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Selectivity and efficacy of herbicides used on wheat to control ryegrass

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ABSTRACT: Weeds, especially ryegrass (*Lolium multiflorum*), interfere with and at the same time reduce the productivity and grain quality of wheat. The objective of this study was to evaluate the selectivity and efficacy of pre-emergent herbicides used in combination with post-emergent herbicides on wheat to control ryegrass. Two experiments were conducted in a randomized block design with four replicates, one to check selectivity and the other to assess ryegrass control. The variables evaluated were: herbicide phytotoxicity to wheat, ryegrass control, number of ears per area, hectolitre weight, thousand-grain mass and grain yield. The results indicate that pinoxaden showed low phytotoxicity to the crop and high control of ryegrass. S-metolachlor showed phytotoxicity, increasing with higher doses. The application of S-metolachlor + pinoxaden (480 + 40 g ha^{-1}) resulted in the highest grain yield for the TBio Duque and TBio Sossego wheat cultivars. The use of pinoxaden in isolation shows better performance of the grain yield components of the TBio Duque and TBio Sossego wheat cultivars.

Key words: *Lolium multiflorum*; pinoxaden; S-metolachlor; *Triticum aestivum*

Seletividade e eficácia de herbicidas usados em trigo para controle de azevém

RESUMO: As plantas daninhas, especialmente o azevém (*Lolium multiflorum*), ocasionam interferência e ao mesmo tempo reduzem a produtividade e a qualidade de grãos do trigo. Diante disso, objetivou-se avaliar a seletividade e a eficácia da aplicação de herbicidas pré-emergentes associados ou não a pós-emergentes na cultura do trigo para controle de azevém. Foram conduzidos dois experimentos em delineamento de bloco casualizados, com quatro repetições, um para verificar a seletividade e o outro para avaliar o controle do azevém. As variáveis avaliadas foram: fitotoxicidade dos herbicidas ao trigo, controle de azevém, número de espigas por área, peso hectolitro, massa de mil grãos e produtividade de grãos. Os resultados indicam que o pinoxaden demonstrou baixa fitotoxicidade à cultura e elevado controle do azevém. O S-metolachlor apresentou fitotoxicidade, aumentando de acordo com o incremento da dose aplicada. A aplicação de S-metolachlor + pinoxaden (480 + 40 g ha^{-1}) ocasiona a maior produtividade de grãos às cultivares de trigo TBio Duque e TBio Sossego. O uso do pinoxaden em isolado demonstra melhor desempenho dos componentes de rendimento de grãos das cultivares de trigo, TBio Duque e TBio Sossego.

Palavras-chave: *Lolium multiflorum*; pinoxaden; S-metolachlor; *Triticum aestivum*

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Introduction

Several factors can influence wheat productivity, such as the cultivar chosen, the technological level adopted, environmental and soil conditions, as well as interference from weeds (Van Der Meulen & Chauhan, 2017). Weeds compete with crops for environmental resources such as nutrients, water, light and space and, when left unchecked, cause losses in the quality and quantity of grain produced (Lamego et al., 2013; Galon et al., 2019; Tavares et al., 2019). They can also release allelopathic substances and become hosts for insects and diseases (Mariani et al., 2016). It is estimated that weeds are capable of reducing grain yields by 18 to 82%, as well as increasing production costs and reducing the profit of the triticulturist (Lamego et al., 2013; Gharde et al., 2018; Galon et al., 2019; Balem et al., 2021).

There are various methods for controlling weeds, the most widely used being chemical control using herbicides, due to their ease, effectiveness and low cost compared to other forms of management (Mariani et al., 2016; Piasecki et al., 2017). The difficulty in controlling post-emergence weeds in the wheat crop is mainly due to the fact that many species are resistant to registered herbicides, as is the case with turnip and ryegrass (Costa & Rizzardi, 2014; Mariani et al., 2016; Heap, 2024).

The most competitive weeds for resources in a field are usually those that belong to the same botanical family as the crop, as they have similar resource requirements (Lamego et al., 2015). Therefore, losses caused by ryegrass (*Lolium multiflorum*) when left unchecked can reduce grain yield and quality (Balem et al., 2021; Galon et al., 2023). In addition, these plants are often used as winter cover or forage species and therefore leave a large seed bank in the soil for natural reseeding (Lamego et al., 2013; Lamego et al., 2015; Galon et al., 2019).

