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SCIENTIFIC ARTICLE

Evaluation of the effectiveness and environmental impact of pre-emergent herbicides for weed control in sugarcane (*Saccharum* spp.)

Evaluación de la efectividad y el impacto ambiental de herbicidas preemergentes para el control de arvenses en caña de azúcar (*Saccharum* spp.)

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The authors declare no conflict of interest.

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DRT: Conceived and designed the study. Conducted literature search and review and drafted the original manuscript (first version). **YPI:** Performed data analysis and interpretation. Prepared tables and figures. Conducted translation and review of the final version of the article. **RNBG:** Performed validation of results. Reviewed the final version of the article and approved the final version.

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ABSTRACT

To evaluate the effectiveness and environmental impact of different pre-emergent herbicide treatments for weed control in sugarcane, two field experiments were conducted at different locations from April 2020 to June 2021. A floristic survey of weed species was performed to determine taxonomic composition and frequency of occurrence. Seven herbicide treatments were evaluated: Unipix GD70 (Imazapic), Merlín Total SC60 (Isoxafluotole + Indaziflan), Mayoral LS35 (Imazapic + Imazapyr), Palmero GD75 (Isoxafluotole), Palmero GD75 + Mayoral LS35, Merlín GD75 + Mayoral LS35, and Merlín GD75 (Isoxafluotole) as the standard treatment, along with an untreated control. Environmental impact coefficients and total costs per hectare were calculated for each treatment. The floristic survey revealed that weed species share close phylogenetic relationships, facilitating management through similar control practices. All herbicide treatments provided excellent weed control. Regarding environmental impact, 50% of treatments posed low risk while the remaining 50% posed very low risk. Unipix GD70 demonstrated the best cost-benefit ratio with the lowest cost per hectare per weed-free day, maintaining weed-free conditions for 90 days post-application. These results expand integrated weed management strategies as alternatives to the conventional Merlín GD75 treatment (0.200 kg ha^{-1}), providing more efficient and environmentally sustainable options for sugarcane weed control.

Keywords: imazapic, isoxafluotole, integrated management, environmental impact coefficient, cost-benefit, sustainable agricultura

RESUMEN

Con el objetivo de evaluar la efectividad y el impacto ambiental de diferentes tratamientos herbicidas preemergentes para el control de especies arvenses en caña de azúcar, se establecieron dos experimentos de campo en diferentes localidades durante el período abril 2020 - junio 2021. Se realizó un inventario florístico de las plantas arvenses para determinar la composición taxonómica de las especies y su frecuencia de aparición. Se evaluaron siete tratamientos herbicidas: Unipix GD70 (Imazapic), Merlín Total SC60 (Isoxafluotole + Indaziflan), Mayoral LS35 (Imazapic + Imazapyr), Palmero GD75 (Isoxafluotole), Palmero GD75 + Mayoral LS35, Merlín GD75 + Mayoral LS35, y Merlín GD75 (Isoxafluotole) como testigo estándar, además de un testigo absoluto sin aplicación de herbicidas. Para cada tratamiento se calculó el coeficiente de impacto ambiental y se evaluó el costo total por hectárea. El inventario florístico confirmó que las especies arvenses presentan una relación filogenética cercana, lo cual facilita su manejo mediante prácticas de control similares. Todos los tratamientos herbicidas evaluados lograron un control excelente de las especies arvenses. En cuanto al impacto ambiental, el 50% de los tratamientos presentaron un nivel de riesgo bajo y el 50% restante un riesgo muy bajo. El tratamiento Unipix GD70 mostró la mejor relación costo-beneficio con el menor costo por hectárea por días libres de malezas, manteniendo el cultivo limpio durante 90 días posteriores a la aplicación. Los resultados obtenidos permiten ampliar las estrategias de manejo integrado de malezas como alternativas al tratamiento convencional Merlín GD75 (0.200 kg ha^{-1}), ofreciendo opciones más eficientes y ambientalmente sostenibles para el control de arvenses en caña de azúcar.

Palabras clave: imazapic, isoxafluotole, manejo integrado, coeficiente de impacto ambiental, costo-beneficio, agricultura sostenible

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INTRODUCTION

The Cuban sugarcane agroindustry faces multiple challenges that significantly affect productivity, including rural depopulation, pest presence, deficiencies in cultural practices, and adverse climatic conditions such as drought, factors that favor the proliferation of weed species. Unwanted plants constitute the second leading cause of yield reduction in sugarcane, causing losses ranging from 33% to 66% in harvests, reaching up to 97.5% due to their constant competition for resources such as water, nutrients, and light (Rodríguez Tassé, Barbosa García, Puchades Isaguirre, Rodríguez Rodríguez & García Perú, 2020; Barrera Fontanet, Cervera Duverger & Barquié Pérez, 2020).

