Universidade Federal Rural do Semi-Árido
Pró-Reitoria de Pesquisa e Pós-Graduação
https://periodicos.ufersa.edu.br/index.php/caatinga
ISSN 1983-2125 (online)

http://dx.doi.org/10.1590/1983-21252025v3811681rc

Scientific Article

Pre-emergent herbicide screening for wheat

Seleção de herbicidas pré-emergentes para o trigo

Celso A. S. Teixeira[1], Ana P. W. Witter[1]*, Luiz A. I. Ferreira[1], Ana K. S. Sanches[1], Rubem S. de Oliveira Junior[1], Denis F. Biffe[1]

[1]Department of Agronomy, Universidade Estadual de Maringá, Maringá, PR, Brazil.

ABSTRACT - Weed control is a challenge in crop management due to the limited number of registered herbicides, especially for pre-emergent application. This study aimed to investigate the selectivity of pre-emergent herbicides with different mechanisms of action for wheat. The experiment consisted of two stages: the first involved screening under greenhouse conditions, and the second assessing the selected treatments under field conditions, with a focus on crop yield. Plant phytointoxication, crop stand, and shoot dry weight were assessed in the greenhouse experiment, and tillering, crop stand, plant height, canopy closure, yield, 1000-grain weight, and hectoliter weight in the field. Under greenhouse conditions, [imazapic + imazapyr], pendimethalin, isoxaflutole, florpyrauxifen, and halosulfuron-methyl produced the best results and were selected for the field experiment. Florpyrauxifen was the only herbicide that was selective both in greenhouse and field experiments. Isoxaflutole and trifluralin did not damage wheat in any of the field evaluations. Despite reducing crop performance in some assessments, pendimethalin and flumioxazin provided yield, hectoliter weight, and 1000-grain weight results equivalent to the herbicide-free control. Florpyrauxifen (1.08 g ha^{-1}) was the most promising herbicide. Trifluralin (900 g ha^{-1}), pendimethalin (1750 g ha^{-1}), isoxaflutole (60 g ha^{-1}), and flumioxazin (40 and 60 g ha^{-1}) also produced grain yields equivalent to the control without herbicide.

Keywords: Phytointoxication. Mechanisms of action. Tolerance. *Triticum aestivum.*

RESUMO - Uma das dificuldades encontradas no manejo da cultura é o controle de plantas daninhas, pois existem poucas opções de herbicidas registrados, principalmente em pré-emergência. O objetivo deste estudo foi investigar a seletividade dos herbicidas pré-emergentes com diferentes mecanismos de ação para a cultura do trigo. Os experimentos foram divididos em duas etapas: na primeira, foi realizada uma seleção preliminar em casa de vegetação e na segunda, os tratamentos selecionados foram avaliados em campo, visando principalmente a produtividade da cultura. Em casa de vegetação foram avaliadas a fitointoxicação, o estande e a massa seca da parte aérea. Em condições de campo, foram avaliados o estande, o perfilhamento, a altura das plantas, o fechamento do dossel, o rendimento, a massa de mil grãos e o peso hectolitrico. Em estufa, [imazapic + imazapyr], pendimethalin, isoxaflutole, florpyrauxifen e halosulfuron-methyl apresentaram os melhores resultados e foram selecionados para os experimentos em condições de campo. O florpyrauxifen foi o único herbicida que se destacou positivamente na estufa e nas experiências de campo. Isoxaflutole e trifluralin não prejudicaram a cultura em nenhuma das avaliações de campo. Pendimethalin e flumioxazin, embora tenham reduzido o desempenho da cultura em algumas avaliações, forneceram resultados em rendimento, peso de hectolitros e mil massa de grãos equivalente ao controle. Florpyrauxifen (1,08 g ha^{-1}) foi o herbicida mais promissor. Trifluralin (900 g ha^{-1}), pendimethalin (1750 g ha^{-1}), isoxaflutole (60 g ha^{-1}) e flumioxazin (40 e 60 g ha^{-1}) apresentaram um rendimento de grãos equivalente ao controle sem herbicida.

Palavras-chave: Fitointoxicação. Mecanismos de ação. Tolerância. *Triticum aestivum*.

Conflict of interest: The authors declare no conflict of interest related to the publication of this manuscript.

Received for publication in: January 26, 2023.
Accepted in: July 9, 2024.

***Corresponding author:**
<anapaulawerkhausenwitter@gmail.com>

INTRODUCTION

Wheat (*Triticum aestivum* L.) is one of the main cereals produced worldwide, with a harvested area of about 221 Mha in 2021 and final production of 770 Mt. Asia and Europe account for almost 80% of global wheat production and the Americas less than 13%. Despite its continental area of arable land, Brazil is only the 16th largest producer, with approximately 2.75 Mha and 7.87 Mt in 2021 (FAO, 2023). Sustainable wheat production is considered critical to meeting global food security needs due to its importance as a significant source of starch, energy, and components that are essential or beneficial for health, such as protein, B vitamins, dietary fiber, and phytochemicals (SHEWRY; HEY, 2015).