Ryegrass is an annual grass that is considered to be quite hardy, aggressive, tillers abundantly and is easily adapted to climatic variations. It is most commonly grown in Rio Grande do Sul state, Brazil, where it is used mainly to form pastures and in consortium with other species (Sune et al., 2020).

Ryegrass competition reduced the height of wheat plants by more than 36% when in competition, and also reduced the number of tillers, which consequently caused damage to grain yield, this result being linked to the shading that the weed caused to the crop (Lamego et al., 2015; Galon et al., 2023).

Among the ACCase (Acetyl Coenzyme-A Carboxylase) inhibiting herbicides that can be used to control weeds in wheat, pinoxaden stands out, discovered by Syngenta Crop Protection (Basel, Switzerland). This herbicide was recently launched in Brazil and is the only one in the family represented by the chemical group phenylpyrazolines - DENs (Tang et al., 2014). It is a selective herbicide applied post-emergently to control grasses in cereal crops (Leon, 2019; Agrofit, 2024) and was introduced globally in 2006 under the Axial™ trademark.

The recommended doses of pinoxaden are 30 to 60 g ha^{-1}, acting to control a wide range of important weed species, such as *Alopecurus myosuroides*, *Avena strigosa*, *Lolium multiflorum*, and *Setaria* spp. (Basak et al., 2020; Agrofit, 2024). Due to its activity on a broad spectrum of weeds, pinoxaden has been indicated for weed control in cereal crops, including wheat and barley (Basak et al., 2020; Agrofit, 2024).

Although pinoxaden has been on the world market for a long time, it was only recently registered for use in Brazil. There are therefore few studies involving this herbicide, especially in the Southern region of the country, which has a climate and soils that are different from other wheat-growing areas in Brazil. These factors can interfere with the control effect of the product in relation to ryegrass and black oats (species registered for control), winter crop weeds.

Another selective herbicide recently recommended for use in pre-emergence for weed control in wheat was S-metolachlor (Agrofit, 2024). This product is mainly absorbed by the coleoptile and hypocotyl of monocotyledonous and dicotyledonous plants, respectively. The visible signs and symptoms of the effect are characterized by hardening of the tissues and retraction of the stems in monocots. In dicotyledons, however, chlorosis, necrosis of plant tissues and plant death can be seen slowly and gradually, and this process often takes place even before the first germination flows from the plant onto the soil surface (Quintaneiro et al., 2017). S-metolachlor inhibits cell division and mitosis by interfering with a series of enzymes, thus acting as a pre-emergent in different weed species, preventing their emergence, as well as preventing the formation of long-chain fatty acids (Rose et al., 2016).

In Brazil, S-metolachlor is registered for various weed species, the most targeted being those belonging to the Poaceae family (*Digitaria insularis*, *Urochloa plantaginea*, *Digitaria ciliares*, and *Eleusine indica*) and species that are difficult to control and have proven resistance to other herbicides, such as *Amaranthus hybridus* and *Echinochloa crusgalli* (Heap, 2024).

When applied to crops, herbicides can have direct or indirect effects on plant growth and development, causing changes in physiological and metabolic processes, causing intoxication, deregulation of defense mechanisms, cell oxidation, changes in nutrient absorption, among others (Taylor et al., 2013; Zakariyya et al., 2022).

The use of herbicides can also cause negative interference with the grain yield components of crops or be ineffective at controlling weeds, or even cause negative impacts on agroecosystems when used incorrectly (Zakariyya et al., 2022; Galon et al., 2023).

New studies evaluating the selectivity and efficacy of herbicides are therefore important in the search for new chemical control alternatives with different mechanisms of action. Thus, in addition to controlling mainly grass species that weed wheat, the use of S-metolachlor in combination with other herbicides (pinoxaden) can make it possible

to control or even prevent the emergence of resistant biotypes.

