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RESEARCH ARTICLE

Broad- spectrum weed control of the new herbicide pyroxasulfone

Espectro de controle do novo herbicida pyroxasulfone

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Abstract: **Background**: There is not sufficient information about the efficiency of pyroxasulfone to the control of the main weeds that infest Brazilian agricultural areas.

Objective: The objective of this study was to evaluate the efficiency of the pyroxasulfone treatments to control some of the main weeds present in Brazil in comparison to S-metolachlor and trifluralin.

Methods: The treatments consisted of five doses of pyroxasulfone (50, 100, 150, 200 and 250 g ha^{-1}), two doses of S-metolachlor (960 and 1920 g ha^{-1}), two doses of trifluralin (562.5 and 1125 g ha^{-1}) and a untreated control. The visual control (scale from 0 to 100%) was evaluated at 14, 28 and 42 days after herbicide application and the fresh shoots mass were collected at 42 DAT for biomass quantification. Independent experiment was performed for each of the following weed species: *Amaranthus viridis*, *Chloris elata*, *Conyza* spp., *Echinochloa crus-galli*, *Urochloa decumbens*, *Digitaria horizontalis*, *Digitaria insularis*, *Eleusine indica*, *Lolium perenne* ssp. *multiflorum*, *Panicum maximum*, *Raphanus raphanistrum*, *Spermacoce latifolia*, *Spermacoce verticillata.*

Results: The results suggest that the application of 100 g ha^{-1} of pyroxasulfone in pre-emergence was an effective treatment to control all weeds evaluated.

Conclusions: The application of 100 g ha^{-1} of pyroxasulfone had similar or higher control than the highest doses of S-metolachlor and trifluralin. These results confirm that pyroxasulfone is an important tool for weed management in many crops as well as it might help to mitigate herbicide resistance.

Keywords: pre-emergence, S-metolachlor, trifluralin, VLCFA, chemical control.

Resumo: **Introdução**: Não existem muitas informações sobre a eficiência de controle do pyroxasulfone para as principais plantas daninhas que infestam as áreas agrícolas brasileiras.

Objetivo: O objetivo deste estudo foi avaliar a eficiência da aplicação de pyroxasulfone visando ao controle de algumas das principais plantas daninhas presentes no Brasil, comparando-o com o S-metolachlor e a trifluralin.

Métodos: Os tratamentos foram compostos por cinco doses crescentes de pyroxasulfone (50, 100, 150, 200 e 250 g ha^{-1}), duas doses de S-metolachlor (960 e 1920 g ha^{-1}), duas doses de trifluralin (562,5 e 1125 g ha^{-1}) e um tratamento testemunha. Avaliou-se o controle (escala de 0 a 100%) aos 14, 28 e 42 dias após a aplicação e a massa seca da parte aérea das plantas aos 42 DAT. Cada espécie de planta daninha constituiu um experimento independente, sendo elas: *Amaranthus viridis*, *Chloris elata*, *Conyza* spp., *Echinochloa crusgalli*, *Urochloa decumbens*, *Digitaria horizontalis*, *Digitaria insularis*, *Eleusine indica*, *Lolium perenne* ssp. *multiflorum*, *Panicum maximum*, *Raphanus raphanistrum*, *Spermacoce latifolia*, *Spermacoce verticillata.*

Resultados: Os resultados obtidos neste estudo sugerem que a aplicação de 100 g ha^{-1} de pyroxasulfone em pré-emergência foi eficaz no controle das plantas daninhas avaliadas.

Conclusões: A aplicação de 100 g ha^{-1} de pyroxasulfone foi semelhante ou superior as maiores doses de S-metolachlor e trifluralin testadas. O pyroxasulfone é uma ferramenta importante no controle de plantas daninhas e no manejo da resistência a herbicidas.

Palavras-chave: pré-emergência, S-metolachlor, trifluralin, VLCFA, controle químico.

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1. Introduction

Pyroxasulfone is a new pre-emergence (PRE) herbicide discovered by Kumiai Chemical Industry CO., LTD. (4-26, Ikenohata 1-chome, Taito-ku, Tokyo 110-8782, Japan), which has collaborated with several companies to register this herbicide for specific uses in certain crops (Tanetani et al., 2009). This herbicide is registered in Japan, Australia, United States, Canada, Saudi Arabia, and South Africa, being traded alone or in mixture with other active ingredients through partner companies in each country (Nakatani et al., 2016). Currently, the molecule is under registration in New Zealand and Chile and was recently approved in Brazil.

Pyroxasulfone has herbicidal activity inhibiting the very long chain fatty acids biosynthesis - VLCFA (Tanetani et al., 2009). It is classified in the group 15 by the Weed Science Society of America (WSSA) and in the group K3 by the Herbicide Resistance Action Committee (HRAC). These classifications also include herbicides derived from chloroacetamides, such as S-metolachlor and propisochlor.

This herbicide mostly promotes control of grasses but also can contribute in the control of some broadleaf species, mainly those originated from small seeds. It is effective to control weeds with lower doses than other herbicides from the same group (Yamaji et al., 2014). Its main physical and chemical characteristics are: water solubility (20 °C) of 3.49 mg L^{-1}, vapor pressure (25 °C) of $2x10^{-6}$ Pa, Log Kow of 2.39, and half-life ranging from 33 to 89 days (Westra et al., 2015). Recent studies show its selectivity for corn, soybeans, and wheat, among others crops (Nakatani et al., 2016).

The efficiency of pyroxasulfone has been studied in different environments across the world promoting a broad spectrum of weed control. However, there is not much information on the effectiveness of pyroxasulfone for the main weeds that infest Brazilian agricultural areas. As already verified in other countries, we hypothesize that pyroxasulfone can demonstrate good performance for the control of grasses and broadleaf derived from small seeds, through PRE treatments.

Therefore, the objective of this study was to evaluate the effectiveness of pyroxasulfone in the control of the weeds present in Brazil and compare it to the herbicides S-metolachlor and trifluralin.

