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Performance of Lipophilic Pre-Emergence Herbicides in no-Till and Conventional Soybean Cultivation Systems

Desempenho de Herbicidas Pré-Emergentes Lipofílicos em Sistema de Plantio Direto e Cultivo Convencional da Soja

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Abstract

Soybean cultivation is main agricultural commodity of Brazil and has been expanding in different regions of this country, notably in the Amazon-Cerrado transition region, where studies on the integrated management of glyphosate-tolerant weeds (MIPD) and their impact on productivity are still in progress. In this sense, the objective was to analyze the performance of lipophilic pre-emergence herbicides on glyphosate-tolerant weeds in conventional and no-till production systems. For this purpose, a randomized block experiment was conducted under a 5×2 factorial arrangement with four replicates. The first factor consisted of five pre-emergence treatments, namely: Control (without herbicide), flumioxazin + pyroxasulfone, flumioxazin + imazethapyr, S-metolachlor, and S-metolachlor + fomesafen; while the second factor corresponded to two production systems: conventional and no-till. We looked at weed control efficiency, weed population, weed phenology, as well as leaf chlorophyll content, NDVI (Normalized Difference Vegetation Index), phytotoxicity, and soybean productivity. The results pointed to the occurrence of ten weeds shared by the conventional and no-till systems, among which five species have a record of herbicide resistance in brazilian soybean cultivation.

The use of flumioxazine + pyroxasulfone in a no-till system (SPD) achieved a 37% higher yield than the control (without herbicide and without straw). The presence of straw on the soil (±17 t ha-1) contributed to the integrated management of glyphosate-tolerant weeds and increased the performance of lipophilic pre-emergence herbicides.

Keywords: *Glycine max* (L.) Merrill. Weed Seed Bank. Weed Survey. Integrated Weed Management. Herbicide Resistance.

Resumo

A cultura da soja é a principal commoditie agrícola do Brasil e vem sendo expandida em diferentes regiões do país, notadamente na região de transição Amazônia-Cerrado, onde são incipientes estudos referentes ao manejo integrado de plantas daninhas (MIPD) tolerantes ao glifosato e seu impacto na produtividade. Neste sentido, objetivou-se analisar o desempenho de herbicidas pré-emergentes lipofílicos sobre plantas daninhas tolerantes a glifosato, em sistemas de produção convencional e plantio direto. Para isto, realizou-se um experimento delineado em blocos casualizados, sob arranjo fatorial 5×2 e quatro repetições. O primeiro fator consistiu em cinco tratamentos pré-emergentes, sendo eles: Testemunha (sem herbicida), flumioxazina + piroxasulfona, flumioxazina + imazetapir, S-metolacloro e S-metolacloro + fomesafem; enquanto o segundo fator correspondeu a dois sistemas de produção: convencional e plantio direto. Avaliaram-se a eficiência no controle de plantas daninhas, população de plantas daninhas, fenologia de plantas daninhas, bem como, o índice de clorofila foliar (a, b e total), índice NDVI (Índice de Vegetação por Diferença Normalizada), fitotoxicidade e produtividade da soja. Os resultados apontaram a ocorrência de dez plantas daninhas compartilhadas pelos sistemas convencional e plantio direto, dentre as quais, cinco espécies têm registro de resistência a herbicidas na sojicultura brasileira. O uso de flumioxazina + piroxasulfona em sistema de plantio direto (SPD) obteve uma produtividade 37% superior à testemunha (sem herbicida e sem palha). A presença de palha sobre o solo (±17 t ha-1) contribuiu para o manejo integrado de plantas daninhas tolerantes a glifosato e aumentou o desempenho dos herbicidas pré-emergentes lipofílicos.

Palavras-chave: *Glycine max* L. Banco de Sementes de Plantas Daninhas. Levantamento de Plantas Daninhas. Manejo Integrado de Plantas Daninhas. Resistência a Herbicidas.

1 Introduction

Soybean [*Glycine max* (L.) Merrill] is among the main global agricultural commodities due to its diversified use in food, its role as an important source of bioenergy, and its value as an industrial raw material (Andrade Neto; Raiher, 2024). In the 2024/25 crop season, it stood out as one of the most produced agricultural crops in the world, reaching 421 million tons, of which Brazil accounted for 40% (Embrapa, 2025). The Brazilian area cultivated with soybean increased from 10 million hectares in 1990 to 47 million hectares in 2025. Currently, the greatest expansion has occurred in the Cerrado areas, notably in the Matopiba region, which includes the states of Maranhão, Tocantins, Piauí, and Bahia (Gale *et al*., 2019).

As soybean cultivation has expanded in Brazil, there has also been a high consumption of pesticides, estimated at approximately 52% of the total used in Brazilian agricultural crops. More than 60% correspond to the use of herbicides, especially glyphosate (La Cruz *et al*., 2021). The intensive use of glyphosate, mainly in transgenic soybean crops, has resulted in the selection of weed species tolerant and/or resistant to herbicides, with annual control costs exceeding US$ 2.7 billion (Adegas *et al*., 2022).