Weed management is crucial following planting or harvest to prevent losses in cane and sugar production, and has evolved from manual methods to the use of machinery and herbicides (Comastri, 2022). Chemical control is essential due to the large extension of crops and labor shortages (Naranjo Landero, Obrador Olán, García López, Valdez Balero & Domínguez Rodríguez, 2020). Pre-emergent herbicides are efficient and economical, preventing seed germination through their residual action and are widely used in both irrigated and rainfed crops (Miranda, 2021).

However, continuous and indiscriminate use of herbicides can generate ecological imbalances and favor the development of resistance in weed species (Jáquez-Matas, Pérez-Santiago, Márquez-Linares & Pérez-Verdín, 2022). Environmental impact assessment enables identification, avoidance, and minimization of negative effects from agricultural activities, with prevention being more efficient than subsequent remediation. In this context, the use of indices to evaluate the environmental risk of herbicides becomes fundamental for increasing the sustainability of management strategies, allowing comparison of different programs and selection of the most environmentally sound products (Jáquez-Matas et al., 2022).

The Environmental Impact Quotient (EIQ) is a tool developed by the Integrated Pest Management Program at Cornell University that allows comparison of different herbicides or management programs through a dimensionless numerical value. This index considers physical and chemical properties of pesticides, ecotoxicological aspects, and effects on human health (Kovach, Petzold, Degni & Tette, 1992).

The objective of this study was to evaluate the effectiveness, environmental impact, and costs of different pre-emergent herbicide treatments for weed control in sugarcane cultivation.

MATERIALS AND METHODS

The study was conducted in two sugarcane production units (UPC) in Santiago de Cuba province: UPC Juan José Verdecía in Julio Antonio Mella municipality and UPC Niguabo in Dos Ríos municipality, both located in Palma Soriano (Cauto plain or Tayaba valley) at coordinates 20°12′50″N 75°59′31″W.

The research was conducted between April 2020 and June 2021, evaluating both plant cane and ratoon with three cuts, using varieties C86-12 and C90-530. The experiments were established on two soil types: Mollisol and Pellic Vertisol, according to the Cuban soil classification system (Hernández et al., 2015).

To determine the taxonomic composition and frequency of occurrence of weed species, a floristic inventory was conducted at the research sites using the visual method of Martínez, Zuaznábar-Zuaznábar & Rodríguez-García (2022). Fields were traversed diagonally and major weed species were recorded. Taxonomic identification was performed using specialized manuals cited by Martínez et al. (2024) and Rodríguez (2007) and the automated PC Malezas system, which includes information on 35 common species in sugarcane and a photographic gallery of these weeds (Instituto de Investigaciones de la Caña de Azúcar (INICA), 2020).

With the phytosociological data obtained, the frequency of occurrence (FA) of weed species was determined according to Amador, Mederos, Bojórquez, Díaz & Partida (2013). Species were classified according to their frequency of occurrence following Martínez et al. (2022): Accidental (0-24.9%), Infrequent (25-49.9%), Moderately frequent (50-74.9%), and Very frequent (>75%).

Two field studies were conducted to evaluate different herbicide treatments (Table 1). The experimental design was randomized complete blocks with five replications and plots of four rows 7.5 m long, with a surface area of 48 m² per experimental unit. An untreated control without herbicide application and a standard control with isoxaflutole (Merlín GD75) were included. Treatments were evaluated after planting and following crop harvest, applied with a 16 L Matabi manual backpack sprayer with deflector nozzle at 2 bar pressure to ensure uniform distribution of the solution.

Herbicide effectiveness was determined at 30, 60, and 90 days after application (DAA) through visual evaluation according to Domínguez (2008). The percentage of weed species control was classified according to the scale proposed by ALAM (1974) (Table 2). Crop phytotoxicity was evaluated at 7, 14, 21, and 28 days after application, using the nine-point scale of the European Weed Research Society (EWRS) (CIBA-GEIGY, 1981).

An analysis of variance was performed to study differences between treatments and replications in the different evaluations, excluding the untreated control. Data were verified for normality and homogeneity of variances, transforming when necessary, according to $x = 2 \arcsin\sqrt{p}$. For multiple comparisons, Tukey's test ($p = 0.05$) was used, employing STATISTICA version 8.0 software (STATSOFT, 2007).

