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Evaluation of Herbicides on the Control of Weeds and Phytotoxicity in a Habanero Pepper Crop (*Capsicum chinense* Jacq.) in the State of Yucatan, Mexico

Wilson Avilés-Baeza[1], Mónica Guadalupe Lozano-Contreras[1*], Jorge H. Ramírez-Silva[2], Juan Jasso-Argumedo[1], Rubén Guerrero-Medina[1]

[1]Campo Experimental Mocochá del Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (INIFAP), Mocochá, México
[2]Centro de Investigación Regional Sureste del Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (INIFAP), Mérida, México
Email: *lozano.monica@inifap.gob.mx

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Abstract

Herbicides play a major role in any crop as they are an essential part of the inputs used by farmers to control weeds. However, their excessive and continuous use can induce human health and environmental problems; the risk of provoking weed resistance to herbicides is also a potential problem. The objective of this work was to evaluate different commercial herbicides on the control of weeds present in a habanero pepper crop and their phytotoxic effect on crop development. The experiment was carried out during the Autumn-Winter 2021 cycle in the municipality of Muna, Yucatan, Mexico. Sixteen treatments were evaluated in a randomized complete block design with four replications. 14 dominant weed species were recorded of which 12 were broad-leaved and 2 narrow-leaved ones. The weed coverage in all herbicide-based treatments was statistically different as compared to the control at 14 days after application (DAA) with values ranging from 0.25% to 8.13%. Highlighting *Pendimethalin* (0.25%), *Ammonium Glufosinate* (1.13%), *Trifluralin* (1.5%) and *Chlorthal dimethyl* (1.88%) with the lowest weed coverage values. The greatest phytotoxic effect, on the crop, was caused by *Clomazone*. The treatments with the lowest costs were *Glyphosate* and *Paraquat* whilst *Bensulide* was of the highest ones. Except for the latter, all herbicides significantly reduced costs relative to the grower's practice.

Subject Areas

Agricultural Engineering

Keywords

Inputs, Pollution, Costs, Environment

1. Introduction

One of the main problems of modern agriculture is the growing weed resistance to herbicides during the longtime of weed control [1]. Agricultural intensification has induced the appearance of new weed species that are difficult to control due to higher population density and the emergence of new weed genotypes tolerant or resistant to herbicides [2]. Herbicides have a main role in any crop because they play a fundamental economic role to farmers when avoiding the use of highly expensive extra labor.

However, continuous overuse of a single herbicide, in a growing season, will provoke an acquired resistance of weeds to that herbicide [3]. A clear example is *Glyphosate*, considered the most widely used herbicide in the world [4]. *Glyphosate* is a non-selective, broad-action herbicide, able to kill all types of plants, either narrow or broad-leaved ones. It is a post-emergent herbicide not absorbed by roots but by leaves [4]. Because of its systemic action, it is transported internally from the point of contact with other parts of the weeds controlling both herbaceous and woody plants, annual or perennial in various growth stages [4].

The intensive use of *Glyphosate* increases the risk that new herbicide-resistant plants will emerge [5]. In addition, the risk of polluting the environment and increasing soil erosion is eminent [6]. On the other hand, in the particular case of the Yucatan Peninsula in Mexico, the intensive use of herbicides has adverse effects on aquifers, which are the main source of water for human consumption [7].

To replace gradually the use, acquisition, distribution, promotion and import of *Glyphosate* in Mexico, on December 31, 2020, a presidential decree was issued to replace that herbicide in the country [8] with sustainable, human-healthy and culturally appropriate alternatives. In this sense, a transition period, until January 31, 2024, was established to achieve the total substitution of *Glyphosate* in Mexico [8]. Based on the foregoing, the objective of this work was to evaluate the effect of different commercial herbicides on the control of weeds and their phytotoxic effects on a habanero pepper crop considering a cost-benefit analysis.

