Colegio de Postgraduados

A Review of the Current Panorama of Glyphosate Resistance among Weeds in Mexico and the Rest of the World

Arispe-Vázquez, José L.[1]; Cadena-Zamudio, Daniel A.[1]; Tamayo-Esquer, Luis M.[2]; Noriega-Cantú, David H.[1]; Toledo-Aguilar, Roció[1]; Felipe-Victoriano, Moisés[3]; Barrón-Bravo, Oscar G.[3]; Reveles-Hernández, Manuel[4]; Ramírez-Sánchez, Susana E.[5]; Espinoza-Ahumada, César A.[6*]

[1] Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias, Km 2.5 Carretera Iguala-Tuxpan, Colonia Centro Tuxpan C.P. 40000, Iguala de la Independencia Guerrero, México.
[2] INIFAP-CIRNO–Campo Experimental Norman E. Borlaug, Cd. Obregón, Sonora.
[3] Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias, Campo Experimental Las Huastecas, Altamira, Tamaulipas, México. Carretera Tampico-Mante Km 55, Altamira, C.P 89610.
[4] Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias, Campo Experimental Zacatecas-INIFAP. Carretera Zacatecas-Fresnillo Km 24.5, Calera de VR., Zacatecas, México. CP. 98500.
[5] INIFAP C.E. Centro Altos Jalisco.
[6] Tecnológico Nacional de México, Instituto Tecnológico Superior de El Mante, Km 6.7, México 85, 89930 Quintero, Tamaulipas, México.
* Correspondence: caespinoza@itsmante.edu.mx

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ABSTRACT
Objective: Review current knowledge of weed resistance to glyphosate in the México and the rest of the world.
Design/methodology/approach: The bibliographic review included a systematic study based on various databases, including FAOSTAT, FAO, SIAP and Weed science.
Results: With the introduction of resistant transgenic crops, the use of this herbicide has increased fifteenfold since 1996. Just in the last 26 years, 350 cases of glyphosate resistance among weeds have been reported worldwide; however, multiple resistance has been recorded in 23 weed species in 17 countries around the world.
Limitations on study/implications: The knowledge generated is essential to plan strategies to reduce the use of glyphosate.
Findings/conclusions: In the future, the dependence on this herbicide will result in multiple resistance among weeds, not only in Mexico, but in more parts of the world than those that have been reported to date.

Keywords: Herbicide, glyphosate, resistance, systemic, crops, weed.

INTRODUCTION
Agricultural production in Mexico is based on fruit trees (26.7%), cereals (20.3%), vegetables (18.2%), industrial (13.4%), and fodder (12.4%). The remaining percentage is distributed among dry legumes, ornamentals, oilseeds, tubers, and seeds for sowing. The annual volume of the production amounted to 142.8 million t (SIAP, 2017), but it

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increases year after year, partially as a consequence of the use of pesticides —which for years were considered innocuous for human health— to control pests, diseases, and weeds. The word pesticide includes all the chemical products used to control pests and diseases; the most frequently used are: insecticides, fungicides, herbicides, rodenticides, acaricides, and bactericides. Although pesticides have helped to increase the yields of crops, concerns about the environmental risk and their fate have been raised for years (Harner *et al.*, 1999; Tilman *et al.*, 2002; Juraske *et al.*, 2002), partially as a consequence of the secondary effects of these pesticides on the soil and mainly on aquatic microorganisms (Farah *et al.*, 2004).

Weeds compete with crops for sunlight, water, space, and nutrients. Without an adequate control (Figure 1), they can significantly impact harvests (Bayer, 2021); for years, it has been mentioned that herbicides could be used to control weeds (Gruber *et al.*, 2004).

A large number of herbicides are available in the market, and they have different modes of action and agriculture uses; they help to control the weeds present in the crop; however, some farmers still use the plow and animals for weed control (Figure 2).

Figure 1. Corn crop without an adequate weed control, which are larger than native corn plants in Puebla, México.

Figure 2. Farmer using plow and a horse for weed control.

Forming an essential part of the decision-making process involved in weed control. Such is the case of glyphosate, which has become part of the strategies employed to control weeds and to reduce crop yield losses (Danne *et al.*, 2019). More precisely, glyphosate has been part, for approximately 48 years, of the management strategies implemented by farmers in different parts of the world to control weeds. However, the intensive use of this herbicide for weed control in the world's agricultural areas currently needs attention, as a consequence of its toxicity to non-target organisms (Hoodaji *et al.*, 2012).

