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EVALUATION OF GLYPHOSATE-FREE CHEMICAL ALTERNATIVES FOR WEED CONTROL IN MEXICO'S SEMBRANDO VIDA PROGRAM

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Abstract: Weed control in Mexico is usually carried out only at the time of crop establishment, which highlights the lack of implementation and planning of systematic practices in integrated weed management (IWM). This technical deficiency generates production losses ranging from 15% to 80%. It is important to note that weed control is defined according to the type of producer. Based on this approach and considering that Mexico's Sembrando Vida Program (PSV) is for small producers, preferably in marginalized areas, the federal government issued a national decree eliminating the use of glyphosate as a chemical control agent, given its harmful effects and consequences for human health. In the search for alternatives, the National Institute of Forestry, Agricultural and Livestock Research (INIFAP) evaluated five herbicides commercially distributed in the central area of Veracruz, with the aim of finding at least one glyphosate-free substitute product that guarantees more than 85% effectiveness in weed control for PSV MIAF crops. The evaluations were carried out using qualitative and quantitative methods in the field, using visual monitoring and images. The minimum and maximum application doses were those recommended by the manufacturer on the product label and based on Mexican standard NOM-232-SSAI-2009. The results show, according to the classification index of the Latin American Weed Association, two herbicides with excellent efficacy: Paraquat 2 and Ammonium Glufosinate 2, with control percentages of 93.67% and 92.33%, respectively, both products at a high dose of three liters per hectare. It is concluded that there are at least two products that can be used as substitutes for glyphosate within the contex of the PSV, which favors a progressive transition towards agroecological production systems.

Keywords: Weeds, Alternative herbicides,

Paraquat, Ammonium glufosinate

INTRODUCTION

Effective weed management is a crucial challenge for the productivity and sustainability of agricultural systems worldwide. In Mexico, there is a long history of managing "weeds," from the botanical adjective, which grows in crops (RAE, 2024), commonly known as weeds, invasive weeds, among others. They are defined as plants that are unwanted or unfavorable for human purposes (Villareal, 1983) and which, due to their characteristics of adaptation, aggressiveness, reproductive efficiency, and survival, invade and compete with crops for wáter, light, CO_2, space, and nutrients (CONAHCYT, 2021). When left uncontrolled, they can cause losses of up to 80% of yield, in addition to increasing harvesting costs and decreasing product quality (Hernández *et al.*, 2022). Weed management begins with the enormous Mesoamerican agricultural legacy, in which farmers have exploited and controlled weeds without using herbicides for thousands of years. Mesoamerican agriculture is characterized by the use of polycultures (such as the milpa) in which cultivated plants coexist with weeds, which are considered important resources of the agroecosystem. Milpa includes the management of 40 crops grouped by species and native varieties, which in some communities consists of four crops essential for food: a grass (corn), a legume (beans), a cucurbit (squash), and a root crop (sweet potato) (Lara *et al.,* 2012). One of the central characteristics of the milpa is its agrobiodiversity (Latournerie *et al.*, 2005), where it operates as a subsystem of other systems, or vice versa, to form an agroecological model as a whole (Lara *et al.*, 2012b). Over the last three decades, thousands of Mexican farmers (and farmers in much of the world) have suffered from problems of crop profitability and labor, limiting the management of agricultural practices, including weed control. This has led to a heavy dependence on agrochemicals because of their ability to accelerate processes and reduce costs in the short term. Among these, glyphosate-based herbicides stand out, which have become the commercial standard for weed control and, in turn, have generated resistance in more than 50 species, compromising their effectiveness and forcing a rethinking of management strategies (Heap, 2022; Duke, 2019). On the other hand, the World Health Organization (WHO, 2015) classified glyphosate as a probable human carcinogen (Group 2A) after reviewing nearly 1,000 scientific studies and demonstrated that this herbicid can operate through two characteristics: genotoxicity (damage to deoxyribonucleic acid, DNA) and oxidative stress (cell damage due to the presence of free radicals). It has also raised concerns due to its environmental impact and risks to human health (Benbrook, 2016; González *et al.*, 2022; SEMARNAT, 2020; Myers *et al.*, 2016). In 2019, the U.S. Department of Health published a toxicological profile of glyphosate that coincides with the report published by the WHO in 2015. In 2020, the 5th edition of the Toxicological Anthology of Glyphosate was published, which includes 1,108 scientific studies on the effects of glyphosate on health and the environment (CONAHCYT, 2021b). In particular, recent evidence links exposure to glyphosate with adverse effects including liver toxicity, endocrine disruption, and potential carcinogenicity, which has led several countries to implement restrictions or bans on its use (Mink *et al.*, 2021; Zhang *et al.*, 2020, González et al., 2022b). In Mexico, the situation is particularly sensitive due to the use of herbicides in traditional agricultural systems without integrated management protocols. As a result, the use of glyphosate has been a topic of political debate in Mexico since Andrés Manuel López Obrador became president in December 2018. In 2019, with the creation of the Sembrando Vida Program (PSV), the Mexican government consolidated its agricultural policy based on the Milpa Intercalada en Árboles Frutales (MIAF) system, which focuses on agroecological and glyphosate-free production. On the last day of 2020, a presidential decree was published instructing various public agencies to take action to "gradually replace" the glyphosate used in the country. In addition, a transition period was set to achieve the "total replacement" of the agrochemical by January 31, 2024. In a new decree in 2023, this date was posponed to March 31, and government agencies were asked to revoke authorizations and permits for the "import, production, distribution, and use" of glyphosate, as well as to refrain from granting new authorizations and permits (Mayorga, 2024).