The amount of active ingredient (AAI) reaching the soil was calculated considering the percentage of active ingredient of each herbicide and the applied dose (Taylor, 2020), using the formula:

AAI = % Active Ingredient (a.i.) × application dose

Table 1. Herbicide treatments evaluated in the different experiments.

No.	Treatment	Active ingredient	Dose (kg·ha⁻¹)	Supplier
1	Untreated control	----	-	--
2	Merlín GD75 (standard control)	Isoxaflutole	0.200	Bayer C. S.
Experiment 1 (UPC J.J. Verdecía)				
3	Unipix GD 70	Imazapic	0.200	UPL
4	Merlín Total SC60	Isoxafluotole + Indaziflan	0.25	Bayer C. S.
5	Mayoral LS35	Imazapic + Imazapyr	0.5	ADAMA
Experiment 2 (UPC Niguabo)				
6	Palmero GD75	Isoxafluotole	0.230	ADAMA
7	Palmero GD75 + Mayoral LS35	Isoxafluotole + Imazapic + Imazapyr	0.115 + 0.25	
8	Merlín GD75 + Mayoral LS35	Isoxafluotole + Imazapic + Imazapyr	0.115 + 0.25	

Table 2. Evaluation scale for weed control percentage according to ALAM (1974)

Index (%)	Control grade
0 – 40	None or poor
41 – 60	Regular
61 – 70	Sufficient
71 – 80	Good
81 – 90	Very good
91 - 100	Excellent

To determine the environmental impact coefficient, the *Environmental Impact Quotient* (EIQ) index was used following the methodology of Kovach et al. (1992). The field EIQ was calculated from the percentage of active ingredient and the applied dose. For treatments with mixtures, the field EIQs of each ingredient were summed. Environmental impact comparison was performed according to the coefficient of each herbicide, since according to Kovach et al. (1992), baseline EIQ values should not be compared because impact depends on dose and percentage of active ingredient. Environmental risk classification followed that proposed by Stewart, Nurse, Van Eerd, Vyn & Sikkema (2011), where higher numerical values of the index indicate greater environmental impact.

The total cost of each treatment was evaluated considering herbicide prices. Cost per hectare and per weed-free days was calculated by multiplying the price of each product by the dose used and dividing by the days of effective control.

RESULTS AND DISCUSSION

The floristic inventory identified 12 weed species distributed across five botanical families (Table 3). The Poaceae family was the most abundant, representing 58.3% of the total, with predominant species such as *Dichanthium annulatum, Cynodon dactylon,* and *Sorghum halepense*. The Convolvulaceae family represented 16.6% with two species. It is important to note that 50% of the identified species present a perennial vegetative cycle, a characteristic that significantly complicates their control according to Núñez-Rodríguez, Pablos-Reyes, Maceo-Ramírez, Alarcón-Méndez & Nápoles-Vinent (2020).

The identified plants from the Poaceae and Euphorbiaceae families have been previously reported as species present in Cuban agricultural ecosystems by Blanco Valdés, Leyva Galán & Castro Lizazo (2014). Barrera et al. (2019) obtained similar results in their study from the 2006-2015 decade, where they reported the presence of 14 botanical families with predominance of Poaceae (44%) and Euphorbiaceae (9.8%). De Moya Guerra, Martínez Hernández & García (2021) indicated that the Asteraceae and Poaceae families are among 50% of the most harmful weed species worldwide. Aulestia Calala et al. (2021) also reported Poaceae as one of the families present in Ecuadorian agricultural ecosystems. The species *R. cochinchinensis*, *C. rotundus*, *C. dactylon*, *E. colona*, and *S. halepense* recorded in this study are among the 16 species with highest incidence and damage to crops worldwide according to Cabrera, Ansonnaud & Varela (2020).

The frequency of occurrence from the floristic inventory is presented in Figure 1. In the very frequent category (>75%), only *R. cochinchinensis* was classified. As moderately frequent (50-74.9%), *I. trifida*, *R. minima*, *C. dactylon*, and *C. rotundus* were recorded. The species *S. halepense*, *M. quinquefolia*, *D. annulatum*, *E. heterophylla*, *B. fasciculata*, *E. colona*, and *P. maximum* were classified as infrequent (25-49.9%).

