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Alternative herbicides to paraquat in pre-harvest desiccation of soybean plants

Herbicidas alternativos ao paraquate na dessecação pré-colheita das plantas de soja

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ABSTRACT

Diquat, glufosinate and the combination of the latter with carfentrazone or saflufenacil are believed to be as effective for pre-harvest desiccation of soybean plants as paraquat. This work was developed with the objective of evaluating the efficacy of paraquat, diquat, and glufosinate alone or at mixtures of carfentrazone or saflufenacil in pre-harvest desiccation of soybean. Soybean defoliation, maturity and yield were evaluated. Similar efficacy was observed between glufosinate and paraquat in soybean defoliation and maturity, in addition to a greater flexibility of use, in which it could be an anticipator and standardizing agent of the harvest. The application of diquat (200 g of active ingredient [a.i.] ha^{-1}), paraquat (200 g a.i. ha^{-1}) or glufosinate (400 or 500 g a.i. ha^{-1}) was effective for pre-harvest desiccation of soybean at the $R_{7.2}$ stage. As well, it was observed promising results for application of glufosinate + saflufenacil (300 + 24.5 g a.i. ha^{-1}), glufosinate + carfentrazone (200 + 25 g a.i. ha^{-1}), glufosinate + saflufenacil (200 + 35 g a.i. ha^{-1}). Diquat and glufosinate can replace paraquat in pre-harvest desiccation of soybean plants, and glufosinate also provide greater management flexibility, in anticipating the harvest.

KEYWORDS: diquat; glufosinate; saflufenacil; carfentrazone; defoliation; yield.

RESUMO

Acredita-se que o diquate, o glufosinato e a combinação deste último com carfentrazona ou saflufenacil sejam tão eficazes na dessecação pré-colheita da soja quanto o paraquate. Este trabalho foi desenvolvido com o objetivo de avaliar a eficácia de paraquate, diquate, glufosinato isolado e em misturas com carfentrazona ou saflufenacil na dessecação pré-colheita da soja. Foram avaliadas a desfolha, a maturidade e a produtividade da soja. Observou-se eficácia semelhante entre glufosinato e paraquate na desfolha e maturação da soja, além de maior flexibilidade de uso, podendo ser utilizado na antecipação e padronização da colheita. A aplicação de diquate (200 g de ingrediente ativo [i.a.] ha^{-1}), paraquate (200 g i.a. ha^{-1}) ou glufosinato (400 ou 500 g i.a. ha^{-1}) foi eficaz na dessecação pré-colheita da soja no estádio $R_{7.2}$. Além disso, foram observados resultados promissores para aplicação de glufosinato + saflufenacil (300 + 24,5 g i.a. ha^{-1}), glufosinato + carfentrazona (200 + 25 g i.a. ha^{-1}), glufosinato + saflufenacil (200 + 35 g i.a. ha^{-1}). O diquate e glufosinato pode substituir o paraquate na dessecação pré-colheita das plantas de soja, e o glufosinato também proporciona maior flexibilidade de manejo, na antecipação da colheita.

PALAVRAS-CHAVE: diquate; glufosinato; saflufenacil: carfentrazona: desfolha; produtividade.

INTRODUCTION

Herbicides paraquat and diquat are representatives of the chemical group bipyridylium, the mechanism of action of photosystem I inhibitors (PSI). They have contact action, very limited translocation, and rapid foliar uptake, with a broad spectrum of weed control (BROMILOW 2004).

These herbicides act as false electron acceptors in the PSI. Plant death occurs due to the disruption of photosynthesis and the breakdown of fatty acids in the thylakoids and other membranes by the production of free radicals, which cause chlorosis, necrosis and, finally, plant death. Symptoms can be observed within a few hours after application under bright light conditions, and plant death can occur within a day (HAWKES 2014). Some of these characteristics help to explain the widespread adoption of these herbicides, especially paraquat, in pre-harvest desiccation of soybean plants.