In this context, the ban on glyphosate through the decree has prompted the search for chemical and non-chemical alternatives for weed control that are effective and less harmful (Sánchez & Wyckhuys, 2019), which guarantee effective weed control, especially in national social programs such as the PSV, which promote sustainable agriculture among small producers in marginalized areas (Ramírez & Delgado, 2023; García-López *et al.*, 2021). The PSV represents a comprehensive effort not only to eradicate the use of glyphosate, but also to encourage production models that incorporate agroecological practices, promoting food security and environmental conservation (Ramírez & Delgado, 2023b; García-López *et al.*, 2021b).Herbicides such as ammonium glufosinate and paraquat have been evaluated as possible substitutes however, their toxicity and environmental risks require careful management and rigorous evaluation (Norsworthy *et al.*, 2018; Martínez *et al.*, 2019; Duke, 2019b; López *et al.*, 2021). In addition, the transition to agroecological systems requires the holistic integration of cultural, mechanical, and chemical practices to reduce dependence on agrochemicals without compromising productivity (Altieri *et al.*, 2018; Vázquez *et al.*, 2020). Therefore, it is essential to analyze not only the chemical viability of these alternatives, but also their suitability for the PSV, where producers have low levels of technical training, use unfamiliar agrochemicals, and have limited knowledge of their management, which poses a risk to the effectiveness of weed control, environmental safety, and the sustainability of the program. In response to this national problem, the National Institute of Forestry, Agricultural and Livestock Research Institute (INIFAP) evaluated five herbicides that are commercially distributed in central Veracruz, with the aim of providing at least one glyphosate-free substitute product that guarantees more than 85% effectiveness in weed control within the contex of nationwide government programs such as Mexico's Sembrando Vida Program.

MATERIALS AND METHODS

CHARACTERIZATION OF THE STUDY AREA

This research was carried out by the Agricultural Mechanization Program, belonging to the National Institute of Forestry, Agricultural and Livestock Research (INIFAP) Cotaxtla Experimental Field Station, located at coordinates s (18° 56´24´´ N and 96° 11´ 52´´ W), in the central region of the State of Veracruz, México. The climate is classified as AW1: warm subhumid with rainfall in summer, higher humidity (68.67%) and warm subhumid with rainfall in summer, medium humidity (31.33%), with an average annual precipitation of 1,417.8 m. The average annual temperature is 25.3 °C and the average altitude is 20 meters above sea level. This area has agroecological diversity and mixed production (corn-beans, coffee, fruit trees), making it an ideal environment for evaluating alternatives in PSV agroforestry systems in Mexico. For the evaluation, a comparative field trial was conducted during the spring-summer rainy season of 2024. The site selected was an area where basic grains, mainly corn, are produced and where narrow-leaved weeds or grass-type weeds predominate, especially Dichantium annulatum, which covers almost 60% of the land. Other weeds present were Tridax procumbens, Megathyrsus maximus, Ruellia blechum, Emilia sonchifolia, Lagascea mollis, Commelina erecta, Digitaria eriantha, Melochia pyramidata, Priva lappulacea, Cynodon dactylon, Sorghum halepense, Heliotropium indicum, Malvastrum coromandelianum, and Euphorbia heterophylla.