The study results coincide with those obtained by Barrera et al. (2020), who analyzed weed frequency in Guantánamo during the 2006-2011 period, finding that *R. cochinchinensis*, *C. dactylon*, and *I. trifida* were above 25%. Martínez Ramírez (2019) also evaluated changes in weed composition associated with sugarcane cultivation and

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Table 3. Taxonomic results of the floristic inventory.

Family	Species	Class	Life cycle
Poaceae	*Sorghum halepense*	M	Perennial
	Cynodon dactylon	M	Perennial
	Dichanthium annulatum	M	Perennial
	Panicum maximum	M	Perennial
	Rottboellia cochinchinensis	M	Annual
	Brachiaria fasciculata	M	Annual
	Echinochloa colona	M	Annual
Convolvulaceae	*Ipomoea trífida*	D	Annual
	Merremia quinquefolia	D	Annual
Fabaceae	*Rhynchosia minima*	D	Perennial
Cyperaceae	*Cyperus rotundus.*	M	Perennial
Euphorbiaceae	*Euphorbia heterophylla*	D	Annual

(M): Monocotyledons; (D): Dicotyledons

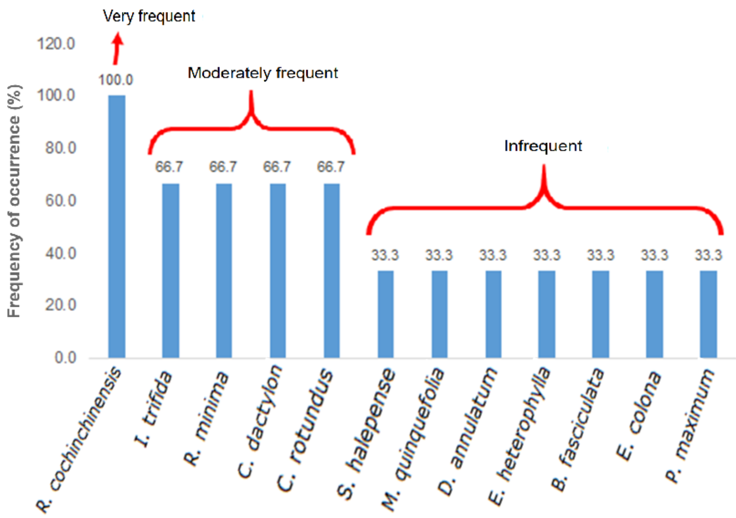

Figure 1. Frequency of occurrence (FO) from the floristic inventory.

identified frequency patterns similar to those observed in this study. In the evaluated areas, a predominance of weed species in the infrequent category was evident, followed by moderately frequent and very frequent, respectively. Núñez-Rodríguez et al. (2020) reported the same trend, with predominance of the infrequent category.

All treatments evaluated at UPC Juan José Verdecía showed good control of weed species (Table 4), without significant differences between them. The Mayoral LS35, Merlín Total SC60, and Unipix GD70 treatments demonstrated effectiveness at all evaluation times, suggesting that viable alternatives exist for weed control in sugarcane, in addition to the conventional Merlín GD75 treatment.

The herbicides used in this study were effective in controlling all predominant weed species. According to Sánchez Zorrilla (2020), the herbicide Merlín Total SC60 showed efficacy in weed control in sugarcane for 90 days after application.

The herbicide treatments studied showed excellent control of species such as *R. cochinchinensis*, *C. rotundus*, *C. dactylon*, *I. trifida*, *D. annulatum*, and *R. minima*. With the application of Merlín Total SC60 herbicide, the lowest percentage of weeds was obtained, followed by Mayoral LS35 and Merlín GD75. The species *R. minima*, *D. annulatum*, and *I. trifida* showed greater coverage with Unipix GD70, although good control of *C. dactylon*, *C. rotundus*, *D. annulatum*, and *R. minima* was verified. Rodríguez Tassé et al. (2020) also demonstrated effective management of these species when using Merlín Total SC60 and Mayoral LS35 herbicides.

When evaluating the phytotoxicity of products applied to sugarcane (cultivar C86-12), no negative symptoms were found in the crop. Araújo, Marinho & Sobrinho (2020) compared several pre-emergent herbicides and observed that they caused little or no phytotoxicity to the sugarcane crop.

Table 4. Control percentage in the different evaluations conducted at UPC Juan José Verdecía.