Pre-harvest desiccation of soybean plants can be used to standardize plant maturity, anticipate harvest, control weeds, and minimize losses in seed quality (BOUDREAUX & GRIFFIN 2011). Several studies highlight the use of paraquat for this purpose (BOUDREAUX & GRIFFIN 2011, PEREIRA et al. 2015). However, paraquat was banned in Brazil (ANVISA 2020), so it is necessary to study the use of other herbicides in pre-harvest desiccation of soybean plants (ALBRECHT et al. 2022a).

As an obvious alternative to paraquat, diquat stands out (FINOTO et al. 2017), other studies highlight the possibility of glufosinate (DELGADO et al. 2015, ALBRECHT et al. 2023), carfentrazone (PEREIRA et al. 2015) among other herbicides. ZAGONEL (2005) observed equivalent efficiencies for the application of diquat, paraquat and glufosinate, all at a dose of 200 g active ingredient (a.i.) ha^{-1}, in pre-harvest desiccation of soybean plants, without reduction at yield.

However, further studies in this regard are essential. For example, as glufosinate has limited contact and translocation action, the first symptoms are yellowing of leaves and other green tissues, followed by wilting and plant death. This herbicide acts by inhibiting the enzyme glutamine synthetase (GS) (TAKANO et al. 2020a). Glufosinate shows promising results in pre-harvest desiccation of soybean plants, it also has a synergistic effect in combinations with protoporphyrinogen oxidase (PPO) inhibitor herbicides, in the control of weeds (TAKANO et al. 2020b). Could this synergistic effect also be observed in pre-harvest desiccation of soybean plants, for combinations of glufosinate with PPO inhibitors (saflufenacil or carfentrazone)?

Diquat, glufosinate and mixtures of the latter with carfentrazone or saflufenacil are believed to be as effective in pre-harvest desiccation of soybean plants as paraquat. Therefore, this work was developed with the aim of evaluating the efficacy of paraquat, diquat, glufosinate and their combinations with carfentrazone or saflufenacil in pre-harvest desiccation of soybean plants.

MATERIAL AND METHODS

Two experiments were carried out in Palotina, state of Paraná (PR), Brazil, 2019-2020 growing season (exp. 1 - 24°20'51.9"S 53°51'50.9"W; exp. 2 - 24°19'31.2"S 53°49'21.2"W). The climate of the region is Cfa, according to the Köppen-Geiger classification (APARECIDO et al. 2016) and the meteorological conditions for the experimental period are shown in Figure 1.

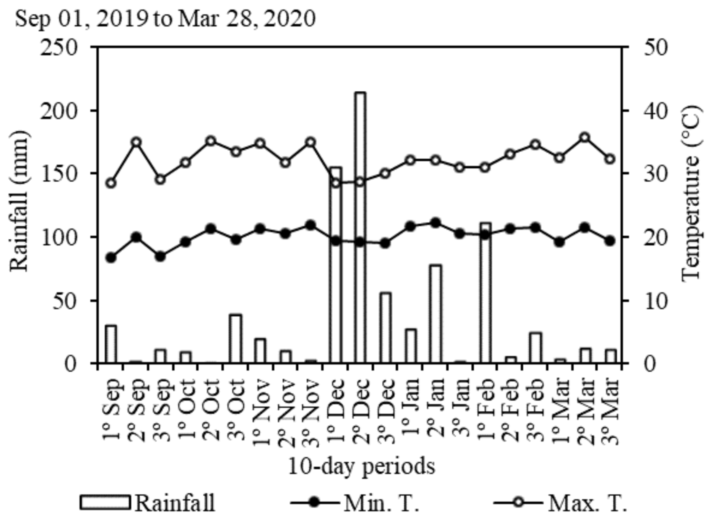

Figure 1. Representation of rainfall and temperature for the 2019-2020 season. Palotina, PR, Brazil

The soil of both areas was classified with a very clayey texture. The treatments used are described in Table 1 (experiment 1) and in Table 2 (experiment 2). The experiments were set up in a randomized block design with four replications. The experimental units consisted of 5 m long plots and 6 rows of soybeans with 0.45 cm spacing between rows. The cultivar M 6210 IPRO was used, with an indeterminate growth habit and relative maturity group 6.2.

