Colegio de Postgraduados

Evaluation of the efficacy and phytotoxicity of synthetic chemical herbicides on sugarcane (*Saccharum* spp. L.) in San Luis Potosí, Mexico

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ABSTRACT

Objective: To evaluate the effectiveness and phytotoxicity of eleven synthetic chemical herbicides in sugarcane (var. CP 72-2086) under field conditions at Experimental centre of INIFAP, Ébano, San Luis Potosí, Mexico, to identify feasible and reliable alternatives for chemical weed management.

Design/methodology/approach: A randomized complete block design with four replications was used, applying herbicide treatments to experimental plots of 56 m^2. Weed control and crop phytotoxicity were assessed at 10, 20, and 30 days after application (DAA), using the nine-class scale proposed by the European Weed Research Society (EWRS). Data were analyzed using the Kruskal-Wallis test and Tukey's mean separation test at a significance level of $P<0.05$.

Findings: Glufosinate ammonium and MSMA provided very good weed control during the first 20 days, although their efficacy decreased slightly by 30 DAA. Glyphosate achieved complete control at 30 DAA but showed the highest phytotoxicity to the crop. Ametryn and Diuron demonstrated a favorable balance between effectiveness and low toxicity. Clomazone, Mesotrione, Saflufenacil, Indaziflam, and Atrazine showed intermediate responses. The untreated control plot exhibited severe weed pressure.

Limitations/implications: This study is limited to a single sugarcane variety and specific agroclimatic conditions; thus, results should be interpreted with caution when extrapolating to other regions or cultivars. Further long-term studies are recommended, including herbicide combinations and their effects on final crop yield.

Conclusions: Chemical control can be an effective approach for weed management in sugarcane, provided that both herbicide efficacy and crop selectivity are considered. Glufosinate, MSMA, Ametryn, and Diuron stand out as feasible and reliable alternatives for integrated weed management programs, while Glyphosate, despite its high efficacy, requires caution due to its phytotoxicity.

Keywords: Weed control, sugarcane, selective herbicides, phytotoxicity.

INTRODUCTION

Mexico is one of the world's leading sugarcane producers, with an annual output of approximately 55 million tons. The state of San Luis Potosí ranks third nationally, producing 5.2 million tons (FAOSTAT, 2022; SIAP, 2022). However, one of the main challenges faced by this crop is the presence of weeds, which directly affect yield by competing for water, light, nutrients, and space (Johnson *et al.*, 2023; Gao & Su, 2024). This competition is particularly critical during the first 100 to 105 days after planting, a period in which sugarcane exhibits slow initial growth and requires higher resource availability from the environment (Zafar *et al.*, 2010; Tadele *et al.*, 2022). During this critical competition period, weeds depending on their density, distribution, and persistence can cause yield losses ranging from 40% to 94.6% (Kadam *et al.*, 2011; Ramesh & Rathika, 2016; Tadele *et al.*, 2022). Therefore, early-stage weed control provides the greatest economic benefits (Rathika *et al.*, 2023). Among the available control methods, chemical control is the most widely used due to its efficiency and practicality in large-scale agricultural systems (Hamuda *et al.*, 2016). Furthermore, Kadam *et al.* (2011) noted that herbicide-based chemical weed control in sugarcane not only improves weed suppression but also significantly enhances crop yield. Herbicides such as 2,4-D, Merlin, and Paraquat have gained relevance in sugarcane cultivation in recent years, with Paraquat being particularly noted for its effectiveness in post-emergent applications (Viera-Barceló & Escobar-Cruz, 2015; Aekrathok *et al.*, 2021). In Mexico, commonly used herbicides include Ametryn, Diuron, and Amicarbazone (Esqueda, 2006). Nevertheless, it is essential to monitor weed populations throughout the growing season, as two to four control operations are typically required to maintain weed pressure at non-damaging levels (Cuellar *et al.*, 2003; Rodríguez & Díaz, 2012).

Despite the widespread use of chemical methods, there is a lack of studies evaluating the effectiveness of alternative herbicidal compounds and their phytotoxic effects on sugarcane under region-specific conditions. Therefore, this study aims to contribute to efficient weed management in sugarcane cultivation and to optimize its production.

MATERIALS AND METHODS

An experiment was conducted to evaluate the effectiveness of herbicides for weed control and phytotoxicity in sugarcane at the Ébano Experimental Site, located in Ébano, San Luis Potosí, Mexico. This site belongs to the National Institute for Forestry, Agricultural, and Livestock Research (INIFAP) and is situated at 22° 15' N, 98° 47' W. The sugarcane variety used was CP 72-2086, planted using the conventional system, which involves placing stalks at the bottom of furrows, chopping and arranging them, followed by covering with soil. A randomized complete block design was used with four replications. Experimental plots measured 56 m^2 (5.6 m×10 m). A pre-sampling was conducted to identify existing weed species using a fixed 100×100 cm quadrat. Herbicide applications were directed specifically at the weeds using a motorized sprayer equipped with a boom containing four flat-fan 8002 nozzles spaced 0.5 m apart, operating at a pressure of 273 kPa and delivering 250 L ha^{-1}. Weed control efficacy was assessed at 10, 20, and 30 days after application (DAA) using the 9-point scale proposed by the European Weed Research Society, where 1=99-100% control (plant death) and 9=0-1% control (no effect). Phytotoxicity was also evaluated using the same scale, where 1=0.0-1.0% (no visible crop damage) and 9=99.0-100.0% (crop death) (Table 1). Control and phytotoxicity data were analyzed using the Kruskal-Wallis test, followed by Tukey's test for mean separation at a significance level of $P<0.05$, using SAS software version 9.2.