In this context, the use of pre-emergent herbicides—which had lost prominence in soybean cultivation with the emergence of transgenic Roundup Ready cultivars and the herbicide glyphosate-once again plays an important role in the prevention and integrated management of herbicide-resistant weeds (Gazola *et al*., 2021). From this perspective, post-emergent herbicides have their efficacy enhanced by the early control of weeds in juvenile stages, while soybean remains protected for a longer period from competition, as a result of the residual activity of pre-emergent herbicides on the seed bank (Silva *et al*., 2024).

Currently, studies related to the use of lipophilic pre-emergent herbicides in soybean under no-tillage and conventional systems are still scarce, especially in the Amazon–Cerrado transition region of Brazil. The adoption of conservationist production systems, such as no-tillage, emerges as a potential alternative to assist in weed management and to mitigate the use of non-selective post-emergent herbicides such as glyphosate, which has 12 resistant weed species reported in Brazilian soybean crops (Patel *et al*., 2023).

The no-tillage system results in lower density and fewer weed seeds in the soil seed bank compared to conventional systems, consequently reducing herbicide use and environmental impacts (Forte *et al*., 2018). However, under certain conditions, the presence of crop residues on the soil surface may alter the dynamics and efficiency of lipophilic pre-emergent herbicides such as flumioxazin, piroxsulam, pyroxasulfone, and S-metolachlor, since these substances must penetrate the straw layer to reach the soil, where the weed seed bank is located (Concenço *et al*., 2019). Thus, pre-emergent herbicides with high or medium lipophilicity may be the most affected and therefore require further study for proper positioning in these scenarios.

The objective of this study is to evaluate the effectiveness of lipophilic pre-emergent herbicides in controlling glyphosate-tolerant weed species in soybean crops under no-tillage and conventional systems in the Amazon–Cerrado transition region of Brazil, aiming to support integrated weed management (IWM) strategies for resistance prevention and yield loss reduction.

2 Material and Methods

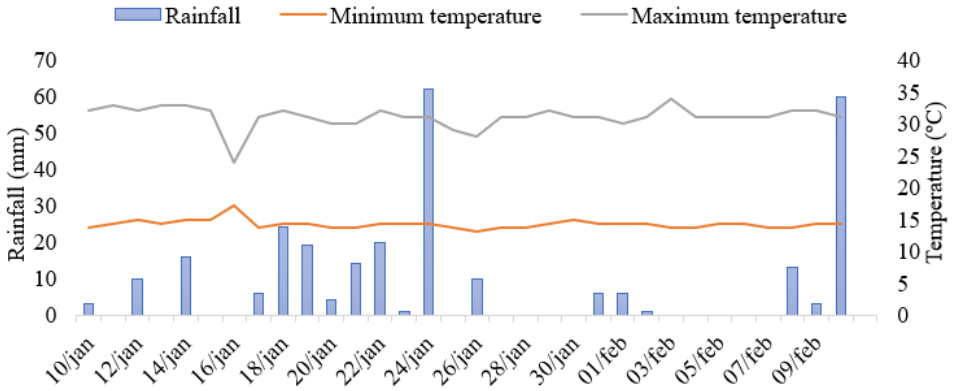
2.1 Description of the study area

The experiments were conducted in two commercial soybean fields located in the municipality of Brejo, Maranhão, Brazil, within the Matopiba region, between January and May 2023, corresponding to the 2022/2023 growing season. The municipality covers an area of 1,074 km² and is situated in the eastern portion of the state of Maranhão (42°40'7.96" W and 03°18’22” S), at an altitude of 50 m. The region is characterized by a hot and humid tropical climate (Aw), with an average

temperature of 27 °C, mean relative humidity of 76%, and an average annual rainfall of 1,835 mm. The Eastern Maranhão mesoregion presents two well-defined climatic seasons: a rainy period (January to June) and a dry period (July to December).

Meteorological data recorded between the days of treatment application and the first soybean stand evaluation are shown in Figure 1.

Figure 1 - Meteorological conditions between the days of treatment application and the first soybean stand evaluation. Brejo, Maranhão, Brazil



Source: INMET (2023).

2.2 Experimental Design

The experiment was arranged in a randomized complete block design, in a 5×2 factorial scheme with four replications. The first factor consisted of five pre-emergent herbicide treatments: control (without pre-emergent herbicide), flumioxazin + pyroxasulfone (60 g a.i. ha^{-1} + 90 g a.i. ha^{-1}; *Kyojin*®), flumioxazin + imazethapyr (60 g a.i. ha^{-1} + 120 g a.i. ha^{-1}; *ZethaMaxx*®), S-metolachlor (1,056 g a.i. ha^{-1}; *Dual Gold*®), and S-metolachlor + fomesafen (1,036 g a.i. ha^{-1} + 228 g a.i. ha^{-1}; *Eddus*®). The second factor consisted of two production systems: conventional (without soil cover) and no-tillage (with soil cover).