In terms of its composition, it is a crystalline, white, odorless powder, with a density of 1.704; it is soluble in water and insoluble in organic solvents and has no significant volatilization (Burger and Fernández, 2004). Glyphosate [N-(phosphonomethyl) glycine] is a post-emergent and systemic broad-spectrum herbicide (Jaworski, 1972; Franz *et al.*, 1997). It was developed and first used in the 1970s. At the time, it was considered harmless to human health; that is to say. Frequency of worldwide cases of glyphosate resistance among weeds previously considered non-toxic to animals and humans (Lu, 1995; Rios *et al.*, 2004) and even one of the least toxic pesticides for animals (Franz *et al.*, 1977; Duke *et al.*, 2003; Cerderia *et al.*, 2006). Its proponents even mentioned that, when it was used according to the instructions, it did not create safety problems for human health (Williams *et al.*, 2000).

It should be noted that this herbicide is the substance most frequently used to control weeds in the world (Franz *et al.*, 1997; Woodbur, 2000; Coutinho *et al.*, 2007; Dill *et al.*, 2008; Duke and Powles, 2008; Vila-Aiub *et al.*, 2008) since it was introduced by Monsanto (currently Bayer) in 1974. The first commercial product to include glyphosate was Round up® (Lee and Ngim, 2000), which was used for agricultural, industrial, recreational, forestry, and even domestic purposes (Baylis, 2000; Veiga *et al.*, 2001). However, its residues can be found everywhere, from the soil and the atmosphere to agricultural products, and even groundwater (Songa *et al.*, 2009). Species of crop plants were genetically modified to make them tolerant to glyphosate. This modification allowed their use in the management of weeds during all stages of growth (Duke, 2018). To be more precise, transgenic crops (crops with genetic modification resulting from gene manipulation) were first used in 1996 in Canada, Chile, Australia, China, Brazil, and Mexico (Lee and Ngim, 2000). In 2015, transgenic soybean and cotton crops reached 489 million dollars in profits (Brookes and Barfoot, 2017). However, the most outstanding achievement was the introduction of crops with a bacterial gene that conferred resistance to glyphosate (Dill *et al.*, 2008). As a result, the use of glyphosate in agriculture increased fifteenfold: from 51 million kg (1995) to 747 million kg (2014) (Benbrook, 2016; CIBIOGEM, 2019). However, after a 23-year period, the first case of resistance was reported for *Eleusine indica* (L) Gaertn in Malaysia (Massieu, 2009; Arellano-Aguilar and Rendón, 2017). Currently, weeds are an agronomic, economic, social, and political problem worldwide. Social problems are the indirect results of the effects on the population of high glyphosate applications.

MATERIALS AND METHODS

The bibliographic review included a systematic study based on various databases, including FAOSTAT, FAO, SIAP and Weed science. This review was carried out from

Table 1. Frequency of worldwide cases of glyphosate resistance among weed.

