Embrapa
Portal de Periódicos da Embrapa
International Journal of Maize & Sorghum
Formerly Revista Brasileira de Milho e Sorgo
ABMS
ISSN 3086-5433

GENETICALLY MODIFIED CROPS FOR WEED MANAGEMENT IN BRAZIL

Décio Karam[1], Isabela Goulart Custódio[1], José Edson Fontes Figueiredo[1]

*Corresponding author: **decio.karam@embrapa.br**

[1] Embrapa Milho e Sorgo, Sete Lagoas, MG, Brazil.

ABSTRACT – The objective of this work is to present the biotechnological events available for cultivation, mainly in Brazil, and to discuss their introduction as part of weed management. Weeds represent a significant challenge in crop production, causing significant losses in both yield and harvest quality. Therefore, effective control of these plants is required. The widely adopted chemical control methods have selected for resistant weed population over the years. To address this issue, Genetically Modified Organisms (GMOs) resistant to the herbicide glyphosate were developed. This innovation revolutionized weed management in crops such as soybeans, maize, and cotton, bringing significant advances to Brazilian agriculture. This technology was well received by producers due to its practicality and low cost. However, the large-scale adoption of these cultivars led to widespread glyphosate use, resulting in a considerable increase in glyphosate resistance weeds. Consequently, weed management has become increasingly challenging, leaving producers with more limited and less effective options. To overcome this situation, new herbicide-tolerant cultivars that combine genes with distinct resistance traits are being introduced to the market. To date, 14 traits in soybean, 9 in corn, and 9 in cotton have been approved for commercial release. These new cultivars represent promising alternatives to the challenges posed by glyphosate-resistant weeds. Nevertheless, they must be used incorporated into integrated weed management system to ensure the long-term effectiveness and sustainability of these technologies.

Keywords: GMOs, chemical control, glyphosate, 2,4-D, dicamba.

The presence of weeds in crops is one of the main challenges for farmers. They can cause both direct damages, such as yield losses, and indirect damage, such as loss of product quality. Furthermore, volunteer plants that emerge between cropping seasons can play a crucial role, serving as hosts (green bridges) for pests and diseases (Oliveira et al., 2013; Silva & Concenço, 2014). This situation not only makes weed management more difficult and expensive, but also negatively impacts subsequent crops (Deen et al., 2006; Adegas et al., 2022). Chemical control remains the most widely used control method due to its effectiveness and cost efficiency.

Since the introduction of herbicides into the agricultural market, the selection of weed species has been observed. This selection results not only from tolerance or resistance, but also from deficiencies in the control spectrum of the herbicides molecules. This phenomenon can lead to competition between weed species and crops. An example is metribuzin, one of the first herbicides used in soybean cultivation. Its use resulted in the selection of species such as *Euphorbia heterophylla* (milkweed) (Vargas et al., 2016). Consequently, this shift caused management difficulties and increased the costs of effective weed control in this oilseed crop.

Due to the challenges faced by farmers, the industry has sought safer environmentally solutions by developing selective and broad-spectrum post-emergent herbicides. However, the increasing use of these products has led to the selection of highly resistant weeds, mainly because of the specificity of their mechanisms of action. Certain herbicides tend to select resistant plants more rapidly than those acting on multiple metabolic sites within cells (multisite).

The rapid evolution of resistant weeds, combined with the scarcity of new selective herbicides with novel mechanisms of action, has made weed management into a major challenge for farmers. In response, the chemical industry introduced Genetically Modified Organisms (GMOs) tolerant to glyphosate (Roundup Ready - RR) (Duke, 2014), especially in crops such as soybeans, maize, and cotton (International Service for the Acquisition of Agri-biotech Applications, 2019). This technology has brought numerous benefits to agriculture, providing a practical option for weed management through broad-spectrum action, ease of use, reduced cost, and greater flexibility of control, which results in a lower risk of crop damage (Adegas et al., 2022). Brazil stands out as the second largest producer of GMOs worldwide, with an adoption rate of 94% in 2019 (International Service for the Acquisition of Agri-biotech Applications, 2019). Of the areas planted with genetically modified crops in the country, 65% exhibit herbicide-tolerant traits (Silva, 2018).

However, the simplicity of resistant crops and their economic benefits have led to weed management being based almost exclusively on chemical control, with little integration of other methods (Lamichhane et al., 2017). The repeated use of the same herbicide, or herbicides with the identical mechanism of action, has resulted in the selection of resistant weeds (Heap & Duque, 2018; Adegas et al., 2022). This situation requires producers to adopt well-planned, integrated control methods to ensure effective weed control.

