategies best suited to local conditions (Neve et al., 2018; Khan et al., 2019).

Preventive and cultural weed control methods aim to increase the competitive power against weeds by ensuring the strong early development of the crop plant (Akhter et al., 2020). Studies have shown that practices such as appropriate tillage, planting time, planting density, crop rotation, and mulching can significantly reduce weed density (Garrison et al., 2014; Bhullar et al., 2015; Gu et al., 2021; Ofosu et al., 2023). Crop rotation and cover crops, in particular, are effective cultural strategies that limit weed pressure by optimizing resource use.

Physical and mechanical control methods are also widely used in developed and developing countries. Physical control methods such as hoeing or manual weed removal have been practiced for centuries and are still preferred in some regions. However, they have limitations in commercial production due to high labor requirements, time consumption, and high costs over large areas. While mechanical control methods are effective in clearing large areas of weeds, they are not always as effective as chemical control due to climate conditions, cropping systems, weed species, operational costs, and risks to biodiversity (Kewat, 2014; Bahadur et al., 2015; Ofosu et al., 2023).

Biological control of weeds is an environmentally friendly approach based on suppressing weeds through their natural enemies (Den Breeyen et al., 2022). In this context, allelochemicals, plant extracts, microorganisms, and insects can be used as bioherbicides. In recent years, studies on the long-term effectiveness and environmental impacts of biological control agents have increased (Tanaka and Murata, 2017; Müller-Schärer et al., 2020). While bioherbicides are effective by disrupting fundamental physiological processes such as photosynthesis and nutrient uptake, factors such as environmental conditions, formulation difficulties, and cost limit their widespread use (Cordeau et al., 2016; Hasan et al., 2021). Nevertheless, biological methods have been shown to be effective when used in combination with other control strategies. For example, the combined use of sheep grazing and herbicide application has been more successful in controlling *Bromus tectorum* L. than herbicide application alone (Lehnhoff et al., 2019).

Furthermore, in recent years, technologies such as organic farming, precision agriculture, robotic systems, remote sensing, artificial intelligence, and modeling have become important components of sustainable weed management (Sims et al., 2018; Westwood et al., 2018; MacLaren et al., 2020). Precision agriculture technologies and site-specific weed management systems enable the spatially targeted application of control measures by identifying weed-infested areas within fields, thereby reducing unnecessary herbicide inputs. Similarly, artificial intelligence-based weed detection systems and autonomous robotic weeders can identify and manage weeds with high accuracy through machine vision and sensor technologies. These approaches have considerable potential to reduce herbicide use, improve application efficiency, and delay the evolution of herbicide resistance (Bybee-Finley and Ryan, 2018; Bajwa et al., 2019; Esposito et al., 2021; Roslim et al., 2021; Zhang et al., 2022).

4. Conclusions and Future Perspectives

This study evaluated 1.776 cases of herbicide resistance reported worldwide to date from various perspectives and clearly demonstrated that resistance is widespread across species, modes of action, and production systems. The findings indicate that relying solely on chemical methods for weed control is unsustainable and that herbicide efficacy has seriously declined in many production systems. In particular, the spread of species that have developed resistance to multiple modes of action necessitates a rethinking of current control strategies.

An effective weed management program requires the balanced and combined application of cultural, mechanical, biological, and chemical methods. Herbicides will continue to play an important role in control programs; however, crop pattern, weed species, application timing, dosage, mode of action, and soil characteristics must be considered when selecting herbicides. In particular, applying herbicides at the correct growth stage and adopting rotation based on the mode of action are critical to slowing the development of resistance.

However, not only producers but also researchers, policymakers, and regulatory agencies must play an active role in resistance management. Preventing the indiscriminate and uncontrolled use of herbicides, enforcing effective legislation, and increasing producers' knowledge are fundamental elements of sustainable weed management. Furthermore, the increasingly complex nature of herbicide resistance necessitates the adoption of interdisciplinary and holistic approaches in weed research.

Ultimately, success in management herbicide resistance will be achieved through long-term strategies adapted to local conditions and developed in line with integrated weed management principles, rather than solutions based on a single method. In this context, the coordinated and balanced application of cultural, mechanical, biological, and chemical control methods is critical to slowing the development of resistance and maintaining the effectiveness of herbicides. Furthermore, adopting herbicide rotations based on their mode of action, selecting appropriate doses and application times, is of great importance in slowing down the development of resistance and maintaining the effectiveness of existing herbicides.

Ethical Statement

The authors declare that ethical approval is not required for this research.

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Author Contributions Statement

The authors declare that they are equal contributors to the article, and that they have seen, read, and agreed to the published version of the manuscript.

Statement of Conflicts of Interest

The authors declare no conflicts of interest.

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