Specie	Year	Country	Specie	Year	Country
Amaranthus hybridus	2013	Argentina	*Conyza sumatrensis*	2009	España
	2014	Argentina		2010	Brasil
	2016	Argentina		2010	Francia
	2018	Brasil		2011	Brasil
Amaranthus palmeri	2005 (2)	Estados Unidos		2012	Grecia
	2006 (3)	Estados Unidos		2016	Francia
	2007	Estados Unidos		2017 (2)	Brasil
	2008 (4)	Estados Unidos		2017	Paraguay
	2009	Estados Unidos		2018	Australia
	2010 (6)	Estados Unidos		2019	Argentina
	2011 (4)	Estados Unidos	*Cynodon hirsutus*	2008	Argentina
	2012 (3)	Estados Unidos	*Digitaria insularis*	2005	Paraguay
	2013 (5)	Estados Unidos		2008	Brasil
	2014 (3)	Estados Unidos		2014	Argentina
	2015	Argentina		2020	Brasil
	2015	Brasil		2020	Paraguay
	2015 (3)	Estados Unidos	*Echinochloa colona*	2007	Australia
	2016	Brasil		2008	Estados Unidos
	2016	México		2008	Venezuela
	2016 (3)	Estados Unidos		2009	Argentina
	2018	Estados Unidos		2009	Australia
	2019	Estados Unidos		2010	Australia
	2020	Estados Unidos	*Echinochloa crus-galli* var. *crus-galli*	2019	Argentina
Amaranthus spinosus	2012	Estados Unidos		2020	Brasil
Amaranthus tuberculatus	2005	Estados Unidos	*Eleusine indica*	1997	Malasia
	2006 (3)	Estados Unidos		2006	Colombia
	2007 (2)	Estados Unidos		2007	Bolivia
	2008	Estados Unidos		2009	Malasia
	2009 (4)	Estados Unidos		2010	China
	2010 (4)	Estados Unidos		2010	Costa Rica
	2011 (3)	Estados Unidos		2010	Estados Unidos
	2012	Estados Unidos		2011	Estados Unidos
	2013	Estados Unidos		2012	Argentina
	2014	Canadá		2012	Indonesia
	2015 (2)	Estados Unidos		2013	Jápon
	2016 (3)	Estados Unidos		2016	Brasil
	2017 (3)	Canadá		2016	Colombia
	2020	Estados Unidos		2016	México
Ambrosia artemisiifolia	2004 (2)	Estados Unidos		2017	Brasil
	2006 (3)	Estados Unidos		2019	Italia
	2007 (4)	Estados Unidos	*Euphorbia heterophylla*	2019	Brasil
	2007	Estados Unidos	*Hedyotis verticillata*	2005	Malasia
	2007	Estados Unidos	*Helianthus annuus*	2015	Estados Unidos
	2007	Estados Unidos	*Hordeum murinum* ssp. *glaucum*	2016	Australia

Table 1. Continues...

Specie	Year	Country	Specie	Year	Country
Ambrosia artemisiifolia	2008 (2)	Estados Unidos	*Hordeum murinum* ssp. *leporinum*	2018	España
	2008	Estados Unidos	*Kochia scoparia*	2007	Estados Unidos
	2010	Estados Unidos		2009	Estados Unidos
	2012	Canadá		2011	Estados Unidos
	2013 (3)	Estados Unidos		2012 (2)	Canadá
	2014	Estados Unidos		2012 (3)	Estados Unidos
	2015	Estados Unidos		2013 (4)	Estados Unidos
	2016 (2)	Estados Unidos		2014	Canadá
	2017	Estados Unidos		2014 (3)	Estados Unidos
Ambrosia trifida	2004	Estados Unidos		2017	Canadá
	2005 (3)	Estados Unidos	*Lactuca saligna*	2017	Australia
	2006 (3)	Estados Unidos	*Lactuca serriola*	2015	Australia
	2007	Estados Unidos	*Leptochloa virgata*	2010	México
	2008	Canadá	*Lolium perenne*	2008	Argentina
	2008	Estados Unidos		2012	Nueva Zelanda
	2009 (2)	Estados Unidos		2013	Portugal
	2010 (2)	Estados Unidos		2015	Nueva Zelanda
	2011	Canadá	*Lolium perenne* ssp. *multiflorum*	2001	Chile
	2011 (2)	Estados Unidos		2002	Chile
Arctotheca calendula	2020	Australia		2003	Brasil
Aster squamatus	2021	México		2004	Estados Unidos
Avena fatua	2018	Australia		2005	Estados Unidos
Avena sterilis ssp. *ludoviciana*	2018	Australia		2006	Chile
Bidens pilosa	2014	México		2006	España
Bidens subalternans	2018	Paraguay		2007	Argentina
Brachiaria eruciformis	2014	Australia		2007	Chile
Brassica rapa	2012	Argentina		2008	Italia
Bromus catharticus	2017	Argentina		2008 (2)	Estados Unidos
Bromus diandrus	2011	Australia		2009	Estados Unidos
Bromus madritensis	2018	España		2010	Argentina
Bromus rubens	2014	Australia		2010	Brasil
Bromus tectorum	2021	Canadá		2010	Estados Unidos
Carduus acanthoides	2019	Argentina		2011	Jápon
Chloris barbata	2018	México		2011	Suiza
Chloris elata	2014	Brasil		2012	Italia
Chloris radiata	2019	Colombia		2012	Nueva Zelanda
Chloris truncata	2010	Australia		2012	Estados Unidos
	2015 (2)	Australia		2014	Estados Unidos
	2015 (2)	Australia		2015	Nueva Zelanda
Conyza bonariensis	2003	Sudáfrica		2015	Estados Unidos
	2004	España		2016	Estados Unidos
	2005	Brasil		2017	Brasil
	2005	Israel		2021	Canadá

Table 1. Continues...