Pre-emergent herbicides were applied one day before soybean sowing using a CO_2-pressurized backpack sprayer equipped with a 3-m central boom and six flat-fan spray nozzles, operating at 2 bar pressure and a spray volume of 120 L ha^{-1}. Weather conditions during application were measured with a thermo-hygro-anemometer and met the requirements of ISO 5682-1:1996 standards: air humidity (55% < RH < 90%), air temperature (25 < T < 30 °C), and wind speed (2 < V < 10 m s^{-1}).

2.3 Experimental Conditions

The soil in both experimental fields was classified as *Argissolo Distrocoeso* (Ultisol), according to the Brazilian Soil Classification System (Santos *et al*., 2018). The chemical analysis of soil samples

collected from the 0–20 cm layer in the no-tillage system showed the following results: pH (water) = 5.67; phosphorus (P) = 35 mg dm^{-3}; organic matter (OM) = 0.93%; sum of bases (SB) = 4.56 cmolc dm^{-3}; and base saturation (V%) = 62%. In the conventional system, the values were: pH (water) = 5.84; P = 40 mg dm^{-3}; OM = 0.81%; SB = 3.95 cmolc dm^{-3}; and V% = 58%.

The soybean crop under the no-tillage system was preceded by an off-season (June to December) intercropping of *Urochloa ruziziensis* (ruzigrass) and maize (*Zea mays* cv. Pioneer 3707). In contrast, the conventional system remained fallow, without cover crop cultivation during the off-season.

The straw input in the no-tillage system was estimated at approximately 17 Mg ha^{-1}, based on 30 randomly collected straw samples obtained using a 0.25 m^2 quadrat. The collected material was oven-dried at 65 °C for 72 hours and then weighed on a semi-analytical balance.

2.4 Weed survey

The weed survey was carried out using the Quadrat Inventory Method, employing a 1 m^2 open quadrat. The study was conducted in two stages:(I) one day before pre-planting desiccation, and (II) 25 days after the application of pre-emergent treatments, in the post-planting phase of soybean, following Silva *et al*. (2021).

In stage I (pre-planting), data were collected from 60 georeferenced samples arranged in a regular 15×15 m grid, with 5 vertical transects and 12 samples per transect in each experimental area. In stage II (post-planting), six samples were taken per treatment. Weed species were identified using specialized literature (Lorenzi *et al*., 2014).

The similarity of weed infestations between the two production systems was determined using the Sørensen Similarity Index (SSI), calculated according to Equation (1):

$$SSI = \left[\frac{2a}{(2a+b+c)}\right] \times 100 \quad Eq.\ (1)$$

where a = species shared by both systems, b = species exclusive to the conventional system, and c = species exclusive to the no-tillage system. Results were illustrated using a Venn diagram.

Weed control percentage (WC) was determined based on the relationship between weed density in the control treatment (without herbicide) and weed density in each treatment, according to Equation (2):

$$WC(\%) = \left[\frac{(\text{density in control} - \text{density in treatment})}{\text{density in control}}\right] \times 100 \quad Eq.(2)$$

The results were classified as: no or poor control (0–40%), regular control (41–60%), sufficient control (61–70%), good control (71–80%), very good control (81–90%), and excellent control (91–100%), following the recommendations of the Brazilian Weed Science Society (SBCPD, 1995).

2.5 Soybean stand evaluation

Soybean plants were evaluated 25 days after treatment application for the following parameters: population (plants ha^{-1}), phenological stage (number of trifoliates), chlorophyll index (a, b, and total) using a *ClorofiLOG*® device, normalized difference vegetation index (NDVI) measured with a *GreenSeeker*® optical sensor, and phytotoxicity (visually estimated on a 0–100% scale). Evaluations were carried out over a 2 m linear section in three useful rows per replication, according to Silva *et al*. (2021).

Soybean yield was estimated by harvesting plants from an area of 16 m² per treatment. After laboratory analyses, data were calculated using Equation (3):

$$YIELD = \frac{(\text{Population}) \times (\text{Pods per plant}) \times (\text{Seeds per pod}) \times (\text{Thousand-grain weight})}{10{,}000} \quad Eq.(3)$$

2.6 Statistical analysis

Data were subjected to residual normality testing using the Shapiro–Wilk test ($p \leq 0.05$), analysis of variance (ANOVA) by the F-test ($p \leq 0.05$), and, when significant differences were observed, means were compared using Tukey's HSD test..

3 Results and Discussion

3.1 Weed Survey

The data presented in Table 1 show 16 weed species belonging to 15 genera and 13 botanical families, with a predominance of eudicot species (75%), annual life cycle (56%), and sexual reproduction (100%).