The major wheat-producing areas in Brazil are concentrated in the South and Central-South, with Paraná state the leading producer, especially the southern and southeastern areas. The main challenges preventing wheat expansion to the central region of the country are the lack of adapted varieties and the limited chemical tools available for weed control in the typically large cultivated areas of the Cerrado.

Pre-emergent herbicides are an important tool in weed control. Herbicides applied before weed emergence are known as pre-emergents and offer a competitive advantage to agricultural crops, since they enable weeds to be controlled before they can compete with the crop for environmental resources.

However, herbicide selection involves several factors, including the target weeds, application time and costs, and especially resistant weeds, which are increasing rapidly (RIEMENS et al., 2022; SWAN et al., 2023).

Expanding the range of pre-emergent herbicides compatible with wheat cultivation is vital for proper phytosanitary management of the crop and the wheat-soybean succession system common in the region. This is because combining pre-and post-emergent herbicides can broaden the spectrum of weed species controlled and increase the range of mechanisms of action facilitating the implementation of one of the main resistance management strategies, namely associating or alternating herbicides with different sites of action (MONQUERO et al., 2011).

When prospecting for new herbicides, molecules that are less phytotoxic to the crop of interest (selective) should be prioritized to prevent damage that could compromise plant development and productivity (ASSUNÇÃO et al., 2017). Thus, the influence of potential pre-emergent herbicides on wheat performance should be evaluated before researching weed control efficacy (MONQUERO et al., 2011).

Considering that the lack of chemical control alternatives hinders weed management and, consequently, limits the expansion of wheat cultivation, this study aimed to evaluate the selectivity of new pre-emergent herbicide alternatives for wheat.

MATERIAL AND METHODS

Two experiments were carried out. The first was conducted in a greenhouse to preliminarily select pre-emergent herbicides for wheat. The most promising herbicides in this first round were then applied in a field experiment to validate their effect on wheat until the grain production phase.

In both cases, treatments consisted of pre-emergent herbicides with different mechanisms of action, applied using a CO_2-pressurized backpack sprayer equipped with Teejet ST 110.015 flat fan nozzles, under a pressure of 2.1 kgf cm^{-2} at a flow rate of 150 L ha^{-1}. Nozzles were positioned 0.5 m from the soil surface during applications, both in the greenhouse and the field. Applications were carried out on May 2 (greenhouse) and May 30 (field), 2019.

Greenhouse experiments

Herbicide screening was conducted in a greenhouse located at the Universidade Estadual de Maringá Irrigation Technology Center (23º23’45’’S and 51º57’03’’W, altitude of 560 m) in Maringá, Paraná state (PR), Brazil. To that end, portions of the 0-20 cm layer of clayey agricultural soil classified as Typical Dystroferric Red Latosol (SANTOS et al., 2018) were collected, homogenized, sieved, and placed in plastic pots (5 dm^3). The main physicochemical characteristics of the soil were sand = 33.3%; clay = 50.3%; silt = 16.4%; pH ($CaCl_2$) = 5.2; CEC = 8.63 cmol$_c$ dm^{-3} and organic matter = 2.6%.

The experiment was installed on May 2, 2019, in a completely randomized design, with twenty treatments (19 herbicides and one herbicide-free control) and four replications. Treatments (and respective doses in a.i. ha^{-1}) were control (no herbicide); [imazapyr + imazapic] [78.75 + 26.25]; pendimethalin (1750); clomazone (800); metribuzin (480); atrazine (2000); isoxaflutole (60); s-metolachlor (1920); sulfentrazone (400); pyroxasulfone (40); flumioxazin (40 and 60); propisochlor (2520); [imazethapyr + flumioxazin] [100 +50]; trifluralin (1800 and 2250); florpyrauxifen (1.08); halosulfuron-methyl (112.5) and indaziflam (15).

Each experimental unit consisted of a pot containing ten wheat (cv. Tbio Toruk) seeds sown at a depth of 3 cm. After sowing, the pots were uniformly irrigated and the herbicides applied at the previously described doses, at a temperature of 28°C, 57% relative humidity, wind speed of 5 km h^{-1}, with moist soil and no clouds.

The effect of the herbicides on wheat was evaluated at 7, 14 and 21 days after sowing and application (DAS) based on the number of live plants per pot and wheat phytointoxication (assessed on a visual percentage scale, where zero indicates no symptoms and 100% plant death). The shoots were removed at 21 DAS and dried by forced air-circulation at 60° C wheat biomass measurement (g pot^{-1}).

The data collected were tested for Hartley homogeneity of variance and then submitted to analysis of variance at 5% probability. When the effects were significant, means were compared by the Scott-Knott clustering test ($p \leq 0.05$) (SCOTT; KNOTT, 1974).

Field experiment

The experiment was conducted at the Cocamar Cooperative Technology Diffusion Unit (23°35’35’’S and 52° 04’11’’W, altitude of 385m), located in Floresta - PR. The soil in the experimental area had the following physicochemical properties: sand =19.5%; clay = 65.5%; silt = 15%; pH ($CaCl_2$) = 4.5; CEC = 11.06 cmol$_c$ dm^{-3} and organic matter = 2.3%.