Specie	Year	Country	Specie	Year	Country
Conyza bonariensis	2006	Colombia	*Lolium rigidum*	1996	Australia
	2007	Estados Unidos		1997	Australia
	2009	Estados Unidos		1998	Estados Unidos
	2010	Australia		1999	Australia
	2010	Grecia		1999	Australia
	2010	Portugal		2001	Sudáfrica
	2011 (2)	Australia		2003	Australia
	2011	Australia		2003	Sudáfrica
	2012	Argentina		2005	Francia
Conyza canadensis	2000	Estados Unidos		2006	España
	2001	Estados Unidos		2007	Israel
	2011	Estados Unidos		2007	Italia
	2002 (5)	Estados Unidos		2008	Australia
	2003 (5)	Estados Unidos		2010	Australia
	2005	Brasil		2013	Australia
	2005 (3)	Estados Unidos		2016	Grecia
	2005	China		2016	España
	2006 (2)	España	*Parthenium hysterophorus*	2004	Colombia
	2006	España		2014	Estados Unidos
	2006	Estados Unidos		2017	México
	2007	República Checa	*Paspalum paniculatum*	2010	Costa Rica
	2007 (3)	Estados Unidos	*Plantago lanceolata*	2003	Sudáfrica
	2009	Estados Unidos	*Raphanus raphanistrum*	2010	Australia
	2010	Canadá	*Salsola tragus*	2015 (2)	Estados Unidos
	2010	Polonia		2016	Estados Unidos
	2010 (2)	Estados Unidos		2019	Argentina
	2011	Canadá	*Sonchus oleraceus*	2014	Australia
	2011	Italia	*Sorgo halepense*	2005	Argentina
	2011	Portugal		2007	Estados Unidos
	2011	Estados Unidos		2008	Estados Unidos
	2012	Grecia		2010	Estados Unidos
	2013 (2)	Estados Unidos		2015	Argentina
	2014	Jápon		2018	Australia
	2014	Estados Unidos	*Tridax procumbens*	2016	Australia
	2015	Estados Unidos	*Urochloa panicoides*	2008	Australia
	2016	Hungría		2017	Argentina
	2017	Corea del Sur			
	2019	Francia			

January 2022 to December 2022. The keywords for the search were: weeds, weeds and resistance, resistant weeds, resistance among weeds, glyphosate and weeds, glyphosate, glyphosate resistant weeds, weeds and glyphosate, weeds resistant to glyphosate in Mexico and the world, weeds resistant to glyphosate worldwide.

RESULTS Y DISCUSION

Weed families and damage they cause to crops

In previous years, reports have been published in different parts of the world about the evolution of glyphosate resistance among weeds, based on producer surveys and laboratory, greenhouse, and field experiments (Beckie, 2011). The main weed families that developed the greatest resistance —according to their incidence in several countries, the number of sites of action as they acquired resistance to herbicides, and the number of crops in which they appeared— were: Poaceae, Asteraceae, Amaranthaceae, Brassicaceae, and Chenopodiaceae (Heap, 2011). After 24 years, the families that have developed the greatest resistance to the greatest number of herbicides are: Poaceae, Asteraceae, Brassicaceae, Cyperaceae, and Amaranthaceae (Heap, 2022).

Poaceae is a cosmopolitan family, capable of colonizing all kinds of environments. They are annual or perennial herbaceous plants, with alternate leaves with a linear blade and parallel venation, primary spikelet inflorescence, panicles or racemes, and small and inconspicuous flowers located on the sides of the rachis. They are hermaphrodite and have caryopsis fruits with a single seed. This family has a group of small-sized plants that includes oats (Avena), barley (Hordeum), marram (Ammophilla), and grass (Cynodon) (Soreng *et al.*, 2015; HV, 2022).

The Asteraceae family is represented by chrysanthemums, daisies, dahlias, sunflowers, thistles, chicory, and lettuce. These weeds are distributed all over the world. They are characterized by their capitular reproductive structure, in which the flowers have a sessile arrangement on a widened receptacle (Katinas *et al.*, 2007; Britto and Arana, 2014).