EXPERIMENTAL DESIGN

The experimental design was completely randomized with five treatments on an area measuring 5 m x 2 m, considering a unit of measurement of 1 m^2 and six replicates for each treatment. Table 1 shows the five treatments (1-5) evaluated at two different doses: low and high, as recommended by the manufacturer.

HERBICIDE APPLICATION

Four fan nozzles (Figure 1) with the nomenclature 8001, 8002, 8003, and 8004 were evaluated for application calibration. The first two digits refer to the nozzle angle, and the last two digits refer to the flow volume in gallons per minute. In order to select an average flow rate of 200 liters per hectare, one liter of water was added to a 20-liter capacity manual spray pump and the equivalent dose of the corresponding product was applied. The test area for measuring water flow was 10 m^2 and the calibration speed was determined by the operator's walking pace.

For the chemical application of the five different products evaluated, a Jacto PHJ model double-piston backpack-type mechanical pump (Figure 2) was used, which reaches 100 psi (6.8 bar) with a 20-liter capacity tank. For the application volume, calculations were made for the dose to be used at a capacity of 200 liters per hectare. The application of the herbicides was randomized in the design, and the dose was described above.

EVALUATION

Determination of the percentage of weed control efficacy.

To determine the percentage of weed control efficacy, monitoring began with the taking of photographs in each of the plots every day after application (DDA) for a period of 7 days. One photograph was taken for each of the five different treatments and for each of the two doses (low and high). Subsequently, at 13 (DDA), the maximum efficiency of weed control was evaluated through image analysis. The 10 m^2 experimental plot was divided into 10 equal parts, where the six squares in the center were evaluated and the squares at both ends were discarded as they were considered the operator's entry and exit points for application. Six photographs were taken corresponding to six replicates (one square meter) for each of the five different treatments and each of the doses (low and high), for a total of 60 photographs. For the analysis of the photographic image, a base or square of one square meter divided into eight equal parts was used, which was then evaluated visually on the computer. The image was divided into eight sections (Figure 3), where the maximum value would be 12.5%. Based on this consideration, each of the eight sections was evaluated, and then the percentages were added and averaged to determine the effectiveness of weed control.

Treatments	Commercial product	Low dose	High dose
0*	Glyphosate control *	NA	NA
1	Paraquat 1 (200 g a.i./L)	1.5 L	2 L
2	Paraquat 2 (200 g of active ingredient/L)	1.5 L	3 L
3	Paraquat + Diuron (200 + 100 g a.i./L)	1.5 L	3 L
4	Ammonium glufosinate 1 (200 g a.i./L)	1.125 L	1.5 L
5	Ammonium glufosinate 2 (150 g a.i./L)	1 L	3 L

*(The control treatment was not applied because its use is prohibited by national decree)

Table 1. Description of treatments for herbicide evaluation

Figure 1. Fan nozzle (available online)

https://www.tipsytemasagronomicos.com/que-boquillas-utilizar-para-las/

Figure 2. Application of herbicides with a manual piston-type mechanical pump.

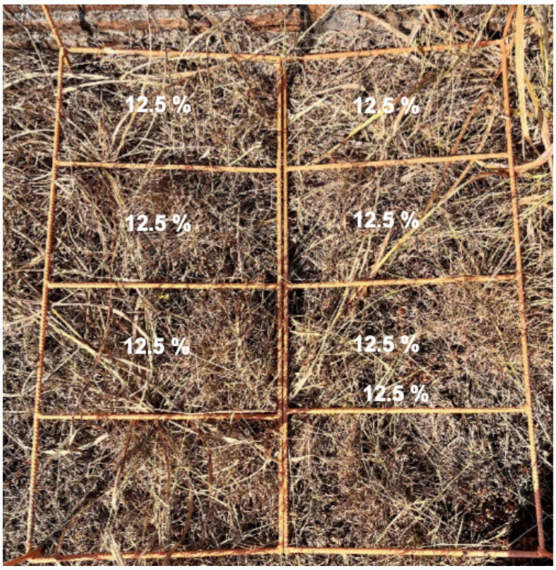

Figure 3. Example image for determining weed control efficacy.