2. Materials

2.1. Location

The research was carried out in the "Leopoldo Arana Cabrera" Agricultural Unit, in the municipality of Muna, Yucatan, Mexico, located at coordinates 20˚24'52'' north latitude and 89˚44'31'' west longitude in a soil classified as

*K'ankab lu'um*for the Mayan classification and *Luvisol* for the World Reference Base of soils (WRB) [9]. Peanuts (*Arachis hypogaea*) were the previous crop before planting the habanero pepper.

2.2. Identification of Weed Species

The species, in the field, were identified one week before the establishment of the treatments; and by using three unit squared areas of 50 × 50 cm (0.25 m^2), per each replication, the next variables were recorded: coverage, frequency of appearance, abundance and dominance of each species. The Value of Relative Importance (VRI) of the weeds were calculated according to the methodology by Gámez López *et al.* (2011) [10] for weeds characterization.

3. Methods

3.1. Management and Herbicides Application

The study was carried out from September to October 2021 (Autumn-Winter cycle). The land was prepared by a combination of manual clearing from the third week of September until October 2. A pre-sowing herbicide *Paraquat* (200 g a·i·L^{-1}) of contact action was applied (10 mL of commercial material per liter of water to eliminate the first vegetation. Once the weeds started recovering, the treatments were applied in October 9 in pre-transplantation using manual backpack sprinklers.

The transplant was carried out on October 11, two days after the first herbicide application (DAA), using 12 cm high seedlings of the "*Jaguar*" variety, 15 treatments with different herbicides were established and a 16th, treatment as the control with no herbicide application was considered.

The doses used (**Table 1**) were determined using the sheets of each herbicides published by the manufacturers and those suggested by INIFAP [11]. Legal authorization for Mexico and USA, for peppers cultivation (*Capsicum* spp.), was also considered. Crop management was carried out according to recommendations of Avilés *et al.* (2010) [11] for habanero pepper under outdoor conditions of Yucatan, Mexico.

3.2. Experimental Design and Statistical Analysis

Sixteen treatments with four replications were established, under drip irrigation conditions, and analyzed in a randomized complete block design in experimental unitsof 14.25 m^2 (1.5 × 9.5 m). The seedlings were transplanted 40 cm apart with a projected population density of 16,750 plants ha^{-1}. Data were subjected to an Analysis of Variance (ANOVA), Mean Comparison Test by Tukey's method ($p \leq 0.05$) using the Statgraphics Centurión program, version 16.1.2.0.

3.3. Total Coverage of Weeds (%)

The percentage of coverage was measured visually, adapting the methodology described by Rodríguez *et al.* (2008) [12] and Gámez López *et al.* (2011) [10] for

Table 1. Herbicide treatments for weeds control in a habanero pepper crop (Autumn-Winter period 2021-22).

Treatment (N˚)	Herbicide	g of active ingredient (a·i) Kg^{-1} or L^{-1}	Commercial Dose (L or $Kg·ha^{-1}$)	Dose of a·i (Kg a·i Kg^{-1} or L^{-1})	Chemical Group (HRAC)^y	C
1	*Pendimethalin*	328	6.76	2.21	Dinitroanilines	V
2	*Glyphosate*	360	3.60	1.29	Glycines	IV
3	*Natural Herbicide* 1 (*SN*)	84%*	5.41	4.54	No classified	V
4	*Ammonium Glufosinate*	280	4.50	1.26	Fosfínic Acidsos	IV
5	*Bensulide*	480	18.02	8.65	Phosphoroditioates	IV
6	*Paraquat*	200	4.50	0.90	Pyridiniums	II
7	*Trifluralin*	600	4.05	2.43	Dinitroanilines	IV
8	*Fomesafen*	250	2.03	0.50	Diphenil Ethers	IV
9	*Ethalfluralin*	371	4.05	1.50	Dinitroanilines	IV
10	*Carfentrazone Ethyl*	240	0.81	0.19	H-Peniltriazolinones	IV
11	*Clorthal Dimethil*	750	5.63	4.22	Benzoic Acids	IV
12	*Natural Herbicide* 2 (*SB*)	73%*	5.41	3.94	No classified	V
13	*Oxadiazon*	250	2.25	0.56	N-Phenil-Oxadiazolones	V
14	*Metolachlor*	960	2.70	2.59	Alpha-Chloroacetamides	IV
15	*Clomazone*	360	3.60	1.29	Isoxasolidinones	IV
16	*Weedy* (*Control*)					

*Weight percentage of main components; yHRAC = Herbicides Resistance Action Committee 2020; zTC = Toxicological Category.

weed populations. In this case, sixteen unit-squared areas of 50 × 50 cm (0.25 m^2) were used per treatment (four squares per repetition) at 7 and 14 days after herbicides application (DAA). The data were then, transformed to the Arcsine Root of *x* for statistical Analysis of Variance (ANOVA) [13].