RESULTS AND DISCUSSION

The following weed species were identified: *Tithonia tubaeformis* (Mexican sunflower), *Bidens pilosa* (Spanish needle), *Convolvulus arvensis* (field bindweed), *Amaranthus hybridus* (smooth pigweed), *Malva sylvestris* (common mallow), *Solanum nigrum* (black nightshade), *Argemone mexicana* (Mexican poppy), and *Euphorbia heterophylla* (wild poinsettia), as well as narrow-leaved grasses such as *Sorghum halepense* (Johnson grass), *Cynodon dactylon* (Bermudagrass), *Echinochloa crusgalli* (barnyardgrass), and *Cyperus rotundus* (purple nutsedge).

Weed control evaluations showed that at 10 and 20 days after application (DAA), ammonium glufosinate and MSMA achieved "very good" control levels, with EWRS scores ranging from 2.00-2.75 and 2.75-3.00, respectively (Table 2). By 30 DAA, these values slightly decreased to between 2.75 and 3.00, still within the "good control" category. These findings align with results reported by Gur *et al.* (2006) and Shaw & Arnold (2002), who observed control rates of 95.5% and at least 90% with MSMA and ammonium glufosinate, respectively. Although effective, a decline in efficacy over time was noted.

This decline, likely due to weed regrowth, is a well-documented pattern with contact herbicides, which often show diminished control months after application (Eskandari *et al.*, 2022).

Regarding visual phytotoxicity (Table 3), the highest scores were recorded at 20 DAA. Ammonium glufosinate reached an EWRS score of 3.75 (visible symptoms), characterized by chlorosis and necrosis, followed by tissue death. These effects are typical of contact herbicides and can be attributed to glutamine synthetase inhibition, resulting in toxic ammonia accumulation, photosynthetic disruption, and multisystem metabolic failure (Takano *et al.*, 2020). MSMA, a contact herbicide with limited systemic action and primarily active in growing tissues (Keese & Camper, 1994), exhibited moderate phytotoxicity (3.25), likely due to disrupted chlorophyll and/or carotenoid biosynthesis or degradation (Pimmongkol & Camper, 2003).

Table 1. Scale proposed by the European Weed Research Society (EWRS) to evaluate weed control by herbicides.

Value	Weed Control (%)	Effect on Weeds	Crop Phytotoxicity (%)	Effect on the Crop
1	99.0-100.0	Plant death	0.0-1.0	No effect
2	96.5-99.0	Very good control	1.0-3.5	Very slight symptoms
3	93.0-96.5	Good control	3.5-7.0	Slight symptoms
4	87.5-93.0	Sufficient control	7.0-12.5	Visible symptoms without yield impact
5	80.0-87.5	Moderate control	12.5-20.0	Moderate damage
6	70.0-80.0	Fair control	20.0-30.0	High damage
7	50.0-70.0	Poor control	30.0-50.0	Very high damage
8	1.0-50.0	Very poor control	50.0-99.0	Severe damage
9	0.0-1.0	No effect	99.0-100.0	Crop death

Table 2. Effectiveness of synthetic chemical herbicides in sugarcane crops at 10, 20 and 30 days after application.

Treatment	10 DDA		20 DDA		30 DDA	
Control	9.00	a	9.00	a	9.00	a
Atrazine	7.75	ab	7.00	b	4.00	cd
Clomazone	7.75	ab	7.25	ab	5.50	bc
Mesotrione	7.50	b	6.50	b	6.25	ab
Indaziflam	7.50	b	6.75	b	6.00	ab
Diuron	6.75	bc	4.25	cd	4.50	bcd
Salflufenacil	4.50	dc	6.00	bc	6.00	ab
Ametryn	4.25	dc	4.00	de	4.75	bcd
Glyphosphate	4.00	de	1.50	f	1.00	e
MSMA	2.75	de	3.00	def	3.00	de
Glufosinate-Ammonium	2.00	e	2.00	ef	2.75	de
R^2	0.928		0.920		0.856	
Coefficient of Variation	16.8		38.6		23.6	

Table 3. Phytotoxicity of synthetic chemical herbicides in sugarcane crops at 10, 20 and 30 days after application.

