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Research Article

Agronomic performance of wheat under post-emergence herbicide application[1]

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ABSTRACT

In addition to the herbicides already registered for the wheat crop, others may be selective, such as saflufenacil, atrazine, mesotrione and triclopyr. This study aimed to assess the selectivity of herbicides via crop yield analysis, alone and in mixtures, applied to wheat in post-emergence, at the end of tillering. Two experiments were conducted using a randomized blocks design. The first experiment (E1) involved 13 and the second one (E2) 7 treatments, consisting of the application of 2,4-D, diclofop, iodosulfuron, clodinafop, saflufenacil, pyroxsulam, atrazine, mesotrione and triclopyr, alone or in mixtures. Wheat injury symptoms, plant height, number of spikelets per plant, number of grains per spikelet, 1,000-grain weight and yield were assessed. The application of diclofop and iodosulfuron was selective to the wheat, maintaining yield even under the water stress conditions observed in E1. Under the same conditions, applying 2,4-D, clodinafop, saflufenacil, pyroxsulam, atrazine/mesotrione, triclopyr or saflufenacil + atrazine/mesotrione reduced the wheat yield, with different injury levels. Under greater water availability (E2), 2,4-D, clodinafop, saflufenacil, pyroxsulam and triclopyr were selective to the wheat, with no negative effect on yield. The application of atrazine/mesotrione showed a high injury potential for the crop and reduced the wheat yield.

KEYWORDS: *Triticum aestivum* L., synthetic auxins, grain injury, herbicide selectivity.

RESUMO

Desempenho agronômico de trigo sob aplicação de herbicidas em pós-emergência

Além dos herbicidas já registrados para a cultura do trigo, outros podem ser seletivos, como o saflufenacil, atrazine, mesotrione e triclopyr. Objetivou-se avaliar a seletividade de herbicidas em análise da produtividade de cultivo, isolados e em associações, aplicados em pós-emergência do trigo, no final do perfilhamento. Foram conduzidos dois experimentos utilizando-se delineamento de blocos casualizados, sendo o primeiro (E1) com 13 e o segundo (E2) com 7 tratamentos, compostos pela aplicação de 2,4-D, diclofop, iodosulfuron, clodinafop, saflufenacil, pyroxsulam, atrazine, mesotrione e triclopyr, isolados ou em associações. Foram avaliados sintomas de injúria no trigo, altura de plantas, número de espigas por planta, número de grãos por espiga, massa de 1.000 grãos e produtividade. A aplicação de diclofop e iodosulfuron foi seletiva ao trigo, com manutenção da produtividade mesmo sob as condições de estresse hídrico observadas no E1. Sob as mesmas condições, a aplicação de 2,4-D, clodinafop, saflufenacil, pyroxsulam, atrazine/mesotrione, triclopyr ou saflufenacil + atrazine/mesotrione reduziu a produtividade do trigo, com diferentes níveis de injúria. Sob maior disponibilidade hídrica (E2), 2,4-D, clodinafop, saflufenacil, pyroxsulam e triclopyr foram seletivos ao trigo, sem efeito negativo à produtividade. A aplicação de atrazine/mesotrione apresentou elevado potencial de injúria para o cultivo e reduziu a produtividade do trigo.

PALAVRAS-CHAVE: *Triticum aestivum* L., auxinas sintéticas, injúria de grãos, seletividade de herbicidas.

INTRODUCTION

Wheat losses due to crop-weed competition may be greater than 50 % (Galon et al. 2019, Manalil & Chauhan 2019). Another aggravating factor in wheat management is herbicide-resistant weeds, which include 53 resistant biotypes in Brazil (Heap 2021). Nine of them have already been reported for wheat, highlighting plants of the Poaceae family, such as *Lolium perenne* ssp. *Multiflorum*, with cases of resistance to acetolactate inhibitors (ALS), acetyl-CoA carboxylase (ACCase) and 5-enolpyruvylshiquimate-3-phosphate synthase (EPSPs) (Heap 2021).