3.4. Evaluation of Phytotoxicity

For phytotoxicity evaluation of herbicides on habanero pepper all plants in the experimental units were taken into account where mortality and the symptomatology of the damage were evaluated using the method proposed by the European Weed Research Society (EWRS) cited by Pérez *et al.* (2014) [14] (**Table 2**).

3.5. Height of Plants

In order to detect any effect on crop growth, the height, from base of the stem to the last apex, of sixteen randomly selected plants (four per replication) was taken twice, in October 11 and October 23 (14 DAT).

Table 2. Reference values suggested by the European Weed Research Society (EWRS) for weeds control and crop phytotoxicity.

Ranking	Effect on weeds	Effect on crops
2	Very good control	Very light symptoms
3	Good control	Light symptoms
4	Enough	Symptomswith no affected yields
	Acceptability limits	
5	Medium control	Medium damage
6	Regular control	High damage
7	Poor control	Very high damage
8	very poor control	Severe damage
9	Without effect	Death
Values	**Weed control (%)**	**Crop Phytotoxicity (%)**
1	99.0 - 100.0	0.0 - 1.0
2	96.5 - 99.0	1.0 - 3.5
3	93.0 - 96.5	3.5 - 7.0
4	87.5 - 93.0	7.0 - 12.5
5	80.0 - 87.5	12.5 - 20.0
6	70.0 - 80.0	20.0 - 30.0
7	50.0 - 70.0	30.0 - 50.0
8	1.0 - 50.0	50.0 - 99.0
9	0.0 - 1.0	99.0 - 100.0

Source: Urzúa (2001), cited by Pérez *et al.* (2014).

3.6. Cost Analysis ($)

A preliminary analysis of profitability per treatment was carried out considering the costs of the products and the application days per hectare as compared to the estimated cost carried out by the producer (combination of manual and chemical control).The cost reduction ($) of each treatment was calculated when comparing the production cost of the producer, as 100%, against the production cost of each treatment.

The farmers usually consider the use of polypropylene tunnels to protect the crop against virus, transmitted by a whitefly, during the first 45 to 60 DAA.

4. Results

4.1. Identification of Weeds

Fourteen dominant weed species were detected in the original vegetation: from which 85.7% (12) are broad-leaved species such as: Xtees (*Amaranthus dubius*), k'iix tees (*Amaranthus spinosus*), k'an tumbuub (*Bidens pilosa*), pants' iil (*Boerthavia erecta*), kidney beans (*Crotalaria incana*), xanamucuy (*Euphorbia hyssopifolia*), xuul (*Lonchocarpus rugosus*), fern grass (*Parthenium hysterophorus*), jabín (*Piscidia piscipula*), purslane (*Portulaca oleracea*), chi'chi'bej (*Sida glabra*) and sac xiw (*Waltheria americana*); while only 14.3% (2) are narrow-leaved ones, such as: nutsedge (*Cyperus ligularis*), and guinea grass (*Megathyrsus maximus*).The predominant species due to their higher Relative Importance Values (RIVs) were *Euphorbia hyssopifolia* (*Euphorbiaceae*), *Megathyrsus maximus* (*Poaceae*) and *Parthenium hysterophorus* (*Asteraceae*) with 61.8%, 52.4% and 33.7%, respectively (**Figure 1**).