Table 1. Herbicides, alone or in mixtures, applied in pre-harvest desiccation of soybean. Palotina, PR, Brazil, 2019-2020 growing season (exp. 1).

Herbicide	Commercial product	Rate
		g ha^{-1} ai[1]
Checkplots (without application)	-	-
Paraquat[2]	Gramoxone® 200	400
Diquat[2]	Reglone®	400
Glufosinate[3]	Finale®	400
Glufosinate[3]	Finale®	500
Glufosinate + saflufenacil[3]	Finale® + Heat®	200 + 24.5
Glufosinate + saflufenacil[3]	Finale® + Heat®	200 + 35
Glufosinate + saflufenacil[3]	Finale® + Heat®	300 + 24.5
Glufosinate + carfentrazone[3]	Finale® + Aurora® 400 EC	200 + 25

[1]Active ingredient. Addition to spray application of adjuvant [2]Agral® (0,2%) or [3]Mees™ (0,5%).

Table 2. Herbicides, alone or in mixtures, applied in pre-harvest desiccation of soybean. Palotina, PR, Brazil, 2019-2020 growing season (exp. 2).

Herbicide	Commercial product	Rate
		g ha^{-1} a.i.[1]
Checkplots (without application)	-	-
Paraquat[2]	Gramoxone® 200	400
Diquat[2]	Reglone®	400
Glufosinate[3]	Finale®	400
Glufosinate + saflufenacil[3]	Finale® + Heat®	300 + 24,5

[1]Active ingredient. Addition to spray application of adjuvant [2]Agral® (0,2%) or [3]Mees™ (0,5%).

The application in experiment 1 took place on January 03, 2020, under a temperature of 26.3 ºC, a relative humidity (RH) of 77.7% and wind of 1.3 km h^{-1}. In experiment 2, on February 29, 2020, at a temperature of 25.1 ºC, RH of 65.2% and wind of 1.5 km h^{-1}. Both soybean plants were at the $R_{7.2}$ stage, as per observation of pods and phenological classification proposed by FEHR et al. (1971). A CO_2-pressurized backpack sprayer equipped with six AIXR 110 015 nozzles was used at a pressure of 2 kgf cm^{-2} from a distance of 50 cm from the target, providing an application volume of 150 L ha^{-1}.

The percentage of defoliation and maturity of soybean plants at 3, 5 and 7 days after application (DAA) was evaluated. Defoliation was assessed using a diagrammatic scale (HIRANO et al. 2010), while maturation was evaluated with a focus on pods, with percentage values related to full maturation (R_8) (FEHR et al. 1971). The 4 central rows of each plot were harvested at 3 m in length (5.4 m^2). The grain yield was determined, with moisture corrected to 13% and the results were expressed in kg ha^{-1}, as well as grain moisture (%) with an electronic meter.

Data were subjected to analysis of variance by the F-test ($p \geq 0.05$). Treatment means were compared by Tukey's test, at 5% probability. For the analysis, the Sisvar 5.6 software was used (FERREIRA 2011).

RESULTS

In analyzing the results of experiment 1, for defoliation at 7 DAA, stand out the results for the application of diquat (400 g a.i. ha^{-1}), paraquat (400 g a.i. ha^{-1}), glufosinate (400 and 500 g a.i. ha^{-1}) and glufosinate + carfentrazone (200 + 25 g a.i. ha^{-1}), all effective as desiccant. For maturity at 7 DAA, diquat, paraquat and glufosinate provided more than 90% maturity (Table 3), which is satisfactory. These results highlight the validity of using glufosinate as a desiccant in maturity, replacing PSI inhibitor herbicides.

It is also important to point out, with regard to the defoliation and maturity results in experiment 1, that glufosinate was similar to paraquat and diquat from 5 DAA onwards. This is clearer and more significant when the dose of glufosinate is increased, as at this dose the performance did not differ from that of paraquat or diquat at 5 DAA (both in defoliation and maturity) (Table 3). These observations ensure the viability of glufosinate in anticipating soybean as well as in standardizing. Furthermore, they allow to understand that in more critical cases of non-uniformity, green stalk or the presence of weeds that make harvesting difficult, the option of increasing the dose of glufosinate can be adopted.