The hypothesis of this study is that the combination of S-metochlor, applied pre-emergence, and pinoxaden, applied post-emergence to wheat, are selective to the crop and efficient in controlling ryegrass. In view of the above, the objective of this study was to evaluate the selectivity and efficacy of pre-emergent herbicides, associated or not with post-emergent herbicides, in wheat crops to control ryegrass.

Materials and Methods

The experiments were set up in the field, in the experimental area of the Universidade Federal da Fronteira Sul, Campus Erechim, RS, Brazil, at geographical coordinates 27°43'26.54"S, 52°17'42.42"W and altitude of 775 m, in the summer season of 2021. The soil in the experimental area is classified as Latossolo Vermelho Aluminoférrico húmico (Santos et al., 2018), and its pH was corrected and fertilized according to the physico-chemical analysis, following the technical recommendations for growing wheat (CQFS-RS/SC, 2016).

The chemical and physical characteristics of the soil were: pH in water of 5.1; OM = 3.0%; P = 5.2 mg dm^{-3}; K = 118.0 mg dm^{-3}; Al^{3+} = 0.3 $cmol_c$ dm^{-3}; Ca^{2+} = 5.5 $cmol_c$ dm^{-3}; Mg^{2+} = 3.0 $cmol_c$ dm^{-3}; CEC(t) = 7.4 $cmol_c$ dm^{-3}; CEC (pH = 7.0) = 16.6 $cmol_c$ dm^{-3}; H + Al = 7.7 $cmol_c$ dm^{-3}; SB = 53%; and, Clay = 60%. The weather conditions observed during the experiments are shown in Figure 1.

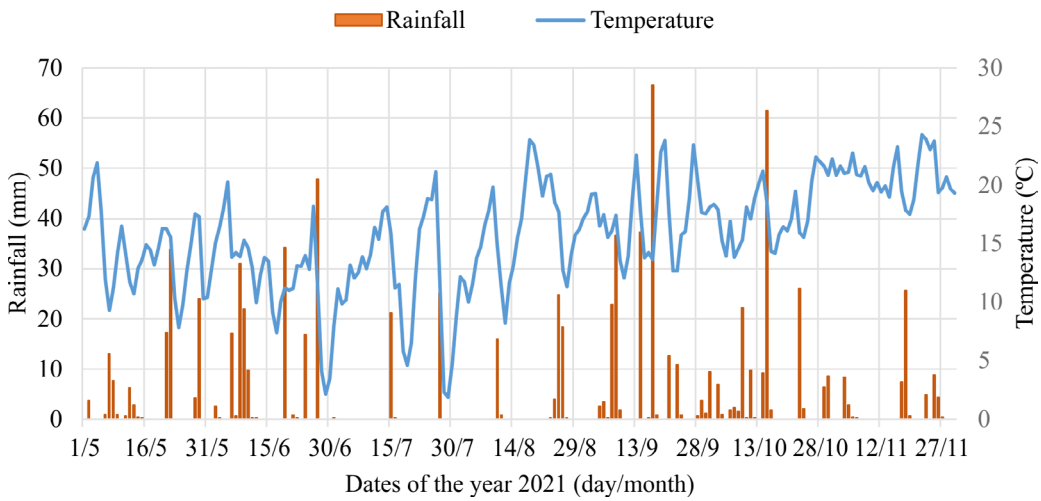
The wheat was sown in a no-till system, and 15 days before this operation the vegetation was desiccated with the herbicide diquat at a dose of 400 g ha^{-1} of active ingredient or 2 L ha^{-1} of commercial product.

Each experimental unit comprised an area of 13.60 m^2 (5 × 2.72 m), with 16 rows spaced 0.17 m apart, a sowing depth of approximately 0.035 m and a final density of around 350 plants m^{-2}. Two wheat cultivars were sown, TBio Sossego and TBio Duque. The base fertilizer used was 400 kg ha^{-1} of the 05-30-15 formula (N-P_2O_5-K_2O), and 52 kg ha^{-1} of nitrogen was applied as a top dressing, in the form of urea (45% de N – 115 kg ha^{-1}), divided into two applications, one when the wheat was beginning to tiller and the other when the internodes were elongating, according to the chemical analysis of the soil and the expected grain yield of the crop. All the other management practices used were those recommended by research for growing wheat.