The climate in the region of the field experiment is classified as Cfa (wet mesothermal, with a dry winter and abundant rainfall and high temperatures in summer) according to the Köppen classification (CAVIGLIONE et al., 2000), and the soil as typical Dystroferric Red Latosol (SANTOS et al., 2018). Figure 1 illustrates rainfall and temperature during the field experiment.

Before sowing, the area was desiccated with glyphosate (720 g a.e. ha^{-1}) and 2,4-D (335 g a.e. ha^{-1}). Wheat (var. Tbio Toruk) was mechanically sown on May 30, 2019, using row spacing of 0.17 m and adjusted to distribute 59 seeds m^{-1}. Base dressing consisted of 320 kg ha^{-1} of a 10-15-15 (N-P_2O_5-K_2O) fertilizer and topdressing (stage V3) 50 kg ha^{-1} of urea. The plots were composed of thirteen 5-meter-long rows, disregarding 0.5 m along the border for the study area. Weeds were controlled by manual weeding until the crop canopy provided complete soil cover, since the aim was to assess selectivity for wheat and whether the weeds caused negative effects on the crop.

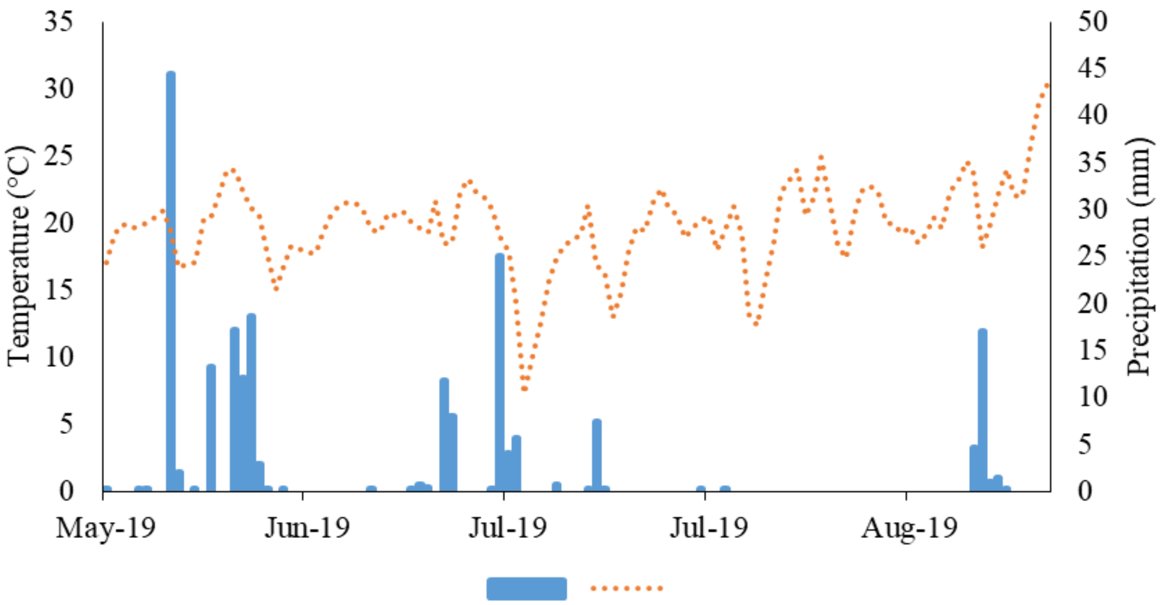

Figure 1. Average rainfall and temperature from 01/05/2019 to 09/09/2019. Floresta, PR, Brazil. Sowing in the field was carried out on 30/052019 and harvesting on 09/09/2019, totaling water availability of 222 mm.

The experiment was completely randomized, with 11 treatments (10 herbicides + one manually weeded control with no herbicide application) and four replications. Treatments with the respective herbicides and doses (g a.i. ha^{-1}) were as follows: control; [imazapyr + imazapic] ([78.75 +26.25]); pendimethalin (1750); isoxaflutole (60); pyroxasulfone (40); flumioxazin (40 and 60); [imazethapyr + flumioxazin] ([100 +50]); trifluralin (900); florpyrauxifen (1.08) and halosulfuron -methyl (112.5).

Herbicides were applied on May 30, 2019, at a temperature of 24°C, 55% relative humidity, average wind speed of 5 km h^{-1}, with dry soil and no clouds, using the same equipment, pressure and flow rate previously described for the greenhouse experiment.

The variables analyzed were crop stand, tillering, plant height, canopy closure between rows, grain yield, and yield components. The crop stand was counted at 14 DAS, based on the average number of plants per linear meter in two 1-meter-long sections of the two center rows of each plot. Tillering was assessed at 14 and 28 DAS by counting the number of tillers in two 1-meter-long samples from the two center rows of each plot. Plant height was measured at 85 DAS in 10 plants per plot, from the two center rows. Canopy closure was visually assessed at 28, 42 and 56 DAS on a scale from 0 to 100% scale, where 0 indicates no soil cover and 100% complete soil cover.