Subsequently, the results obtained from the evaluation were compared with the scale used by the Latin American Weed Association (ALAM, 2020) in order to determine the percentage of control according to the efficacy index (Table 2).

Index	% control
0 - 40	None or poor
41 - 60	Fair
61-70	Sufficient
71 - 80	Good
81 - 90	Very good
91-100	Excellent

Table 2. Degree of weed control according to the Latin American Weed Association Weeds, (2020).

RESULTS AND DISCUSSION

Results of nozzle calibration in manual mechanical pump

Nozzle number	Area (m^2)	Initial quan-tity (L)	Final quanti-ty (L)	Amount expen-ded (L)	Con-sump-tion L/ha
8001	10	1	0.770	0.230	230
8002	10	1	0.785	0.215	215
8003	10	1	0.550	0.450	450
8004	10	1	0.645	0.355	355

Table 3. Flow rates of the different types of calibrated nozzles

Table 3 shows the difference in expenditure in liters per hectare for each nozzle, with 8003 having the highest expenditure and 8002 the lowest, respectively. After calibration, the nozzle selected for evaluation was 8002, as it was the closest to the 200 liters that are culturally applied as a dose of chemicals in the field.

Results of efficacy monitoring 7 days after application (DDA)

Figures 4 and 5 show the visual evaluation of weed control efficacy at low and high doses, respectively, with the same herbicide over a period of 7 days (DDA).

The figures show the different stages of control of the herbicide "Paraquat 2" as examples of the five commercial herbicides monitored over a period of 7 days (DDA) with low and high doses recommended by the manufacturer. The product "Paraquat 2" showed noticeable changes in weeds the day after application, while the products "Paraquat 1" and "Paraquat + diuron" began to show changes after the second day. Finally, the products "Ammonium glufosinate 1 and 2" began to act after the fourth day, and this behavior was reflected in both application doses.