No.	Treatment	Dose (kg or L·ha⁻¹)	Control Percentage (%)		
			30 DDA	60 DDA	90 DDA
1	Untreated control	-	0.00	0.00	0.00
2	Merlín GD75	0.200	95.5	94.2	90.0
3	Unipix GD70	0.200	99.2	94.2	90.0
4	Merlín Total SC60	0.25	95.5	94.3	90.1
5	Mayoral LS35	0.5	95.3	94.2	89.9
	Standard error	---	2.96	4.24	4.55
	CV	---	0.252	0.376	0.399

Legend: DAA = days after application; CV = coefficient of variation

Table 5. Control percentage in the different evaluations conducted at UPC Niguabo.

No.	Treatment	Dose (kg or L ha⁻¹)	Control Percentage (%)		
			30 DDA	60 DDA	90 DDA
1	Untreated control	-	0.00	0.00	0.00
2	Merlín GD75 (estándar)	0.230	96.4	96.9	97.0
3	Palmero GD75	0.230	96.5	96.8	96.9
4	Palmero + Mayoral LS35	0.115 + 0.25	97.2	97.5	97.9
5	Merlín GD 75 + Mayoral LS35	0.115 + 0.25	97.3	97.4	97.9
	Error estándar	---	4.61	6.35	6.92
	CV	---	0.336	0.424	0.474

Legend: DAA = days after application; CV = coefficient of variation

At UPC Niguabo, all herbicide treatments achieved good weed control compared to the untreated control, without significant differences between them (Table 5). Control was similar when using Palmero GD75 at 0.230 kg ha^{-1} and Merlín GD75 at 0.230 kg ha^{-1}. The mixtures of Palmero GD75 (0.115 kg ha^{-1}) with Mayoral LS35 (0.25 L ha^{-1}) and Merlín GD75 (0.115 kg ha^{-1}) with Mayoral LS35 (0.25 L ha^{-1}) offered similar control, with a slight tendency to be superior to individually applied treatments, although without statistically significant differences.

This study demonstrated that it is possible to control various weed species using pre-emergent herbicides with the same active ingredient, but from different suppliers, either alone or in combination. Rodríguez Tassé et al. (2020) verified that Merlín Total SC60 and Mayoral LS35 achieved effective control for up to 120 days without affecting agricultural yield when using recommended doses. Vargas (2021) evaluated the effectiveness of the herbicide isoxaflutole (GD75) for weed control and concluded that the product prevents weed development for up to 120 days after application in sugarcane.

The evaluated treatments achieved good control of various weed species, highlighting the low coverage percentage observed in *R. cochinchinensis* and *C. rotundus*. The most effective combinations were Palmero GD75 (0.115 kg ha^{-1}) with Mayoral LS35 (0.25 L ha^{-1}) and Merlín GD75 (0.115 kg ha^{-1}) with Mayoral LS35 (0.25 L ha^{-1}). The species with highest coverage at 90 days was *P. maximum*. Previous studies also showed that Guateque GD75 (isoxaflutole GD75) controls *E. colona* and *P. oleracea*, frequent species in sugarcane, at doses of 0.150, 0.175, and 0.200 kg ha^{-1} (Martínez et al., 2022).

During the evaluated period, herbicide treatments showed high selectivity with the sugarcane crop, as no damage symptoms were observed in the crop. Gómez Vásquez (2020) mentions that proper application of herbicides before weed growth allows good control without damaging the crop. Herrera-Murillo & Picado-Arroyo (2023) also indicate that pre-emergent application achieves effective control without causing crop damage.

The amount of active substance effective in weed control that reaches the soil per hectare is small, in some cases due to low percentages of active ingredients and in others due to the low dose applied (Table 6). The lowest amounts were presented by Mayoral LS 35, Merlín GD 75, and Merlín Total SC 60.

The Unipix GD70 treatment presented the highest amount of active ingredient reaching the soil, with an AAI value = 0.18, equivalent to 0.01 g of the product per m². Rodríguez, Barbosa García, Gracia Perú, Zamora Fuentes & Rodríguez Hechavarria (2019) found that the Mayoral LS35 herbicide only contributes between 0.140 and 0.175 L of active ingredient per hectare, suggesting a low risk of retention in crops and soils.

Table 6. Amounts of active ingredient (a.i.) reaching the soil.