Table 1 - Classification of weed species by botanical family, scientific name, EPPO code, botanical class, life cycle, and mode of reproduction. Results were obtained during the pre-sowing and post-sowing stages of soybean under conventional and no-tillage production systems

Class	Family	Scientific name	EPPO code	Life cycle	Reproduction
E	*Amaranthaceae*	*Alternanthera tenella Colla*	ALRTE	A/P	As/S
E	*Amaranthaceae*	*Amaranthus viridis* L.	AMAVI	A	S
E	*Euphorbiaceae*	*Euphorbia heterophylla* L.	EPHHL	A	S
E	*Euphorbiaceae*	*Euphorbia hirta* L.	EPHHI	A	S
E	*Boraginaceae*	*Heliotropium indicum* L.	HEOIN	A	S
E	*Convolvulaceae*	*Ipomoea ramosissima (poir.) Choisy*	IPOCZ	A	S
E	*Fabaceae*	*Mimosa pudica* L.	MIMPU	P	S
E	*Portulacaceae*	*Portulaca oleracea* L.	POROL	A	S
E	*Plantaginaceae*	*Scoparia dulcis* L.	SCFDU	A	S
E	*Rubiaceae*	*Spermacoce verticillata* L.	BOIVE	P	S
E	*Turneraceae*	*Turnera subulata* Sm.	TURSU	P	S

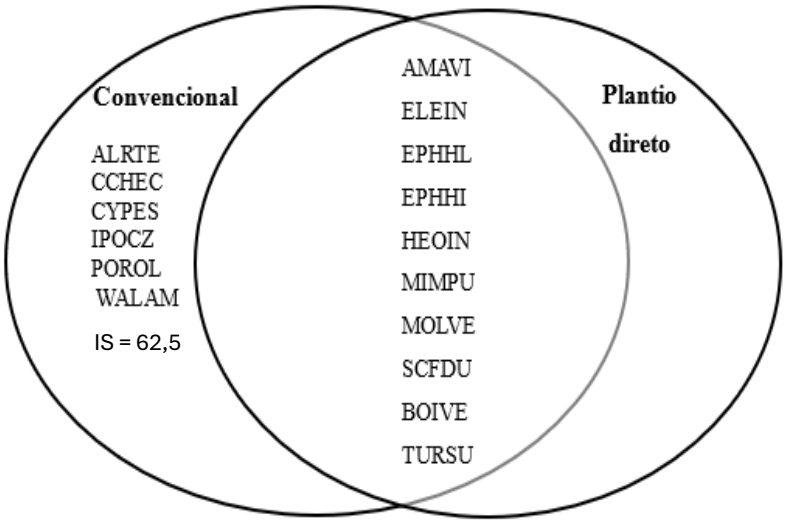
E	*Malvaceae*	*Waltheria indica* L.	WALAM	P	S
M	*Poaceae*	*Cenchrus echinatus* L.	CCHEC	A	S
M	*Cyperaceae*	*Cyperus esculentus* L.	CYPES	P	As/S
M	*Poaceae*	*Eleusine indica (*L.) Gaertn.	ELEIN	A/P	S
M	*Molluginaceae*	*Mollugo verticillata* L.	MOLVE	A	S

Abbreviations – EPPO: *European and Mediterranean Plant Protection Organization*; E: eudicotyledon; M: monocotyledon; A: annual; P: perennial; As: asexual; S: sexual.
Source: research data.

The families Amaranthaceae (2), Euphorbiaceae (2), and Poaceae (2) showed the highest number of identified species, consistent with the results obtained by Silva et al. (2021) and Ponte *et al*. (2024) in soybean crops located in the Amazon–Cerrado transition region. Weed species with an annual life cycle and sexual reproduction (by seeds) predominated, possibly selected by the history of annual crops, which require greater dynamism from the weed populations inhabiting these fields (Santos *et al*., 2024).

Regarding the similarity in weed occurrence between the two production systems, an index of 62.5% was obtained, indicating an excellent adaptation of the species to both management systems (conventional and no-tillage) (Figure 2).

Figure 2 - Illustration of exclusive and shared species between the conventional and no-tillage production systems in the Amazon–Cerrado transition region, Brazil



Source: research data.

The results obtained in this study differ from those of Forte *et al*. (2018), who reported lower weed density under the no-tillage system compared to the conventional system, due to the suppressive effect of crop residue on the germination of positively photoblastic weeds. Therefore, it is likely that

the increase in weed density in the no-tillage system observed in the present study is related to failures in cover crop distribution, improved soil fertility, and a higher occurrence of neutral or negatively photoblastic weeds.

The species ALRTE, CCHEC, CYPES, IPOCZ, POROL, and WALAM occurred exclusively in the conventional system (Figure 2), possibly due to the physical or allelopathic inhibitory effect of cover crops on the germination of these weeds in the no-tillage system (Castro *et al*., 2023; Zhao *et al*., 2023). Conversely, the species AMAVI, ELEIN, EPHHL, EPHHI, HEOIN, MOLVE, SCFDU, BOIVE, and TURSU were not affected by the management system and, therefore, occurred in both production systems (Figure 2).

