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Effectiveness and phytotoxicity of selective post-emergent herbicides in the sugarcane variety Mex 68-1345

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ABSTRACT

Objective: This study assessed the effectiveness and phytotoxicity of selective post-emergent herbicides for managing major weed species in a tropical agroecosystem.

Design/methodology/approach: A randomised complete block design with four replicates was implemented, testing nine herbicide treatments and one untreated control on the Mex 68-1345 variety. Weed control and crop phytotoxicity were assessed visually at 7, 14, and 21 days after application (DAA) using the EWRS scale. In addition, SPAD chlorophyll index readings were recorded as an indicator of foliar phytotoxicity. The herbicide combinations Ametryn+Atrazine (AMT+ATZ), Ametryn+Atrazine+Diuron (AMT+ATZ+DIU), and Ametryn+2,4-D (AMT+2,4-D) achieved "adequate control" (87.5-93%) with mild and transient phytotoxicity ($<3.5\%$).

Results: A significant negative correlation ($P<0.0001$) was observed between herbicide effectiveness and SPAD index values, indicating a physiological cost associated with weed suppression and short-term stress in sugarcane. Environmental conditions particularly low soil moisture ($<50\%$) and high temperatures (>34 °C) negatively affected herbicide efficacy and favoured weed regrowth.

Limitations on study/implications: The study was conducted under specific environmental conditions and assessed only short-term herbicide effects (up to 21 DAA), without assessing yield or economic return. Species-specific resistance was not confirmed by bioassays. Despite these limitations, the findings provide practical insight into herbicide performance under field conditions and highlight the need for integrated weed management strategies that include environmental monitoring, resistance awareness, and longer-term assessments.

Findings/conclusions: These findings support the strategic use of post-emergent herbicides as a component of integrated weed management (IWM) programmes aimed at sustainable sugarcane production.

Keywords: Sugarcane (*Saccharum officinarum* L.); post-emergent herbicides; phytotoxicity.

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INTRODUCTION

Impact of weeds on sugarcane productivity

Sugarcane (*Saccharum officinarum* L.) is a major crop in the agricultural economy of Mexico, due to both its extensive farming system and its socioeconomic relevance. The

sugarcane agro-industry is one of the country's primary agricultural sectors, covering over 800,000 hectares across 15 states and generating approximately 440,000 direct and 2.2 million indirect jobs (CONADESUCA, 2023). However, sugarcane productivity can be significantly reduced by weed competition for essential resources such as sunlight, water, macro- and micronutrients, and space (Suganthi *et al.*, 2019). Under conditions of high infestation, yield losses can range from 10 to 70% (Rathika *et al.*, 2023). In large-scale production systems, weed infestation is among the leading causes of low yields. Moreover, the continuous and indiscriminate use of herbicides contributes to environmental pollution. Therefore, it is essential to identify herbicides that provide effective weed control with fewer agrochemical applications, aiming to mitigate ecological impacts (Rodríguez-Tassé *et al.*, 2024).

Invasive flora and predominant weed species in sugarcane

In Mexico, approximately 700 non-native wild plant species have been recorded, representing 2.8% of the estimated 23,000 native flora. Of these, around 80% are considered naturalised, and between 58 and 180 species have been classified as invasive weeds with potential ecological and socio-economic impacts (Espinosa-García and Villaseñor, 2017). Studies have shown that floristic variability is influenced by factors such as soil type, rainfall regime and distribution, agricultural production systems, and weed management history highlighting the need for localised chemical and integrated weed control strategies (Aekrathok *et al.*, 2021).

Weed control practices have evolved from manual removal and rudimentary tools to mechanisation and herbicide-based approaches. Although various control methods are available, chemical weed management remains essential due to the vast cultivated areas, limited labour availability, and the high cost of manual operations (Rodríguez-Tassé *et al.*, 2024). The effectiveness of integrated weed management is positively influenced by the maintenance of a current inventory of dominant weed species within cultivated areas (Martínez-Ramírez *et al.*, 2024).