In addition to glyphosate tolerance, herbicide-tolerant traits have been introduced into various crops. When used appropriately, these biotechnological traits can significantly contribute to the management of resistant weeds while helping to preserve the effectiveness of glyphosate as part of an integrated weed management strategy. Therefore, this review aims to highlight and evaluate the latest herbicide-tolerant biotechnological traits and their role in weed management.

Weed resistance to glyphosate

Over the years, the use of glyphosate in resistant crops has led to the selection of glyphosate-resistant weeds (Baek et al., 2021). The first documented case occurred in 1996 in Australia, involving *Lolium rigidum* in an apple orchard after 15 years of continuous glyphosate application (Pratley et al., 1999; Baek et al., 2021; Heap, 2025).

With the introduction of the first glyphosate-resistant (RR) soybean cultivar in the United States in 1995, glyphosate use increased significantly, accelerating the global selection of resistant weeds. In 1998, the first U S. case was reported, also involving *L. rigidum* (Heap, 2025), just three years after the glyphosate-tolerant cultivars entered the market. Since then, the number of species exhibiting glyphosate resistance has grown continuously, currently totaling 58 worldwide (Heap, 2025).

In Brazil, glyphosate-tolerant soybeans were officially launched in 2005, although more than 3 million hectares had already been illegally cultivated in previous years. As a result of this early use, the first case of glyphosate resistance was reported in 2003 in Rio Grande do Sul, *L. perenne* ssp. *multiflorum*, two years before the official launch of the trait in the country (Roman et al., 2004). Since then, 12 species in the country have been identified as resistant to glyphosate which inhibits the enzyme 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS) (Figure 1).

Herbicide-resistant cultivars

In Brazil, the use of GMOs and their derivatives is regulated by Law No. 11.105, of March 24, 2005 (Biosafety Law) and Decree No. 5.591, of November 24, 2005. These regulations establish safety standards, registration procedures, and monitoring mechanisms for activities involving GMOs and their derivatives (Brasil, 2005, 2010).

To authorize the use of a genetically modified cultivar, the National Technical Commission on Biosafety (CTNBio) must evaluate potential risks to human health, living organisms, and the environment. Since its creation in 2005, CTNBio has issued opinions on 131 cultivated plants, 56 vaccines, 67 microorganisms, 10 medicines, and three

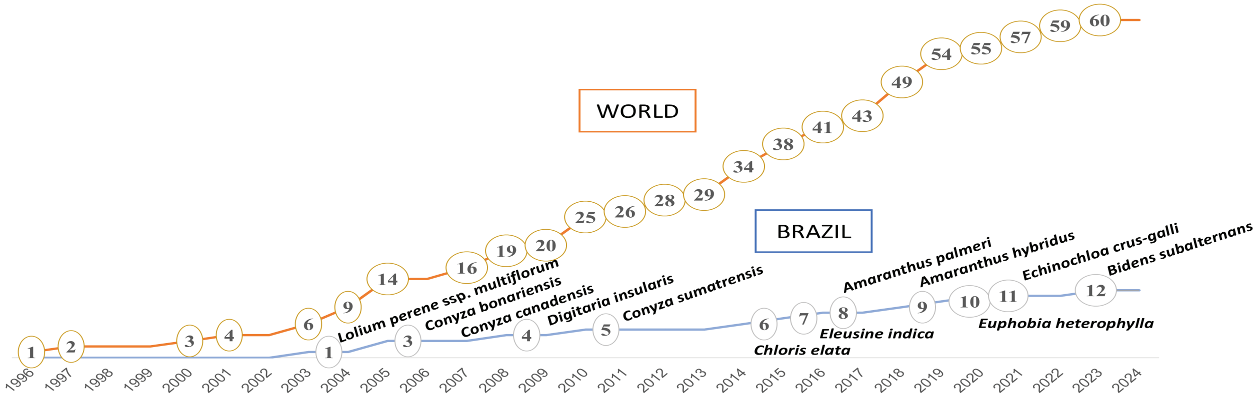

Figure 1. Number of species resistant to the herbicide glyphosate. Adapted from Heap (2025).

modified insects (CTNBio, 2025).