To evaluate the effect of treatments on grain yield, a 6.12 m^2 area in the center of each plot was harvested using an automatic plot harvester (Wintersteiger Classic) and weighed on a precision scale. The resulting weight was corrected to 13% moisture (BRASIL, 2009) and grain yield expressed in kg ha^{-1}. The 1000-grain weight was obtained with an automatic seed counter (Automatic Seed Counter), and represents the sum of the weight of two samples per plot containing 500 grains. Hectoliter weight was determined by weighing a known volume of seeds (225 mL) on an Agrologic Al-101 electronic scale, and the results expressed in kg hL^{-1} (BRASIL, 2009).

The data were tested for Hartley homogeneity of variance and then submitted to analysis of variance at 5% probability. When the effects were significant, the means were compared by the Scott-Knott clustering test ($p \leq 0.05$) (SCOTT; KNOTT, 1974).

RESULTS AND DISCUSSION

Greenhouse experiments

The crop stand results indicated that treatments with s-metolachlor, pyroxasulfone, propisochlor, trifluralin (both doses) and indaziflam drastically reduced the number of emerged plants in all assessments, demonstrating poor selectivity for wheat. On the other hand, treatments with [imazapic + imazapyr], pendimethalin, isoxaflutole, florpyrauxifein-benzyl and halosulfuron-methyl maintained a plant population per pot similar to that of the herbicide-free control throughout the assessment period (Table 1).

A third class of treatments consisting of clomazone, metribuzin, atrazine, sulfentrazone, flumioxazin (both doses) and [imazethapyr + flumioxazin] produced a stand similar to that of the control at the first and or second assessment, but caused losses in the final assessment (Table 1). A possible explanation for this latter effect on wheat may be related to greater herbicide absorption by different plant structures. While trifluralin, pendimethalin and s-metolachlor are absorbed by young undifferentiated plant tissues during germination and emergence, herbicides in this third class are absorbed both via the root system (metribuzin, atrazine, sulfentrazone, flumioxazin), apical meristems, root collar, and roots (clomazone) (OLIVEIRA JR.; BACARIN, 2011).

Table 1. Wheat stand response to pre-emergent herbicide application under greenhouse conditions.

Herbicides and doses (g a.i. ha^{-1})	Stand (plants pot^{-1})		
	7 DAS	14 DAS	21 DAS
Control	8.75 a	8.75 a	8.75 a
[Imazapyr + Imazapic] [78.75 +26.25]	9.0 a	9.25 a	9.5 a
Pendimethalin (1750)	8.75 a	9.5 a	9.5 a
Clomazone (800)	10.0 a	10.0 a	6.75 b
Metribuzin (480)	9.25 a	9.25 a	6.5 b
Atrazine (2000)	10.0 a	10.0 a	6.0 b
Isoxaflutole (60)	9.75 a	10.0 a	9.75 a
S-metolachlor (1920)	0.5 c	0.75 e	0.25 d
Sulfentrazone (400)	9.0 a	2.25 d	3.75 c
Pyroxasulfone (40)	0.75 c	2.0 d	3.0 c
Flumioxazin (60)	9.5 a	8.0 b	7.5 b
Flumioxazin (40)	9.25 a	7.25 b	7.0 b
Propisochlor (2520)	0.0 c	0.25 e	0.5 d
[Imazethapyr + Flumioxazin] [100 +50]	8.75 a	8.0 b	6.25 b
Trifluralin (1800)	4.0 b	5.0 c	4.25 c
Trifluralin (2250)	0.5 c	0.5 e	0.5 d
Florpyrauxifen (1.08)	9.5 a	9.50 a	9.5 a
Halosulfuron-methyl (112.5)	9.5 a	9.75 a	9.75 a
Indaziflam (15)	0 c	2.25 e	0.25 d
F	104.87*	76.90*	33.95*
CV (%)	11.95	14.16	20.83

*Significant according to the F test ($p<0.05$).
According to the Scott-Knott clustering criterion, means followed by the same letter in the column belong to the same group ($p<0.05$).
DAS = days after sowing and application.
[ ] = formulated mixtures.

In regard to phytointoxication, conclusive results were obtained in treatments with s-metolachlor, propisochlor and indaziflam, responsible for the most serious damage to wheat, regardless of assessment time (Table 2). Florpyrauxifen was the only treatment to match the control in terms of phytointoxication, and surpassed it with respect to dry weight (Table 2). Except for this active ingredient and pendimethalin, all the treatments resulted in lower shoot dry weight than the control (Table 2). Promising results were also obtained with halosulfuron, which did not affect the crop stand and had a limited effect on crop damage and shoot biomass.

Herbicides such as s-metolachlor, pyroxasulfone, trifluralin and indaziflam have been reported as toxic to some agricultural grass species (DIAS et al., 2019). For s-metolachlor, Xu et al. (2020) reported reduced dry weight in wheat seedlings between 7 and 14 days after application, albeit with no physiological changes (chlorophyll content and antioxidant enzyme activity). The harmful effects of s-metolachlor on wheat include a decline in the taproot length of seedlings, and in the length and number of lateral roots (LIU et al., 2012). Furthermore, when applied in pre-emergence under field conditions, s-metolachlor was phytotoxic to wheat and corn, resulting in smaller plants and stand reductions of up to 50% (PIMENTEL et al., 2019).