2. Material and Methods

Thirteen different experiments were conducted from 05/09/2018 to 06/21/2018, each one composed by a different weed species. The experiments were installed in a greenhouse, and the experimental units were 5.0 dm^{-3}-pots, filled with dystrophic Red Latosol with pH ($CaCl_2$) 5.2, 2.6% M.O.; 33.3% sand; 16.4% silt; and 50.3% clay.

The experimental design was completely randomized, with 10 treatments and six replications. The treatments consisted of five doses of pyroxasulfone (50, 100, 150, 200 and 250 g ha^{-1}; Yamato, concentrated suspension, 500 g a.i. L^{-1}; Iharabras S.A. Indústrias Químicas), two doses of S-metolachlor (960 and 1920 g ha^{-1}; Dual Gold, emulsifiable concentrate, 960 g a.i. L^{-1}; Syngenta Proteção de Cultivos Ltda.), two doses of trifluralin (562.5 and 1125 g ha^{-1}; Trifluralin Nortox Gold, emulsifiable concentrate, 450 g a.i. L^{-1}; Nortox S/A) and a untreated control.

The herbicide treatments mentioned above were apply in: *Amaranthus viridis*, *Chloris elata*, *Conyza* spp., *Echinochloa crus-galli*, *Urochloa decumbens*, *Digitaria horizontalis*, *Digitaria insularis*, *Eleusine indica*, *Lolium perenne* ssp. *multiflorum*, *Panicum maximum*, *Raphanus raphanistrum*, *Spermacoce latifolia* and *Spermacoce verticillata*. Twenty seeds of each weed species were sown per pot, approximately 1.0 to 2.0 cm depth.

After the sowing, treatments were applied in PRE. At the time of application, the soil was humid at field capacity, the air temperature was 28°C, the relative humidity was 76%, the sky was partially cloudy, and the winds were 1.6 km h^{-1}. For all applications, a CO_2-based constant pressure backpack sprayer was used, equipped with a boom with three like-fan nozzles XR-110.02, under pressure of 206.8 kPa (30 psi), delivering 200 L ha^{-1}. During the experiment conduction period, the pots were irrigated with 9 mm day^{-1} divided into three irrigations.

The control efficiency of the treatments was quantified at 14, 28 and 42 days after treatment (DAT) by counting the number of plants per pot, and by attributing visual control percentages in comparison to the untreated control, considering zero for absence of symptoms and 100% plant death (SBCPD, 1995).

At 42 DAT, the shoots from each experimental unit were collected, properly packaged, and identified. Subsequently, the samples were conditioned for drying in a forced air circulation oven, at a temperature of 60°C to quantify the dry shoot biomass.

The data were submitted to normality analysis (Shapiro-wilk, $p<0.05$). The dry shoot biomass data were transformed ($\sqrt{x+1}$). When the assumption was met, the data were subjected to analysis of variance (F test) and subsequent comparison of means by Student's t test, both at 5% of probability.

3. Results and discussion

The application of doses equal to or higher than 100 g ha^{-1} of pyroxasulfone achieved a control of *Amaranthus viridis* superior to S-metolachlor at 14 DAT (Table 1). In the evaluation performed at 28 DAT, all doses of pyroxasulfone and S-metolachlor provided 100% control of *A. viridis* and these treatments resulted in at least 7-8% more efficiency than trifluralin.

Table 1. Control of *Amaranthus viridis* at 14, 28 and 42 days after treatment (DAT) with herbicides in pre-emergence and shoot biomass at 42 DAT.

	Treatments	Dose (g ha^{-1})	Control of *Amaranthus viridis* (%)			Shoot biomass
			14 DAT	28 DAT	42 DAT	(g pot^{-1})*
1	Untreated check	-	0 c	0 c	0 d	0.91 a
2	Pyroxasulfone	50	81 b	100 a	99 a	0.00 b
3	Pyroxasulfone	100	90 a	100 a	100 a	0.00 b
4	Pyroxasulfone	150	92 a	100 a	100 a	0.00 b
5	Pyroxasulfone	200	93 a	100 a	100 a	0.00 b
6	Pyroxasulfone	250	95 a	100 a	100 a	0.00 b
7	S-metolachlor	960	79 b	100 a	100 a	0.00 b
8	S-metolachlor	1920	76 b	100 a	100 a	0.00 b
9	Trifluralin	562.5	82 b	92 b	87 b	0.00 b
10	Trifluralin	1125	91 a	93 b	93 b	0.00 b
MSD			6.6	2.0	4.0	0.02
CV (%)			7.3	2.0	3.9	2.3

The means followed by the same letter in the column are not significant different at 5% probability by the Student t test; *Transformed data ($\sqrt{x+1}$) for statistical analysis; MSD: minimum significant difference; CV: coefficient of variation.

At 42 DAT, all doses of pyroxasulfone and S-metolachlor provided greater levels of A. viridis control than trifluralin. All treatments resulted in greater than 80% control. The dry shoot biomass at 42 DAT were similar among all herbicide treatments.

The effectiveness of pyroxasulfone in controlling

Amaranthus spp. has already been reported (Nakatani et al., 2016). Boydston et al. (2012) observed excellent control of *A. retroflexus* when 90 g ha-1 of pyroxasulfone was applied. Studies have not observed differences in the effectiveness of the application of pyroxasulfone and S-metolachlor in the control of *A. palmeri* (Currie et al., 2005; Steele et al., 2005; Geier et al., 2006). Yamaji et al. (2014) observed that a dose of 32 g ha-1 of pyroxasulfone was sufficient to achieve more than 90% control of *A. retroflexus.* Nurse et al. (2011) estimated that 93 g ha-1 of pyroxasulfone are necessary to reach 90% control. Taziar et al. (2017) observed excellent levels of control of *A. powelli* and *A. retroflexus* with the application of 100 g ha-1 of pyroxasulfone. Belfry et al. (2015) also observed efficacy in the control of *A. powellii* with the application of pyroxasulfone at doses of 100 and 150 g ha-1.

In the evaluations performed at 14 and 28 DAT, all herbicide treatments provided 100% control of *Chloris elata* (Table 2). At 42 DAT, only the lowest dose of pyroxasulfone (50 g ha-1) did not result in 100% control, but still kept providing excellent levels (97%). These results indicate the high effectiveness of pyroxasulfone in the control of *C. elata*, promoting similar control to the herbicides S-metolachlor and trifluralin. No differences were observed in the dry shoot biomass among the herbicide treatments.