Brassicaceae is a family composed of annual or perennial plants, which have a worldwide distribution, but prefer temperate regions. They include subshrubs (or rarely shrubs), with typically herbaceous stems. Their leaves have a varied morphology (alternate or sometimes opposite). They have hermaphroditic flowers mostly arranged in terminal clusters (rarely in axillary or solitary clusters). Their capsule-type fruits have a highly varied morphology and their seeds have variable color and a smooth or diversely reticulated surface (Monsalve and Cano, 2003).

For its part, the Cyperaceae family has a cosmopolitan distribution: it is frequently found in open areas, ponds, and other humid places (Gómez, 2009). These annual or perennial herbs are hermaphroditic, monoecious or (rarely) dioecious. They have erected or ascending stems (culms), which are often trigonous and solid. They have simple leaves, with sometimes solitary and terminal inflorescence, which is frequently arranged in spikes, clusters, and panicles (among others arrangements), with small, bisexual or unisexual flowers and achenes as fruits (Gómez, 2003).

Finally, the Amaranthaceae family is composed of herbaceous plants, with simple alternate leaves, axillary or terminal inflorescences arranged in clusters or panicles, hermaphroditic or unisexual flowers, and actinomorphic and pixidium fruit, with lenticular, smooth, black, and often shiny seeds (HV, 2022).

The direct damage caused by this weeds diminishes crop yields, as a consequence of the competition for water, nutrients, space, and light. Likewise, their presence increases the investment cost of weeding (labor) and the acquisition of herbicides for their control.

On one hand, producers are penalized when they sell their harvest, as a consequence of the content of weed seeds in the grain and the increase in the moisture percentage. On the other hand, weeds provide refuge for pests and some diseases or they can be alternative hosts; in addition, plots with high weed populations diminish the value of the land (Altieri, 2001; Cordova, 2021). The control strategy will be adjusted to the type of growth of the weeds found on each site, evaluating the presence of broad leaves and narrow leaves and differentiating weeds from crops when there have morphological similarities, such as is the case of *Avena fatua* L. (Poaceae) and wheat regarding species of the *Lolium* and *Phalaris* minor genera, respectively (Malik *et al.*, 2003). Therefore, it is important to determine the morphological characteristics that differentiate these species in their vegetative state (García *et al.*, 2014). Presently, the resistance of weeds to herbicides has become an ecological and evolutionary phenomenon with a broad impact on agricultural production systems (Bonilla *et al.*, 2000; Pinto *et al.*, 2000).

Cases of glyphosate resistance in Mexico and the world

Glyphosate is a widely used systemic herbicide. It belongs to the organophosphate family, although it does not inhibit cholinesterases (Bourgeois *et al.*, 2016). Its mode of action includes several factors, such as: depletion of essential biomolecules synthesized from the shikimic acid pathway, energy reduction in the form of adenosine 59-triphosphate; and carbon diversion in the form of PEP and D-erythrose 4-phosphate, in order to accumulate superfluous shikimic acid and other alicyclic hydroxyacid intermediates of the shikimic acid pathway (Domínguez-Valenzuela *et al.*, 2017). In other words, glyphosate kills plants by suppressing the shikimic metabolic pathway (Diamond and Durkin, 1997). As a consequence of the inappropriate and irresponsible use of glyphosate in agriculture, weed species resistant to this pesticide have been reported in Mexico and all over the world. The countries with the highest number of resistant weed species are: USA (17), Australia (13), and Argentina (9). Worldwide, 45 weed species —including 23 dicotyledons and 21 monocotyledons— are currently resistant to glyphosate, placing it in second place, just behind atrazine (to which 66 species have developed resistance) (Heap, 2022). In just 26 years (1996-2021), 350 cases of glyphosate resistance among weeds have been reported worldwide (Heap, 2022). In Mexico, seven cases of resistance have been reported (Figure 3). Meanwhile, the weed genera with the highest frequency of reports are *Amaranthus*, *Conyza*, and *Lolium* sp.; the United States and Canada stand out with the highest resistance incidents (Figure 4).