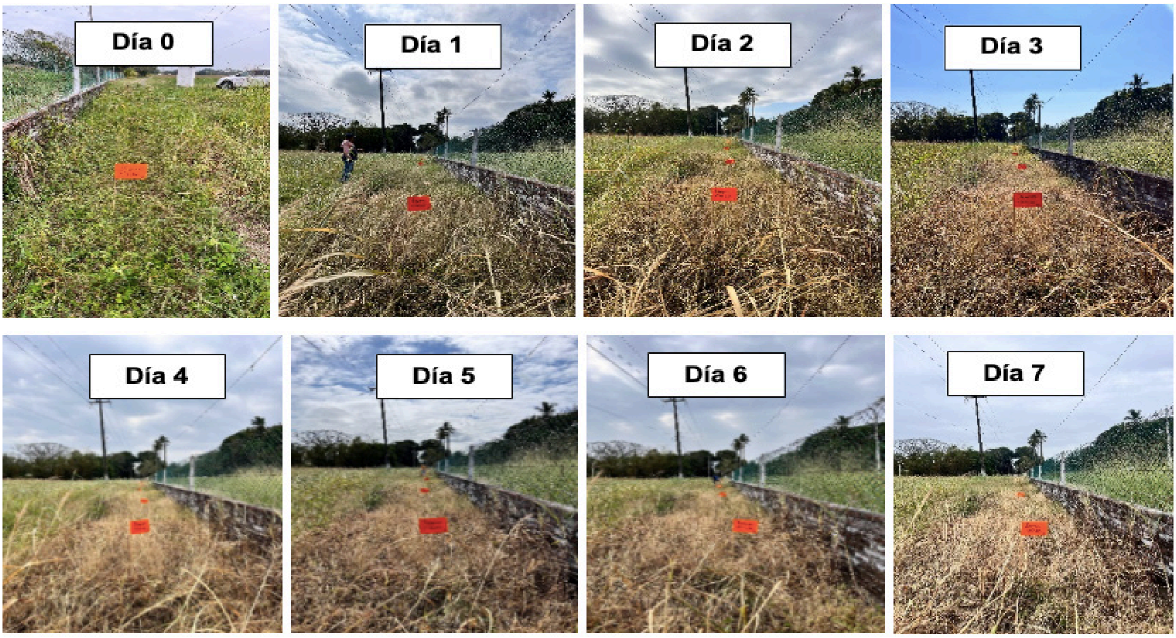

Figura 4. Example of high-dose efficacy of the commercial product "Paraquat 2" monitored over a period of 7 days (DD7).

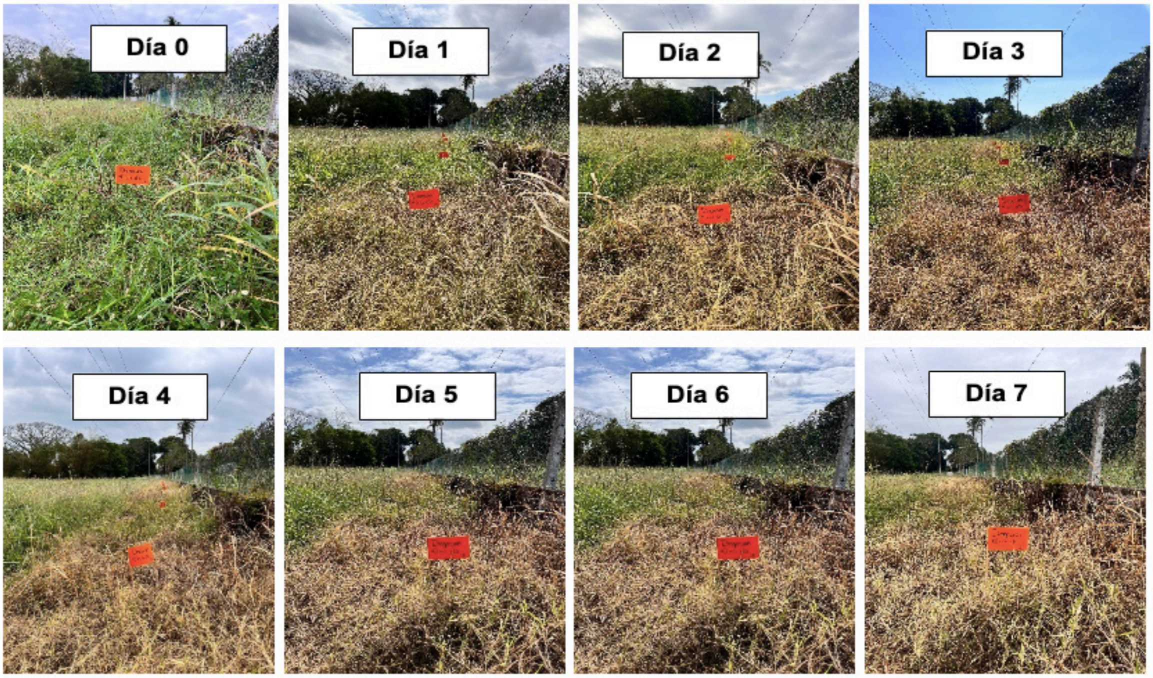

Figure 5. Example of high-dose efficacy of the commercial product "Paraquat 2" monitored over a period of 7 days (DD7).

RESULTS OF THE PERCENTAGE OF WEED CONTROL EFFICACY AT 13 (DDA)

LOW DOSE

Table 4 shows, as an example, the result of the average values of the product's efficiency at 13 (DDA) at low doses: Paraquat 1 (200 g of active ingredient/L) = 72.50%.

Table 5 shows the average values of the visual assessment of weed control efficacy at after application (DAA) at low doses for all herbicide treatments.

Table 6 shows that, in terms of weed control percentage, the two herbicides paraquat 1 and paraquat 2 can be considered a good option for low-dose application.

HIGH DOSE

Table 7 shows, as an example, the results of the average values for product efficiency at 13 DDA at high doses: Paraquat 1 (200 g of active ingredient/L) = 65.67%.