In tropical agroecosystems such as the Huasteca region, high infestations of both narrow- and broadleaf weed species have been documented, many of which exhibit traits that favour persistence under conventional agricultural management practices. The most common grasses include *Sorghum halepense* (Johnson grass), *Panicum maximum* (Guinea grass), *Cyperus* spp. (nutgrass), *Cynodon dactylon* (Bermudagrass) (Wright *et al.*, 2025), *Setaria viridis* (green foxtail), *Brachiaria plantaginea* (Alexandergrass), *Eleusine indica* (goosegrass), and *Digitaria* spp. (crabgrass), all noted for their capacity to regenerate following herbicide application and for their tolerance to drought conditions.

Among broadleaf species, *Convolvulus arvensis* (field bindweed), *Tithonia tubaeformis*, *Euphorbia heterophylla* (wild poinsettia), *Caperonia hirtus*, *Amaranthus hybridus* (pigweed), *Portulaca oleracea* (purslane), *Taraxacum officinale* (dandelion), *Raphanus raphanistrum* (wild radish), *Physalis angulata*, *Rumex crispus* (curled dock), *Mimosa pudica* (sensitive plant), *Melilotus indicus* (yellow sweet clover), *Solanum nigrum* (black nightshade), and *Cucumis anguria* (bur gherkin) are among the dominant species. Other weeds of concern include *Bidens pilosa* (Spanish needle), *Xanthium strumarium* (cocklebur), and several locally recognised species such as "valpichichi", "amargoso", and "frijolillo" (CONABIO, 2025). Weed management systems are a fundamental component of agricultural production and can be implemented through various strategies. The key lies in achieving effective control using methods that are both economically viable and operationally practical (Monteiro and Santos, 2022).

Critical stages of weed management: sprouting and tillering

Sugarcane canopy closure plays a crucial role in the competitive dynamics between the crop and weeds during the early stages of development. It is defined as the overlapping of leaf blades between adjacent rows, which helps reduce weed infestation and moisture loss through evaporation (CIDCA, 2025). Regarding sugarcane, canopy closure typically occurs between 90 and 120 days after planting, coinciding with the phenological stages of bud emergence and tillering (Leon and Odero, 2018; TNAU, 2025). The speed of canopy closure is influenced by several factors, including cultivar, planting density, production system, and edaphoclimatic conditions (Ali *et al.*, 2017; Muhammad Zafar *et al.*, 2010). This period represents the critical window for weed management, as it is characterized by high infestations of grasses and broadleaf species (Aekrathok *et al.*, 2021; Yirefu *et al.*, 2012). Weed competition during this phase reduces shoot emergence, tillering, and the development of millable stalks, ultimately decreasing stalk population, yield, and sucrose concentration (TNAU, 2025). Yield losses can exceed 50%, with no potential for later recovery (Chauhan, 2020; Yirefu *et al.*, 2012).

The application of selective herbicides in sugarcane cultivation constitutes an effective strategy for weed control. According to Espinosa-García and Villaseñor (2017), pre-emergent herbicides exhibit high efficacy when applied within 8 to 10 days after planting, under adequate soil moisture conditions and prior to bud emergence. On the other hand, post-emergent herbicides have demonstrated "very good control" when applied to weeds at a height of ≤10 cm and when their coverage exceeds 40% of the cultivated area (Servín-Niz *et al.*, 2018).

An ideal weed management programme in sugarcane comprises the use of a pre-emergent herbicide at planting, followed by shallow mechanical cultivation and a post-emergent treatment during the critical growth stage. However, implementation under field conditions may be hindered by asynchronous weed emergence, environmental variability, limited availability of agrochemicals, and logistical constraints (Chauhan, 2020). Moreover, the recurrent use of herbicides has been associated with environmental pollution, including a decline in soil biodiversity and the degradation of soil fertility (Polanco-Rodríguez *et al.*, 2019). Within this context, the aim of this study was to evaluate the effectiveness and phytotoxicity of selective post-emergent herbicides in sugarcane, with a focus on the agronomic management of the predominant weed species in the region.