Economic importance of weeds

Yield losses to global agriculture caused by weeds range from 30 to 50% (Quintero-Pértuz and Carbonó-DelaHoz, 2016): from 5 to 10% in developed countries, and from 20 to 30% in developing countries (FAO, 2006). In Mexico, yield losses range from 30% (corn and beans) to up to 70% and even 100% (Zita, 2010). For example, during the 2016 agricultural year, the production of corn (a crop affected by 17 species of weeds resistant to glyphosate in the world) (Heap, 2022) amounted to 27,762,480.90 t in Mexico, with a production value of MXN $100,206,306.15 (SIAP, 2017); if we assume that weeds caused 70% losses

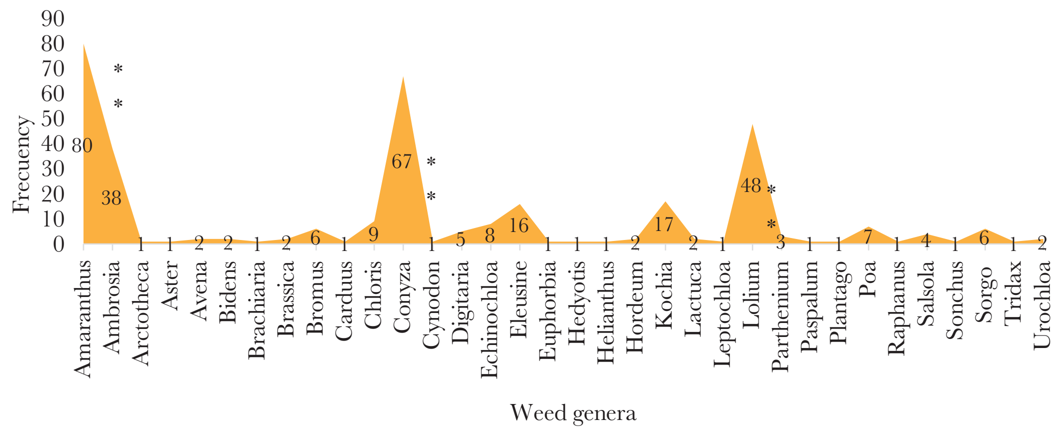

Figure 3. Current perspective of the weed genera based on worldwide reports of glyphosate resistance, **=weed genera with the highest resistance reports.

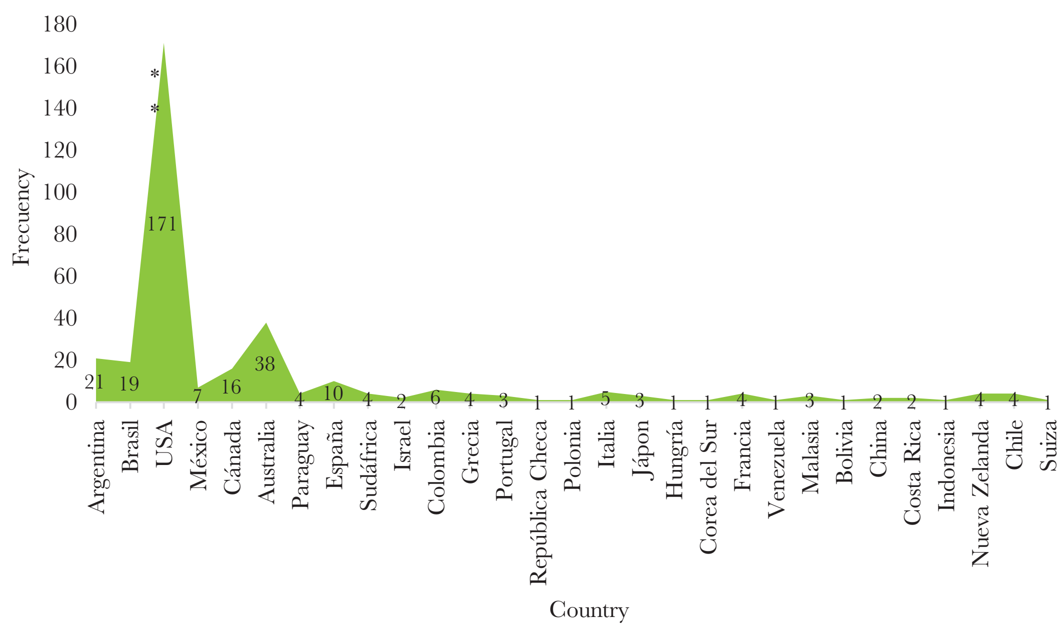

Figure 4. Countries with reports of glyphosate resistant weed species in the world, **= countries with the highest reports of glyphosate resistant.

during the said cycle in Mexico, then the losses amounted to 19,433,736.63 t and MXN $70,144,414.305. In the same year, worldwide production amounted to 1,134,746,667 million t (FAOSTAT, 2022); taking 50% as a reference, the worldwide corn losses caused by weeds during 2016 reached 567,373,333.5 million t. Consequently, in addition to the losses caused by weeds, production costs for the farmers increase, as a result of the increase in the demand for herbicides and practices for their control.