Table 2. Control of *Chloris elata* at 14, 28 and 42 days after treatment (DAT) with herbicides in pre-emergence and shoot biomass at 42 DAT.

	Treatments	Rate (g ha-1)	Control of *Chloris elata* (%)			Shoot biomass
			14 DAT	28 DAT	42 DAT	(g pot-1)*
1	Check	-	0 b	0 b	0 c	0.40 a
2	Pyroxasulfone	50	100 a	100 a	97 b	0.00 b
3	Pyroxasulfone	100	100 a	100 a	100 a	0.00 b
4	Pyroxasulfone	150	100 a	100 a	100 a	0.00 b
5	Pyroxasulfone	200	100 a	100 a	100 a	0.00 b
6	Pyroxasulfone	250	100 a	100 a	100 a	0.00 b
7	S-metolachlor	960	100 a	100 a	100 a	0.00 b
8	S-metolachlor	1920	100 a	100 a	100 a	0.00 b
9	Trifluralin	562.5	100 a	100 a	100 a	0.00 b
10	Trifluralin	1125	100 a	100 a	100 a	0.00 b
MSD			-	-	2.6	0.02
CV (%)			0.0	0.0	2.5	2.3

The means followed by the same letter in the column are not significant different at 5% probability by the Student t test; *Transformed data ($\sqrt{x+1}$) for statistical analysis; MSD: minimum significant difference; CV: coefficient of variation.

The highest levels of control of Conyza spp. at 14 DAT were observed with 250 g ha-1 of pyroxasulfone (Table 3). From 28 DAT, all doses of pyroxasulfone promoted 100% control, similar to the highest dose of S-metolachlor (1920 g ha-1). The lowest dose of pyroxasulfone provided 96% control, higher than that observed with trifluralin or S-metolachlor at 960 g ha-1.

Table 3. Control of *Conyza* spp. at 14, 28 and 42 days after treatment (DAT) with herbicides in pre-emergence and shoot biomass at 42 DAT.

	Treatments	Rate (g ha-1)	Control of *Conyza* spp. (%)			Shoot biomass
			14 DAT	28 DAT	42 DAT	(g pot-1)*
1	Check	-	0 f	0 e	0 e	1.08 a
2	Pyroxasulfone	50	23 e	96 a	99 a	0.00 c
3	Pyroxasulfone	100	37 c	97 a	99 a	0.00 c
4	Pyroxasulfone	150	32 cde	97 a	100 a	0.00 c
5	Pyroxasulfone	200	56 b	99 a	100 a	0.00 c
6	Pyroxasulfone	250	77 a	100 a	100 a	0.00 c
7	S-metolachlor	960	26 de	81 b	89 b	0.12 c
8	S-metolachlor	1920	52 b	96 a	97 a	0.00 c
9	Trifluralin	562.5	34 cd	43 d	17 d	0.51 b
10	Trifluralin	1125	31 cde	71 c	78 c	0.15 c
MSD			8.3	8.2	7.6	0.09
CV (%)			19.5	9.0	8.4	7.4

The means followed by the same letter in the column are not significant different at 5% probability by the Student t test; *Transformed data ($\sqrt{x+1}$) for statistical analysis; MSD: minimum significant difference; CV: coefficient of variation.

At 42 DAT, the highest levels of control were observed after pyroxasulfone (50 to 250 g ha-1) and S-metolachlor (1920 g ha-1) treatments. Pyroxasulfone (50 g ha-1) provided 99% control of *Conyza* spp., resulting in greater performance than trifluralin and S-metolachlor (960 g ha-1). The lowest dose of trifluralin promoted the lowest levels of control at the end of the experiment. As expected, the highest dry shoot biomass of *Conyza* spp. were obtained from the untreated check. Due to the high efficiency of the herbicide treatments, it was not possible to obtain the shoot biomass present in the units that received the application of pyroxasulfone and the highest dose of S-metolachlor.

Pyroxasulfone at 150 g ha-1 resulted in good levels of *Echinochloa crus-galli* control at 14 DAT, similar to the highest doses of S-metolachlor (1920 g ha-1) and trifluralin (1125 g ha-1) (Table 4). The application of 50 and 100 g ha-1 of pyroxasulfone started demonstrating control of ≥80% in the evaluation performed at 28 DAT. However, superior performance was observed by the highest doses of S-metolachlor and trifluralin in this evaluation period.

Table 4. Control of *Echinochloa crus-galli* at 14, 28 and 42 days after treatment (DAT) with herbicides in pre-emergence and shoot biomass at 42 DAT.

	Treatments	Rate (g ha-1)	Control of *Echinochloa crus-galli* (%)			Shoot biomass
			14 DAT	28 DAT	42 DAT	(g pot-1)*
1	Check	-	0 d	0 d	0 d	0.85 a
2	Pyroxasulfone	50	72 c	82 c	92 c	0.03 b
3	Pyroxasulfone	100	78 b	85 bc	98 a	0.02 b
4	Pyroxasulfone	150	97 a	99 a	100 a	0.00 b
5	Pyroxasulfone	200	94 a	100 a	100 a	0.00 b
6	Pyroxasulfone	250	96 a	99 a	100 a	0.00 b
7	S-metolachlor	960	81 b	88 bc	98 a	0.00 b
8	S-metolachlor	1920	97 a	100 a	100 a	0.00 b
9	Trifluralin	562.5	77 bc	82 c	94 bc	0.04 b
10	Trifluralin	1125	93 a	90 b	95 b	0.02 b
MSD			5.3	6.6	2.6	0.05
CV (%)			5.8	6.8	2.5	4.4

The means followed by the same letter in the column are not significant different at 5% probability by the Student t test; *Transformed data ($\sqrt{x+1}$) for statistical analysis; MSD: minimum significant difference; CV: coefficient of variation.