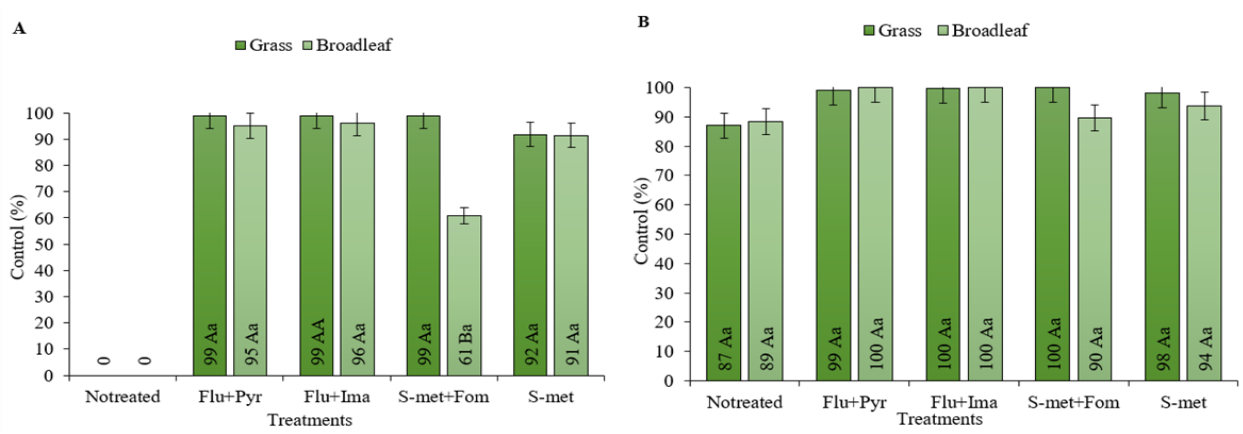
Among the species shared between conventional and no-tillage management, ELEIN and EPHHL have been described by Correia *et al*. (2022) as glyphosate-resistant weeds in soybean crops in Brazil. Furthermore, BOIVE has shown glyphosate tolerance and is referenced as one of the most problematic species in the agricultural frontier of grain production in northern and northeastern Brazil (Kalsing *et al*., 2020).

In this context, it is important to highlight that these species are generally selected by the successive and non-rotational use of glyphosate. Therefore, the adoption of pre-emergence herbicides, such as flumioxazin, pyroxasulfone, and S-metolachlor, can serve as a complementary control strategy to soil cover, enabling the prevention of herbicide-resistant weed biotypes and the reduction of soybean yield losses.

3.2 Performance of Pre-emergence Herbicides on Botanical Classes of Weeds

In the no-tillage system, a control rate of 87% for monocotyledonous species and 89% for eudicotyledonous species was obtained, even without the use of pre-emergence herbicides. These results confirm the importance of soil cover as an effective weed control method, particularly for mitigating herbicide-tolerant and/or resistant species, such as those resistant to glyphosate (Figure 3).

Figure 3 - Percentage of control of monocotyledonous and eudicotyledonous weed species under the conventional production system (A) and no-tillage system (B). Uppercase letters inside the bars compare the effects of pre-emergence treatments, whereas lowercase letters compare the production systems

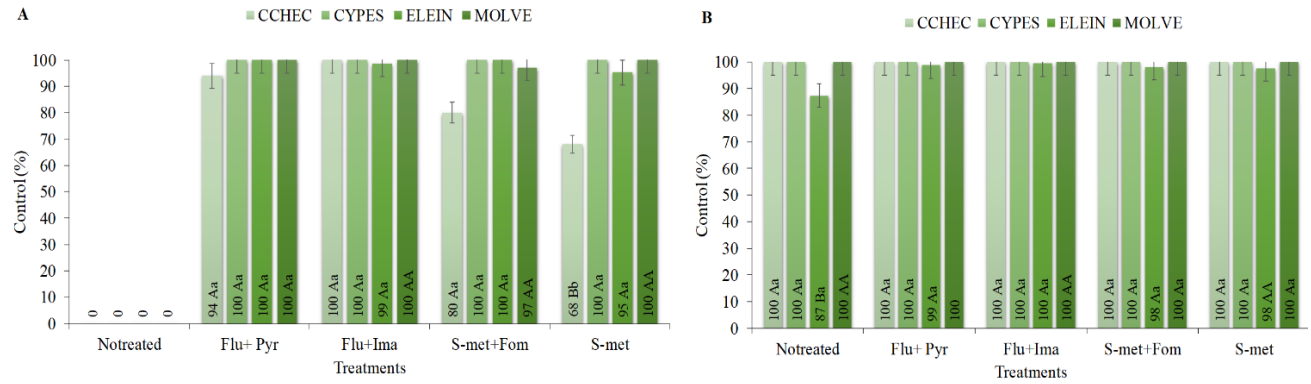


Source: research data.