Chowdhury et al. (2020) studied Brachiaria, rice, corn, wheat and oat and observed severe crop damage and reduced plant height and mass resulting from indaziflam, with the sensitivity of wheat demonstrating its potential for use as a bioindicator of the presence of residues of this active ingredient in the soil (DIAS et al., 2019). Irreversible phytotoxicity in wheat has also been reported for trifluralin and atrazine (CHOWDHURY et al., 2020).

In regard to sulfentrazone, detrimental effects on crops after soybean cultivation have been reported (FREITAS et al., 2014). In corn and oat, the herbicide compromised growth and grain yield, whereas in wheat its toxic effect was absent to moderate at lower doses (between 25 and 600 g a.i. ha^{-1}) and acute at higher doses (1200 g a.i. ha^{-1}). The results obtained for sulfentrazone in the present study (400 g a.i. ha^{-1}) reinforce the importance of dose as a key factor in determining wheat's susceptibility to this herbicide (DUQUE; MACIEL; SANTOS, 2020).

Table 2. Phytointoxication at three assessment times and shoot dry weight of wheat plants in response to pre-emergent herbicides under greenhouse conditions.

Herbicides and doses (g a.i. ha^{-1})	Phytointoxication (%)			Shoot dry weight (g pot^{-1})
	7 DAS	14 DAS	21 DAS	
Control	0.0 e	0.0 f	0.0 c	0.75 b
[Imazapyr + Imazapic] [78.75 +26.25]	25.0 d	23.75 e	33.75 b	0.44 d
Pendimethalin (1750)	28.75 d	21.25 e	11.25 c	0.67 b
Clomazone (800)	60.0 c	80.0 b	99.0 a	0.03 f
Metribuzin (480)	20.0 d	73.75 b	97.75 a	0.04 f
Atrazine (2000)	10.0 e	61.25 c	98.0 a	0.05 f
Isoxaflutole (60)	28.75 d	37.5 d	40.0 b	0.27 e
S-metolachlor (1920)	100.0 a	100.0 a	100.0 a	0.00 f
Sulfentrazone (400)	52.5 c	80.0 b	98.0 a	0.01 f
Pyroxasulfone (40)	0.0 e	47.5 d	87.5 a	0.01 f
Flumioxazin (60)	27.5 d	40.0 d	33.75 b	0.30 e
Flumioxazin (40)	18.25 d	32.5 d	25.0 b	0.34 e
Propisochlor (2520)	100.0 a	100.0 a	100.0 a	0.00 f
[Imazethapyr + Flumioxazin] [100 +50]	25.0 d	41.25 d	38.75 b	0.24 e
Trifluralin (1800)	13.75 e	55.0 d	38.75 b	0.13 f
Trifluralin (2250)	78.75 b	87.5 a	87.5 a	0.01 f
Florpyrauxifen (1.08)	5.0 e	0.0 f	0.0 c	0.89 a
Halosulfuron-methyl (112.5)	10.0 e	11.25 e	5.0 c	0.58 c
Indaziflam (15)	96.25 a	97.5 a	99.5 a	0.02 f
F	39.12*	37.14*	86.62*	69.02*
CV (%)	29.58	20.87	14.86	27.46

*Significant according to the F test ($p<0.05$).
According to the Scott-Knott clustering criterion, means followed by the same letter in the column belong to the same group ($p<0.05$).
DAS = days after sowing and application.
[ ] = formulated mixtures.

Clomazone damages rice in the initial growth stages, soon after application, but symptoms disappear during development (CARVALHO; CAVAZZANA; CESTARE, 2000). This same behavior has also been observed in other cereals such as corn, oat, and rye, whereas phytointoxication was irreversible in sunflower, corn, vegetables and citrus (KARAM et al., 2003). However, unlike reports in the literature, in our study the negative effect of clomazone was observed later, in both the stand and phytointoxication assessments (Table 2). In addition to the varying sensitivity of the cereal species used in each study, a possible explanation for this difference may also be related to the experimental conditions. The clomazone dose used here was 800 g a.i. ha^{-1}, while Carvalho, Cavazzana and Cestare (2000) applied 500 g ha^{-1} and Karam et al. (2003) 62.45 to 4000 g ha^{-1} associated with a safener, which protects plants from herbicide toxicity.

Metribuzin doses from 30 to 2000 g ha^{-1} did not compromise wheat yield (cv. PBW-343), with similar behavior observed at 750 and 1000 g ha^{-1} for cv. BeniSuef (SHABA et al., 2015). By contrast, in other cultivars and that used here, the wheat plant population declined at doses of 420 and 144 g ha^{-1}, respectively (CORNELIUS; BRADLEY, 2017). Recent molecular genetic studies indicate that the susceptibility of wheat to this molecule involves metabolic responses that vary according to the cultivar (PILCHER et al., 2017). This could explain the different results reported for this active ingredient in studies with wheat, including those obtained here.

Based on the results obtained in the greenhouse experiment, the [imazapic + imazapyr], pendimethalin, isoxaflutole, florpyrauxifen and halosulfuron-methyl treatments were identified as having potential for pre-emergent use in wheat and thus selected for assessment under field conditions in the following stage. The field treatments also consisted of pyroxasulfone, flumioxazin, imazethapyr + flumioxazin and trifluralin, since some field observations indicate that they may also be promising under these conditions.