Among the plant species approved for commercialization, several cultivars exhibit tolerance to different herbicides, including inhibitors of the enzymes 5-enolpyruvylshikimate 3-phosphate synthase (EPSPs - glyphosate), glutamine synthetase (ammonium glufosinate), p-hydroxyphenylpyruvate dioxygenase (HPPD - isoxaflutole), acetolactate synthase (ALS – ‘sulfonylureas and imidazolinones), acetyl-CoA carboxylase – (ACCase - haloxyfop-p-methyl), and auxin mimics (2,4-D; dicamba) (Table 1).

New cultivars with herbicide-resistance traits, containing combined or separate genes for glyphosate resistance, are available on the Brazilian market (Green et al., 2008; Green & Owen, 2011; Duke, 2014). These innovations enable the diversification of mechanisms of action used during the cycle of resistant crops, helping to prevent weed escapes and providing producers with greater options for resistance management (Duke, 2014; Korres et al., 2019).

An example of new herbicide tolerance traits is the development of varieties that exhibit resistance to auxin mimics, which may or may not be associated with tolerance to other mechanisms of action. These cultivars became available on the market during the 2021/2022 growing season. With the introduction of these cultivars, farmers now have access to additional weed management technologies, which should reduce the difficulties in controlling resistant biotypes or those that are challenging to manage within exixting herbicides groups.

Auxin-mimicking herbicides, such as 2,4-D and dicamba, were commercially released in 1945 and 1967, respectively. These herbicides are classified as having a moderate to high tendency to volatilize due to their high vapor pressure, which varies depending on the formulation. For

Table 1. Events approved in Brazil for herbicide-tolerant soybeans, maize, and cotton.

Crop	Commercial Name	Gene
	glyphosate	
	Roundup Ready	cp4-epsps
	Intacta™ Roundup Ready™ 2 Pro	cp4-epsps
	HB4 × GTS 40-3-2	cp4-epsps
	glufosinate	
	Liberty Link™	pat
	Conkesta	pat
	DBN8002-3	pat
	imidazolinone	
	Cultivance	Csr-1-2
	sulfonilylurea	
	Treus™, Plenish™*	gm-hra
	HPPD-inhibiting herbicides	
	GMB151*	hppdPf4Pa
	glyphosate and glufosinate	
Soybean	HB4 e HB4 × RR	pat, cp4-epsps
	DBN-09004-6	cp4-epsps, pat
	Roundup Ready (RR) and Liberty Link (LL)	cp4-epsps, pat
	glyphosate and dicamba	
	Xtend	cp4-epsps, dmo
	Genuity® Roundup Ready™ 2 Xtend™	cp4-epsps, dmo
	Intacta 2 Xtend®	cp4-epsps, dmo
	glyphosate and isoxaflutole	
	FG72	hppd, 2mepsps
	glyphosate and sulfonylurea	
	Plenish™ x Plenish™; Plenish™ RR1*	cp4-epsps, and gmhra
	glufosinate and 2,4-D	
	Enlist™	pat, aad-12
	glyphosate, glufosinate, and 2,4-D	
	Enlist E3	2mepsps, pat, and aad-12

	Conkesta Enlist E3	pat, aad-12, and 2mepsps
	glyphosate, glufosinate, and isoxaflutole	
	Liberty Link® GT27™	2mepsps, pat, hppd
	glyphosate, glufosinate, 2,4-D, and HPPD-inhibiting herbicides	
	GMB151 × DAS-44406-6	2mepsps, pat, aad-12, and HPPD-4
	DAS44406 × DAS81419 × GMB151	2mepsps, pat, aad-1, aad-12, and hppdPf4Pa
	glufosinate, dicamba, 2,4-D, and mesotrione	
	MON94313	pat, dmo, ft_t, and tdo
	glyphosate, glufosinate, 2,4-D, dicamba, and mesotrione*	
	MON87701 × MON87754 × MON89788 × MON94313 × MON94637	cp4-epsps, dmo, ft_t, PAT, and tdo
Maize	**glyphosate**	
	Roundup Ready™ Maize / MON87427	cp4-epsps
	Roundup Ready™ 2 Maize / NK603	cp4-epsps
	TG / Roundup Ready™ Maize, Agrisure™GT	mepsps
	YieldGard™ CB + RR	cp4-epsps
	YieldGard™, MaizeGard™ / MON810	cp4-epsps
	TL TG Viptera / Agrisure® Viptera™ 3110	mepsps
	Genuity® VT Double Pro™ / MON89034 × NK603	cp4-epsps
	YieldGard™ VT™ Rootworm™ RR2 / MON88017	cp4-epsps
	Genuity® VT Triple Pro™ / MON89034 × MON88017	cp4-epsps
	MIR162 x NK603	cp4-epsps
	MON87411	cp4-epsps
	MON87427 × MON89034 × MIR162 × NK603 (and subcombinations)	cp4-epsps
	MON87427 × MON95379 × MON87411	cp4 epsps
	MON87427 × MON89034 × MIR162 × MON87411	cp4 epsps
	DAS1131	dgt-28 epsps