MATERIALS AND METHODS

Location and experimental plot establishment

The experiment was conducted in López Rayón, within the municipality of González, Tamaulipas, Mexico, located at an altitude of 25 m above sea level, at geographical coordinates 22° 29' 5.33" N and 98° 28' 59.08" W. The study was carried out between April and July 2025. Soil preparation involved ploughing, harrowing, and ridging, with a row spacing of 1.6 m. The sugarcane variety Mex 68-1345 was sown in single rows; this cultivar was selected for its regional adaptability and late maturity, making it suitable for mechanical harvesting during the final third of the sugarcane industrialisation period. Surface irrigation was applied to promote uniform crop emergence. Following herbicide application, a cumulative rainfall of 350 mm was recorded during the evaluation period. Herbicide treatment was performed 60 days after planting, under soil moisture conditions of approximately 45%, with an estimated plant density of 44,000 plants ha^{-1}.

Herbicide selection and application

Based on previous assessments, nine post-emergence herbicides were applied to 60-day-old sugarcane (Table 1). These herbicides have demonstrated good overall weed control and caused only mild and short-term phytotoxicity symptoms in the CP 72-2086 sugarcane variety. Applications were carried out using a tractor-mounted boom sprayer equipped with 22 flat-fan nozzles (F110-02 type). The operating pressure was set at 160 psi, and the

Table 1. Active ingredients, acronyms, application rates, chemical families, target weed types, and modes of action of the post-emergence herbicides evaluated in sugarcane.

Herbicide (active ingredient)	Acronym	Dose (ha^{-1})	Chemical family	Target weed type	Mode of action
No herbicide	Control	-	-	-	-
Ametryn (80%)	AMT80	2.5 kg	Triazines	Broadleaf and grasses	PSII
Atrazine (90%)	ATZ90	2.0 L	Triazines	Broadleaf and grasses	PSII
Diuron (80%)	DIU80	2.25 L	Urea-derived compound	Broadleaf and grasses	PSII
Ametryn (23.8%) + 2,4-D (16.36%)	AMT+2,4-D	5.0 L	Triazines + Phenoxyacetic acid	Broadleaf and grasses	AAS
Ametryn (25.5%) + Acid 2,4-D (16.4%)	AMT+Acid 2,4-D	6.5 L	Triazines + Phenoxyacetic acid	Broadleaf	PSII + AAS
Ametryn (38.2%) + Atrazine (38.2%)	AMT+ATZ	2.5 kg	Triazines	Broadleaf and grasses	PSII
Clomazone (19.61%) + Ametryn (29.42%)	CLZ+AMT	4.0 L	Isoxazolidinone + Triazines	Broadleaf and grasses	ISC + PSII
Diuron (44.49%) + Hexazinone (5.59%)	DIU+HEX	3.0 L	Substituted urea + Triazinones	Broadleaf and grasses	PSII
Ametryn (38.2%) + Atrazine (38.2%) + Diuron (38.2%)	AMT+ATZ+DIU	4.5 kg	Triazines + Substituted urea	Broadleaf and grasses	PSII

Note: The evaluated herbicides act through the inhibition of Photosystem II (PSII), synthetic auxin activity (AAS; Beffa *et al.*, 2019), or the inhibition of carotenoid biosynthesis (ISC; Laborde, 2024).

spray volume was 200 L ha^{-1}. To reduce water pH, Phase® was added at a concentration of 1 mL per litre of herbicide solution, adjusting the final pH to approximately 5.5. In addition, a surfactant (ADH®) was added at a dose of 1 mL L^{-1} to enhance herbicide adherence and efficacy.