Table 8 shows the average values of the visual assessment of weed control efficacy at 13 days after application (DAA) at high doses for all herbicide treatments.

Table 9 shows the percentage and index of weed control for the two herbicides, paraquat 2 and ammonium glufosinate 2, both of which can be considered as options for high-dose application. Figures 6 and 7 show the results of the visual evaluation and photographic analysis at 13 (DDA) with a low dose of T2, where it can already be seen that the weeds have been completely eliminated.

An important consideration in the evaluation results is that in the continuous monitoring for all treatments T1, T2, T3, T4, and T5, the observed control time for each of the herbicides at low doses reached a maximum control of 22 (DDA) for the low doses with the determined efficacy. This was not the case for the high dose, where ammonium glufosinate (T5) reached a maximum control of 27 (DDA) for the low dose with the determined efficacy.

Monitoring 27 days after low- and high-dose application for weed control of the five different herbicide treatments.

Figure 8 shows a photograph of each of the evaluation plots with each of the five herbicides at low doses. It can be seen that there is no longer any damage to the weeds; on the contrary, new weeds have begun to sprout, so it is assumed that the products applied at low doses do not have very long-lasting control.

Figure 9 shows the five different commercial herbicides at high doses, 27 days after their application in the field, and it can be seen that the only herbicide that controlled weeds was (T5) "Ammonium glufosinate 2. "

Another important factor to consider in this evaluation is the price or cost of each of the commercial herbicides in order to interpret the best option from a technical and economic point of view.

Commercial product	Price per liter
Paraquat 1	$102.8*
Paraquat 2	$66.36
Paraquat + diuron	$119.63
Ammonium glufosinate 1	$224.53
Ammonium glufosinate 2	$160.00

* List prices for July 2024

Table 10. List prices of commercial herbicides

Table 10 shows the price per liter for each product. The most expensive herbicide is "Ammonium glufosinate 2" with a market price of $160, and the least expensive product is "Paraquat 2" with a price of $66.36 per liter. Given the price conditions and the results of the evaluation, option 1 for weed control is ammonium glufosinate 2 (T5) and option 2 is paraquat 2 (T2).

		Paraquat 1 at low dose									
	C1*	C2*	C3*	C4*	C5*	C6*	C7*	C8*	Sum	Maximum %	Average (%)
R1	5	10	6	10	11	10	7	7	66	100	72.50
R2	10	11	7	9	6	10	10	10	73		
R3	10	6	10	10	10	6	11	11	74		
R4	11	11	10	11	11	8	8	11	81		
R5	6	10	10	10	5	10	12	11	74		
R6	5	5	11	12	5	7	10	12	67		

C1*- C8*: Represent each of the 8 divisions for visually evaluating the efficacy of the product in the photograph.

Table 4. Example of a treatment (T1) with repetitions and the average value of the visual image evaluation and analysis at 13 (DDA) at low dose.

Product	Paraquat 2	Paraquat + Diuron	Ammonium glufosinate 1	Ammonium glufosinate 2
Efficacy	76.17	60.67	58	58.83

Table 5. Average values in the visual evaluation and analysis of efficacy at 13 (DDA) in low doses of T2, T3, T4, and T5 commercial products.

Herbicide	Percentage of efficiency (%)	Index	% weed control weeds
Paraquat 1	72.50	71-80	GOOD
Paraquat 2	76.17	71-80	GOOD
Paraquat + diuron	60.67	41-60	AVERAGE
Ammonium glufosinate 1	58.00	41-60	REGULAR
Ammonium glufosinate 2	58.53	41-60	REGULAR

Table 6. Efficacy control rates in percentage and index according to ALAM of commercial products at low doses.

		Paraquat 1 at high dose									
	C1*	C2*	C3*	C4*	C5*	C6*	C7*	C8*	Sum	Maximum %	Average (%)
R1	6	6	2	6	6	6	2	10	44	100	65.67
R2	8	8	8	10	8	10	6	8	66		
R3	10	6	6	8	10	6	6	8	60		
R4	10	8	6	8	10	8	6	10	66		
R5	10	10	10	10	10	10	10	10	80		
R6	10	10	10	10	10	8	10	10	78		

C1*- C8*: Represent each of the 8 divisions to visually evaluate the effectiveness of the product in the photograph.