	MIR162 × MON87427 × MON88017 × MON94804 × MON95379	cp4-epsps
	MIR162 × MON89034 × GA21	mepsps
	MON87427 × MON94804 × NK603	cp4-epsps
	MON89034 × GA21	mepsps
	glufosinate	
	Liberty Link™ Maize	pat
	TL/ Agrisure™ CB/LL	pat
	Herculex™ I, Herculex™ CB	pat
	Herculex XTRA™ maize	pat
	TC1507 × MON810	pat
	TC1507 × MIR162	pat
	TC1507 × MON810 × MIR162	pat
	VIP2 / Agrisure® Viptera™ 2100	pat
	VIP4 / Bt11 × MIR162 × MON89034	pat
	Bt11 × 5307	pat
	Agrisure® Viptera™ 3100	pat
	Bt11 × MIR162 × MIR604 × TC1507	pat
	Bt11 × MIR162 × MIR604 × TC1507 × 5307	pat
	Agrisure™ CB/LL/RW / Bt11 × MIR604	pat
	Bt11 × MON89034	pat
	Bt11 × TC1507	pat
	MIR162 × MIR604 × TC1507	pat
	MIR162 × MIR604 × TC1507 × 5307	pat
	glyphosate and glufosinate	
	TL/TG / Agrisure™ GT/CB/LL	mepsps, pat
	Herculex™ I RR / TC1507 × NK603	cp4-epsps, pat
	Power Core PW/Dow	cp4-epsps, pat
	Optimum™ Intrasect / TC1507 × MON810 × NK603	cp4-epsps, pat
	Agrisure® Viptera™ 4	mepsps, pat
	Genuity® SmartStax ™ / MON89034 × TC1507 × MON88017 × 59122	cp4-epsps, pat
	Roundup Ready™ Liberty Link™ Maize / NK603×T25	cp4-epsps, pat

	Leptra / TC1507 × MON810 × MIR162 × NK603	cp4-epsps, pat
	TC1507 × MIR162 × NK603	cp4-epsps, pat
	Agrisure® Duracade™ 5222	mepsps, pat
	PowerCore Ultra	cp4-epsps, pat
	3272 × Bt11 × MIR604 × GA21	pat, mepsps
	Agrisure® Viptera™ 3110 / Bt11 × MIR162 × GA21	pat, mepsps
	VIP4TG / Bt11× MIR162 × MON89034 × GA21	pat, mepsps
	Agrisure® Viptera™ 2100 Roundup Ready™ 2 Maize / Bt11 x MIR162 x NK603	pat, cp4 epsps
	MIR162 × MIR604 × TC1507 × 5307 × GA21	pat, mepsps
	glufosinate and dicamba	
	MON87419	pat, dmo
	glyphosate, glufosinate, and 2,4-D	
	SmartStax™ Pro x Enlist™ / MON-87427-7 × MON-89034-3 × DAS-01507-1 × MON-87411-9 × DAS-59122-7 × DAS-40278-9	cp4-epsps, pat, and aad-1
	glyphosate, glufosinate, and dicamba	
	MON87427 × MON87419 × NK603	cp4-epsps, pat, and dmo
	2,4-D and certain ACCase-inhibiting herbicides	
	Enlist™	aad-1
	glyphosate, 2,4-D, and certain ACCase-inhibiting herbicides	
	Enlist™ RR	cp4 epsps, aad-1
	glyphosate, glufosinate, and dicamba	
	MON87427 × MON87419 × NK603	cp4-epsps, pat, and dmo
	glyphosate, glufosinate, 2,4-D, and FOPs	
	PowerCore Enlist	cp4-epsps, pat, and aad-1
	PowerCore Ultra Enlist / Power Core™ x MIR162 x Enlist™	cp4-epsps, pat, and aad-1
	glyphosate	
Cotton	Roundup Ready™ Cotton	cp4-epsps
	Roundup Ready™ Bollgard™ Cotton	cp4-epsps
	GlyTol™	2mepsps