Field experiments

Corroborating the results recorded in the greenhouse, florpyrauxifen had no adverse effects on wheat in the field experiment, since the plant height, stand, number of tillers, yield, thousand-grain weight and hectoliter weight results were always similar to those of the herbicide-free control. Likewise, isoxaflutole and trifluralin did not differ from the control under field conditions, with results comparable to those of florpyrauxifen (Table 3).

Table 3. Number of tillers and canopy closure of wheat crops in response to pre-emergent herbicides.

Herbicides and doses (g a.i. ha^{-1})	Number of tillers m^{-1}		Canopy closure (%)		
	28 DAS	42 DAS	28 DAS	42 DAS	56 DAS
Control	80.00 a	94.67 a	49.17 a	69.17 a	82.50 a
[Imazapyr + Imazapic] [78,75 + 26.25]	35.00 c	43.25 d	9.17 e	17.50 e	22.50 d
Pendimethalin (1750)	84.75 a	85.33 b	51.67 a	70.00 a	85.00 a
Isoxaflutole (60)	78.00 a	95.67 a	51.67 a	65.00 a	83.33 a
Pyroxasulfone (40)	59.17 b	80.66 b	29.17 c	57.50 b	65.00 b
Flumioxazin (60)	83.42 a	84.58 b	40.83 b	57.50 b	80.00 a
Flumioxazin (40)	82.25 a	94.17 a	45.00 b	61.67 a	76.67 a
[Imazethapyr + Flumioxazin] [100 + 50]	50.00 b	64.50 c	19.17 d	37.50 d	50.83 c
Trifuralin (900)	81.08 a	101.75 a	51.67 a	65.00 a	83.33 a
Florpyrauxifen (1.08)	83.67 a	96.08 a	53.33 a	66.67 a	85.00 a
Halosulfuron-methyl (112.5)	67.58 a	79.75 b	25.83 c	51.67 c	66.67 b
F	10.90*	15.77*	37.51*	34.48*	74.21*
CV (%)	17.24	12.52	15.91	11.77	7.76

*Significant according to the F test ($p<0.05$).
According to the Scott-Knott clustering criterion, means followed by the same letter in the column belong to the same group ($p<0.05$).
DAS = days after sowing and application.
[ ] = formulated mixtures.

Although treatments with pendimethalin and flumioxazin occasionally influenced tillering, canopy closure, or plant height, wheat yield and its components (plant height - PH and 1000 grain weight – 1000GW) were unaffected. The remaining herbicides ([imazapic + imazapyr], pyroxasulfone, halosulfuron-methyl and [imazethapyr + flumioxazin]) decreased grain yield in relation to the control. The [imazapic + imazapyr] treatment was the least selective and produced the most significant yield decrease (Table 4). Halosulfuron-methyl had no effect on the crop stand, PH and 1000GW, but a minor effect on tillering. However, grain yield was 20% lower when compared to the control, likely related to limited plant growth (canopy closure and PH) (Table 4).

Table 4. Stand (14 DAS), plant height (PH), hectoliter weight (HW), 1000-grain weight (1000GW) and crop yield in response to pre-emergent herbicides.

Herbicides and doses (g a.i. ha^{-1})	Stand (plants m^{-1}) (14 DAS)	Plant Height (cm)	HW (kg hL^{-1})	1000GW (g)	Yield (kg ha^{-1})
Control	50.58 a	33.56 a	72.06 a	53.21 a	2254.61 a
[Imazapyr + Imazapic] [78,75 + 26.25]	41.83 b	21.70 d	44.97 c	22.31 c	343.97 d
Pendimethalin (1750)	48.75 a	34.8 a	70.9 a	53.77 a	2418.89 a
Isoxaflutole (60)	53.67 a	35.93 a	71.2 a	46.86 a	2266.61 a
Pyroxasulfone (40)	36.33 c	30.1 b	69.03 b	39.64 b	1706.86 b
Flumioxazin (60)	48.33 a	33.8 a	71.5 a	54.65 a	2125.66 a
Flumioxazin (40)	47.92 a	32.88 b	72.07 a	50.28 a	2226.03 a
[Imazethapyr + Flumioxazin] [100 + 50]	44.5 b	27.68 c	66.1 b	34.11 b	1069.66 c
Trifuralin (900)	46.0 a	34.03 a	70.57 a	51.97 a	2399.91 a
Florpyrauxifen (1.08)	48.41 a	35.97 a	72.33 a	56.31 a	2344.73 a
Halosulfuron-methyl (112.5)	50.58 a	32.58 b	70.96 a	51.52 a	1761.9 b
F	5.39 *	18.76*	36.11*	23.65*	30.13*
CV (%)	10.66	7.44	4.74	11.36	15.39

*Significant according to the F test ($p<0.05$).
According to the Scott-Knott clustering criterion, means followed by the same letter in the column belong to the same group ($p<0.05$).
DAS = days after sowing and application.
[ ] = formulated mixtures.