Two experiments were conducted, one to check selectivity and the other to assess ryegrass control, in a randomized block design, arranged in a 2 × 11 factorial scheme, with four replicates. In both experiments, the first factor was the wheat cultivars (TBio Duque and TBio Sossego) and the second was the herbicides, as shown in Table 1.

The herbicides were applied using a CO_2-pressurized precision knapsack sprayer equipped with four DG 110.02 fan spray tips and a travel speed of 3.6 km h^{-1}, which provided a flow rate of 150 L ha^{-1} of herbicide mixture. For each season (pre- and post-emergence) when the products were applied, meteorological data and soil conditions were collected, which are described in Table 2. S-metolachlor was applied in the pre-emergence of the wheat cultivars (TBio Duque and TBio Sossego), one day after sowing the crop (plant and apply) and pinoxaden when the wheat was in full tillering.

Ryegrass was the only weed evaluated in the efficacy experiment, coming naturally from the soil seed bank at a density of 67 plants m^{-2}. The post-emergence herbicides (pinoxaden) were applied when the ryegrass had 4 leaves and 1 tiller. Evaluations of phytotoxicity to wheat and ryegrass control were carried out visually by two evaluators at 7, 14, 21, 28 and 35 days after application of the treatments (DAT). In order to assess the phytotoxicity and control provided by the herbicides, percentage scores of zero (0%) were assigned to treatments with no ryegrass control or phytotoxicity to wheat and a score of one hundred (100%) for weed control or death of the crop plants (SBCPD, 1995).



Source: INMET (2024).

Figure 1. Rainfall (mm) and average temperature (°C) during the period when the experiments were conducted, from May to November 2021.

Table 1. Treatments used in the experiments, respective doses of active ingredient (AI), commercial product (CP), application method and wheat cultivars. UFFS, Erechim-RS, Brazil.

Treatments	Doses – AI (g ha^{-1})	Doses – CP (g/L ha^{-1})	Type of application	Wheat cultivars
Weeded control	---	---	---	TBio Duque and TBio Sossego
Infested control	---	---	---	
S-metolachlor	0.48	0.50	Pre-emergence	
S-metolachlor	0.72	0.75	Pre-emergence	
S-metolachlor	0.96	1.00	Pre-emergence	
S-metolachlor	1.44	1.50	Pre-emergence	
S-metolachlor+pinoxaden	0.48 + 0.04	0.50 + 0.80	Pre + post-emergence	
S-metolachlor+pinoxaden	0.72 + 0.04	0.75 + 0.80	Pre + post-emergence	
S-metolachlor+pinoxaden	0.96 + 0.04	1.00 + 0.80	Pre + post-emergence	
S-metolachlor+pnoxaden	1.44 + 0.04	1.50 +0.80	Pre + post-emergence	
Pinoxaden	0.04	0.80	Post-emergence	

Table 2. Weather conditions recorded at the time of application of the pre- and post-emergence treatments to the wheat crop for the two experiments. UFFS, Erechim-RS, 2023, Brazil.

Time of application	Luminosity (%)	Air temperature (°C)	Soil temperature (°C)	Wind speed (km h^{-1})	Soil conditions	Relative humidity (%)
Pre-emergence	100	26	22.1	3.2	Friable	65
Post-emergence	100	22	22.4	4.6	Friable	62

The number of ears of wheat per area (0.25 m²) was determined pre-harvest and measured in the center of each experimental unit, using a PVC square measuring 0.5 × 0.5 m. After harvesting the wheat by hand and threshing it in a plot threshing machine over an area of 6.8 m², the hectolitre weight (kg hl^{-1}), thousand-grain mass (g) and grain yield (kg ha^{-1}) were determined. The hectolitre weight was determined using a Dalle Molle model 40 scale. The thousand-grain mass was measured by counting eight sub-samples of 100 grains each, weighed on an analytical scale and their average value multiplied by 10. Grain yield was then estimated and the data extrapolated to kg ha^{-1}. For the analyses, the water content of the grains was adjusted to 13%.