4.2. Total Coverage of Weeds (%)

According to the ANOVA, there was a highly significant difference between treatments at 7 and 14 DAT. At seven DAT, Tukey's test ($p \leq 0.05$) identified the *Clomazone* herbicide as the only one statistically similar to the *Weedy-Control* treatment with coverage of 2.78% and 3.75% respectively. On the other hand, the other treatments were statistically different with values ranging from 0.28 to 2.22%, highlighting *Pendimethalin*, *Glyphosate*, *Natural Herbicide* 1, *Ammonium Glufosinate*, *Bensulide*, *Paraquat*, *Carfentrazone Ethyl*, *Oxadiazon* and *Metolachlor*. Particularly *Pendimethalin* and *Ammonium Glufosinate* recorded the lowest coverage values with 0.28 and 0.31%, respectively (**Table 3**).

At 14 DAT, weed coverage in all herbicide-based treatments were statistically different as compared to the weedy control, with values ranging from 0.25 to 8.13%, highlighting *Pendimethalin* (0.25%), *Glufosinate ammonium* (1.13%), *Trifluralin* (1.5%) and *Chlorthal dimethyl* (1.88%) with the lowest values. With the exception of *Pendimethalin*, all those herbicides were recommended by Avilés *et al.* (2010) [10] for good weed control in habanero pepper in Yucatan as an alternative to reduce the weed control costs (**Table 3**).

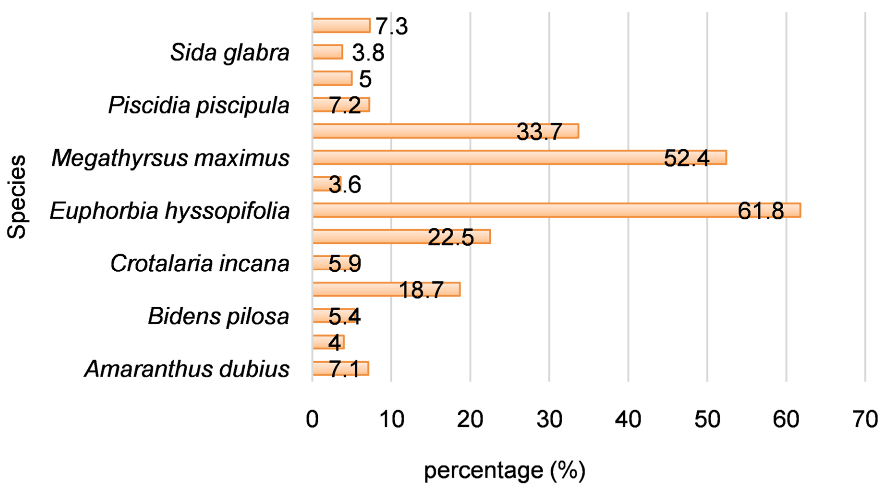

Figure 1. Relative Importance Values (RIVs) of weeds in percentage.

Table 3. Weed coverage (%) as related to weeds herbicides in a habanero pepper crop at 7 and 14 DAT.

Treatment	Herbicide	Commercial dose (L or Kg·ha^{-1})	Coverage (%)	
			7 DAT	14 DAT
1	*Pendimethalin*	6.76	0.28a	0.25 a
2	*Glyphosate*	3.60	0.94abc	4.06 a
3	*Natural Herbicide* 1 (*SN*)	5.41	0.48ab	2.75 a
4	*Ammonium Glufosinate*	4.50	0.31a	1.13 a
5	*Bensulide*	18.02	0.76ab	4.50 a
6	*Paraquat*	4.50	1.18abc	8.13 a
7	*Trifluralin*	4.05	2.22cd	1.50 a
8	*Fomesafen*	2.03	1.76bcd	6.94 a
9	*Ethalfluralin*	4.05	2.09cd	6.31 a
10	*Carfentrazone Ethil*	0.81	1.45abc	3.44 a
11	*Clorthal Dimethil*	5.63	1.76bcd	1.88 a
12	*Natural Herbicide* 2 (*SB*)	5.41	1.58abcd	7.76 a
13	*Oxadiazon*	2.25	0.76ab	6.19 a
14	*Metolachlor*	2.70	1.51abcd	3.00 a
15	*Clomazone*	3.60	2.78de	4.44 a
16	*Weedy* (*Control*)		3.75e	25.25c

Note: Different letters mean Statistical Significant Differences ($p < 0.05$, Tukey).

