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Alternatives for Pre-Harvest Soybean Desiccation and Buttonweed (*Spermacoce verticillata* L.) Control

Alternativas para Dessecação Pré-Colheita da Soja e Controle de Vassourinha-de-Botão (*Spermacoce verticillata* L.)

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Abstract

The desiccation of soybeans before harvest has been used for to even out plant maturity, earlier harvest, control weeds and/or reduce losses in the quality of the commercial product. Following the ban on paraquat in Brazil, many questions have occurred about the herbicides use in the soybean harvest. The aim was to evaluate the herbicide performance of the photosystem I, glutamine synthase and protoporphyrogen oxidase inhibitors, in the soybean harvest desiccation and buttonweed control. The experiment was carried out on a soybean field located in Mata Roma, Maranhão, Brazil. The area was selected due to its history of conventional management and high buttonweed density in many soybean phenological phases. The experiment was designed in a randomized blocks arrangement, with seven treatments and four replications. The treatments consisted in a no-treated (without herbicide), diquat (400 g a.i. ha^{-1}), glufosinate (400 g a.i. ha^{-1}), carfentrazone (30 g a.i. ha^{-1}), flumioxazin (40 g a.i. ha^{-1}), fomesafen (250 g a.i. ha^{-1}) and saflufenacil (35 g a.i. ha^{-1}). The herbicides were applied at phenological stage R7.2 in a Monsoy 8644 cultivar, nine days before the harvest. We evaluated the defoliation and maturation percentage, light intensity ratio, NDVI index, grain moisture and buttonweed control. We concluded that the use of diquat, flumioxazin or saflufenacil are effective for soybean desiccation and weed control. But, the flumioxazin (87%) and saflufenacil (91%) applcation have a pre-emergence effect in the soil, and thus, they are better options for preventive buttonweed control in soybean fields.

Keywords: Glycine max L. Diquat. PROTOX inhibitors. Ripening. Paraquat.

Resumo
A dessecação pré-colheita da soja está em crescente utilização por uniformizar a maturação de plantas, antecipar a colheita, controlar plantas daninhas e/ou reduzir perdas na qualidade do produto comercial. Após a proibição do paraquat no Brasil, muitas incógnitas tem surgido quanto ao posicionamento de herbicidas em pré-colheita da soja. Objetivou-se avaliar a performance de herbicidas inibidores do fotossistema I, glutamina sintase e protoporfirogênio oxidase, na dessecação pré-colheita da soja e controle de vassourinha-de-botão. O experimento foi realizado numa lavoura comercial de soja, situada em Mata Roma, Maranhão, Brasil. A área foi selecionada pelo histórico de manejo convencional e ocorrência de uma alta infestação de vassourinha-de-botão em diferentes fases do cultivo. O delineamento experimental foi em blocos casualizados, com sete tratamentos e quatro repetições. Os tratamentos consistiram na testemunha (sem herbicida), diquat (400 g i.a. ha^{-1}), glufosinato (400 g i.a. ha^{-1}), carfentrazona (30 g i.a. ha^{-1}), flumioxazina (40 g i.a. ha^{-1}), fomesafem (250 g i.a. ha^{-1}) e saflufenacil (35 g i.a. ha^{-1}). Os herbicidas foram aplicados no estádio fenológico R7.2 da cultivar de soja Monsoy 8644, nove dias antes da colheita mecanizada. Avaliaram-se a porcentagem de desfolha e maturação de grãos, relação de intensidade luminosa, índice NDVI, teor de umidade do grão e porcentagem de controle de vassourinha-de-botão. Ao término do estudo, conclui-se que o uso de diquat, flumioxazina ou saflufenacil é efetivo para dessecação da soja e controle de vassourinha-de-botão remanescente. Contudo, considera-se que a flumioxazina (87%) e saflufenacil (91%) por terem ação pré-emergente no solo, são melhores opções com enfoque no manejo preventivo de vassourinha-de-botão em lavouras de soja.

Palavras-chave: Glycine Max L. Diquat. Inibidores da PROTOX. Maturação. Paraquat.

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1 Introduction

Soybean [*Glycine max* (L.) Merrill] is one of the most important agricultural crops worldwide due to its diverse use in food, high economic potential, and excellent adaptation to different edaphoclimatic conditions (Seixas *et al.,* 2020). As a commodity, it generates significant trade balance gains and directly contributes to strengthening the global economy (Montoya *et al*., 2019).