The presence of plant residues on the soil surface inhibits weed emergence through the release of allelochemical compounds, the filtering of solar radiation reaching the soil, and the maintenance of soil temperature and moisture, all of which act as regulatory factors in the germination process (Ferreira *et al*., 2018). Therefore, in all pre-emergence treatments, the use of mulch maximized weed control efficiency.

Regarding the performance of pre-emergence herbicides under the no-tillage system, control rates of 97% for monocotyledonous species and 94% for eudicotyledonous species were recorded (Figure 4), representing increases of 19% and 27%, respectively, compared with the conventional system. The combinations flumioxazin + pyroxasulfone and flumioxazin + imazethapyr stood out, achieving control percentages equal to or very close to 100% (Figure 4).

Figure 4 - Percentage of control of pre-emergence herbicides on target monocotyledonous weed species under conventional (A) and no-tillage (B) production systems. Uppercase letters within columns compare the effects of pre-emergence treatments, whereas lowercase letters compare the production systems



Source: research data.

In contrast, the application of S-metolachlor + fomesafen was not effective against eudicotyledonous species under the conventional production system, achieving only 61% control. This can be explained by the broader spectrum of activity of S-metolachlor against monocotyledonous weeds and, in some cases, eudicotyledonous plants with small seeds, i.e., those with limited energy reserves for germination (Gazola *et al*., 2021). In this context, the use of S-metolachlor or S-metolachlor + fomesafen resulted in 98–100% control of monocotyledonous species, confirming the excellent efficacy of this herbicide for that botanical class.

Regarding the performance of flumioxazin and S-metolachlor in both the conventional and no-tillage systems, results indicated that soil cover did not interfere with the efficiency of these active ingredients. On the contrary, it enhanced control percentages, even though these compounds are classified as highly or moderately lipophilic, respectively. Lipophilicity refers to the affinity of a herbicide for the polar phase (represented by water) and nonpolar phase (represented by octanol); thus, the higher the partition coefficient (Kow), the greater the herbicide's lipophilicity (Soltani; Shrosphore; Sikkema, 2018). Consequently, a highly lipophilic herbicide shows greater affinity for organic materials, leading to increased adsorption to organic matter and/or stronger binding to epicuticular waxes on the leaf surface of emerged plants (Patel *et al*., 2023).

Therefore, the satisfactory performance of these herbicides under the no-tillage system may be related to rainfall events following spraying (Roncatto *et al*., 2023). Rainfall records showed 18 mm immediately after application, 119 mm during the first week, and 249 mm by the fourth week after application (Figure 1). The occurrence of rainfall after applying lipophilic pre-emergence herbicides, particularly under no-tillage conditions, aids in the transport of herbicide molecules into the soil, where the weed seed bank is located, thus enabling the herbicide to act effectively at the site of weed emergence (Khalil *et al*., 2019).

3.3 Performance of Pre-emergence Herbicides on Target Weed Species

Firstly, regarding the target monocotyledonous species—CCHEC, CYPES, ELEIN, and MOLVE—the pre-emergence herbicides showed control percentages above 67% under the conventional system and 87% under the no-tillage system (Figure 4). The species CCHEC exhibited tolerance to S-metolachlor in the conventional system, particularly when the herbicide was applied alone (68% control). In contrast, the combinations S-metolachlor + fomesafen, flumioxazin + pyroxasulfone, and flumioxazin + imazethapyr increased the control percentage of this species to 80–100%.

Furthermore, all pre-emergence treatments were effective in controlling CYPES, ELEIN, and

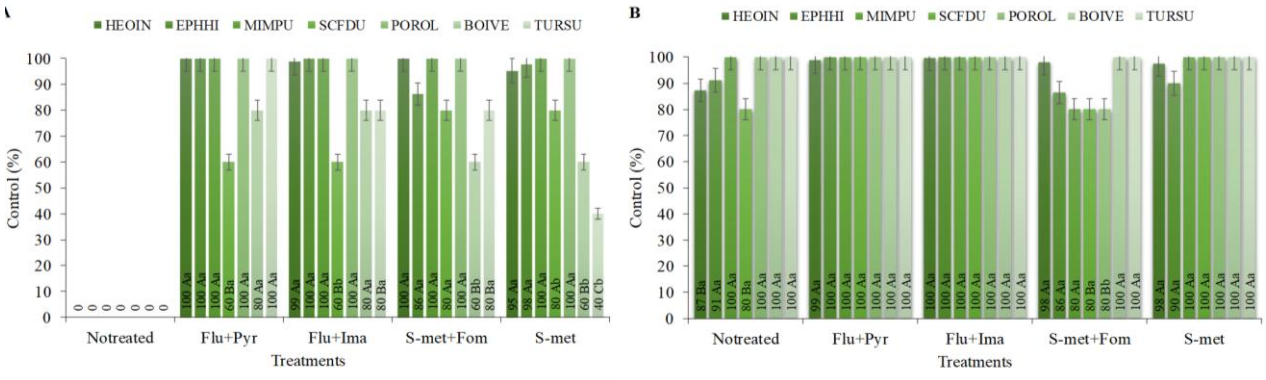
MOLVE, with control rates reaching 100%. When pre-emergence herbicides were not applied, cultural control through the no-tillage system achieved control percentages ranging from 87% to 100%, confirming it as an excellent alternative for the integrated management of these target species.