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Chemical control via herbicides is one of the most widely used methods. These products can be applied in pre- or post-weed or crop emergence (Krähmer et al. 2021). Pre-emergence herbicides decrease the weed development, thereby reducing future infestations (Amim et al. 2016). These herbicides have been losing ground to their post-emergence counterparts, due to the advent of new molecules and technologies, which highlight the concept of selectivity (Oliveira & Vivian 2012).

Selectivity is the different response that a crop exhibits to the application of a particular herbicide, and injury may or may not occur (Carvalho et al. 2009). Injury levels change according to the crop, herbicide and dose used, application methods and physiological status. Selectivity is also associated with the ability of a plant to recover after herbicide application through inactivation/metabolization of the molecule, in addition to being influenced by plant morphology (Carvalho et al. 2009, Nandula et al. 2019).

In order to assess the degree of herbicide selectivity, it is important to monitor visual changes in the crop, as well as those that characterize the degree of injury caused by the herbicide (Maldaner & Scheneider 2019). In this respect, it is expected that the molecules used in the post-emergence wheat crop, such as 2,4-D, diclofop, iodosulfuron, clodinafop and pyroxsulam, exhibit selectivity (Piasecki et al. 2017, Zobiole et al. 2018, Bayat & Zargar 2020).

In addition to the herbicides already used for the crop, others may be selective for wheat in some situations, such as saflufenacil, atrazine, mesotrione and triclopyr. Thus, this study aimed to assess the post-emergence herbicide selectivity by analyzing the crop yield, alone or in mixtures, applied to wheat in the final tillering phase.

MATERIAL AND METHODS

Two experiments were conducted in Palotina, Paraná state, Brazil (24º20'43.1"S; 53º51'30.8"W), in the second crop of 2019 (E1) and 2020 (E2), in a very clayey soil. The climate in the region is Cfa (humid subtropical), according to the Köppen-Geiger classification, with average temperatures of 15-37 ºC and annual rainfall of approximately 1,650 mm (Aparecido et al. 2016). The meteorological conditions during the experiments are presented in Figure 1.

Direct sowing of the early-cycle CD 1303 wheat cultivar occurred on May 20, 2019 (E1) and May 18, 2020 (E2), with a sowing density of 412 seeds m^{-2}. The weeds were desiccated in the area at 14 days before sowing, with the application of metsulfuron (2 g of active ingredient [a.i.] ha^{-1} - Ally®) and 2,4-D (670 g of acid equivalent [a.e.] ha^{-1} - DMA® 806 BR), with mineral oil (0.1 % v/v). Undesirable plants were controlled by manual weeding, in order to avoid interfering with the wheat crop.

A randomized blocks design was used, with 13 (E1) and 7 (E2) treatments (Tables 1 and 2) and 5 replications. Each plot consisted of sixteen 5-m-long rows spaced 0.17 m apart. The study area corresponded to a 2-m-long section of the ten central rows. The treatments were applied to post-emergent wheat at the end of tillering, that is, stage 5 in the Feeks phenological classification (Large 1954), on