Weed infestation and evaluation of herbicide efficacy and phytotoxicity

The predominant weed species identified in this experiment were *Cynodon dactylon* (Bermudagrass), *Convolvulus arvensis* (field bindweed), *Tithonia tubaeformis*, *Euphorbia heterophylla* (wild poinsettia), *Caperonia hirtus*, *Bidens pilosa* (Spanish needle), *Cucumis anguria* (bur gherkin), as well as locally recognised species such as "amargoso" and "frijolillo". The effectiveness of herbicides for weed control and their phytotoxic effects on sugarcane were evaluated at 7, 14, and 21 days after application (DAA). The effectiveness of herbicides for weed control and their phytotoxic effects on sugarcane were evaluated at 7, 14, and 21 days after application (DAA). Each plot covered an area of 1,250 m^2 and was treated as a replicate. Overall weed control, species-specific control, and sugarcane phytotoxicity were assessed using the visual scale proposed by the European Weed Research Society (EWRS, EWRS, 2025) following the methodology described by Flores *et al.* (2005), (Figure 1).

Relative chlorophyll content measurement: SPAD index

Relative chlorophyll content was measured using SPAD index readings (Soil Plant Analysis Development) with a portable SPAD-502Plus meter (Konica Minolta, Japan). The SPAD index was used as an indicator of phytotoxicity in sugarcane leaves. Three readings were taken per plant in each replicate, directly on the leaf lamina. Measurements were consistently recorded from fully expanded leaf blades of the sugarcane plants.

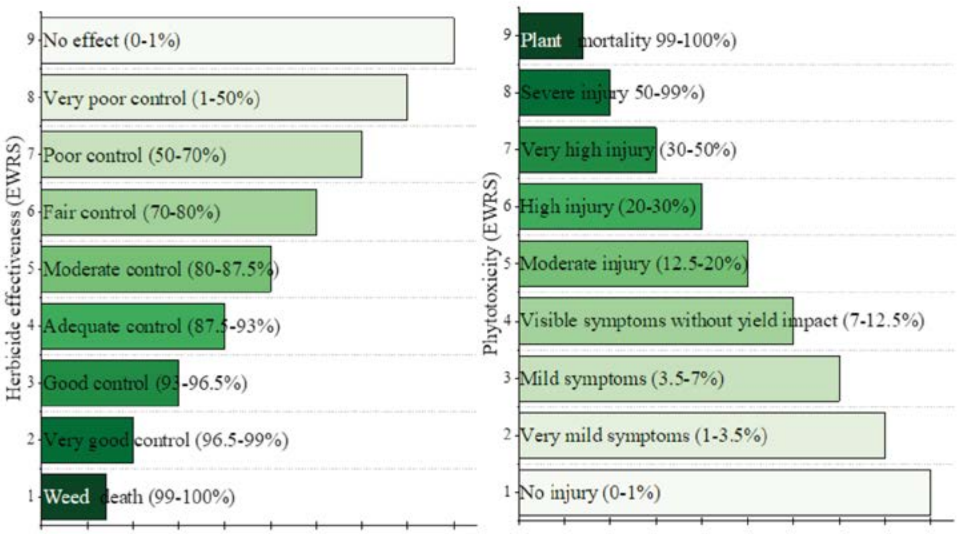

Figure 1. Adapted EWRS scale for herbicide effectiveness (EWRS, 2025) and phytotoxicity in sugarcane (Flores *et al.*, 2005).

Experimental design and statistical analysis

A randomised complete block design (RCBD) with four replications was employed. Each experimental unit covered an area of 1,250 m^2. Data on general herbicide effectiveness, species-specific weed control, and sugarcane phytotoxicity at 7, 14, and 21 DAA were subjected to statistical analysis. A one-way analysis of variance (ANOVA) was performed for each variable and sampling time, with herbicide treatment considered as the source of variation. When significant differences were detected ($P<0.05$), Tukey's multiple comparison test was applied ($\alpha=0.05$). All statistical analyses were conducted using SAS software (SAS, 2013) and Python (McKinney, 2010).

RESULTS AND DISCUSSION

Overall weed control effectiveness and sugarcane phytotoxicity

Significant differences in weed control effectiveness were observed among herbicide treatments (Tukey, $P\leq0.05$; Figure 2). According to the threshold proposed by Flores *et al.* (2005), an acceptable level of weed control corresponds to a score of 4 on the visual scale, equivalent to 87.5-93%. Based on this criterion, three treatments achieved "good control" at 7, 14, and 21 DAA: AMT+ATZ), AMT+ATZ+DIU, and AMT+2,4-D.