	Roundup Ready™ Flex™ Cotton	cp4-epsps
	Roundup Ready™ Flex™ Bollgard II™ Cotton	cp4-epsps
	Bollgard® III x Roundup Ready™ Flex™	cp4 epsps
	glufosinate	
	Fibermax™ Liberty Link™	pat
	Widestrike	pat
	TwinLink™ Cotton	pat
	T304-40 × GHB 119 × COT102	bar
	T304-40 × GHB119 × COT102	bar
	glyphosate and glufosinate	
	Glytol™ x Twinlink™	2mepsps, bar
	GlyTol™ Liberty Link™	2mepsps, bar
	GlyTol LibertyLink TwinLink® Plus	2mepsps, bar
	glufosinate and 2,4-D	
	Enlist	pat, aad-12
	DAS-21023-5 × DAS-24236-5 × SYN-IR102-7 × DAS-81910-7	pat, aad-12
	glufosinate and dicamba	
	DGT	bar, dmo
	glufosinate and isoxaflutole	
	GHB811 × T304-40 × GHB119 × COT102	bar, hppd
	glyphosate, glufosinate, and 2,4-d	
	DAS-21023-5 × DAS-24236-5 × MON-88913-8 × SYN-IR102-7 × DAS-81910-7	cp4-epsps, pat, and aad-12
	glyphosate, glufosinate, and dicamba	
	RRFlexDGT	cp4-epsps, pat, and dmo
	BGIIIRRFlexDGT	cp4-epsps, pat, and dmo
	glyphosate, glufosinate, and HPPD-inhibiting herbicides	
	GHB811 × T-304-40 × GHB119 × COT102 × COT102	2mepsps, pat, and hppd W336
	GLI	pat, 2mepsps, and hppdpf W336
Eucalyptus	**glyphosate**	

	751K032	cp4-epsps
	955S019	cp4-epsps
	751K022	cp4-epsps
	955S024	cp4-epsps
	955P082	cp4-epsps
	H421 × 751K032	cp4-epsps
	H421 × 955P082 × 1521K059	cp4 epsps
	H421 × 955S024 × 1521K059	cp4 epsps
Wheat flour	**glufosinate**	
	HB4	bar

Adapted from CTNBio (2025) and International Service for the Acquisition of Agri-biotech Applications (2025). *Approved for food and feed.

example, the vapor pressure is 1.25 x 10^{-5} mm Hg for the DMA of dicamba and 3.0 x 10^{-4} mm Hg for the ester of 2,4-D. In addition to vapor pressure, environmental conditions at the time of application, such as temperature, humidity, wind, and characteristics of the treated surface, can influence the volatilization of these products (Sosnoskie et al., 2015; Mueller & Steckel, 2021; Striegel et al., 2021).

Scientific evidence demonstrates that the vapor from auxin mimicking herbicides can drift beyond the target and reach neighboring fields for up to 48 hours after application (Matthews et al., 2014; Soltani et al., 2020). This drift has caused damage to sensitive non-target crops, due to a low toxicity threshold during vegetative and reproductive growth phases and rapid physiological effects of these compounds (Kalsing et al., 2018; Costa et al., 2020). It has been shown that non-tolerant soybeans are vulnerable to low concentrations during both vegetative and reproductive growth phases. The most significant yield reductions were observed at the V5 stage with 2,4-D and at the R2 stage with dicamba (Silva et al., 2018).

Problems related to auxin-mimicking herbicide drift can be minimized by adopting specific practices. These include choosing less volatile formulations, strictly following the instructions on product labels and package inserts, considering weather conditions at the application time, and correctly using the application technology. Proper selection of nozzle type, boom height, and spraying pressure, among other factors, is essential (Paula et al., 2021).

Cultivars tolerant to the herbicides 2,4-D (Enlist) and dicamba (Xtend) represent effective options for managing broadleaf weeds that are difficult to control and resistant to other herbicide groups. These cultivars provide a broad spectrum of action and flexibility in application timing. Enlist cultivars are genetically modified organisms (GMOs) that allow post-emergence application of 2,4-D, glyphosate, and Ammonium glufosinate, while Xtend cultivars confer resistance to glyphosate and dicamba. In maize cultivation, Enlist technology also enables the use of haloxyfop-p-methyl, an herbicide that inhibits the enzyme acetyl-CoA carboxylase. This compound is particularly useful for controlling grass species, a group with few post-emergence control options. Limited alternatives for grass management remain one of the main challenges in conventional crops (Adegas et al., 2022).