Pre-harvest desiccation of soybeans is increasingly being used, as it standardizes plant maturation, advances harvesting, preserves the quality of the commercial product, improves operational efficiency, and reduces harvest losses (Zuffo *et al*., 2019). Additionally, it helps control remaining weeds (Takano; Dayan, 2020).

Currently, one of the most problematic weed species is buttonweed (*Spermacoce verticillata* L.), for which preventive management has been essential for its control (Fadin; Monquero, 2019).

This is a hardy plant that disperses easily (Castilho; Forti; Monquero, 2022), germinates in low-light conditions (Gallon *et al*., 2019), adapts well to dry periods (Nepomuceno *et al*., 2018), and, when not properly controlled, causes serious damage due to yield loss and decreased efficiency in mechanized harvesting (Diesel *et al*., 2018).

The correct selection of herbicides is a key aspect of successful pre-harvest desiccation of soybeans (Albrecht *et al.*, 2022). Until 2020, paraquat was the main herbicide used in Brazil. However, after its ban (ANVISA, 2020), several uncertainties arose regarding substitute molecules. Currently, diquat (a photosystem I inhibitor) and glufosinate (a glutamine synthetase inhibitor) have been the most commonly used herbicides (Diniz *et al*., 2023). However, it is believed that some protoporphyrinogen oxidase (PROTOX) inhibitors, such as carfentrazone, flumioxazin, fomesafen, and saflufenacil, may also be effective alternatives due to their excellent performance in pre-plant desiccation (Silva *et al*., 2022).

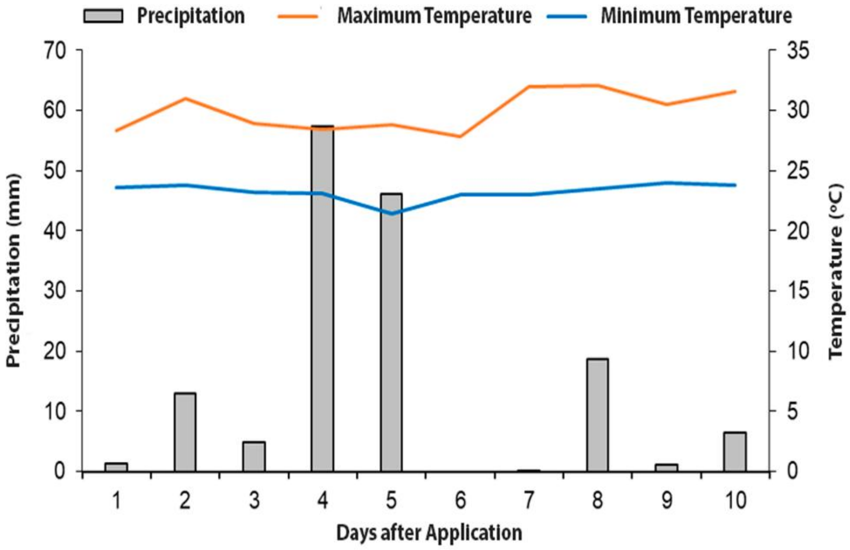
Following the paraquat ban, there have been few conclusive results regarding the best pre-harvest options, particularly for soybean desiccation and the control of remaining weeds such as buttonweed. Given this context, this study aimed to evaluate the performance of photosystem inhibitors, glutamine synthetase inhibitors, and PROTOX inhibitors in pre-harvest soybean desiccation and the control of remaining buttonweed.

2 Material and Methods

2.1 Study location

The experiment was conducted in May 2022 in a commercial soybean field, cultivar Monsoy 8644 IPRO. The experimental area was located in the municipality of Mata Roma (3º 14’ 50” S, 43º 11’ 13” W), Maranhão, Brazil. The municipality's climate is classified as hot and humid tropical (Aw). During the study period, meteorological data recorded a total accumulated rainfall of 149 mm, a maximum temperature of 32 °C, and a minimum temperature of 21 °C. The meteorological data for rural property are presented in Figure 1.

Figure 1 - Information on meteorological conditions of rainfall and temperature in the experimental area between the treatment application period and harvest. Mata Roma, Brazil, 2022



Source: research data.

The soil in the experimental area was classified as a Yellow Argisol (Santos *et al.*, 2018), with a chemical analysis revealing the following characteristics in the 0–20 cm layer: pH (water) = 5.2; Phosphorus (P) = 1.9 mg dm^{-3}; Organic matter (O.M.) = 1.2%; Sum of bases (SB) = 2.0 cmolc dm^{-3}; Base saturation (V%) = 54%.