The lowest dose of S-metolachlor, which up to 28 DAT did not achieve 90% control, started providing excellent control at 42 DAT (98%). At 42 DAT, all treatments were excellent for *E. crus-galli* control. The herbicide pyroxasulfone at 100 g ha-1 was considerate similar to treatments with S-metolachlor and at least 5% higher than trifluralin.

Despite the differences found for the visual control evaluation, all treatments resulted in more than 95% dry shoot biomass reduction in comparison to the untreated control. This results indicates good herbicides performance for *E. crus-galli* control. Pyroxasulfone at 100 g ha-1 was sufficient to result in final control (42 DAT) similar to S-metolachlor and greater than trifluralin. Nakatani et al. (2016) also observed that pyroxasulfone was effective in controlling *E. crus-galli*. Yamaji et al. (2014) found that 16 g ha-1 of pyroxasulfone was sufficient to provide control of *E. crus-galli* above 90%.

In evaluations performed up to 28 DAT, there were no differences in the levels of control of *Urochloa decumbens* achieve with the application of herbicide in PRE (Table 5). The application of 50 g ha-1 of pyroxasulfone was sufficient to provide similar control to the two doses of S-metolachlor and trifluralin.

The 562.5 g ha-1 of trifluralin was inferior to the other herbicide treatments at 42 DAT, however, it still resulted in 97 % control. The application of 50 g ha-1 of pyroxasulfone was enough to control 98% of *U. decumbens* plants up to 42 DAT.

The applications of the lowest dose of pyroxasulfone, S-metolachlor at 960 g ha-1 and trifluralin at 562.5 g ha-1 resulted in less shoot biomass reduction compared to the other herbicide treatments. Even so, these treatments were able to reduce the shoot biomass of *U. decumbens* by more than 95% compared to the untreated control.

There is no information about the efficiency of the application of pyroxasulfone in the control of *U. decumbens*. However, studies that evaluated another species of the same genus (*Urochloa platyphylla*) demonstrated levels of control above 90% with 32 g ha-1 of pyroxasulfone in PRE (Yamaji et al., 2014). Mueller and Steckel (2011) observed a similar control of *U. platyphylla* when applying 209 g ha-1 of pyroxasulfone and 1500 g ha-1 of S-metolachlor.

In all evaluations, all herbicide treatments were excellent to control (99 to 100%) *Digitaria horizontalis*, including reducing shoot biomass by 100% at the end of the experiment (Table 6). Studies have evaluated the control performed with pyroxasulfone (67.2 g ha-1) and S-metolachlor (575.5 g ha-1) in PRE of *Digitaria sanguinalis*, a close species, and there were no differences between both herbicides (Currie et al., 2005).

Table 5. Control of *Urochloa decumbens* at 14, 28 and 42 days after treatment (DAT) with herbicides in pre-emergence and shoot biomass at 42 DAT.

	Treatments	Rate (g ha-1)	Control of *Urochloa decumbens* (%)			Shoot biomass
			14 DAT	28 DAT	42 DAT	(g pot-1)*
1	Check	-	0 b	0 b	0 c	0.47 a
2	Pyroxasulfone	50	100 a	98 a	98 ab	0.02 b
3	Pyroxasulfone	100	100 a	100 a	100 a	0.00 c
4	Pyroxasulfone	150	100 a	100 a	100 a	0.00 c
5	Pyroxasulfone	200	100 a	100 a	100 a	0.00 c
6	Pyroxasulfone	250	100 a	100 a	100 a	0.00 c
7	S-metolachlor	960	98 a	100 a	99 ab	0.01 b
8	S-metolachlor	1920	100 a	100 a	100 a	0.00 c
9	Trifluralin	562.5	98 a	98 a	97 b	0.02 b
10	Trifluralin	1125	100 a	100 a	100 a	0.00 c
MSD			2.0	2.0	2.2	0.02
CV (%)			1.9	1.9	2.1	1.8

The means followed by the same letter in the column are not significant different at 5% probability by the Student t test; *Transformed data ($\sqrt{x+1}$) for statistical analysis; MSD: minimum significant difference; CV: coefficient of variation.

Table 6. Control of *Digitaria horizontalis* at 14, 28 and 42 days after treatment (DAT) with herbicides in pre-emergence and shoot biomass at 42 DAT.

	Treatments	Rate (g ha-1)	Control of *Digitaria horizontalis* (%)			Shoot biomass
			14 DAT	28 DAT	42 DAT	(g pot-1)*
1	Check	-	0 b	0 b	0 b	2.44 a
2	Pyroxasulfone	50	100 a	100 a	100 a	0.00 b
3	Pyroxasulfone	100	100 a	100 a	100 a	0.00 b
4	Pyroxasulfone	150	100 a	100 a	100 a	0.00 b
5	Pyroxasulfone	200	100 a	100 a	100 a	0.00 b
6	Pyroxasulfone	250	100 a	100 a	100 a	0.00 b
7	S-metolachlor	960	100 a	100 a	100 a	0.00 b
8	S-metolachlor	1920	100 a	100 a	100 a	0.00 b
9	Trifluralin	562.5	100 a	100 a	100 a	0.00 b
10	Trifluralin	1125	100 a	100 a	100 a	0.00 b
MSD			-	-	-	0.08
CV (%)			0.0	0.0	0.0	6.5

The means followed by the same letter in the column are not significant different at 5% probability by the Student t test; *Transformed data ($\sqrt{x+1}$) for statistical analysis; MSD: minimum significant difference; CV: coefficient of variation.

In the present study, the application of 50 g ha-1 of pyroxasulfone was sufficient to provide control levels ≥99%. Nurse et al. (2011) found that pyroxasulfone applied at 31.25 g ha-1 promoted more than 90% control of *D. sanguinalis*. Yamaji et al. (2014) observed in their studies that 16 g ha-1 of pyroxasulfone was sufficient to promote more than 90% of control. This variation in the results may have been caused by the different edaphic conditions in which the studies were conducted, considering that clay content, M.O. and soil pH can interfere with the effectiveness of pyroxasulfone (Tidemann et al., 2014a; Szmigielski et al., 2014).