Libert Link cultivars, already commercially available for agricultural use, allow the application of the herbicide ammonium glufosinate, which provides a useful alternative for managing resistance in specific weed species, such as horseweed (*Conyza sumatrensis*) and pigweed (*Amaranthus hybridus*). However, ammonium glufosinate is less effective than glyphosate in both grasses and dicotyledons and offers limited flexibility in targeting weed growth stages.

Despite the benefits offered by genetically modified cultivars, the continuous use of a single technology, without rotation of herbicides with different mechanisms of action, has resulted in restricted weed control due to resistance and has limited the long-term sustainability of this technology (Duke, 2014). Resistance to ammonium glufosinate was first reported in 2009 in *Eleusine indica* (Figure 2). Since then, only five additional species have been documented as resistant to this mechanism of action (Heap, 2025). In contrast, many species resistant to the herbicides 2,4-D and dicamba have been documented worldwide (Figures 3 and 4). In Brazil, however, only a single case of 2,4-D resistance has been reported so far, involving *Conyza sumatrensis*. This species is particularly significant because it shows resistance to five distinct herbicides modes of action (Heap, 2025). This situation highlights the importance of proper and responsible use of these tools to ensure effective weed control.

In addition to tolerance to the mentioned previously herbicides, cultivars resistant to other herbicides, such as acetolactate synthase (ALS) inhibitors and 4-hydroxyphenylpyruvate dioxygenase (HPPD) inhibitors have been introduced into crops.

The main advantage of having genetically modified organisms with different events is the possibility of rotating cultivars with distinct tolerances. This promotes the alternation of herbicides with different mechanisms of action, a strategy that contributes significantly to the management of resistant and difficult-to-control weeds, acting as a complementary tool within integrated weed management.

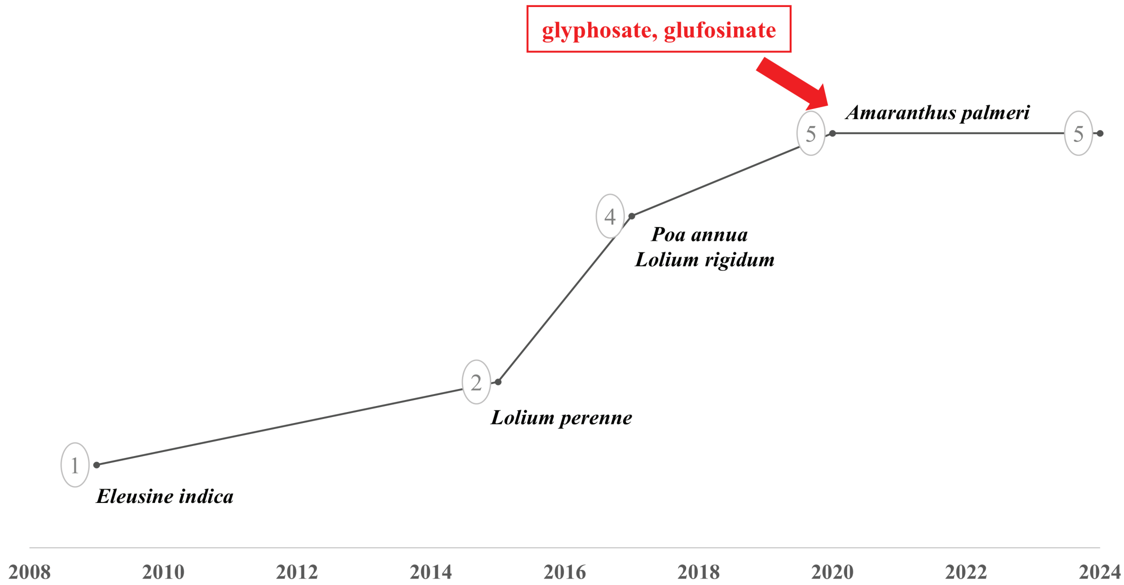

Figure 2. Herbicide glufosinate ammonium resistant weed species reported worldwide. Adapted from: Heap (2025).