Table 3. Defoliation and maturation of soybean plants at 3, 5, and 7 days after application (DAA) of herbicides, isolated or in mixtures, in pre-harvest desiccation. Palotina, PR, Brazil, 2019-2020 growing season (exp. 1).

		Defoliation			Maturation		
Herbicide	Rate	3 DAA	5 DAA	7 DAA	3 DAA	5 DAA	7 DAA
	g ha^{-1} a.i.[1]			%			
Checkplot	-	37.5 c	63.8 d	79.0 b	32.5 d	58.8 d	68.8 d
Paraquat	400	85.5 a	95.8 a	98.5 a	85.5 a	87.0 a	97.3 a
Diquat	400	80.5 a	94.3 a	97.5 a	80.5 ab	86.5 a	97.5 a
Glufosinate (glu)	400	71.0 ab	89.5 abc	97.3 a	71.0 bc	82.0 abc	91.5 ab
Glu	500	76.8 ab	93.5 ab	97.5 a	76.5 abc	84.0 ab	94.0 a
Glu + saflufenacil	200 + 24.5	65.8 b	80.8 c	94.3 a	65.8 c	75.0 c	83.3 c
Glu + saflufenacil	200 + 35	68.8 ab	85.0 bc	94.0 a	68.8 bc	80.0 abc	87.0 bc
Glu + saflufenacil	300 + 24.5	68.3 ab	83.0 c	92.3 a	68.3 bc	77.3 bc	87.0 bc
Glu + carfentrazone	200 + 25	66.0 b	86.8 abc	97.3 a	66.0 c	78.8 bc	82.5 c
	MSD	17.3	9.1	6.7	12.8	7.3	7.0
	CV (%)	10.5	4.4	3.0	7.8	3.9	3.3
	F	*	*	*	*	*	*

Commercial products: Gramoxone® 200 (paraquat), Reglone® (diquat), Finale® (glufosinate), Heat® (saflufenacil), Aurora® 400 EC (carfentrazone). [1]Active ingredient. *Means followed by the same letter do not differ from each other by the Tukey's test, at the 5% probability level.

Still for experiment 1, in relation to the moisture of harvested grains, the smallest percentages, in absolute values, were observed for diquat, paraquat and glufosinate, which places them as preferable among the desiccant options. For yield, only glufosinate + saflufenacil (200 + 24.5 g a.i. ha^{-1}) did not differ from the checkplot, with lower values (Table 4). In terms of yield, all the others were statistically similar, that is, the absence of difference between treatments shows that none of them negatively affected yield and places them on an equal level, in the conditions of the experiment.

Table 4. Grain moisture (GM) and soybean plant yield under herbicide application, alone or in mixtures, in pre-harvest desiccation. Palotina, PR, Brazil, 2019-2020 growing season (exp. 1).

Herbicide	Rate	GM	Yield
	g ha^{-1} a.i.[1]	%	kg ha^{-1}
Checkplot	-	28.6 d	4,309 c
Paraquat	400	17.4 a	4,930 ab
Diquat	400	16.1 a	5,125 a
Glufosinate (glu)	400	18.4 bc	4,976 a
Glu	500	17.6 abc	5,014 a
Glu + saflufenacil	200 + 24.5	19.3 bc	4,462 bc
Glu + saflufenacil	200 + 35	18.1 abc	4,955 ab
Glu + saflufenacil	300 + 24.5	18.7 bc	4,916 ab
Glu + carfentrazone	200 + 25	19.7 c	5,002 a
	MSD	2.2	509.4
	CV (%)	4.7	4.4
	F	*	*

Commercial products: Gramoxone® 200 (paraquat), Reglone® (diquat), Finale® (glufosinate), Heat® (saflufenacil), Aurora® 400 EC (carfentrazone). [1]Active ingredient. *Means followed by the same letter do not differ from each other by the Tukey's test, at the 5% probability level.