Atrazine, included in two of the most effective herbicide combinations in this study, is among the most widely used herbicides globally. While its broad-spectrum weed control efficacy is well established, its persistence, leaching potential, and frequent detection in surface and groundwater have raised environmental concerns (Hansen *et al.*, 2013). Atrazine has also been associated with chronic toxicity in aquatic organisms and is considered a recalcitrant compound, resulting in restrictions in the United States and bans in several European Union countries (Bethsass and Colangelo, 2006).

In contrast, atrazine remains widely used in Mexico, where it is not subject to specific regulation (Lagunas-Basave *et al.*, 2022). Its environmental mobility depends on factors such as soil texture, organic matter content, pH, and application rate (Hansen *et al.*, 2013). Although natural attenuation mechanisms such as adsorption and microbial degradation

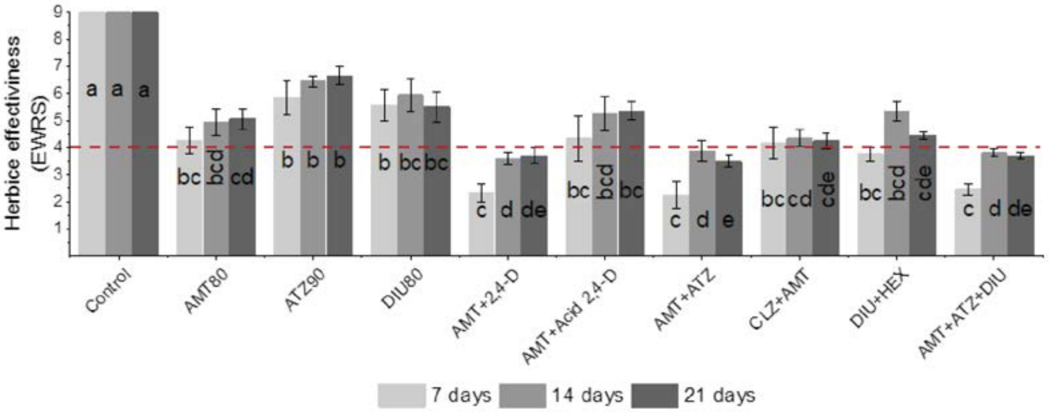

Figure 2. Weed control effectiveness of evaluated herbicides. Note: Control scale based on the European Weed Research Society (EWRS), where 1=total control and 9=no control. Control is considered adequate when EWRS ≤ 4 (87.5-93 % efficacy, red dashed line). Error bars represent significant differences among herbicides (Tukey test, $P\leq0.05$).

can mitigate its impact, risks increase under high rainfall or in soils with low organic matter. These considerations emphasise the need to balance agronomic effectiveness with environmental sustainability. Despite its strong performance in this trial, the potential ecological risks associated with atrazine highlight the importance of integrated weed management and the exploration of environmentally safer alternatives.

Weed control effectiveness and species-specific responses

The evaluated herbicides demonstrated effectiveness classified from "very good control" to "weed death" (≤96.5%) against predominant broadleaf weed species in this study, including *Tithonia tubaeformis*, *Caperonia hirtus*, and *Cucumis anguria*. These outcomes indicate high sensitivity of these species to the active ingredients applied. However, Bidens pilosa exhibited a distinct response. The DIU80 treatment achieved only "fair control" (70-80%), whereas other treatments reached 93-96.5%, categorised as "good control". This diminished effectiveness may be attributed to specific resistance mechanisms in *B. pilosa*, a species widely recognised for herbicide resistance (Alcántara-de la Cruz *et al.*, 2019). To date, more than 214 weed species with confirmed herbicide resistance have been documented, including *B. pilosa*, which may explain the limited effectiveness of diuron (Muniz *et al.*, 2019). These findings underscore the importance of considering herbicide-use history and resistance potential when selecting chemical control strategies.