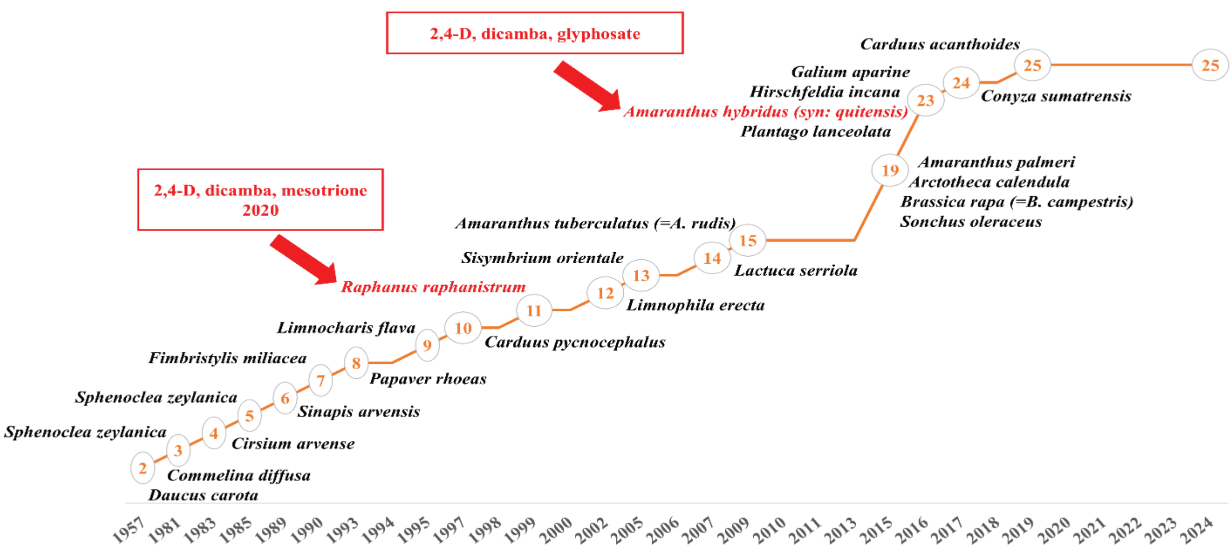

Figure 3. Herbicide 2,4-D resistant weed species reported worldwide. Adapted from: Heap (2025).

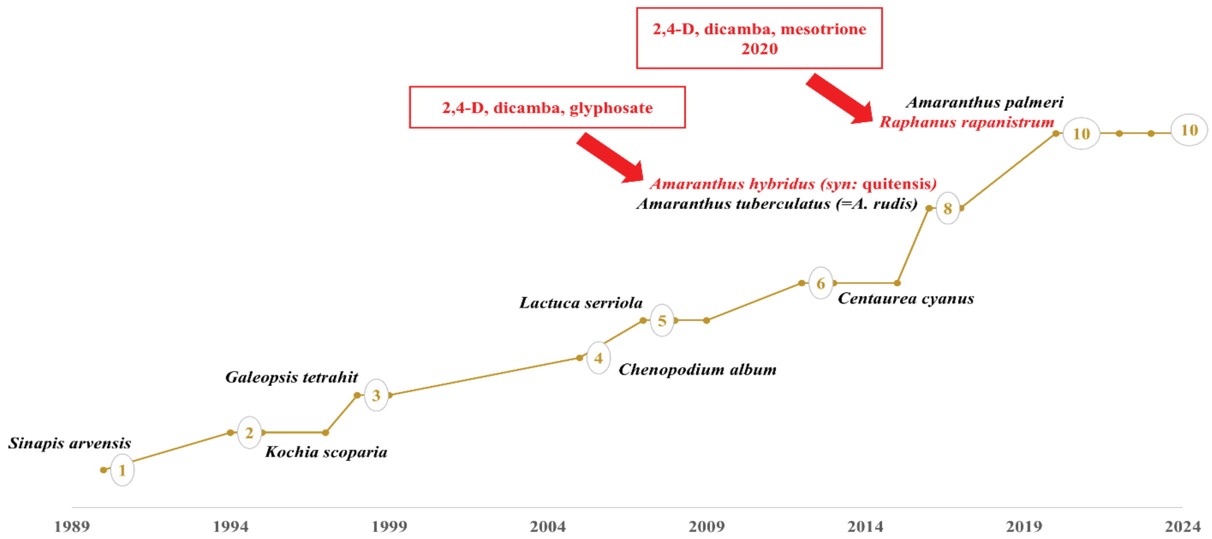

Figure 4. Weed species resistant to the herbicide dicamba worldwide. Adapted from: Heap (2025).

In several countries, beyond soybean, maize, and cotton crops resistant to glyphosate and glufosinate, other genetically modified crops have also been released for cultivation. In Canada and the United States, glyphosate-resistant potatoes, alfalfa, canola, and sugar beets have been grown, and in the United States, rice and canola glufosinate-resistant f rice and canola are also available (International Service for the Acquisition of Agri-biotech Applications, 2025).