The area was selected due to its history of conventional management, with successive glyphosate use for over 10 years and a high occurrence of buttonweed in the last four years, peaking at 117 plants m^{-2} during the 2021/2022 growing season. At harvest time, this weed was predominantly in the juvenile stage, with an average density of 16 plants m^{-2}.

2.2 Experimental Design

The experimental design was a randomized complete block design (RCBD) with seven treatments and four replications. The treatments consisted of a control (no herbicide), diquat (400 g a.i. ha^{-1}; Offer®), glufosinate (400 g a.i. ha^{-1}; Finale®), carfentrazone (30 g a.i. ha^{-1}; Aurora®), flumioxazin (40 g a.i. ha^{-1}; Sumyzin®), fomesafen (250 g a.i. ha^{-1}; Flex®), and saflufenacil (35 g a.i. ha^{-1}; Heat®). In all treatments, except for the control, 0.5% vegetable oil (Aureo®) was added to the spray solution.

Herbicides were applied at the R7.2 phenological stage of the Monsoy 8644 cultivar, 10 days before harvest. A CO_2-pressurized backpack sprayer was used, equipped with a 3 m central boom, six spray nozzles, single flat-fan tips, a working pressure of 2 bar, and a spray volume of 100 L ha^{-1}.

2.3 Experimental analyses

The soybean stand was evaluated 10 days after treatment application based on the following parameters:Defoliation percentage and grain maturation – estimated by visual diagnosis on a 0 to 100% scale; Light intensity ratio – estimated as the quotient between the light intensity in the upper and lower thirds of the soybean canopy, measured with a lux meter (Minipa Mlm-1011®); NDVI index – estimated using an active light source optical sensor (GreenSeeker®).Grain moisture content (%) – measured with a grain moisture sensor (Al-102 Eco Agrologic®); Buttonweed control percentage (%) – estimated using the following equation:

$$\text{Control (\%)} = \left[\frac{\text{density of control} - \text{density of treatment}}{\text{density of control}}\right] \text{x100} \qquad \text{(Eq.1)}$$

The evaluation scales for soybean defoliation/maturation percentage and buttonweed control included the following control classes: none or scarce (0–40%), regular (41–60%), sufficient (61–70%), good (71–80%), very good (81–90%), and excellent (91–100%).

In the soybean stand assessments, four useful rows of 2 linear meters per replication were evaluated, covering a useful area of 16 m² per treatment. Meanwhile, the weed survey was conducted using the Inventory Quadrat Method, by randomly placing a 1 m² open quadrat in the central portion of each replication.

2.4 Statistical analysis

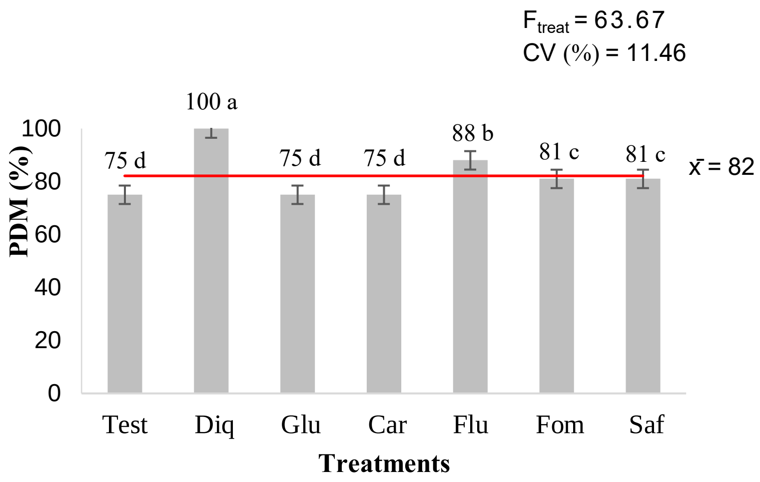
The data were subjected to analysis of variance (ANOVA) using the F-test, and significant contrasts between means ($p<0.05$) were analyzed using Duncan's test. Additionally, a simple correlation analysis was performed for the variables, with correlation coefficients (r) classified as follows: weak ($0.10 < r \leq 0.30$), moderate ($0.30 < r \leq 0.60$), strong ($0.60 < r \leq 0.90$), and very strong ($0.90 < r \leq 1.00$), using the QuantumGIS (QGIS) software.