Excellent control of *Digitaria insularis* was observed for all herbicides up to 42 DAT (Table 7). The lowest dose of pyroxasulfone showed slightly lower levels of control than the other herbicide treatments, promoting 99 and 97% at 28 and 42 DAT, respectively. No difference was observed in the shoot biomass of the plants of *D. insularis* when herbicides were applied in PRE, differing only from the untreated control. There is no published information about the performance of pyroxasulfone on *D. insularis*.

Table 7. Control of *Digitaria insularis* at 14, 28 and 42 days after treatment (DAT) with herbicides in pre-emergence and shoot biomass at 42 DAT.

	Treatments	Rate (g ha^{-1})	Control of *Digitaria insularis* (%)			Shoot biomass
			14 DAT	28 DAT	42 DAT	(g pot^{-1})*
1	Check	-	0 b	0 c	0 C	0.70 a
2	Pyroxasulfone	50	100 a	99 b	97 b	0.00 b
3	Pyroxasulfone	100	100 a	100 a	100 a	0.00 b
4	Pyroxasulfone	150	100 a	100 a	100 a	0.00 b
5	Pyroxasulfone	200	100 a	100 a	100 a	0.00 b
6	Pyroxasulfone	250	100 a	100 a	100 a	0.00 b
7	S-metolachlor	960	100 a	100 a	100 a	0.00 b
8	S-metolachlor	1920	100 a	100 a	100 a	0.00 b
9	Trifluralin	562.5	100 a	100 a	100 a	0.00 b
10	Trifluralin	1125	100 a	100 a	100 a	0.00 b
MSD			-	0.7	1.5	0.04
CV (%)			0.0	0.7	1.4	4.0

The means followed by the same letter in the column are not significant different at 5% probability by the Student t test; *Transformed data ($\sqrt{x+1}$) for statistical analysis; MSD: minimum significant difference; CV: coefficient of variation.

There were no significant differences in *Eleusine indica* control between herbicide treatments up to 42 DAT, as well as for the dry shoot biomass values (Table 8). The application of 50 g ha^{-1} of pyroxasulfone was sufficient to achieve 100% control, which suggests the effectiveness of the herbicide even at low doses. Yamaji et al. (2014) also observed that low doses of pyroxasulfone are sufficient to promote excellent control of *E. indica*, these authors observed that 16 g ha^{-1} of pyroxasulfone applied in PRE was sufficient to result levels of control higher than 90%.

Table 8. Control of *Eleusine indica* at 14, 28 and 42 days after treatment (DAT) with herbicides in pre-emergence and shoot biomass at 42 DAT.

	Treatments	Rate (g ha^{-1})	Control of *Eleusine indica* (%)			Shoot biomass
			14 DAT	28 DAT	42 DAT	(g pot^{-1})*
1	Check	-	0 b	0 b	0 b	1.29 a
2	Pyroxasulfone	50	100 a	100 a	100 a	0.00 b
3	Pyroxasulfone	100	100 a	100 a	100 a	0.00 b
4	Pyroxasulfone	150	100 a	100 a	100 a	0.00 b
5	Pyroxasulfone	200	100 a	100 a	100 a	0.00 b
6	Pyroxasulfone	250	100 a	100 a	100 a	0.00 b
7	S-metolachlor	960	100 a	100 a	99 a	0.01 b
8	S-metolachlor	1920	100 a	100 a	100 a	0.00 b
9	Trifluralin	562.5	100 a	100 a	99 a	0.01 b
10	Trifluralin	1125	100 a	100 a	100 a	0.00 b
MSD			-	-	1.0	0.05
CV (%)			0.0	0.0	0.9	4.2

The means followed by the same letter in the column are not significant different at 5% probability by the Student t test; *Transformed data ($\sqrt{x+1}$) for statistical analysis; MSD: minimum significant difference; CV: coefficient of variation.

Applications of doses ≥100 g ha^{-1} of pyroxasulfone were necessary to provide ≥80% control of *Lolium perenne* ssp. *multiflorum* at 14 DAT (Table 9). The highest levels of control were observed with the application of pyroxasulfone (150 to 250 g ha^{-1}), S-metolachlor and the highest dose of trifluralin. At 28 DAT, doses equal to or lower than 100 g ha^{-1} were insufficient to result in ≥80% control.

Table 9. Control of *Lolium perenne* ssp. multiflorum at 14, 28 and 42 days after treatment (DAT) with herbicides in pre-emergence and shoot biomass at 42 DAT.

	Treatments	Rate (g ha^{-1})	Control of *Lolium perenne* ssp. *multiflorum* (%)			Shoot biomass
			14 DAT	28 DAT	42 DAT	(g pot^{-1})*
1	Check	-	0 e	0 e	0 d	2.13 a
2	Pyroxasulfone	50	75 d	71 d	57 c	0.28 b
3	Pyroxasulfone	100	84 c	80 c	91 b	0.21 bc
4	Pyroxasulfone	150	94 ab	89 b	94 b	0.04 c
5	Pyroxasulfone	200	99 a	98 a	100 a	0.00 c
6	Pyroxasulfone	250	100 a	100 a	100 a	0.00 c
7	S-metolachlor	960	99 a	100 a	100 a	0.00 c
8	S-metolachlor	1920	100 a	100 a	100 a	0.00 c
9	Trifluralin	562.5	89 bc	89 b	95 ab	0.02 c
10	Trifluralin	1125	100 a	97 a	99 ab	0.01 c
MSD			6.8	6.7	5.5	0.11
CV (%)			7.0	7.0	5.8	8.6

The means followed by the same letter in the column are not significant different at 5% probability by the Student t test; *Transformed data ($\sqrt{x+1}$) for statistical analysis; MSD: minimum significant difference; CV: coefficient of variation.

In the subsequent evaluation (42 DAT), only the lowest dose of pyroxasulfone did not result in ≥80% control of L. *multiflorum*. The other doses of pyroxasulfonein used on this study promoted good control, similar to S-metolachlor and trifluralin. The increase in the control levels observed with 100 g ha^{-1} of pyroxasulfone from 28 to 42 DAT was caused by the inhibition of the shoot biomass. As suggested by Tanetani et al. (2009), it was found that the germination itself was not strongly inhibited by pyroxasulfone, at the same time it inhibited the development of the shoot of *L. multiflorum* plants.