It is important to note that all pre-emergence treatments achieved control levels above 90% for ELEIN in both conventional and no-tillage systems. ELEIN is a difficult-to-control weed currently present in approximately 75% of soybean cultivation areas in Brazil. It exhibits single and multiple resistance to herbicides from Group A (lipid synthesis inhibitors) and Group G (aromatic amino acid synthesis inhibitors) (Procópio *et al*., 2024).

Thus, the results obtained in this study reinforce that the use of pre-emergence herbicides is essential for the prevention and effective control of herbicide-resistant weeds, as they act directly on the seed bank, inhibiting germination and/or emergence of these species (Pitol *et al*., 2022). The findings indicate that the combinations flumioxazin + pyroxasulfone, flumioxazin + imazethapyr, and S-metolachlor + fomesafen are efficient alternatives for managing weed species tolerant or resistant to herbicides such as glyphosate.

Regarding the eudicotyledonous target species, control percentages exceeded 79% in the no-tillage system and 39% in the conventional system. Once again, the presence of soil cover enhanced weed control performance (Figure 5).

Figure 5 - Control efficiency of pre-emergence herbicides on eudicotyledonous target species under conventional (A) and no-tillage (B) production systems. Uppercase letters within columns compare the effects of pre-emergence treatments, whereas lowercase letters compare the production systems



Source: research data.

The most tolerant species to the tested treatments were SCFDU, BOIVE, and TURSU, particularly under the conventional production system. In this system, SCFDU showed 60% control with the combination of flumioxazin + pyroxasulfone or flumioxazin + imazethapyr. A similar result

was obtained for BOIVE with the use of S-metolachlor, either alone or combined with fomesafen. Meanwhile, TURSU exhibited a low control level (40%) when S-metolachlor was applied alone.

With the application of flumioxazin + pyroxasulfone and flumioxazin + imazethapyr mixtures, the control of BOIVE and TURSU increased to 80% or higher. On the other hand, SCFDU proved to be more sensitive to S-metolachlor and S-metolachlor + fomesafen. These findings suggest that triple combinations, such as flumioxazin + pyroxasulfone + imazethapyr or flumioxazin + S-metolachlor + imazethapyr, could be effective for the simultaneous control of these species in future studies.

It is worth noting that pyroxasulfone and S-metolachlor belong to the same herbicide group (Group K). Therefore, their joint use in triple mixtures should be avoided to ensure multiple mechanisms of action are involved. Additionally, dual mixtures of S-metolachlor and flumioxazin may also represent effective solutions for controlling these eudicotyledonous species, particularly those with control levels below 80%.

Conversely, reactive use of chemical control can compromise the sustainability of production systems in the face of global food production challenges. From this perspective, the no-tillage system enhanced the performance of pre-emergence treatments, achieving control rates above 79%. Thus, it stands out as an important integrated weed management strategy and a sustainable practice for large-scale food production.

3.4 Selectivity of pre-emergence herbicides on soybean under conventional and no-tillage management

The results indicate that pre-emergence herbicides and soybean production systems significantly ($p \leq 0.05$) affected, both individually and in interaction, the contents of chlorophyll “a”, “b”, and total, the Normalized Difference Vegetation Index (NDVI), plant height, number of trifoliates, plant density, and soybean yield.In contrast, phytotoxicity and the number of trifoliates were not influenced by any of the treatments or their interactions (Tables 2 and 3).

Table 2 - Chlorophyll a (Chl a), chlorophyll b (Chl b), total chlorophyll (Chl t), Normalized Difference Vegetation Index (NDVI), and phytotoxicity (Phyto) of soybean under different pre-emergence herbicide treatments and production systems (conventional and no-tillage)

Herbicides	Phyto	Chl a	Chl b	Chl t	NDVI
	Conv	NT	Conv	NT	Conv
Control	1.0	1.0	24.0Aa	22.0Ab	6.9Aa
Flu+Pir	1.6	1.0	23.5Aa	21.4Ab	6.4Aa
Flu+Ima	1.4	1.0	20.8Ba	20.6Aa	5.4Ba
S-met+Fom	1.0	1.0	20.9Ba	20.5Aa	5.5Ba
S-met	1.0	1.0	24.7Aa	20.0Ab	6.9Aa

Mean	1.2	1.0	22.8a	20.9b	6.2a
CV (%)	22.3	—	5.6	—	14.7

Means followed by the same letters — uppercase in columns and lowercase in rows — do not differ by Tukey's HSD test ($p \leq 0.05$). **Abbreviations:** Conv – conventional system; NT – no-tillage system; CV – coefficient of variation; Flu – flumioxazin; Ima – imazethapyr; Pir – pyroxasulfone; S-met – S-metolachlor; Fom – fomesafen.
Source: research data.