The data was subjected to analysis of variance, using the F test, and the residues were subjected to the normality and homogeneity of variance tests, and when a significant effect of the factors (cultivars × herbicides) was observed, the Scott-Knott test was used to identify the differences between the treatments. For the grain yield components in the two experiments (selectivity and efficacy) the wheat cultivars were not compared with each other, only the effect of the herbicides within each cultivar, because genetically they differ, making it difficult to separate what is the effect of the treatments applied or the genetic characteristics of the plants themselves. All tests were carried out at $p \leq 0.05$.

Results and Discussion

There was an interaction between the factors tested (cultivars × herbicides) for phytotoxicity (experiment I) and control (experiment II), assessed at 14, 21, 28 and 35 DAT. No phytotoxicity or ryegrass control effect was observed, i.e. there were no symptoms of herbicide damage to the wheat cultivars and the weed in the evaluation carried out at 7 DAT (data not shown). As previously reported, the response variables related to grain yield components and grain yield in the selectivity and efficacy experiments were not compared between the two wheat cultivars because they are genetically different. Therefore, the analyses of these variables were only carried out for the effect of the herbicide factor.

Herbicide selectivity experiment on wheat

The phytotoxic effect of the herbicides was seen from the 14 DAT evaluation on both wheat cultivars, as shown in Table 3. At 7 DAT, no phytotoxicity was seen, either for the increasing doses of S-metolachlor applied pre-emergence, or for use alone, as well as the association with pinoxaden, applied post-emergence. The herbicide pinoxaden, when applied post-emergence in all evaluations (14, 21, 28 and 35 DAT), did not cause phytotoxicity to the wheat cultivars (TBio Duque and TBio Sossego), demonstrating high selectivity to the crop.

Pinoxaden is a herbicide that inhibits ACCase, controlling grasses, and selectivity occurs through the action of a safener called cloquintocet mexyl, which increases the expression of xenobiotic detoxifying enzymes, such as glutathione transferases (GSTs). In addition, this safener exerts a series of protective and growth-promoting activities in wheat, as well as increasing tolerance to herbicides (Taylor et al., 2013).

In general, it can be seen that S-metolachlor caused visual phytotoxicity in the wheat crop depending on the dose and cultivar tested. As the doses of the herbicide increased, the phytotoxicity to wheat increased considerably, regardless of the cultivar in all the seasons evaluated (Table 3). Doses of S-metolachlor of 480 g ha^{-1}, combined with post-emergence applications of pinoxaden or the use of pinoxaden alone were the most selective for the crop, yet at 14 DAT there was 9.38% phytotoxicity on average for the two wheat

Table 3. Phytotoxicity (%) of herbicides applied to wheat cultivars TBio Duque and TBio Sossego. UFFS, Erechim-RS, Brazil.

Treatments	Doses (g ha^{-1})	Phytotoxicity to wheat cultivars (%)			
		Duque	Sossego	Duque	Sossego
		14 DAT[1]		21 DAT	
Weeded control	---	0.00 Ac[1]	0.00 Ad	0.00 Ae	0.00 Ae
Infested control	---	0.00 Ac	0.00 Ad	0.00 Ae	0.00 Ae
S-metolachlor	480	15.00 Ab	11.25 Ac	6.25 Ad	8.25 Ad
S-metolachlor	720	20.00 Ab	17.50 Ab	12.00 Ac	12.50 Ac
S-metolachlor	960	28.75 Aa	23.75 Aa	15.75 Ab	17.00 Ab
S-metolachlor	1440	31.25 Aa	30.00 Aa	18.75 Ba	22.00 Aa
S-metolachlor +pinoxaden	480+40	18.75 Ab	11.25 Bc	7.00 Ad	7.75 Ad
S-metolachlor +pinoxaden	720+40	23.75 Ab	18.75 Ab	13.75 Ac	11.75 Ac
S-metolachlor +pinoxaden	960+40	31.25 Aa	26.25 Aa	16.50 Bb	20.00 Aa
S-metolachlor+pinoxaden	1440+40	30.00 Aa	28.75 Aa	20.00 Aa	23.00 Aa
Pinoxaden	40	0.00 Ac	0.00 Ad	0.00 Ae	0.00 Ae
Overall average	---	16.65		19.86	
CV (%)	---	25.80		10.57	
		28 DAT		35 DAT	
Weeded control	---	0.00 Ac	0.00 Ae	0.00 Ad	0.00 Ac
Infested control	---	0.00 Ac	0.00 Ae	0.00 Ad	0.00 Ac
S-metolachlor	480	3.25 Ac	2.50 Ae	0.00 Ad	1.75 Ac
S-metolachlor	720	9.50 Ab	10.25 Ad	10.25 Bc	15.75 Ab
S-metolachlor	960	16.25 Ab	16.75 Ac	11.75 Ac	12.75 Ab
S-metolachlor	1440	21.25 Ba	31.25 Aa	22.50 Ab	24.50 Aa
S-metolachlor +pinoxaden	480+40	5.00 Ac	3.25 Ae	2.75 Ad	2.00 Ac
S-metolachlor +pinoxaden	720+40	11.75 Ab	13.75 Ac	9.50 Ac	12.25 Ab
S-metolachlor +pinoxaden	960+40	13.50 Bb	20.00 Ac	9.50 Bc	25.50 Aa
S-metolachlor+pinoxaden	1440+40	21.50 Aa	26.25 Ab	27.50 Aa	22.25 Ba
Pinoxaden	40	0.00 Ac	0.00 Ae	0.00 Ad	0.00 Ac
Overall average	---	10.27		9.57	
CV (%)	---	32.41		33.42	