When the shoot biomass of *L. multiflorum* plants were evaluated, it was observed that the application of 50 g ha^{-1} of pyroxasulfone was sufficient to reduce the shoot biomass by more than 86% in relation to the untreated control. This result suggests that the herbicide pyroxasulfone, when applied in low doses, has the potential to reduce the competition imposed by this weed. As expected, doses from 100 g ha^{-1} can completely prevent its emergence.

The efficiency of pyroxasulfone to control *L. multiflorum* in PRE has been extensively studied in wheat. Nakatani et al. (2016) report that pyroxasulfone has little effect on the germination of *L. multiflorum* and *Echinochloa* spp., however, it inhibits the stretching of plant tissues in emerged plants. Among the species studied in the present study, *L. multiflorum* showed less sensitivity. Even so, doses of 100 g ha^{-1} or higher provided good control. In some studies, the effectiveness of pyroxasulfone in controlling *L. multiflorum* and *L. rigidum* with doses higher than 100 g ha^{-1} has also been observed (Hulting et al., 2012; Boutsalis et al., 2014).

Pyroxasulfone demonstrated good control of *L. perenne* and *L. rigidum*, one of the main weeds in Australia, also found in the southern United States (Hulting et al., 2012; Hausman et al., 2013; Meyers et al., 2013; Busi et al., 2014; Tidemann et al., 2014a; Tidemann et al., 2014b). Walsh et al. (2011) verified the selectivity and effectiveness of pyroxasulfone in the control of *L. rigidum* in wheat. However, studies have reported that *L. rigidum* is capable of developing resistance to pyroxasulfone if it is repeatedly exposed to low doses over four generations (Busi et al., 2012; Busi et al., 2014; Busi et al., 2018). Apparently, resistance may be related to rapid metabolism due to the combination of pyroxasulfone and glutathione (GSH) (Busi et al., 2018).

All herbicide treatments promoted similar control of *Panicum maximum* up to 42 DAT (Table 10). It stands out that Pyroxasulfone with the lowest dose (50 g) achieved 100% control. Due to the effectiveness of herbicide treatments in controlling *P. maximum*, the shoot biomass was similar between herbicide treatments.

There is no information about the effectiveness of this herbicide for this weed. However, there are studies with other species of this genus, where pyroxasulfone resulted in effective control of *P. dichotomiflorum* and *P. texanum*. In another study, pyroxasulfone provided similar or higher levels of control of *P. texanum* to that resulted by S-metolachlor (Currie et al., 2005). Steele et al. (2005) reported that pyroxasulfone (125 g ha^{-1}) and S-metolachlor (1070 g ha^{-1}) provided similar control of *P. texanum*. According to Yamaji et al. (2014) a dose of 16 g ha^{-1} of pyroxasulfone was sufficient to achieve control higher than 90.0% of *P. dichotomiflorum*.

All treatments using pyroxasulfone provide control levels of ≥80% of *Raphanus raphanistrum* at 14 DAT (Table 11). The doses applied from 100 to 250 g ha^{-1} of pyroxasulfone result in the highest levels of control of *R. raphanistrum*. The applications of S-metolachlor and trifluralin did not provide more than 50% control.

Table 10. Control of *Panicum maximum* at 14, 28 and 42 days after treatment (DAT) with herbicides in pre-emergence and shoot biomass at 42 DAT.

	Treatments	Rate (g ha^{-1})	Control of *Panicum maximum* (%)			Shoot biomass
			14 DAT	28 DAT	42 DAT	(g vaso^{-1})*
1	Check	-	0 b	0 b	0 b	1.01 a
2	Pyroxasulfone	50	100 a	100 a	100 a	0.00 b
3	Pyroxasulfone	100	100 a	100 a	100 a	0.00 b
4	Pyroxasulfone	150	100 a	100 a	100 a	0.00 b
5	Pyroxasulfone	200	100 a	100 a	100 a	0.00 b
6	Pyroxasulfone	250	100 a	100 a	100 a	0.00 b
7	S-metolachlor	960	100 a	100 a	100 a	0.00 b
8	S-metolachlor	1920	100 a	100 a	100 a	0.00 b
9	Trifluralin	562.5	100 a	100 a	100 a	0.00 b
10	Trifluralin	1125	100 a	100 a	100 a	0.00 b
MSD			-	-	-	0.01
CV (%)			0.00	0.00	0.00	1.13

The means followed by the same letter in the column are not significant different at 5% probability by the Student t test; *Transformed data ($\sqrt{x+1}$) for statistical analysis; MSD: minimum significant difference; CV: coefficient of variation.

Table 11. Control of *Raphanus raphanistrum* at 14, 28 and 42 days after treatment (DAT) with herbicides in pre-emergence and shoot biomass at 42 DAT.

	Treatments	Rate (g ha^{-1})	Control of *Raphanus raphanistrum* (%)			Shoot biomass
			14 DAT	28 DAT	42 DAT	(g pot^{-1})*
1	Check	-	0 d	0 d	0 c	3.10 bc
2	Pyroxasulfone	50	85 b	91 b	91 b	0.13 d
3	Pyroxasulfone	100	92 ab	97 ab	98 a	0.01 d
4	Pyroxasulfone	150	95 a	93 ab	98 a	0.03 d
5	Pyroxasulfone	200	90 ab	99 ab	100 a	0.01 d
6	Pyroxasulfone	250	98 a	100 a	100 a	0.00 d
7	S-metolachlor	960	47 c	3 d	0 c	3.09 bc
8	S-metolachlor	1920	45 c	15 c	0 c	2.44 c
9	Trifluralin	562.5	5 d	0 d	0 c	4.09 a
10	Trifluralin	1125	6 d	0 d	0 c	3.44 ab
MSD			8.6	8.9	2.7	0.24
CV (%)			13.2	15.3	4.9	13.6

The means followed by the same letter in the column are not significant different at 5% probability by the Student t test; *Transformed data ($\sqrt{x+1}$) for statistical analysis; MSD: minimum significant difference; CV: coefficient of variation.