The results obtained here for treatments with [imazapic + imazapyr] and [imazethapyr + flumioxazin] are similar to those reported by Galon et al. (2015), who also observed their detrimental effect on wheat, with damage to seedlings and reduced yield. For halosulfuron-methyl, laboratory studies using low doses labeled with radioactive isotopes demonstrated that the tolerance provided by rapid detoxification of this molecule by plant tissues enabled wheat cell suspensions to metabolize this active ingredient (DUBELMAN et al., 1997). However, the significant effects on wheat growth at the dose used in our study (112.5 g ha^{-1}) suggest that selectivity may be limited by the dose or by interactions between soil properties and herbicides, which control herbicide availability to crops.

Of the herbicides studied, florpyrauxifen produced the most relevant positive results in both the greenhouse and field experiments. Since it is a relatively new molecule, most research has focused on weed control and characterizing its chemical properties (WRIGHT et al., 2020). In rice, florpyrauxifen is considered a selective option with no effect on yield (WRIGHT et al., 2020), which some authors attribute to rice's ability to metabolize the active ingredient into non-toxic molecules (WRIGHT et al., 2020). In theory, this may explain the promising results obtained in the present study with wheat, another species from the Poacea family. Since florpyrauxifen has very low water solubility and high soil sorption (S = 0.011 mg L^{-1} and Koc = 32308 - ARENA et al., 2018), another explanation for the wheat selectivity observed may be its limited mobility in the soil profile.

In regard to the other treatments that were also equivalent to the control in grain yield, for pendimethalin (a molecule registered in some countries as a pre-emergent in wheat), selectivity is conferred by its position in the soil position (SANTOS et al., 2011). The selectivity of flumioxazin for wheat seems to be based on plant metabolism, with simultaneous and synergistic mechanisms acting as differential transport, enzymatic overexpression, and/or compartmentalization of the molecule (ASSUNÇÃO et al., 2017).

According to the literature, trifluralin can compromise wheat establishment, evident in the greenhouse results obtained (Table 1). However, a recent study suggests that, despite emergence delays, soil trifluralin concentrations of 0.15 mg kg^{-1} did not affect wheat establishment (CHOWDHURY et al., 2020), which could explain the favorable results observed with this treatment in the field assay (Table 2). A more plausible explanation is that like pendimethalin, trifluralin has low solubility and high sorption to soil particles, which, in theory, may have favored position selectivity.

Isoxaflutole is also promising in wheat. Once applied to the soil, it is converted into diketonitrile, a more stable and more persistent compound than isoxaflutole that is effectively responsible for weed control (CAVALIERI et al., 2008). Based on selectivity studies with grass crops such as corn and sugarcane, it is reasonable to suggest that the good wheat performance observed here may be related to the ability of the species or cultivar analyzed to rapidly metabolize diketonitrile into benzoic acid, which has no herbicidal action (CAVALIERI et al., 2008).

In addition to the factors previously mentioned, all the herbicides that produced yield similar to that of the control exhibit low water solubility (florpyrauxifen, trifluralin, pendimethalin, isoxaflutole and flumioxazin) (Table 1). This also helps explain the yields obtained in these treatments, since a larger volume of water is needed to dissolve herbicides with limited solubility, which can result in lower or slower availability in the soil solution, thus reducing its potential for absorption by the crop (PRATA; LAVORENTI, 2000).

This study demonstrated different effects of herbicides on wheat grown in greenhouse and field environments. Florpyrauxifen stood out as a promising option, exhibiting effectiveness with no significant adverse effects on parameters such as plant height, crop stand, tillering, yield, and grain traits.

However, limitations were identified, especially in the [imazapic + imazapyr], pyroxasulfone, halosulfuron-methyl, and [imazethapyr + flumioxazin] treatments, which resulted in lower yields. Future studies should investigate the underlying mechanisms of these differential effects. Furthermore, the pursuit of integrated management strategies aimed at optimizing herbicide effectiveness while minimizing negative effects on yield is relevant in sustainable and effective agricultural practices. Additionally, research should explore wheat responses to different environmental conditions, such as soil texture, leaching, and herbicide interaction with soil organic matter and pH, in order to ensure a more comprehensive approach to agricultural decision-making.

CONCLUSIONS

The most promising results obtained were for florpyrauxifen (1.08 g ha^{-1}), the only herbicide that did not compromise wheat performance in the greenhouse or field experiments. Despite occasional phytotoxic effects, especially under greenhouse conditions, trifluralin (900 g ha^{-1}), pendimethalin (1750 g ha^{-1}), isoxaflutole (60 g ha^{-1}) and flumioxazin (40 and 60 g ha^{-1}) also showed potential for use in wheat, since they produced grain yields equivalent to those of the control and florpyrauxifen.

REFERENCES

ARENA, M. et al. Peer review of the pesticide risk assessment of the active substance florpyrauxifen (variant assessed florpyrauxifen-benzyl). **EFSA Journal**, 16: 1-21, 2018.

ASSUNÇÃO, N. S. et al. Selectivity of flumioxazin to wheat. **Revista Brasileira de Herbicidas**, 16: 122-129, 2017.