4.3. Phytotoxicity in Habanero Pepper

The only phytotoxic effects, in the habanero pepper, were detected when using the herbicide *Clomazone* at 14 DAT with 1.3% of affected plants. The percentage of the canopy affected per plant was 28.0%. The visible symptom was noted with a marked decolorating of young leaves close to the apical bud. However, no mortality was observed in any plant.

4.4. Height of Habanero Pepper Plants (cm)

No statistical differences were found between treatments at any measured growing stage. Height was not affected, at all, during the first two weeks of plant development (Table 4). The highest height was observed in plots with *Pendimethalin* (14.9 cm), *Fomesafen* (14.6 cm), *Glyphosate* (14.5 cm), *Clomazone* (14.4 cm) and the *Weedy Control* (14.3 cm), while the plants with the lowest height were those treated with *Carfentrazone ethyl* (12.6 cm). Although *Clamozone* provoked symptoms of toxicity, the results presented here indicate that growth was not affected by this herbicide and by any other.

Table 4. Height (cm) of habanero plants at 14 days after herbicides application (DAA).

Treatment	Herbicide	Commercial Dose (L or Kg·ha^{-1})	Height* (cm)	
			Initial	14 DAA
1	*Pendimethalin*	6.76	12.9	14.9
2	*Glyphosate*	3.60	13.3	14.5
3	*Natural Herbicide* 1 (*SN*)	5.41	12.7	14.0
4	*Ammonium Glufosinate*	4.50	12.3	13.3
5	*Bensulide*	18.02	11.6	13.3
6	*Paraquat*	4.50	12.5	14.2
7	*Trifluralin*	4.05	12.4	14.2
8	*Fomesafen*	2.03	12.3	14.6
9	*Ethalfluralin*	4.05	11.5	13.8
10	*Carfentrazone Ethil*	0.81	10.9	12.6
11	*Clorthal Dimethil*	5.63	11.6	13.2
12	*Natural Herbicide* 2 (*SB*)	5.41	11.9	13.1
13	*Oxadiazon*	2.25	12.3	13.8
14	*Metolachlor*	2.70	12.5	13.3
15	*Clomazone*	3.60	12.2	14.4
16	*Weedy* (*Control*)	0	13.1	14.3

*No Significant Differences (NS).

4.5. Cost Analysis ($)

Table 5 describes the unit costs of herbicides and treatments as of September 2021, according to the doses per hectare used; all compared to the estimated costs of the combined control used by the producer in the first 30 days after transplanting.

It is observed that the cheapest treatments with respect to the producer's practice were the herbicides *Paraquat* ($1987.00) and *Glyphosate* ($2210.20), both showing the lowest unit costs with a cost reduction between 73.4% and 70.4% respectively. The crop system of the producer includes the use of polypropylene tunnels to protect the crop, for the first 45 to 60 DAA, against viral infections transmitted by the whitefly *Bemisia tabaci* Genn. In that way, it is not possible to apply these herbicides from outside the tunnels without damaging the crop.

On the other hand, except for the herbicide *Bensulide*, which was the treatment with the highest cost ($20321.61) and *Chlorthal dimethyl*, which only reduced the cost by 7.1%, all the other treatments were also highly profitable. The cost reduction ranged between 45.5% (*Ammonium Glufosinate*) and 68.7% (*Ethalfluralin*) (**Table 5**).

Table 5. Profitability of different herbicides applied for weed control in a habanero pepper crop (Autumn-Winter period 2021-2022).