In the United States, farmers have cultivars available that exhibit resistance to oxynil and sulfonylurea herbicides. Oxynil herbicides, which are phenolic molecules, act by blocking photosystem II and are effective in controlling broadleaf weeds (FAO, 2024). Furthermore, in Canada and Japan, a variety of canola tolerant to oxynil is available for cultivation (International Service for the Acquisition of Agri-biotech Applications, 2025).

Observations Regarding the Use of Herbicide-Resistant Crops

Although companies holding these biotechnologies have modified the formulations of certain herbicides registered for use in GMOs, farmers must remain vigilant and carefully follow the application technology recommendations provided on product labels. For crops tolerant to auxin-mimicking herbicides, the risk of drift and/or volatilization during application is particularly significant, as already reported on farms in the state of Rio Grande do Sul (Rio Grande do Sul, 2022). To minimize these risks, it is essential to review all recommendations before each application and ensure that the team responsible is properly trained and qualified.

Farmers should pay attention to several factors: (i) selecting appropriate spray nozzles and using adjuvants that reduce drift and/or volatility; (ii) monitoring weather conditions, such as temperature and relative humidity, both during and after application; (iii) avoiding application under windy condition; and (iv) ensuring product compatibility in tank mixture, since incompatibility can increase drift and/or volatility problems. These precautions are necessary for all applications, regardless of whether the cultivars are GMOs.

The availability of cultivars with single or multiple herbicide-tolerance traits provides important benefits for weed management. However, these technologies should not be regarded as stand-alone solutions, but rather as tools within integrated weed management strategies (Adegas et al., 2022).

Improper use can generate problems for farmers, their teams, and surrounding communities, and may also compromise the positive image of Brazilian agriculture, which is internationally recognized for its sustainability (Vieira Filho, 2022).

Implications of the use of genetically modified organisms in weed management

The adoption of genetically modified organisms (GMOs) represents a promising technological advancement with significant implications for agriculture, particularly in weed management. These transgenic organisms enable more practical and flexible herbicide application, and contribute to the management of weed resistance, especially glyphosate resistance. The introduction of cultivars with stacked genes conferring resistance to multiple herbicide groups is a positive development, as it reduces dependence on a single chemical product and broadens weed control options, thereby helping mitigate resistance.

Nevertheless, these technologies do not provide a definitive solution to the challenges posed by weeds. Alongside their adoption, complementary practices such as herbicide rotation and the use of cover crops must be implemented based on technical knowledge. Moreover, it is necessary to continuously update and adapt transgenic technologies throughout growing seasons to maintain their long-term effectiveness.

Although GMOs offer immediate benefits in weed control, their use should be approached with caution. The long-term impacts remain uncertain, including whether they can be integrated with other control methods or lead to intensive herbicide use, which could increase selection pressure on resistant biotypes. These concerns must be carefully evaluated by agronomists, researchers, and producers to ensure the sustainability of these technologies. Excessive herbicide use also poses environmental risks, such as soil and water contamination, with potential negative effects on non-target organisms.

Therefore, the future of modern agriculture will depend on how these new technologies are adopted and integrated into broader, more sustainable production systems. Striking a balance between technological innovation and environmental stewardship will be crucial to ensuring both crop productivity and the sustainability of agricultural systems in the years ahead.

Conclusions

The adoption of glyphosate-tolerant crops has transformed weed management, making it more efficient, cost-effective, and operationally straightforward. However, continuous use of this herbicide has resulted in the selection of resistant weed species, which are no longer controlled by glyphosate and can cause significant crop losses.

New traits should not be considered a stand-alone solution as an isolated solution to the problem of weed resistance, but rather as additional tools that support integrated management strategies and help mitigate the selection pressure associated with the repeated use of the same mode of action.

The development of multi-herbicide-resistant cultivars represents an important advance, contributing to the sustainability of modern agriculture. Yet, their use must follow specific application guidelines and respect the characteristics of each herbicide molecule involved in the tolerance event. Such precautions not only minimize risks associated with herbicide drift but also help delay the emergence of resistant weeds.

Biotechnological innovations should be employed responsibly, ensuring the preservation of both established and emerging technologies. They must be integrated into comprehensive weed management strategies, serving as valuable tools alongside cultural, mechanical, and chemical practices to guarantee effective and sustainable weed control.

Acknowledgments

To the National Council for Scientific and Technological Development (CNPq) for granting the Postdoctoral Junior Scholarship (PDJ).

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