BRASIL. Ministério da Agricultura, Pecuária e Abastecimento. **Rules for seed analysis**. Brasília, DF: Mapa/ACS, 2009. 399 p.

CARVALHO, F. T.; CAVAZZANA, M. A.; CESTARE, M. A. Efficacy of herbicides in weed pre-emergence control in rice crop. **Revista Brasileira de Herbicidas**, 1: 213-218, 2000.

CAVALIERI, S. D. et al. Tolerance of corn hybrids to isoxaflutole. **Planta Daninha**, 26: 901-909, 2008.

CAVIGLIONE, J. H. et al. **Cartas Climáticas do Paraná**

Versão 1.0. (CD ROM). Londrina, PR: IAPAR, 2000.

CHOWDHURY, I. F. et al. Trifluralin and atrazine sensitivity to selected cereal and legume crops. **Agronomy**, 10: 1-16, 2020.

CORNELIUS, C. D.; BRADLEY, K. W. Carryover of common corn and soybean herbicides to various cover crop species. **Weed Technology**, 31: 21-31, 2017.

DIAS, R. C. et al. Selection of bioindicator species for the herbicide indaziflam. **Revista Brasileira de Herbicidas**, 18: 1-11, 2019.

DUBELMAN, A. M. et al. Metabolism of halosulfuron-methyl by corn and wheat. **Journal of Agricultural and Food Chemistry**, 45: 2314-2321, 1997.

DUQUE, T. S.; MACIEL, J. C.; SANTOS, J. B. Potencial de *Triticum aestivum* como bioindicadora de herbicidas em solos contrastantes. **Revista Vozes dos Vales**, 18: 1-18, 2020.

FAO - Food and Agriculture Organization of the United Nations. **FAOSTAT**. Available at: https://www.fao.org/faostat/en/#data/QCL/visualize. Access on: Jan. 13, 2023.

FREITAS, M. A. et al. Sulfentrazone sorption in different soil types determined by bioassays. **Planta Daninha**, 32: 385-392, 2014.

GALON, L. et al. Eficácia e fitotoxicidade de herbicidas aplicados para manejo de plantas daninhas infestantes do trigo. **Revista Brasileira de Herbicidas**, 14: 128-140, 2015.

KARAM, D. et al. Maize crop selectivity to clomazone herbicide using dietholate. **Revista Brasileira de Milho e Sorgo**, 2: 72-79, 2003.

LIU, H. et al. Enantioselective phytotoxicity of metolachlor against maize and rice roots. **Journal of Hazardous Materials**, 217-218: 330-337, 2012.

MONQUERO, P. A. et al. Selectivity of herbicides in varieties of sugarcane. **Bragantia**, 70: 286-293, 2011.

OLIVEIRA JR., R. S.; BACARIN, M. A. Absorption and translocation of herbicides. In: OLIVEIRA Jr, R. S. et al. (Eds.). **Weed biology and management**. Curitiba, PR: Omnipax, 2011. v. 1, cap. 7, p. 141-192.

PILCHER, W. et al. Genome-wide microarray analysis leads to identification of genes in response to herbicide, metribuzin in wheat leaves. **PLoS ONE**, 12: 1-12, 2017.

PIMENTEL, G. V. et al. Selectivity and effectiveness of herbicides in the grain sorghum crop. **Planta Daninha**, 37: 1-10, 2019.

PRATA, F.; LAVORENTI, A. Behavior of herbicides in soil: influence of organic matter. **Revista Biociência**, 6: 17-22, 2000.

RIEMENS, M et al. An Integrated Weed Management Framework: A pan-European perspective. **European Journal of Agronomy**, 133: 126443, 2022.

SANTOS, G. et al. Position selectivity of herbicides to cotton crop. **Revista Brasileira de Herbicidas**, 10: 95-102, 2011.

SANTOS, H. G. et al. **Sistema brasileiro de classificação de solos**. Rio de Janeiro, RJ: EMBRAPA, 2018. 306 p.

SCOTT, A. J.; KNOTT, M. A. Cluster Analysis method for grouping means in the analysis of variance. **Biometrics**, 30: 507-512, 1974.

SHABA, S. A. et al. Effect of some maize herbicides on weeds and yield and residual effect on some following crops (wheat and broad bean). **American-Eurasian Journal of Agricultural & Environmental Sciences**, 15: 1004-1011, 2015.

SHEWRY, P. R.; HEY, S. J. The contribution of wheat to human diet and health. **Food Energy Security**, 4: 178-202, 2015.

SWAN, D. et al. Diverse systems and strategies to cost-effectively manage herbicide-resistant annual ryegrass (*Lolium rigidum*) in no-till wheat (*Triticum aestivum*)-based cropping sequences in south-eastern Australia. **Crop and Pasture Science**, 74: 809-827, 2023.

WRIGHT, H. E. et al. Characterization of rice cultivar response to florpyrauxifen-benzyl. **Weed Technology**, 34: 1-11, 2000.

XU, N. et al. Effects of residual S-metolachlor in soil on the phyllosphere microbial communities of wheat (*Triticum aestivum* L.). **Science of the Total Environment** , 748: 1-7, 2020.