Treatment (N°)	Herbicide	Commercial dose (L or Kg·ha^{-1})	Unit cost ($L^{-1})	Total cost ha^{-1} ($)*	Cost reduction (%)
1	*Pendimethalin*	6.76	390.91	$3442.55	53.96
2	*Glyphosate*	3.60	169.50	$2210.20	70.44
3	*Natural Herbicide* 1 (*SN*)	5.41	507.25	$3544.22	52.60
4	*Ammonium Glufosinate*	4.50	550.04	$4075.18	45.50
5	*Bensulide*	18.02	1083.33	$20321.61	-171.75
6	*Paraquat*	4.50	86.00	$1987.00	73.43
7	*Trifluralin*	4.05	411.85	$2467.99	67.00
8	*Fomesafen*	2.03	762.50	$2347.88	68.60
9	*Ethalfluralin*	4.05	380.00	$2339.00	68.72
10	*Carfentrazone Ethil*	0.81	3000.00	$3230.00	56.81
11	*Clorthal Dimethil*	5.63	1091.29	$6943.96	7.14
12	*Natural Herbicide* 2 (*SB*)	5.41	345.00	$2666.45	64.34
13	*Oxadiazon*	2.25	900.00	$2825.00	62.22
14	*Metolachlor*	2.70	990.00	$3473.00	53.56
15	*Clomazone*	3.60	730.00	$3428.00	54.16
16	*Weedy* (*Control*)			-----------	
	Hand clearing + Herbicide + Tunnels			$7478.00** (Farmers' cost)	

*Total cost includes herbicides and labors of application. Calculated in Mexican pesos; **Cost includes manual control of weeds, use of polypropylene tunnels and one application de *Glyphosate*in dose of 4 L·ha^{-1}. Costs at September 2021.

5. Discussion

The weed species identified, during the crop establishment, are widely distributed in all tropical, subtropical and Mediterranean regions [15]. They are infesting large areas of beans, cotton, corn and soybeans because of their short life cycle and rapid growth and development under a wide range of environmental conditions, ability to germinate up to 20 cm deep, and efficient seed dispersal [15] [16] [17]. On the other hand, the phytotoxic effects observed by the herbicide *Clomazone* agree with those reported by Guerra *et al.* (2002) [18] in *Cucumis melo* L., as well as those reported by Varela Pessolano, (2009) [19], who observed symptoms of phytotoxicity in Bell pepper (*Capsicum annum* L.) crops in doses of 0.36 Kg·a.i·ha^{-1} and 0.72 Kg·a.i·ha^{-1}. Marked sensitivity to the product and well-defined whitish spots, sometimes with a purplish center was also observed.

6. Conclusions

1) Results showed that all herbicide-based treatments-controlled weeds significantly 14 days after spraying (DAS) with values of ground cover ranging from 0.25% to 8.13% *vs* 25.25% of Weedy Control Treatment. *Pendimethalin* (0.25%), *Glufosinate ammonium* (1.13%), *Trifluralin* (1.5%) and *Chlorthal dimethyl* (1.88%) showed the lowest ground cover values.

2) *Clomazone* was the only herbicide causing phytotoxicity in habanero pepper at 14 DAS with 1.3% of affected plants. The percentage of canopy affected per plant was 28.0%. The visible symptom was a marked discoloration of young leaves close to the apical bud. However, no mortality was registered in any plant.

3) Growing of habanero pepper plants was not affected, 14 days after transplanting (DAT). *Pendimethalin* (14.9 cm), *Fomesafen* (14.6 cm), *Glyphosate* (14.5 cm), and *Clomazone* (14.4 cm) showed the highest values of growth, however, these values were not significantly different from the weedy control treatment (14.3 cm). Although *Clomazone* promoted toxicity symptoms, results indicated that growth was not affected by this herbicide.

4) *Paraquat* (\$1987.00 ha^{-1}) and *Glyphosate* (\$2210.20 ha^{-1}) showed the lowest cost per Ha with cost reduction of 73.4% and 70.4%, respectively, regarding the local farmers' methodology of weed control on habanero pepper. Except for *Chlorthal dimethyl* which only reduced 7.14% the weed control cost by regarding the local farmers' methodology and *Bensulide* which was the only treatment exceeding that cost, all other herbicides reduced the cost in a range of 45.5% (*Ammonium Glufosinate*) and 68.7% (*Ethalfluralin*), which is considered an economically acceptable reduction.

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Conflicts of Interest

The authors declare no conflicts of interest.

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