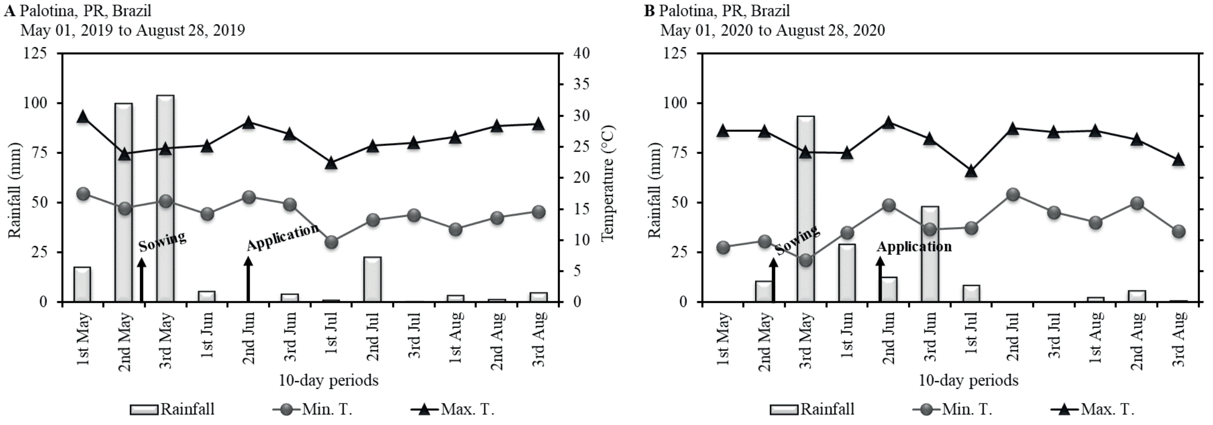

Figure 1. Rainfall and maximum and minimum temperatures in Palotina, Paraná state (PR), Brazil, in 2019 (A) and 2020 (B).

Table 1. Treatments consisting of the post-emergence application of herbicides, alone or in mixtures, in the experiment 1 (Palotina, Paraná state, Brazil, 2019).

Herbicide	Commercial product	Rate[5] (g a.i. ha^{-1})
Control (without application)	-	-
2,4-D	DMA® 806 BR	670
Diclofop	Iloxan® CE	420
Iodosulfuron[1]	Hussar®	5
Clodinafop[2]	Topik® 240 EC	60
Saflufenacil[3]	Heat®	24.5
Saflufenacil[3]	Heat®	35
Pyroxsulam[4]	Tricea®	18
Atrazine/mesotrione[2]	Calaris®	100/10
Atrazine/mesotrione[2]	Calaris®	200/20
Triclopyr	Triclon®	480
Saflufenacil + atrazine/mesotrione[3]	Heat® + Calaris®	35 + 150/15
Saflufenacil + atrazine/mesotrione[3]	Heat® + Calaris®	35 + 300/30

[1] Addition of Agral (0.3 % v v^{-1}). [2] Addition of Assist (0.5 % v v^{-1}). [3] Addition of Dash (0.5 % v v^{-1}). [4] Addition of Aureo (0.5 % v v^{-1}). [5] Rates at a.e. ha^{-1} for 2,4-D and triclopyr.

Table 2. Treatments consisting of the post-emergence application of herbicides, alone or in mixtures, in the experiment 2 (Palotina, Paraná state, Brazil, 2020).

Herbicide	Commercial product	Rate[4] (g a.i. ha^{-1})
Control (without application)	-	-
2,4-D	DMA® 806 BR	670
Clodinafop[1]	Topik® 240 EC	60
Saflufenacil[2]	Heat®	24.5
Pyroxsulam[3]	Tricea®	18
Atrazine/mesotrione[1]	Calaris®	100/10
Triclopyr	Triclon®	480

[1] Addition of Assist (0.5 % v v^{-1}). [2] Addition of Dash (0.5 % v v^{-1}). [3] Addition of Aureo (0.5 % v v^{-1}). [4] Rates at a.e. ha^{-1} for 2,4-D and triclopyr.

June 16, 2019 (E1) and June 15, 2020 (E2). A CO_2 pressurized backpack sprayer equipped with six AIXR 110.015 nozzles was used, at a pressure of 2.0 kgf cm^{-2} and flow rate of 3.6 km h^{-1}, supplying an application volume of 150 L ha^{-1}. In 2019, the conditions during application were: wind speed of 3 km h^{-1}, temperature of 27.2 ºC and relative humidity of 53.3 %, and, in 2020, wind speed of 2.2 km h^{-1}, temperature of 18.5 ºC and relative humidity of 67.6 %.

Injury symptoms were visually assessed in the wheat plants at 7, 14, 21 and 28 days after herbicide application (DHA) in E1, and 7 and 28 DHA in E2. Scores were assigned based on visual analyses of each experimental unit (0 for absence of injury and 100 % for plant death), considering, in this case, significantly visible symptoms in the plants, according to their development (Velini et al. 1995).

With respect to the agronomic performance at harvest, the plant height, number of spikelets per plant, number of grains per spikelet, 1,000-grain weight and yield were assessed in E1, and yield in E2. The plant height was measured from the ground level to the tip of the spikelet in 6 plants per plot. The number of spikelets and grains per spikelet were measured in 6 plants per plot. In order to assess grain yield, the study area of each plot was harvested, with the results expressed in kg ha^{-1}. The weight of four subsamples of 100 grains was measured, and the average multiplied by 10 to obtain the 1,000-grain weight. Moisture was corrected to 13 % for these two variables.