Evolution of herbicide resistant weeds

Herbicide resistance is defined as the evolutionary capacity of a weed population to survive the application of an herbicide that is used to control it (García, 2011). Resistance is attributed to two factors: the frequent use of herbicides in the same place or with the same mode of action, and their propensity to select biotypes of human resources (LeBaron, 1990; Fischer and Valverde, 2000; Beckie *et al*., 2001); and to an accelerated Darwinian evolutionary process (Vila-Aiub *et al*., 2008), caused by the selection pressure imposed by the herbicide and genetic mutations (Jasieniuk *et al*., 1996; FAO, 2022). Herbicides by themselves do not generate mutations in weeds. However, the stress caused by sublethal (low) doses of herbicides could increase the mutation rate (Neve and Powles, 2005; Gressel and Levy, 2006), as has been the case of Australia, where recommended doses are about half the amount used for the same purpose in other parts of the world (Pratley, 1996). However, multiple resistance (in different sites of action) has been recorded in 23 weed species in 17 countries (Table 2) (Heap, 2022) —*i.e.*, in 8.62% of the194 countries recognized by the UN.

Strategies to decrease the use of glyphosate in agriculture

Advances in the search for alternatives to the use of the glyphosate herbicide in Mexico basically comprise three control methods: Cultural, Biological and Chemical. Integrated allow to venture into the agroecological management of weeds in our country. For cultural control, the use of common practices for preparing the land for sowing in production systems that include annual crops is considered, as long as there is a rest period for the land (without sowing: at rest); in which the practices of fallowing, chiseling, tracking, furrow marking and coating are carried out, which spaced at least 20-25 days between them, allows preventing seed production during the rest period and in the case of perennial weeds, expose their underground organs to the sun, achieving their control through dehydration. This practice allows at least 30% control of rhizomes in the case of bindweed *Convolvulus arvensis* L. (Convolvulaceae), which in three consecutive years allows 90% control; although the seed bank remains, which in the case of this species can last at least 20 years.

The black and silver mulches achieve total control (100%) of annual weeds in avocado during the rainy season in Michoacán; which exceeds glyphosate (91%) that requires at least two applications in the season with an approximate cost of MX$2,442.00 against MX$3,500.00 per ha of the cost of the mulch. In walnut, the soil cover mesh controls 100% of annual weeds, dispensing with chemical control with glyphosate; where in the spaces between rows of the crop it is combined with pruning or localized application with bioherbicides, the cost of the soil cover mesh is paid with 1.1 t/ha of conventional walnut or 0.8 t/ha of organic walnut.

The use of cover legumes allows in citrus streets to keep weeds under control, in addition to providing nitrogen, saving water, avoiding erosion, and can be used as fodder or for seed production; Its cost is approximately $7,200.00/ha, compared to the traditional technology at Veracruz that includes four mechanical chaping, as well as three applications of glyphosate with an annual cost of $7,634.00.

Biological control is only available with the use of the morning glory mite *Aceria malherbae* Nuzzaci (Eriophyidae); which is specific for *C. arvensis* and adapts well to the northern regions at Mexico, being considered an alternative to integrate in the management of the species.

Table 2. Multiple resistance in weed species around the world.

Specie	Year	Country	Multiple resistance: sites of action				
A. hybridus	2014	Argentina	c	g			
	2016		g	e			
	2018	Brasil	c	C			
A. palmeri	2008	USA	c	c			
	2008		c	c			
	2009		c	c			
	2010		c	c	g		
	2010		c	g			
	2012		c	g			
	2013		c	g			
	2013		c	g			
	2014		c	g			
	2014		c	g			
	2015		c	f	m	g	e
	2015		j	g			
	2016		c	g			
	2016		c	j	g	d	k
	2016		j	g			
	2016		f	g			
	2019		c	g			
	2020		g	e			
A. tuberculatu	2005	USA	c	j	g		
	2007		c	g			
	2007		c	g			
	2009		c	f	j	g	
	2009		c	g			
	2011		c	f	m	g	
	2014	Canadá	c	g			
	2016	USA	j	g			
	2016		c	g	j	g	
	2016		j	g			
	2017	Canadá	c	f	j	g	
	2017		c	f	g		
	2017		f	g			
	2020	USA	c	f	j	m	g
A. artemisiifolia	2006		c	g			
	2010		c	g			
	2012	Canadá	c	g			
	2015	USA	c	j	g		
	2016		c	j	g		
	2016		c	j	g		
A. trifida	2006		c	g			
	2008		c	g			
	2011	Canadá	c	g			
	2011	USA	c	g			
A. calendula	2020	Argentina	c	i	g		
B. rapa	2012		c	g			
C. acanthoides	2019		g	e			
C. radiata	2019	Colombia	c	g			
C. bonariensis	2009	USA	l	g			
C. canadensis	2003		c	g			
	2007		c	g			
	2010		l	g			

Table 2. Continues...