Up to 42 DAT, applied doses of pyroxasulfone promoted the highest levels of control. The herbicides S-metolachlor and trifluralin were ineffective in controlling *R. raphanistrum*, with an absence of control at 42 DAT. The shoot biomass values in the treatments with S-metolachlor and trifluralin were like the untreated check. The application of 50 g ha^{-1} of pyroxasulfone was sufficient to reduce the shoot biomass in relation to the untreated by more than 95%. This is the first study illustrating that pyroxasulfone in PRE can provide efficient control of *R. raphanistrum*, moreover demonstrating higher performance than S-metolachlor and trifluralin.

The highest levels of control of *Spermacoce latifolia* at 14 DAT were observed with the application of the highest doses of pyroxasulfone (150 to 250 g ha^{-1}), similar to the highest dose of S-metolachlor (Table 12). The lowest levels of control were observed with the application of 50 g ha^{-1} of pyroxasulfone and 562.5 g ha^{-1} of trifluralin. The dose of 100 g ha^{-1} of pyroxasulfone result in 91% control, similar to the higher dose of S-metolachlor and trifluralin.

Table 12. Control of *Spermacoce latifolia* at 14, 28 and 42 days after treatment (DAT) with herbicides in pre-emergence and shoot biomass at 42 DAT.

	Treatments	Rate (g ha-1)	Control of *Spermacoce latifolia* (%)						Shoot biomass (g pot-1)*	
			14 DAT		28 DAT		42 DAT			
1	Check	-	0	e	0	e	0	c	0.20	a
2	Pyroxasulfone	50	78	d	82	d	89	b	0.01	b
3	Pyroxasulfone	100	91	bc	91	c	96	a	0.00	b
4	Pyroxasulfone	150	94	abc	98	ab	98	a	0.00	b
5	Pyroxasulfone	200	97	a	100	a	100	a	0.00	b
6	Pyroxasulfone	250	96	a	100	a	100	a	0.00	b
7	S-metolachlor	960	92	bc	97	ab	97	a	0.00	b
8	S-metolachlor	1920	96	ab	97	ab	99	a	0.00	b
9	Trifluralin	562.5	79	d	95	b	97	a	0.00	b
10	Trifluralin	1125	90	c	97	ab	97	a	0.00	b
MSD			4.2		3.7		4.1		0.01	
CV (%)			4.5		3.8		4.0		0.8	

The means followed by the same letter in the column are not significant different at 5% probability by the Student t test; *Transformed data ($\sqrt{x+1}$) for statistical analysis; MSD: minimum significant difference; CV: coefficient of variation.

At 28 DAT, the application of 50 g ha-1 of pyroxasulfone started resulting ≥80% control. The highest levels of control were visualized with the applications of pyroxasulfone (≥150 g ha-1), S-metolachlor and the highest dose of trifluralin (1125 g ha-1). At 42 DAT, only the lowest dose of pyroxasulfone was inferior to the other treatments. The application of the recommended dose in soybean crop (100 g ha-1) resulted in similar efficiency to the standard herbicides (S-metolachlor and trifluralin).

The shoot biomass of *Spermacoce latifolia* plants were similar for all herbicide treatments. The application of 50 g ha-1 of pyroxasulfone promoted a reduction of 95.0% in the shoot biomass compared to the untreated check.

The initial control (14 DAT) of *Spermacoce verticillata* provided with 100 g ha-1 of pyroxasulfone was similar to the highest doses of S-metolachlor and trifluralin (Table 13). The highest levels of control were obtained with the application of pyroxasulfone in doses ≥150 g ha-1. At 28 DAT, the application of 50 g ha-1 of pyroxasulfone started to result in the highest levels of control (≥80%), considering similar to the 960 g ha-1 of S-metolachlor and higher than 562.5 g ha-1 of trifluralin.

Table 13. Control of *Spermacoce verticillata* at 14, 28 and 42 days after treatment (DAT) with herbicides in pre-emergence and shoot biomass at 42 DAT.

	Treatments	Rate (g ha-1)	Control of *Spermacoce verticillata* (%)						Shoot biomass (g pot-1)*	
			14 DAT		28 DAT		42 DAT			
1	Check	-	0	e	0	g	0	e	0.08	a
2	Pyroxasulfone	50	79	d	83	e	89	cd	0.02	b
3	Pyroxasulfone	100	91	c	91	cd	91	bcd	0.01	b
4	Pyroxasulfone	150	97	ab	95	bc	94	abc	0.01	b
5	Pyroxasulfone	200	99	a	97	ab	99	a	0.00	b
6	Pyroxasulfone	250	100	a	100	a	100	a	0.00	b
7	S-metolachlor	960	83	d	88	de	87	d	0.02	b
8	S-metolachlor	1920	92	c	95	bc	98	a	0.01	b
9	Trifluralin	562.5	89	c	75	f	87	cd	0.01	b
10	Trifluralin	1125	92	bc	92	cd	97	ab	0.00	b
MSD			4.9		5.0		6.3		0.02	
CV (%)			5.2		4.8		6.5		0.9	

The means followed by the same letter in the column are not significant different at 5% probability by the Student t test; *Transformed data ($\sqrt{x+1}$) for statistical analysis; MSD: minimum significant difference; CV: coefficient of variation.

All herbicide treatments were effective in controlling *S. verticillata* up to 42 DAT. The highest levels of control were observed with the applications of pyroxasulfone (≥150 g ha^{-1}), S-metolachlor (1920 g ha^{-1}) and trifluralin (1125 g ha^{-1}). Pyroxasulfone at 100 g ha^{-1} was similar to the highest dose of trifuralin; however, lower than the highest dose of S-metolachlor. The shoot biomass was similar between herbicide treatments. The application of 50 g ha^{-1} of pyroxasulfone promoted a reduction of at least 75% in the shoot biomass. Hence, it is observed in this work that pyroxasulfone was efficient, even applied at 50 g ha^{-1}.