The species, *Convolvulus arvensis*, was effectively controlled by AMT+2,4-D, AMT+ATZ+DIU, and DIU+HEX treatments, with control levels ranging from "adequate" to "very good" across the 7-21 DAA period. *Phaseolus lathyroides* showed a similar pattern in response to AMT+ATZ, AMT+ATZ+DIU, AMT+2,4-D, and DIU+HEX treatments. Regarding *Euphorbia heterophylla*, AMT+2,4-D and AMT+Acid 2,4-D achieved 87.5-96.5% control, also falling within the "adequate" to "very good" categories. These outcomes are consistent with Ferreira *et al.* (2016), who reported effective suppression of several *Euphorbia* species using hexazinone + diuron combinations, even under bagasse-mulched conditions of sugarcane and long-term dry periods. For the perennial grass *Cynodon dactylon*, AMT+ATZ and AMT+ATZ+DIU treatments achieved "sufficient" to "very good" control levels (Figure 3). *Euphorbia hirta* was completely controlled (100%) by both herbicide combinations evaluated. These findings highlight the species-specific performance of the herbicides and reinforce the need to tailor herbicide mixtures to the local weed spectrum.

Notably, *Convolvulus arvensis* and *Euphorbia heterophylla* showed regrowth potential, suggesting partial resistance and the need for a second herbicide application, ideally in combination with mechanical inter-row cultivation. Ametryn 80%+2,4-D amine (58%) has also been reported as effective in the CoM0265 sugarcane variety (Patil and Pachunde, 2024), which supports the present findings. On average, the treatments AMT+ATZ, AMT+ATZ+DIU, and AMT+2,4-D achieved "adequate control" (87.5-93.0%) at 7, 14, and 21 DAA, with an estimated application cost ranging between \$1,260 and \$2,000 MXN ha^{-1}.