The results were submitted to analysis of variance (Anova) ($p \leq 0.05$). When significant, treatment measures were grouped applying the Scott-Knott test ($p \leq 0.05$), using the Sisvar 5.6 software (Ferreira 2011).

RESULTS AND DISCUSSION

The climate conditions during E1 demonstrate that the total rainfall between May 20 and August 21 (2019) was less than 150 mm, a value below that described in the literature as optimal for the crop development, which oscillates between 350 and 600 mm (Souza et al. 2013). The water stress was more pronounced after the herbicide application, which decreased the wheat leaf area, directly impacting number and size, and, consequently, photosynthesis. Deficiency may also reduce the number of grains per spikelet, but without necessarily compromising its weight (Santos et al. 2012).

Water stress may also cause a greater retention and absorption of the active ingredients in the epidermis and/or plant cells, what may strengthen the phytotoxic action of the product in the plant. This injury may not immediately manifest itself in the plant and remain latent, what could affect components and cause subsequent damages (Larcher 2000).

At 28 DHA, the herbicides 2,4-D, diclofop, iodosulfuron, clodinafop and pyroxsulam caused no symptoms to the wheat plants. Applying atrazine/mesotrione (200/20 g a.i. ha^{-1}) and saflufenacil + atrazine/mesotrione increased injuries throughout the assessments, with 26.6 % for the first treatment and 74.4 % for the second one, at the highest dose (Table 3).

Piasecki et al. (2017) observed injury in wheat plants between 9 and 23 % under saflufenacil application (alone or in mixtures), 4 and 12 % for iodosulfuron, 1 and 9 % for pyroxsulam and 1 and 6 % for 2,4-D. Maldaner & Schneider (2019) assessed wheat tolerance for saflufenacil (0, 30, 50 and 70 g a.i. ha^{-1}) at two application times (tillering and elongation), but found no injury for tillering applications. However, for elongation applications, injury was between 14 and 19 %, demonstrating that saflufenacil can be used in wheat, provided it is applied at the tillering phase.

For the agronomic performance, the Anova showed no significant herbicide effects on the number of grains per spikelet and 1,000-grain weight (data not shown). However, treatment differences were observed for plant height, number of spikelets per plant and yield. These variables showed the harmful effect of some herbicide treatments, in line with the aforementioned injury symptoms. Only the diclofop and iodosulfuron applications demonstrated no decrease in wheat plant yield. Wheat yield decreased even for the application of 2,4-D, clodinafop and pyroxsulam, albeit without causing visual injury at 28 DHA. These results may be explained by water stress, as mentioned in the relationship between this condition and herbicide-related plant injuries (Table 4).

In the experiment 2, the rainfall conditions were more favorable to the wheat development, with an accumulation of more than 200 mm throughout the study, and, although less than ideal, correlations between herbicides and water stress were not observed in this experiment. A greater injury was detected for the application of atrazine/mesotrione, and triclopyr at 28 DHA, with 10 and 3 %, respectively. For saflufenacil, 12 % of injury were observed at 7 DHA, with no symptoms at 28 DHA, but no injury for the other herbicides at 28 DHA. Only atrazine/mesotrione was not selective for wheat in this experiment, with a decrease in yield, when compared to the control (no application) and all the other herbicides (Table 5).

The herbicides diclofop and iodosulfuron are selective for wheat, even under the water stress conditions observed in the experiment 1, while 2,4-D, clodinafop, saflufenacil, pyroxsulam and triclopyr were selective in the experiment 2. In other studies, selectivity was determined for 2,4-D (Hooker et al. 2018, Viecelli et al. 2019, Crose et al. 2020, Zargar et al. 2020), clodinafop (Zahid et al. 2013), saflufenacil (Piasecki et al. 2017), pyroxsulam (Viecelli et al. 2019, Zargar et al. 2020), diclofop (Singh et al. 2020) and iodosulfuron (Piasecki et al. 2017).