Table 3 - Plant height, number of trifoliates, plant density per linear meter, and soybean yield under different pre-emergence herbicide treatments and production systems (conventional and no-tillage)

Herbicides	**Height (cm)**	**Trifoliates**	**Density (plants m^{-1})**	**Yield (1,000 kg ha^{-1})**
	Conv	NT	Conv	NT
Control	13.5Aa	13.3ABa	3.0Aa	3.0Aa
Flu+Pir	13.3Aa	13.0ABa	3.4Aa	3.0Aa
Flu+Ima	11.4Bb	14.0Aa	3.0Aa	3.0Aa
S-met+Fom	12.5ABa	12.9Ba	2.8Aa	3.0Aa
S-met	13.8Aa	12.5Bb	3.0Aa	3.0Aa
Mean	12.9a	13.2a	3.0a	3.0a
CV (%)	5.3	—	7.4	—

Means followed by the same letters — uppercase in columns and lowercase in rows — do not differ by Tukey's HSD test ($p \leq 0.05$). **Abbreviations:** Conv – conventional system; NT – no-tillage system; CV – coefficient of variation; Flu – flumioxazin; Ima – imazethapyr; Pir – pyroxasulfone; S-met – S-metolachlor; Fom – fomesafen.
Source: research data.

Chlorophyll "a", "b", and total chlorophyll indices, as well as the NDVI index, were higher in the conventional system compared to the no-tillage system (Table 2). These results can be attributed to the interference caused by straw deposition on the soil surface in the no-tillage system, which affected soybean germination and emergence. This delayed stand establishment, reducing chlorophyll levels in the middle-third leaves and NDVI values. However, no significant effects were observed on plant height at the V4 phenological stage.

Regarding pre-emergence herbicides, the combinations flumioxazin + imazethapyr and S-metolachlor + fomesafen showed greater negative interference with chlorophyll and NDVI levels, presenting lower results than the other treatments, particularly in the conventional system. This may be related to the more immediate availability of herbicides in this production system (Cantu *et al*., 2021). However, it is important to emphasize that no necrosis, chlorosis, or other injuries were observed that would indicate phytotoxic effects of the analyzed pre-emergent treatments, resulting in negligible phytotoxicity (score 1.0).

Soybean plant density was negatively affected by the no-tillage system ($p \leq 0.05$), with an average reduction of five plants per meter (Table 3). It is understood that the high residual biomass on the soil surface (±17 Mg ha^{-1}) affected soybean germination in a similar way to its influence on the weed seed bank. Moreover, operational failures in soybean sowing may have occurred, particularly due to improper adjustment of the cutting system and/or seed deposition depth, as the

study area is characterized by cohesive soils, which enhance the effects of seed placement on crop establishment and yield (Ribeiro *et al*., 2024).

In terms of yield, the best results were obtained with the application of flumioxazin + pyroxasulfone in the no-tillage system (4,476 kg ha^{-1}) and conventional system (4,386 kg ha^{-1}), as well as with S-metolachlor + fomesafen (4,248 kg ha^{-1}) in the no-tillage system. Furthermore, the no-tillage system showed significantly higher productivity ($p \leq 0.05$) than the conventional system, producing 391 kg ha^{-1} more grain, even with a lower plant population (Table 3). This result may be associated with effective control of glyphosate-tolerant weed species, such as *Eleusine indica* and *Boerhavia diffusa*, in this production system.

The untreated control (no herbicide) in the no-tillage system showed an increase of 972 kg ha^{-1} compared to the control in the conventional system (without herbicide and straw) (Table 3). The soil cover contributes to weed management, improves stand establishment, and enhances soil attributes, thereby increasing soybean productivity (Delonzek *et al.,* 2019). This explains the higher yields observed under no-tillage, which also improved the performance of most pre-emergence herbicide treatments evaluated.

The results of this study reinforce the importance of soil cover and the use of pre-emergence herbicides in the integrated management of glyphosate-resistant weeds, given that glyphosate remains the main post-emergence non-selective herbicide used in soybean cultivation in Brazil (Adegas *et al*., 2022). Furthermore, maintaining straw on the soil surface enhanced the performance of lipophilic pre-emergence herbicides, likely due to rainfall events following application that facilitated the leaching of herbicides into the soil.

4 Conclusion

The application of flumioxazin + pyroxasulfone in the no-tillage (4,476 kg ha^{-1}) and conventional systems (4,386 kg ha^{-1}), as well as S-metolachlor + fomesafen (4,248 kg ha^{-1}) in the no-tillage system, resulted in the highest yields, combined with high weed control efficiency.

The succession of crops and maintenance of straw cover enhance weed control efficiency and soybean productivity in the no-tillage system. The use of straw leads to weed control rates above 80% and significant yield gains, with estimated increases of up to 1,700 kg ha^{-1} of grain.

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