In summary, the efficiency in the initial control of *E. crus-galli* and *L. multiflorum* promoted by pyroxasulfone (100 g ha^{-1}) was inferior to S-metolachlor (960 and 1920 g ha^{-1}) and to trifluralin (1125 g ha^{-1}); only the lowest dose of trifluralin (526.5 g ha^{-1}) was similar. This may be a weakness of pyroxasulfone when the objective is to control the initial weed competition of *E. crus-galli* and *L. multiflorum*, being less efficient than the standard herbicides evaluated (S-metolachlor and trifluralin). The levels of final weed control promoted by the three herbicides were similar (Table 14).

Table 14. Summary of initial (I) and final (F) control efficiency of grass weeds with the application of pyroxasulfone (100 g ha^{-1}), S-metolachlor (960 and 1920 g ha^{-1}) and trifluralin (526.5 and 1125 g ha^{-1}) treatments in pre-emergence.

Treatments	Rate (g ha^{-1})	CHREL		ECHCG		BRADC		DIGHO		TRCIN		ELEIN		LOLMU		PANMA	
		I	F	I	F	I	F	I	F	I	F	I	F	I	F	I	F
Pyroxasulfone[1]	100	1	1	3	1	1	1	1	1	1	1	1	1	2	1	1	1
S-metolachlor	960	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1
S-metolachlor	1920	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Trifluralin	526.5	1	1	3	1	1	1	1	1	1	1	1	1	2	1	1	1
Trifluralin	1125	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

[1]Dose that will be recommended for the soybean crop; I: initial control (14 days after application); F: final control (42 days after application); (1): control> 90% - blue; (2): 80 to 90% control - green; (3): control from 60 to 80% - yellow; (4): control <60% - red; CHREL: *Chloris elata*; ECHCG: *Echinochloa crusgalli*; BRADC: *Urochloa decumbens*; DIGHO: *Digitaria horizontalis*; TRCIN: *Digitaria insularis*; ELEIN: *Eleusine indica*; LOLMU: *Lolium perenne* ssp. *multiflorum*; PANMA: *Panicum maximum*.

The application of 100 g ha^{-1} of pyroxasulfone result in an initial control higher than S-metolachlor (960 and 1920 g ha^{-1}) for *A. viridis*, *R. raphanistrum* and then of S-metolachlor at 960 g ha^{-1} for *S. verticillata*; final control greater than S-metolachlor (960 and 1920 g ha^{-1}) for *R. raphanistrum* and greater than S-metolachlor at 960 g ha^{-1} for *Conyza* spp. and *S. verticillata* (Table 15).

Table 15. Summary of initial (I) and final (F) control efficiency of broadleaf weeds with the application of pyroxasulfone (100 g ha^{-1}), S-metolachlor (960 and 1920 g ha^{-1}) and trifluralin (526, 5 and 1125 g ha^{-1}) treatments in pre-emergence.

Treatments	Rate (g ha^{-1})	AMAVI		CNDSS		RAPRA		BOILF		BOIVE	
		I	F	I	F	I	F	I	F	I	F
Pyroxasulfone[1]	100	1	1	4	1	1	1	1	1	1	1
S-metolachlor	960	3	1	4	2	4	4	1	1	2	2
S-metolachlor	1920	3	1	4	1	4	4	1	1	1	1
Trifluralin	526.5	2	2	4	4	4	4	3	1	2	2
Trifluralin	1125	1	1	4	3	4	4	1	1	1	1

[1]Dose that will be recommended for the soybean crop; I: initial control (14 days after application); F: final control (42 days after application); (1): control> 90% - blue; (2): 80 to 90% control - green; (3): control from 60 to 80% - yellow; (4): control <60% - red; AMAVI: *Amaranthus viridis*; CNDSS: *Conyza* spp.; RAPRA: *Raphanus Raphanistrum*; BOILF: *Spermacoce latifolia*; BOIVE: *Spermacoce verticillata*.

The initial and final control of *Conyza* spp., *R. Raphanistrum* and *S. verticillata* provided by pyroxasulfone (100 g ha^{-1}) was superior to the doses of trifluralin. In addition, pyroxasulfone result in initial control of *S. latifolia* superior to trifluralin (526.5 and 1125 g ha^{-1}); and superior to trifluralin (526.5 g ha^{-1}) in the initial and final control of *A. viridis*.

It is known that the use of herbicides applied in PRE offers the advantage of weed control before they can compete with the crop and cause yield reduction and product quality decrease. However, as a result of GMOs, mainly from glyphosate-resistant crops, the use of these herbicides has been reduced, and glyphosate applications are the most frequent practice used for weed control in agricultural areas, resulting in a rapid selection of resistant weed biotypes. Among the species are: *Conyza* spp., *Chloris elata*, *Eleusine indica*, *Digitaria insularis* and *Lolium perenne* ssp. *multiflorum*, *Euphorbia heterophylla* (Heap, 2022). In the last decade, there has been an increased demand for herbicides with residual activity to be used in PRE and selective to crops, caused by the selection of resistant weeds.

As already verified in the literature under different conditions, this research also confirmed the excellent performance of pyroxasulfone for the weed control in Brazil. It was observed that applications of relatively low doses in relation to the herbicides S-metolachlor and trifluralin, such as 50 and 100 g ha^{-1} of pyroxasulfone, were efficient in controlling most of the species studied, which results in a cost and logistics advantage, in addition to enabling a reduction in the chemical load imposed on the environment. Once adopted in Brazil, this herbicide could become an important tool in the weed control and to weed resistance management, especially in the case of grasses.

Pyroxasulfone that will be recommended to soybean at 100 g ha^{-1} in PRE for clayey soil (50.3% clay) with 2.6% M.O. was efficient in controlling the evaluated weeds, resulting in similar control to the main molecules used to the control of grasses and small seeds' broadleaves.

4. Conclusions

This research indicates the excellent performance of pyroxasulfone in PRE for the control of weeds found in Brazilian agricultural areas;

Pyroxasulfone at 100 g ha^{-1} in PRE was efficient in controlling most of the evaluated weeds, being similar to the main molecules used to control grasses and small seeds' broadleaves, such as S-metolachlor and trifluralin;

Pyroxasulfone become an important tool in weed management, especially as a new tool for herbicide rotation and delay herbicide resistance evolution.

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