3 Results and Discussion

3.1 Pre-harvest desiccation of soybean

All herbicide treatments were effective in promoting soybean defoliation and maturation ($p<0.0001$), reaching percentage levels between 75% and 100%, with an overall average of 82% (Figure 2). The best performances were observed with the application of diquat (100%), flumioxazin (81%), fomesafen (81%), and saflufenacil (81%). Glufosinate and carfentrazone achieved 75%, being statistically similar to the control (no herbicide) (Figure 2).

Figure 2 - Effect of photosystem I (PSI) inhibitors, glutamine synthetase (GS) inhibitors, and protoporphyrinogen oxidase (PROTOX) inhibitors on the percentage of soybean defoliation and maturation (PDM) in pre-harvest



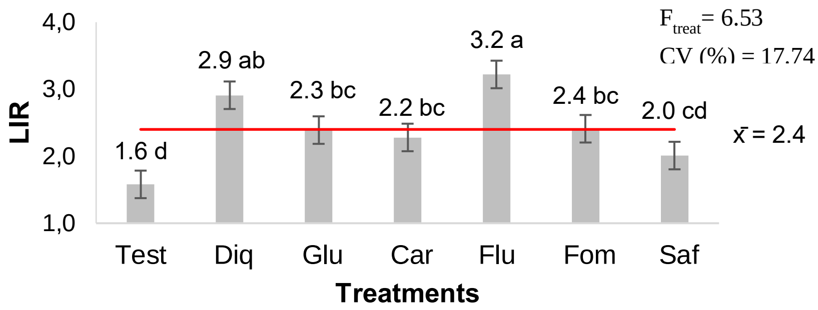
Source: research data.

The herbicide diquat, which achieved a performance of 100%, is a non-selective contact herbicide with rapid foliar absorption (Carmo *et al.*, 2023). Its action is enhanced by the presence of light, causing electron flow deviation in photosystem I and leading to the destruction of cell membranes (Lima-Melo *et al.*, 2019). It is likely that this herbicide was not affected by rainfall between application and harvest due to its rapid absorption kinetics (Figures 1 and 2).

In contrast, glufosinate is a light-dependent herbicide (Albrecht *et al.*, 2023), meaning its effectiveness highly depends on light conditions (solar radiation) after application. Consequently, it showed lower performance than the other treatments (75%).

The different responses in the percentage of defoliation and grain maturation resulted in varying light intensity ratios within the soybean canopy ($p<0.0008$), with better performances associated with higher defoliation/maturation percentages.

Figure 3 - Effect of photosystem I (PSI) inhibitors, glutamine synthetase (GS) inhibitors, and protoporphyrinogen oxidase (PROTOX) inhibitors on the light intensity ratio within the soybean canopy (LIR) in pre-harvest

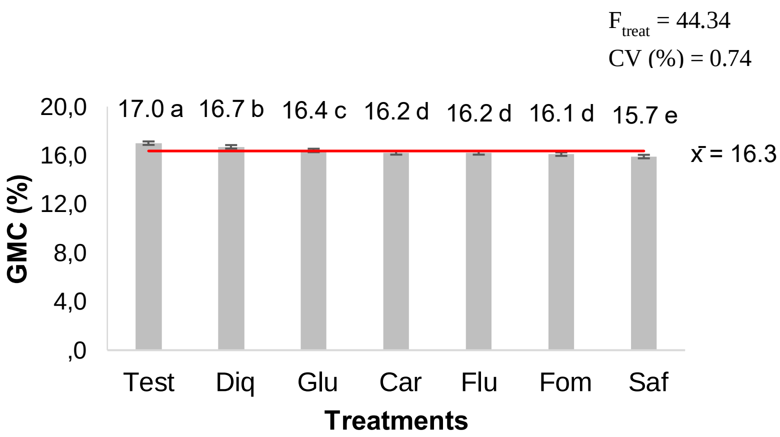


Source: research data.

Thus, the use of flumioxazin (3.2) and diquat (2.9) provided efficient results compared to the untreated control (Figure 3), reinforcing the importance of desiccation for soybean defoliation and stand uniformity, in accordance with the findings of Albrecht *et al*. (2023) and Silva *et al.* (2022).

Meanwhile, the NDVI index estimated by an active light optical sensor ranged from 0.21 to 0.24 (Figure 4) and did not differ statistically among treatments. This indicates a uniform effect of senescence, photosynthesis cessation, and degradation of photosynthetic pigments (Liu *et al*., 2019) across all the treatments, supporting the proper determination of the harvest point.