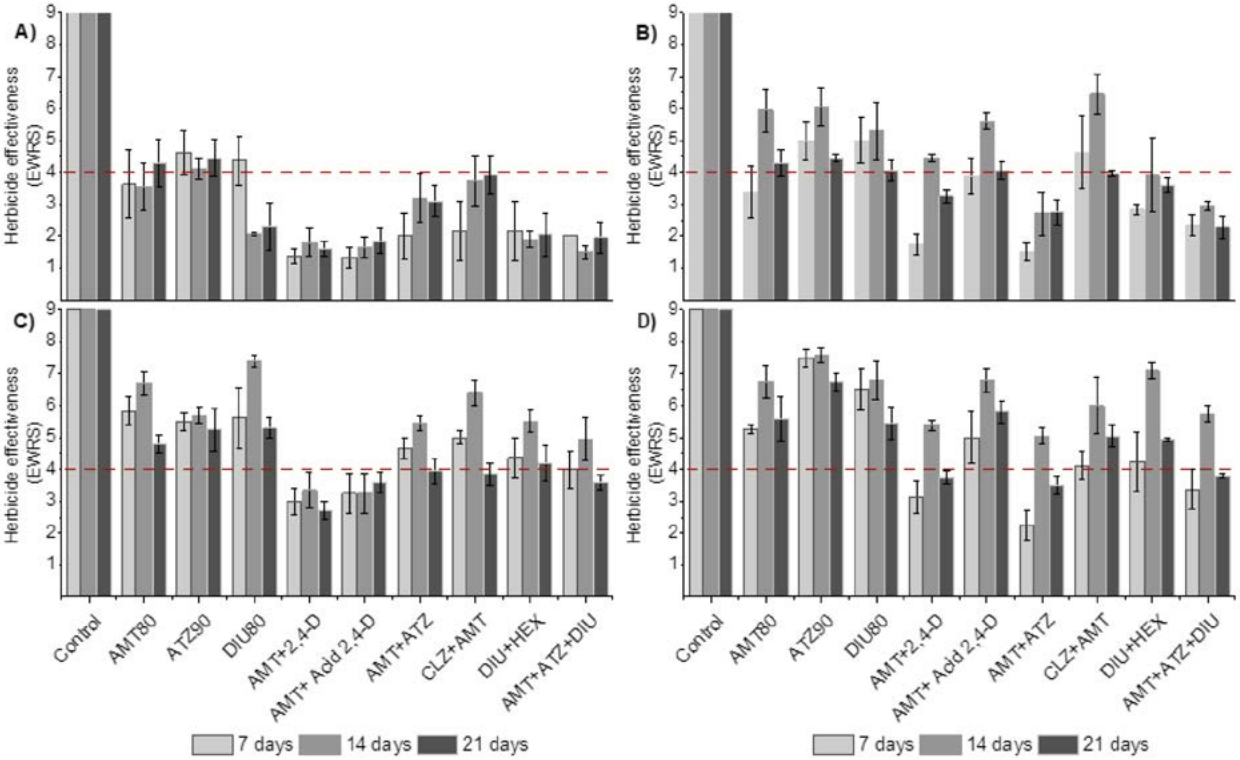

Figure 3. Herbicide efficacy in the control of *Convolvulus arvensis* L. (bindweed, A), frijolillo (B), *Euphorbia heterophylla* L. (wild poinsettia, C), and *Cynodon dactylon* (Bermuda grass, D). Error bars represent standard errors. Red dashed lines indicate the threshold for adequate control (87.5-93 %). Significant differences between herbicides were determined using Tukey's test ($P \leq 0.05$).

Environmental and edaphic influences on herbicide effectiveness

Environmental and edaphic factors may have limited herbicide effectiveness by affecting the uptake and translocation of active ingredients. A critical factor is photodegradation under low humidity, which reduces herbicide persistence on leaf surfaces (Regíl Lux, 2024). Under prolonged drought stress, weeds tend to develop thicker cuticles, leading to lower metabolic activity and restricted systemic herbicide movement. Microclimatic conditions such as elevated temperatures and wind speed, further contribute to herbicide volatilisation. According to Regíl Lux (2024), optimal application conditions are defined as temperatures below 35 °C, relative humidity of at least 60%, and wind speeds below 10 km/h. In addition, high colloid and organic matter content in clay-rich soils can increase herbicide sorption. This effect is particularly relevant in residual soils typical of grass crops, where excessive binding limits the availability of herbicides for root absorption.

Phytotoxicity responses in sugarcane

Significant differences in sugarcane phytotoxicity were observed among herbicide treatments according to the EWRS scale (Figure 4). Atrazine 90% (ATZ90) exhibited the lowest phytotoxicity, classified as "mild symptoms" (3.5-7%) and associated with "fair" weed control (70-80%). In contrast, the AMT+2,4-D, AMT+ATZ+DIU, and AMT+ATZ treatments, which achieved higher levels of weed control, induced "visible symptoms