No.	Treatment	% a.i.	Dose (kg or L ha^{-1})	AAI
1	Untreated control	--	--	
2	Merlín GD75 (standard control)	0.75	0.2	0.15
Experiment 1 (UPC J.J. Verdecía)				
3	Unipix GD70	0.35	0.5	0.18
4	Merlín Total SC60	0.6	0.25	0.15
5	Mayoral LS35	0.7	0.2	0.14
Experiment 2 (UPC Niguabo)				
6	Palmero GD75	0.75	0.23	0.17
7	Palmero GD75 + Mayoral LS35	0.75 + 0.35	0.115 + 0.25	0.17
8	Merlín GD75 + Mayoral LS35	0.75 + 0.35	0.115 + 0.25	0.17

AAI: Amount of Active Ingredient; a.i.: active ingredient

Table 7. Environmental Impact Coefficient and field EIQ of each herbicide treatment applied.

No.	Treatment	EIQ	AAI	Field EIQ	Risk level
1	Untreated control	--	--	--	
2	Merlín GD75 (standard control)	24	0.15	3.6	Very low
Experiment 1 (UPC J.J. Verdecía)					
3	Unipix GD70	43.5	0.18	7.6	Low
4	Merlín Total SC60	39.5	0.15	5.9	Low
5	Mayoral LS35	21.2	0.14	3.0	Very low
Experiment 2 (UPC Niguabo)					
6	Palmero GD75	24	0.17	4.1	Very low
7	Palmero GD75 + Mayoral LS35	45.75	0.17	7.9	Low
8	Merlín GD75 + Mayoral LS35	45.75	0.17	7.9	Low

EIQ: Environmental Impact Quotient; AAI: Amount of Active Ingredient

The environmental impact coefficient of the herbicide treatments indicates that 50% of treatments present low risk and the other 50% present very low risk (Table 7). The products Merlín GD75 and Palmero GD75 presented the lowest level of environmental risk, being classified as very low.

It is essential to have tools that evaluate these risks through simple indicators to optimize herbicide use (Barrantes, 2022). The EIQ index constitutes a useful tool for measuring the environmental impact of herbicides used in sugarcane (Fernández Aurazo, 2021). This index allows evaluation of treatment effects in agroecosystems, quantification of chemical product use, comparison of different pesticides, and selection of those with lower environmental impact.

The economic feasibility evaluation demonstrated that all evaluated treatments presented low costs per hectare per weed-free days (Table 8). The lowest cost per hectare per weed-free days was obtained with the Unipix GD70 treatment. The Merlín Total SC60 treatment had the highest cost.

Weed control during the first 120 days of a plantation is very important, because the losses it can cause in yield can exceed 50% according to Zafar, Tanveer, Cheema & Ashraf (2010). In a study on herbicides in sugarcane cultivation, it was found that treatments with higher doses also cost more, but kept the field clean for longer periods, which could increase expenses (Rodríguez Tassé et al., 2020).

This study demonstrated that the use of new pre-emergent herbicides controls weeds very well, without damaging the sugarcane. Chemical alternatives are proposed to reduce weeds in the initial stages of the crop, with low environmental impact and lower cost.

Table 8. Results of the economic analysis.

No.	Treatment	Price (USD)	Cost/ha (USD)	Weed-free days	Cost/ha/weed-free day (USD)
1	Untreated control	--	--	--	--
2	Merlín GD75 (standard control)	118.4	23.68	90	0.26
Experiment 1 (UPC J.J. Verdecía)					
3	Unipix GD70	35.9	17.95	100	0.18
4	Merlín Total SC60	142.3	35.58	100	0.36
5	Mayoral LS35	74.24	14.85	90	0.16
Experiment 2 (UPC Niguabo)					
6	Palmero GD75	118.4	27.23	100	0.27
7	Palmero GD75 + Mayoral LS35	154.3	22.6	110	0.21
8	Merlín GD75 + Mayoral LS35	154.3	22.6	110	0.21

CONCLUSIONS

The floristic inventory confirmed the predominance of the Poaceae family, particularly the species *R. cochinchinensis*.

All evaluated treatments presented excellent control of weed species in pre-emergence in sugarcane cultivation, which allows expanding chemical management strategies in relation to the conventional Merlín GD75 treatment (0.200 kg ha^{-1}).

The treatments Merlín GD75, Unipix GD70, and Palmero GD75 presented very low environmental risk, while Mayoral LS35, Merlín Total SC60, and treatment combinations showed low risk, indicating that the evaluated herbicides are environmentally sustainable.

The Unipix GD70 treatment (0.200 kg ha^{-1}) presented the lowest cost per hectare per weed-free days (0.16) with 90 days of control after application, which is economically feasible.

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