Figure 4 - Effect of photosystem I (PSI) inhibitors, glutamine synthetase (GS) inhibitors, and protoporphyrinogen oxidase (PROTOX) inhibitors on the NDVI (Normalized Difference Vegetation Index) of the soybean canopy in pre-harvest

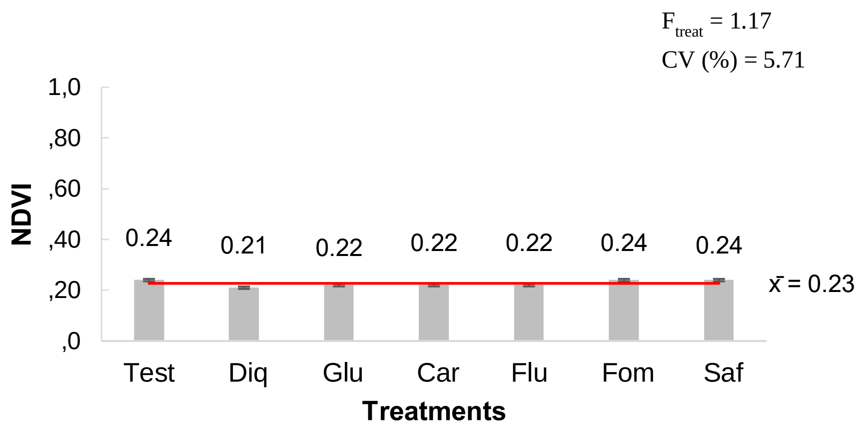


Source: research data**.**

Regarding grain moisture content, all herbicide treatments were effective compared to the control (without herbicide) ($p<0.0001$) (Figure 5).

Figure 5 - Effect of photosystem I (PSI) inhibitors, glutamine synthetase (GS), and protoporphyrinogen oxidase (PROTOX) herbicides on grain moisture percentage (GMP) in pre-harvest soybeans

Source: research data**.**



Moisture content is one of the main indicators for soybean harvesting, with recommended values for grain commercialization ranging between 13% and 14% (Kakade *et al*., 2019). In the present study, moisture levels ranged from 15.9% to 17.0%, exceeding the recommended range for commercialization. This was due to rainfall occurring between the treatment application period and harvest (Figure 1), although lower moisture values were estimated with the use of PROTOX-inhibiting herbicides (Figure 5).

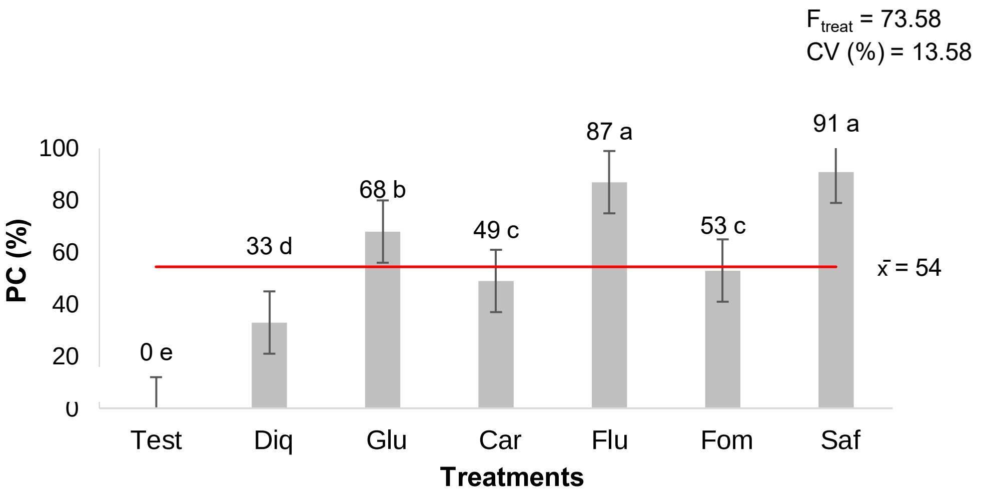
These results differed from those obtained by Silva *et al.* (2022) and Kamphorst and Paulus (2019), in which the application of diquat, glufosinate, flumioxazin, and saflufenacil did not result in statistical differences in moisture content. This discrepancy may be explained by the complex interaction among climatic conditions at the study site, cultivar, and application technology (Polli *et al*., 2022), which can influence the performance of pre-harvest herbicides.