The herbicides 2,4-D, clodinafop, saflufenacil, pyroxsulam and triclopyr were selective for wheat plants in the experiment that exhibited a greater water stress. Even herbicides recommended for post-

Table 3. Wheat injury at 7, 14, 21 and 28 days after herbicide application (DHA), in the post-emergent crop, in the experiment 1 (Palotina, Paraná state, Brazil, 2019).

Herbicide	Rate[1] (g a.i. ha^{-1})	Injury (%)			
		7 DHA	14 DHA	21 DHA	28 DHA
Control (without application)	-	0.0 a	0.0 a	0.0 a	0.0 a
2,4-D	670	3.2 b	0.6 a	0.0 a	0.0 a
Diclofop	420	3.6 b	0.2 a	0.0 a	0.0 a
Iodosulfuron	5	1.0 a	0.0 a	0.0 a	0.0 a
Clodinafop	60	2.8 b	0.0 a	0.0 a	0.0 a
Saflufenacil	24.5	8.0 c	7.0 c	9.4 c	5.0 b
Saflufenacil	35	12.0 d	12.6 e	13.6 d	8.2 b
Pyroxsulam	18	0.8 a	0.2 a	0.0 a	0.0 a
Atrazine/mesotrione	100/10	7.4 c	9.2 d	9.0 c	7.4 b
Atrazine/mesotrione	200/20	11.8 d	12.6 e	18.8 e	26.6 c
Triclopyr	480	3.8 b	4.0 b	5.4 b	5.4 b
Saflufenacil + atrazine/mesotrione	35 + 150/15	19.0 e	22.3 f	24.8 f	33.5 d
Saflufenacil + atrazine/mesotrione	35 + 300/30	29.4 f	36.4 g	56.8 g	74.4 e
Mean		7.9	8.1	10.6	12.4
CV (%)		20.7	19.6	20.1	25.9

[1] Rates at a.e. ha^{-1} for 2,4-D and triclopyr. Means followed by the same letter in the rows do not differ according to the Scott-Knott test at 5 % of probability.

Table 4. Height, number of spikelets per plant and wheat plant yield under post-emergence herbicide application, in the experiment 1 (Palotina, Paraná state, Brazil, 2019).

Herbicide	Rate¹ (g a.i. ha^{-1})	Height (cm)	Spikelets	Yield (kg ha^{-1})
Control (without application)	-	51.8 a	3.4 a	1,590 a
2,4-D	670	50.8 a	3.7 a	1,144 c
Diclofop	420	50.8 a	3.7 a	1,451 a
Iodosulfuron	5	51.2 a	3.6 a	1,543 a
Clodinafop	60	50.7 a	3.9 a	1,280 b
Saflufenacil	24.5	51.4 a	3.7 a	1,346 b
Saflufenacil	35	49.4 b	3.2 b	1,197 c
Pyroxsulam	18	48.7 b	3.4 a	986 d
Atrazine/mesotrione	100/10	48.7 b	3.2 b	535 e
Atrazine/mesotrione	200/20	45.8 b	3.1 b	449 e
Triclopyr	480	48.4 b	3.2 b	899 d
Saflufenacil + atrazine/mesotrione	35 + 150/15	46.9 b	3.0 b	389 e
Saflufenacil + atrazine/mesotrione	35 + 300/30	38.9 c	2.5 b	182 f
Mean		48.7	15.9	999
CV (%)		5.2	3.4	14.8

¹ Rates at a.e. ha^{-1} for 2,4-D and triclopyr. Means followed by the same letter in the rows do not differ according to the Scott-Knott test at 5 % of probability.

Table 5. Wheat yield and plant injury at 7 and 28 days after post-emergence herbicide application (DHA), in the experiment 2 (Palotina, Paraná state, Brazil, 2019).