Specie	Year	Country	Multiple resistance: sites of action				
C. canadensis	2011	Canadá	c	g			
	2014	USA	c	g			
	2015		l	g			
C. sumatrensis	2011	Brasil	c	g			
	2016	Francia	c	g			
	2017	Brasil	c	l	g		
	2017		f	l	j	g	e
	2017	Paraguay	c	l	g		
D. insularis	2020	Brasil	b	g			
	2020	Paraguay	b	g			
E. colona	2008	Venezuela	b	g			
E. indica	1997	Malasia	b	g			
	2009		b	g	g	h	
	2012	Indonesia	l	g			
	2016	Colombia	l	g			
	2017	Brasil	b	g			
H. verticillata	2005	Malasia	l	g			
K. scoparia	2012	Canadá	c	g			
	2012		c	g			
	2013	USA	c	f	g	e	
	2013		g	e			
	2013		c	g			
	2014	Canadá	c	g			
	2017		c	g	e		
L. perenne	2015	Nueva Zelanda	o	g	h		
L. perenne ssp. *multiflorum*	2002	Chile	c	g			
	2006		b	g			
	2007		b	c	g		
	2008	Italia	b	g			
	2010	Argentina	c	g			
	2010	Brasil	c	g			
	2010	USA	h	g			
	2012	Italia	c	g			
	2015	Nueva Zelanda	o	h	g		
	2015	USA	b	l	g		
	2016		b	c	l	g	
	2017	Brasil	c	g			
L. rigidum	199	Australia	b	c	g	d	
	2003	Sudáfrica	b	l	g		
	2007	Israel	b	c	g		
	2008	Australia	o	g			
	2010		b	c	f	l	g
	2013		l	g			
	2016	España	j	g			
P. annua	2017	Argentina	c	f	g	d	a
R. raphanistrum	2010		c	i	g	e	
S. halepense	2015		b	g			

1=Weed species reported as resistant to glyphosate, 2=Year when the weed was reported as resistant, 3=Location of report, 4=Sites of action as resistant in glyphosate-resistant weeds, a=site of action unknown, b=acetyl CoA carboxylase inhibition, c=acetolactate synthase inhibition, d=microtubule 2 assembly inhibition, e=auxin mimetics, f=PSII-serine 264 Binders inhibitors, g=enolpyruvyl shikimate phosphate synthase inhibition, h=glutamine synthetase inhibition, i=phytoene desaturase inhibitors, j=protoporphyrinogen oxidase inhibition, k=very long-chain fatty acid synthesis inhibitors, l=PS I electron deflection, m=hydroxyphenylpyruvate dioxygenase inhibition, n=inhibition of cellulose synthesis, o=inhibition of lycopene cyclase.

In the case of synthetic herbicides, the use of glufosinate ammonium and paraquat have allowed the control of glyphosate-resistant species such as *Bidens pilosa* L. (Asteraceae), whose control was 35% with glyphosate and 96.5 and 99.8% with alternatives evaluated, with similar or lower costs in the state of Veracruz. In Colima, the lemon crop is kept under control for six months with the application of paraquat + indaziflam; with a cost of MX$1,833.00 against MX$3,342.00 of the six required applications with glyphosate in this period. In addition, in the banana crop, with the application of glufosinate ammonium + indaziflam, costs are reduced by 31%, maintaining control of the annual weed complex for five months, where at least five applications of glyphosate are required.

CONCLUSIONS

In just 26 years, 350 cases of glyphosate-resistant weeds have been reported worldwide, however, multiple resistance has been recorded in 23 weed species in 17 countries around the world. In the future, dependence on this herbicide will result in multiple resistance among weeds, not just in Mexico, but in an increasing number of regions of the world where glyphosate continues to be used irrationally.

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