Treatment	10 DDA		20 DDA		30 DDA	
Ammonium Glufosinate	3.5	ab	3.75	abc	3	ab
MSMA	3.5	ab	3.25	abc	2.25	b
Glyphosphate	3.5	ab	5.5	a	9	a
Clomazone	2.5	ab	3.75	ab	4	a
Salflufenacil	2	ab	2	bcd	2.25	b
Ametryn	1.5	ab	1.5	d	2	bc
Mesotrione	1.75	ab	1.25	d	1.75	bc
Diuron	1	b	2	bcd	2	bc
Indaziflam	1	b	1.75	cd	2	bc
Atrazine	1	b	1.25	d	2.25	b
Control	1	b	1.25	d	1.25	c
R2	0.721		0.806		0.801	
Coefficient of Variation	30.6		26.4		24.8	

Despite these effects, both herbicides remained within acceptable phytotoxicity ranges for selective sugarcane applications. In contrast, glyphosate was the most phytotoxic, with a score of 9.0 at 30 DAA, indicating severe crop damage or death according to the EWRS scale. This aligns with its systemic mode of action, which inhibits EPSPS (5-enolpyruvylshikimate-3-phosphate synthase) and translocates to meristematic tissues (Duke & Powles, 2008; Kirkwood *et al.*, 2000).

The irreversible cellular damage caused by glyphosate was also evident in its weed control performance, improving from moderate (4.00) at early stages to very good (1.50) at 20 DAA, and achieving complete weed death (1.00) by 30 DAA. Similar results were reported by Eskandari *et al.* (2022), where three doses of glyphosate (754.4, 1131.6, and 1508.8 g a.i. ha^{-1}) reduced Imperata cylindrica height and biomass by 58-100% depending on the timing of application. Likewise, Almubarak *et al.* (2012) found glyphosate to be the most effective treatment for weed control in sugarcane, significantly reducing weed dry weight (34.1 g m^2 compared to 126.2 g m^2 in the untreated control).

On the other hand, Ametryn demonstrated "sufficient" control (score of 4.0) at 30 DAA and low visual phytotoxicity (between 1.5 and 2.0), suggesting good crop selectivity. These findings align with those of Martins *et al.* (2010), who evaluated Ametryn's effects on ten sugarcane varieties and identified it as the active ingredient with the least severe phytotoxic action. Additionally, all tested varieties exhibited full visual recovery 35 days after application.

Similarly, Diuron exhibited low phytotoxicity (1.0 to 2.0), and its control effectiveness improved over time, progressing from 6.75 at 10 DAA to 4.50 at 30 DAA classified as "good control." However, it is important to note that both Ametryn and Diuron offer a protection window that does not exceed 60 days, potentially requiring follow-up applications (Morcote-Católico, 2013).

Clomazone showed "very poor" to "moderate" control (7.75 to 5.50) over the 30-day period and induced moderate phytotoxicity (2.5 to 4.0). This response may be explained by its mode of action as a carotenoid biosynthesis inhibitor, which can cause chlorosis without resulting in severe damage (Johnen *et al.*, 2022). Although Clomazone shares this mechanism with Mesotrione, the latter exhibited lower phytotoxicity (1.75) in this study but delivered only "fair" to "very poor" weed control.

Indaziflam, though less studied in sugarcane, has shown promise as a residual herbicide due to its persistence in controlling annual weeds, demonstrating greater efficacy against monocotyledons than dicotyledons (Da Silva *et al.*, 2021). This characteristic may be particularly useful in perennial crops like sugarcane, where sustained weed control is essential (Sebastian *et al.*, 2017). Finally, Salflufenacil, Indaziflam, and Atrazine exhibited intermediate values in both weed control and phytotoxicity. While none were the most effective or the safest, their performance was stable and balanced. Salflufenacil, a protoporphyrinogen oxidase (PPO) inhibitor, and Atrazine, a photosystem II inhibitor, possess different modes of action, making them strategic molecules in herbicide resistance management programs especially when combined with contact or residual herbicides. Furthermore, it has been documented that integrating herbicides with consistent, moderate efficacy can help extend the lifespan of more aggressive molecules, such as glyphosate, by reducing the frequency of their application (Heap & Duke, 2018).

CONCLUSIONS

The evaluated herbicides exhibited varied behaviors in terms of efficacy and phytotoxicity in sugarcane cultivation. Ammonium glufosinate and MSMA demonstrated high weed control efficacy within the first 20 days post-application, although their effects slightly declined by day 30, suggesting limited persistence and the potential need for follow-up treatments. Glyphosate achieved complete control at 30 DAA but caused the highest phytotoxicity, limiting its direct use in sugarcane and requiring targeted applications. In contrast, Ametryn and Diuron provided acceptable weed control with low phytotoxicity, positioning them as selective and safer options. Herbicides such as Clomazone, Mesotrione, Salflufenacil, Indaziflam, and Atrazine showed intermediate efficacy and phytotoxicity levels, making them viable alternatives within herbicide rotation or tank-mix strategies. Based on the results, herbicide selection should prioritize both weed control efficacy and observed crop phytotoxicity. While some products have certain limitations, they may still serve as valuable tools within integrated weed management programs, herbicide rotation schedules, and resistance management strategies.

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