Herbicide	Rate¹ (g a.i. ha^{-1})	Injury (%)		Yield (kg ha^{-1})
		7 DAA	28 DHA	
Control (without application)	-	0.0 a	0.0 a	2,572 a
2,4-D	670	5.0 b	0.0 a	2,180 a
Clodinafop	60	0.5 a	0.0 a	2,520 a
Saflufenacil	24.5	12.0 c	0.0 a	2,384 a
Pyroxsulam	18	3.3 b	0.0 a	2,348 a
Atrazine/mesotrione	100/10	15.0 d	10.0 c	1,079 b
Triclopyr	480	10.8 c	3.0 b	1,954 a
Mean		6.6	1.9	2,148
CV (%)		28.5	38.4	12.6

¹ Rates at a.e. ha^{-1} for 2,4-D and triclopyr. Means followed by the same letter in the rows do not differ according to the Scott-Knott test at 5 % of probability.

emergence application in the crop and considered selective may, in some situations, cause visual injury to plants, or reduce yield. Zargar et al. (2019) reported a 5-20 % lower wheat yield with 2,4-D (360 g a.e. ha^{-1}) and 14-28 % for pyroxsulam (150 g a.i. ha^{-1}), in two growing seasons.

The contrast in herbicide selectivity, depending on the study, may be related to climate, crop development phase, dose, location or type of herbicide action, combination with other products or interaction among these factors. The degradation/metabolization of molecules in wheat occurs fast, reducing the occurrence of crop damage (Roman et al. 2005). However, at more advanced growth stages or under unfavorable conditions, such as low rainfall, this capacity is affected, and damage to the crop may occur, even with the application of selective products.

In addition to these factors, applying herbicides combined with insecticides or fungicides may exacerbate any injury. Viecelli et al. (2019) observed a decrease in wheat plant yield with herbicide application, for 2,4-D and pyroxsulam, in combination with the insecticide chlorpyrifos, in relation to the application of herbicides alone. Hooker et al. (2018) observed that herbicides, including 2,4-D, exhibited an increase in potential injury and a decrease in wheat yield when applied in combination with insecticides and/or fungicides. Adverse conditions, such as water stress, or the application of other pesticides that affect the optimal development of wheat plants could aggravate injury, even for the application of selective herbicides.

For the atrazine/mesotrione application, there was an obvious potential for injury. Both the experiments showed a decrease in yield, especially in E1, combined with saflufenacil. The isolated or combined application of atrazine and mesotrione is commonly used to control weeds in maize (Matte et al. 2018), with selectivity for the crop (Giraldeli et al. 2019). However, this was not observed in the wheat crop of the present study. For mesotrione alone in post-emergent wheat, Soltani et al. (2011) found yield decreases of up to 14 %, but the pre-emergence application of this herbicide did not cause significant yield losses (Soltani et al. 2011, Soltani et al. 2014).

The knowledge of the effects of different products and/or combinations has made it possible to increase weed management options in wheat crops. In the case of saflufenacil, although this product displayed injury, its use in pre-sowing desiccation cannot be ruled out (Soltani et al. 2015) in the management of difficult-to-control plants.

In wheat crop, applying herbicides in the tillering phase tends to result in a better recovery from injury (when it occurs) (Piasecki et al. 2017). Thus, some herbicide treatments may have produced less recovery during water stress when applied at the end of tillering (stage 5), in E1. As such, it is essential to consider the conditions of the years, which were atypical in this experiment, meaning that the effect of some treatments may have been intensified. The recovery of the crop with the application of herbicides in the vegetative phase tends to be better in years with adequate rainfall, as observed in E2, demonstrating the need for more studies focused on the agroclimatic conditions of the growing season, cultivars and application stage.

CONCLUSIONS

1. The post-emergence application at the final tillering stage for the herbicides diclofop and iodosulfuron is selective for the wheat crop, maintaining yield even under the water stress conditions of the experiment 1. Under the same conditions, applying 2,4-D, clodinafop, saflufenacil, pyroxsulam, atrazine/mesotrione, triclopyr and saflufenacil + atrazine/mesotrione reduced the wheat yield, with different injury levels;
2. With the higher water availability in the experiment 2, the post-emergence application of 2,4-D, clodinafop, saflufenacil, pyroxsulam and triclopyr at the end of tillering was selective for the wheat crop, with no negative effect on yield. Applying atrazine/mesotrione showed a high injury potential, with a decrease in yield.

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