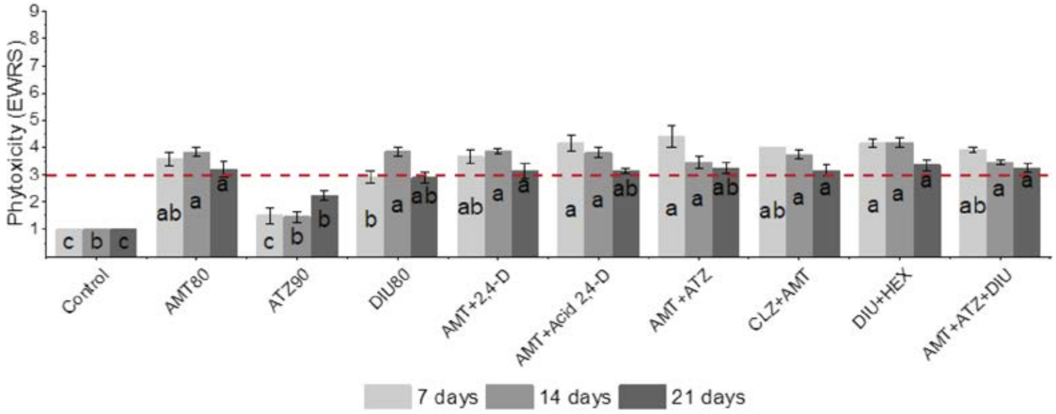

Figure 4. Phytotoxicity in sugarcane caused by the evaluated herbicides. Note: Phytotoxicity was assessed using the European Weed Research Society (EWRS) scale, where 1=no effect and 9=plant death. "Very mild symptoms" correspond to EWRS=3 (3.5-7% toxicity, red dashed line). Error bars represent standard errors. Significant differences between herbicides were determined using Tukey's test ($P \leq 0.05$).

without yield impact" (7-12.5%) at 7 days after application (DAA), which declined to "mild symptoms" (1-3.5%) by 21 DAA. This trend indicates progressive physiological recovery, with an estimated recovery period of approximately three weeks, and aligns with the findings reported by Aekrathok *et al.* (2021).

SPAD index and phytotoxicity expression

There was a significant negative correlation ($P<0.0001$) between herbicide effectiveness and SPAD index values, suggesting that less effective weed control corresponded to higher SPAD readings. This may be attributed to reduced exposure to phytotoxic compounds, which helped preserve foliar chlorophyll content. The expression of phytotoxicity varies depending on genotype, the type of active ingredient, crop growth stage, and the plant's nutritional status (da Silva *et al.*, 2014). Herbicides can induce subvisual symptoms or physiological disorders such as chlorosis, necrosis, or cell death, depending on their mode of action and the sensitivity of the crop (Sakadzo *et al.*, 2018).

Soil moisture effects on weed control

Effectiveness weed control in sugarcane typically requires a three-step management approach: pre-emergent herbicide application, mechanical cultivation, and post-emergent herbicide treatment (Sutthiwaree *et al.*, 2010). In this study, differences in herbicide effectiveness were associated with soil moisture at the time of application. The first herbicide treatment was applied under conditions of less than 50% soil moisture, which may have limited the performance of some active ingredients. Species-specific responses were observed under these suboptimal conditions: *P. lathyroides* showed minimal regrowth, *E. heterophylla* and *C. arvensis* showed moderate regrowth, and *C. dactylon* exhibited high regrowth potential. These findings agree with Aekrathok *et al.* (2021), who reported significant reductions in herbicide efficacy under low soil moisture conditions. The assessments for herbicide effectiveness at 14 and 21 DAA indicated that elevated soil moisture levels (>90%) with high temperatures (34-37 °C) adversely affected the performance of certain treatments. According to Hess (2018), waterlogged soils can interfere with herbicide uptake by limiting root absorption, reducing mobility, and impairing translocation, ultimately decreasing herbicide efficacy and persistence. These edaphoclimatic fluctuations may explain the observed variability in both phytotoxicity and weed control following the initial application. Therefore, effective and timely weed management should consider not only the type and timing of herbicide application but also prevailing environmental and soil conditions.

CONCLUSIONS

Selective post-emergent herbicides differed significantly in their effectiveness and phytotoxic impact on sugarcane. The combinations AMT+ATZ, AMT+ATZ+DIU, and AMT+2,4-D provided "adequate control" (87.5-93%) of major weed species such as *Cynodon dactylon*, *Euphorbia heterophylla*, and *Convolvulus arvensis*, while inducing only minimal phytotoxicity with no observable yield impact. The negative correlation between herbicide effectiveness and SPAD index values indicates that increased weed suppression may be temporarily associated with reduced chlorophyll content. Moreover, soil moisture and temperature fluctuations influenced both the efficacy of treatments and the regrowth capacity of weed species. These findings highlight the importance of integrating timely chemical applications with environmental monitoring and species-specific herbicide selection. Such strategies can enhance weed control, minimise crop stress, and contribute to the long-term sustainability and productivity of sugarcane-based cropping systems.

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