Table 7. Example of a treatment (T1) with repetitions and the average value in the evaluation and visual analysis of the image at 13 (DDA) in high doses.

Product	Paraquat 2	Paraquat + Diuron	Ammonium glufo-sinate 1	Ammonium glufosinate 2
Efficacy	93.67	74.67	85	92.33

Table 8. Average values in the visual evaluation of efficacy at 13 days after application (DAA) at high doses of T2, T3, T4, and T5 commercial products.

Herbicide	Percentage of efficacy (%)	Index	% weed control weeds
Paraquat 1	65.67	61-70	SUFFICIENT
Paraquat 2	93.67	91-100	EXCELLENT
Paraquat + diuron	74.67	71-80	GOOD
Ammonium glufosinate 1	85.00	81-90	VERY GOOD
Ammonium glufosinate 2	92.33	91-100	EXCELLENT

Table 9. Degrees of control efficacy in percentage and index according to ALAM of commercial products at high doses.

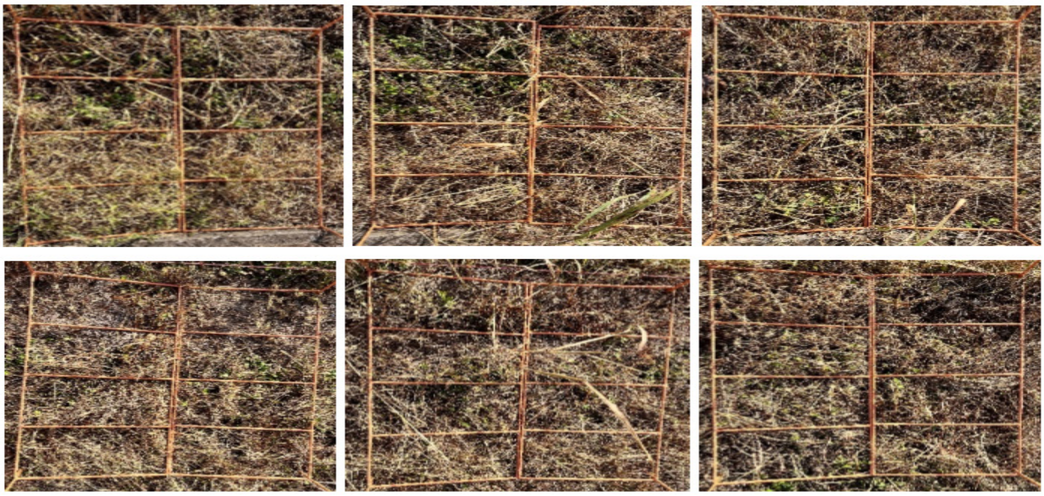

Figura 6. Evaluación visual de la eficiencia en dosis baja del segundo herbicida comercial "Paraquat 2",13 DDA y calificado como "BUENO" según la ALAM.