As to experiment 2, for defoliation at 7 DAA, higher percentages were observed for the application of diquat, paraquat and glufosinate. The same was observed for maturity at 7 DAA (Table 5). For moisture and yield, all herbicides differed from the control (without application), with no differences between herbicides (Table 6). The combination of glufosinate + saflufenacil, in this experiment, was not effective as the other treatments for defoliation and maturity. The performance of glufosinate characterizes this herbicide as a potential and effective substitute for paraquat in pre-harvest desiccation, with similar efficacy to PSI-inhibitor herbicides from 5 DAA onwards, which puts it with a slower or gradual effect, but effective in final results.

Table 5. Defoliation and maturation of soybean plants at 3, 5, and 7 days after application (DAA) of herbicides, isolated or in mixtures, in pre-harvest desiccation. Palotina, PR, Brazil, 2019-2020 growing season (exp. 2).

Herbicide	Rate	Defoliation			Maturation		
		3 DAA	5 DAA	7 DAA	3 DAA	5 DAA	7 DAA
	g ha^{-1} a.i.[1]	%					
Checkplot	-	40.5 d	52.0 c	73.3 c	56.3 c	60.8 c	73.3 c
Paraquat	400	84.3 a	94.5 a	98.0 a	86.8 a	91.3 a	100.0 a
Diquat	400	79.3 ab	92.8 a	97.5 a	81.8 ab	88.5 a	98.5 a
Glufosinate (glu)	400	67.5 bc	86.5 a	97.3 a	69.8 bc	80.8 ab	98.5 a
Glu + saflufenacil	300 + 24.5	62.0 c	75.0 b	87.8 b	61.3 c	68.5 ab	87.5 b
	MSD	15.5	10.1	6.2	16.6	14.3	9.1
	CV (%)	10.3	5.6	3.0	10.3	8.1	4.4
	F	*	*	*	*	*	*

Commercial products: Gramoxone® 200 (paraquat), Reglone® (diquat), Finale® (glufosinate), Heat® (saflufenacil). [1]Active ingredient. *Means followed by the same letter do not differ from each other by the Tukey's test, at the 5% probability level.

Table 6. Grain moisture (GM) and soybean plant yield under herbicide application, alone or in mixtures, in pre-harvest desiccation. Palotina, PR, Brazil, 2019-2020 growing season (exp. 2).

Herbicide	Rate	GM	Yield
	g ha^{-1} a.i.[1]	%	kg ha^{-1}
Checkplot	-	22.3 b	3,482 b
Paraquat	400	14.2 a	4,180 a
Diquat	400	14.2 a	3,966 a
Glufosinate (glu)	400	14.2 a	4,226 a
Glu + saflufenacil	300 + 24.5	15.5 a	3,966 a
	MSD	4.1	495.6
	CV (%)	16.1	5.5
	F	*	*

Commercial products: Gramoxone® 200 (paraquat), Reglone® (diquat), Finale® (glufosinate), Heat® (saflufenacil). [1]Active ingredient. *Means followed by the same letter do not differ from each other by the Tukey's test, at the 5% probability level.

DISCUSSION

Other studies highlight the efficacy of glufosinate (ZAGONEL 2005, DELGADO et al. 2015, ALBRECHT et al. 2023), diquat (ZAGONEL 2005, FINOTO et al. 2017, ALBRECHT et al. 2022b), and carfentrazone (BOUDREAUX & GRIFFIN 2011, PEREIRA et al. 2015) for soybean desiccation. There are few studies evaluating the efficacy of saflufenacil for pre-harvest desiccation of soybean plants, but in the present study, the herbicide was shown to be potentially effective in some combinations with glufosinate. It should be noted that smaller amounts of glufosinate were used in the combinations (200 or 300 g a.i. ha^{-1}), compared to the isolated application (up to 500 g a.i. ha^{-1}). In this sense, more information needs to be generated, with combinations of different doses of glufosinate with PPO inhibitors, such as saflufenacil or carfentrazone, as these combinations show promising results in the control of eudicot weeds (TAKANO et al. 2020b), and the present also indicates potential for soybean desiccation at pre-harvest.