Thus, it is believed that some herbicides, such as glufosinate, could have performed better under conditions of low cloud cover and minimal rainfall. Under these circumstances, the herbicides metabolic activity would be enhanced, promoting the synthesis of ethylene and abscisic acid (Albrecht *et al*., 2023), which accelerate plants' senescence. Additionally, the synergistic effect of climatic factors—particularly high light intensity and high temperatures would further amplify the deleterious effects of herbicides on the plant.

3.2 Buttonweed Control

The use of flumioxazin (87%) and saflufenacil (91%) showed higher efficacy in controlling buttonweed compared to the other treatments ($p<0.001$) (Figure 6).

Figure 6 - Effect of photosystem I (FSI), glutamine synthetase (GS), and protoporphyrinogen oxidase (PROTOX) inhibitor herbicides on the control percentage (PC) of buttonweed (*Spermacoce verticillata* L.) in pre-harvest soybean



Source: research data.

The control percentages obtained with these herbicides ranged from "very good" to "excellent," corroborating the results found by Fadin and Monquero (2019), Galon *et al.* (2020), and Kalsing *et al.* (2020), who used PROTOX inhibitor herbicides in managing buttonweed. The application of PROTOX inhibitor herbicides has allowed effective control levels over buttonweed (Diesel *et al.*, 2018).

According to Brunetto *et al.* (2023), flumioxazine and saflufenacil offer the additional advantage of pre-emergence weed control due to their residual effect in the soil. This is very important for the preventive management of buttonweed, starting from the soil seed bank, as it is a herbicide-tolerant species (Lucio *et al.*, 2019) with high adaptability to different climatic conditions (Gallon *et al.*, 2019).

3.3 Simple Correlation Matrix

The estimation of the simple correlation coefficients revealed a strong negative correlation (-0.91) between the grain moisture content and the control of buttonweed, indicating that increased competition corresponded to an increase in the grain moisture content (Table 1).

Table 1 – Simple linear correlation matrix between the percentage of leaf drop and grain maturation (PDM), light intensity ratio (RIL), NDVI index (NDVI), grain moisture content (GMC), and percentage of control of buttonweed (PC)

V/V	PDM	LIR	NDVI	GMC	PC
PDM	--	0.43	-0.22	0.02	0.01
RIL	0.43	--	-0.16	-0.25	0.32
NDVI	-0.21	-0.16	--	-0.18	-0.03
TUG	0.02	-0.25	-0.18	--	-0.91*
PC	0.01	0.32	-0.03	-0.91*	--

Abbreviations: V/V = variable/variable. PDM = percentage of leaf drop and grain maturation. LIR = light intensity ratio. NDVI = NDVI index. GMC = grain moisture content. PC = percentage of control. * = significant ($p<0.05$).
Source: research data.

Thus, it is believed that the infestation of buttonweed during soybean harvest is detrimental, as the moisture content is considered one of the main indicators for harvest, and its increase becomes harmful to the commercial product quality. Moderate correlations were also estimated (0.43) between the percentage of defoliation and grain maturation (PDM), and the light intensity ratio in the canopy (RIL). Additionally, a correlation of 0.32 was observed between the light intensity ratio and buttonweed control, indicating that pre-harvest desiccation is crucial for stand uniformity and the control of remaining weeds during harvest.

The estimated results for soybean defoliation and maturation percentage, as well as buttonweed control, suggest that future studies should investigate the combination of active ingredients, given that the best defoliation and control outcomes were achieved with different herbicides. According to Sousa *et al.* (2023), herbicide mixing is one of the strategies used to prevent resistant biotypes and facilitate soybean desiccation, as the interaction between products can result in synergistic chemical reactions and desired inhibitory biochemical effects (Costa *et al.*, 2019). In this context, mixing diquat and/or glufosinate with PROTOX-inhibiting herbicides may enhance buttonweed control percentages while simultaneously improving soybean defoliation efficiency.

4 Conclusion

The use of diquat (400 g a.i. ha^{-1}), flumioxazin (40 g a.i. ha^{-1}), and saflufenacil (35 g a.i. ha^{-1}) is recommended for pre-harvest desiccation of soybeans as an alternative to paraquat, a herbicide recently banned in Brazil. Due to their pre-emergent action in the soil, flumioxazin and saflufenacil are better options for the preventive management of herbicide-tolerant weeds, such as wild poinsettia (*Richardia brasiliensis*).

The use of glufosinate (200 g a.i. ha^{-1}) shows low efficiency in defoliation/maturation and wild poinsettia control. It is believed that this limitation can be mitigated by applying the herbicide under favorable climatic conditions (low cloud cover and full sunlight) or in combination with PROTOX-inhibiting herbicides.

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