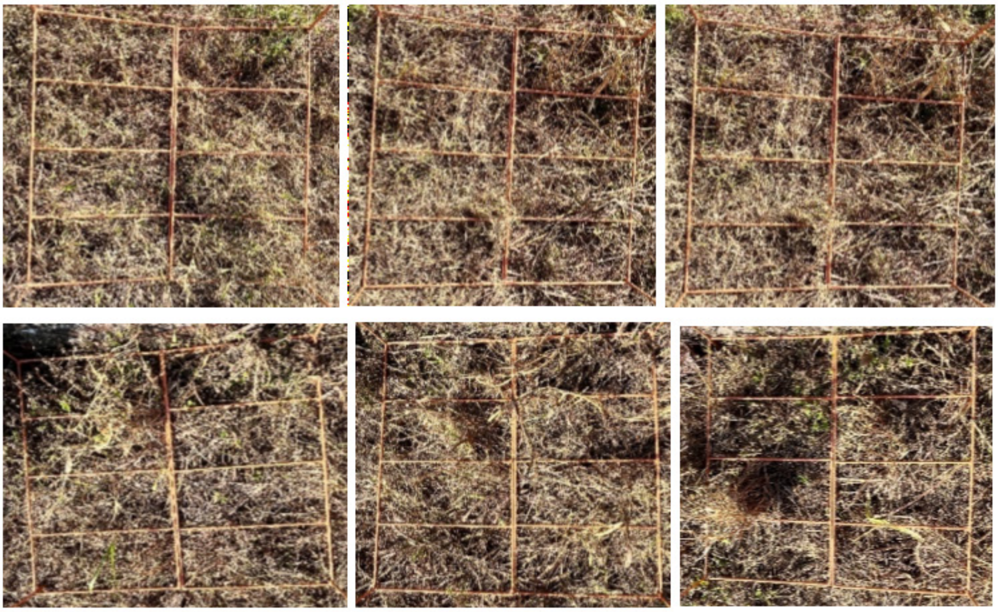

Figure 7. Visual assessment of the high-dose efficiency of the second commercial herbicide, Paraquat 2,13 DDA, rated as "EXCELLENT" according to ALAM.

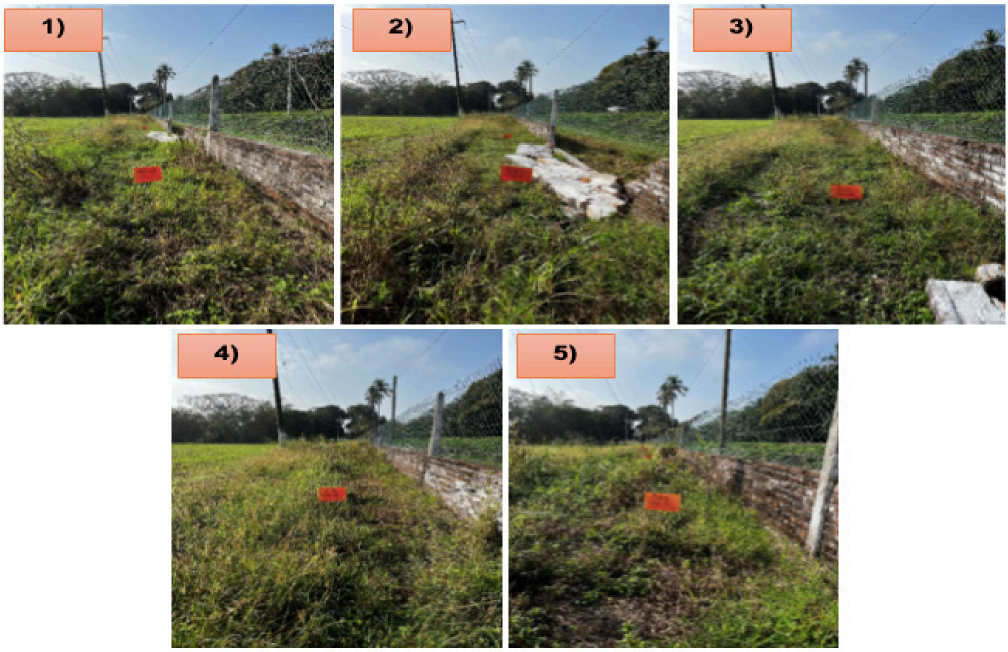

Figure 8. Monitoring of the efficiency of the five herbicides at low doses 27 DDA.

Figure 9. Efficiency monitoring at 27 DDA of the five herbicides at high doses.

CONCLUSIONS

Treatment with ammonium glufosinate 2 (150g. of a.i./L) at a dose of three liters per hectare of commercial product is the best technical and economic alternative to replace the use of glyphosate in the milpa system under the conditions prevailing in the central region of the state of Veracruz, with an efficiency of 92.33%, a lower amount of active ingredient, greater penetration, and a longer control period of 27 days after application. Treatment 2, paraquat 2 (200 g a.i./L) at a dose of three liters per hectare of commercial product is the second alternative to replace the use of glyphosate in the milpa system under the conditions prevailing in the central region of the state of Veracruz, with an efficiency of 93.67% and a control period of 22 days after application.

It is recommended for future research to conduct toxicological tests on the products proposed here, since Mexican standard NOM-232-SSAI-2009 only regulates or controls the characteristics of the product on the label. The products evaluated are in precaution category four, blue band, and hazard three, yellow band.

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