The effectiveness of other herbicides, in addition to paraquat, is remarkable and characterizes these herbicides as potential substitutes for paraquat, which was banned for use and trade in Brazil in the second half of 2020 (ANVISA 2020). Diquat has been proposed as an immediate substitute of paraquat, as it has the same mechanism of action, and is reported to be effective at desiccation without reducing the soybean yield (ZAGONEL 2005, ALBRECHT et al. 2022b), which was also observed in the present study.

The performance of glufosinate can be highlighted, which showed slower or less progressive defoliation and maturity than PSI-inhibitor herbicides, however, with similar final performance. This finding is relevant, as it places it at a level of almost maturing agent, due to its speed of action, which is derived from its physiological action and physical and chemical characteristics of the product. After glufosinate absorption, plants show rapid ammonia accumulation (ALBRECHT et al. 2020), accompanied by chloroplast destruction, reduced photosynthesis levels, and decreased amino acid production (BARNETT et al. 2012). Inhibition of

GS also rapidly increases levels of reactive oxygen species that are extremely phytotoxic and cause loss of membrane integrity due to lipid peroxidation (TAKANO et al. 2019).

The fact that maturation caused by glufosinate is slower should be considered as positive. Because, when applied to indeterminate cultivars, it will not incur losses. Applications of PSI inhibitor herbicides at the $R_{7.2}$ stage or earlier are not always beneficial, as they can lead to soybean yield losses or other deleterious effects (ZANATTA et al. 2018, PEREIRA et al. 2020, ALBRECHT et al. 2022b), especially in typically indeterminate cultivars. This is due to the speed of action of these PSI herbicides, associated with the fact that pods in the upper third of indeterminate cultivars may still be completing grain filling. It is observed that the $R_{7.2}$ stage is characterized by more than 50% pods with mature color in the plant. The crop, to be characterized at $R_{7.2}$, needs to have more than 50% plants at this stage in the sample areas (FEHR et al. 1971). Therefore, in years with greater non-uniformity in the soybean emergence process, and consequently, greater non-uniformity in harvesting, glufosinate represents a more desirable option, as it has a slower action.

In this sense, the ideal would be to apply diquat only with the objective of standardizing the harvest and controlling weeds, in some situations, from the $R_{7.3}$ stage onwards. While glufosinate could be safely applied from the $R_{7.2}$ stage to standardize, control weeds and anticipate harvesting. From this comparison mentioned above, and considering the results of these experiments presented, glufosinate had similar effectiveness to paraquat in defoliation and maturity, as a desiccant agent, in addition to having greater flexibility of use, in which it could be a real anticipator and better standardizer of the harvest. However, more research is required, in order to evaluate the different herbicide options, and combinations, on different genotypes, environmental conditions and stages of application.

Another point to be highlighted is the importance of pre-harvest desiccation of soybeans at the recommended stage, since in both experiments the checkplot showed lower yield compared to herbicide treatments, which was also observed in other studies (ERGIN & KAYA 2020, ALBRECHT et al. 2022b). This result is directly related to the higher moisture content of the grains, which with the correction to the 13% content results in a reduction in yield, which highlights the importance of pre-harvest desiccation in anticipating harvest and standardizing the crop with the objective of avoiding possible losses resulting from discounts due to humidity, impurities and damaged grains.

CONCLUSION

The application of diquat (200 g a.i. ha^{-1}), paraquat (200 g a.i. ha^{-1}) or glufosinate (400 or 500 g a.i. ha^{-1}) was effective for pre-harvest desiccation of soybean plants at the $R_{7.2}$ stage. As well, it was observed promising results for application of glufosinate + saflufenacil (300 + 24.5 g a.i. ha^{-1}), glufosinate + carfentrazone (200 + 25 g a.i. ha^{-1}), glufosinate + saflufenacil (200 + 35 g a.i. ha^{-1}). Diquat and glufosinate can replace paraquat in the pre-harvest desiccation of soybean plants, and glufosinate also provide greater management flexibility, by anticipating harvest.

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