[1] Averages followed by different uppercase letters in the row (for the same DAT) and lowercase letters in the column differ by the Scott-Knott test ($p < 0.05$).

cultivars (Table 3). With the exception of the application of S-metolachlor + pinoxaden (480 + 40 g ha^{-1}) in pre- and post-emergence, respectively, there was no difference in phytotoxicity between the cultivars at 14 DAT.

It was observed that the highest dose of S-metolachlor (1440 g ha^{-1}) when applied alone or in combination with pinoxaden showed the greatest phytotoxicity at 21 DAT in the two wheat cultivars in which it was used (Table 3). The results also show that the treatments involving the lowest doses of S-metolachlor applied pre-emergence in isolation or using pinoxaden post-emergence showed the lowest phytotoxicity to the TBio Duque and TBio Sossego cultivars at 21 DAT. At the same time (21 DAT), pinoxaden applied in isolation showed no phytotoxicity and was statistically equal to the weeded control, without herbicide. The selectivity of S-metolachlor to wheat occurs toponically, so that the herbicide does not reach the coleoptile node, the absorption zone. If there is contact through the use of high doses, precipitation after sowing and shallower application and/or sowing, phytotoxicity can occur, reducing the initial and final establishment of plants (Schaeffer et al., 2024). Once the herbicide has been absorbed, whether or not it is detoxified is up to the plant metabolism (Schaeffer et al., 2024).

Studies conducted by Salem & El-Sobki (2021), showed that among the herbicides tested, pinoxaden was the most phytotoxic, but this characteristic could only be observed for chlorophyll content and a significant decrease in the activity of antioxidant enzymes, regardless of the wheat cultivar evaluated.

When comparing the wheat cultivars with each other, it was observed at 21 DAT that the application of S-metolachlor (1440 g ha^{-1}) and S-metolachlor + pinoxaden (960 + 40 g ha^{-1}) showed less phytotoxicity to TBio Duque than TBio Sossego (Table 3). For all the other treatments, there was no difference in phytotoxicity between the cultivars. Wheat cultivars respond differently in terms of their ability to metabolize or degrade herbicides, especially S-metolachlor when applied pre-emergence to the crop (Schaeffer et al., 2024), which is a characteristic related to the genetic differences between them. According to Schaeffer et al. (2024), some wheat cultivars may have different emergence speeds, but if they are fast enough, they are able to stay clear of the herbicide-treated zone more easily and thus show less phytotoxicity to the product.

At 28 and 35 DAT, the symptoms were less expressive for the 480 g ha^{-1} dose of S-metolachlor or even the dose associated with pinoxaden, which indicates that it can be used in the field, and did not differ significantly from the control without herbicide application (Table 3). Since S-metolachlor is a herbicide that depends on soil and climate conditions, these results are valid for the reality in which the experiment was conducted. When comparing

the cultivars at 21, 28 and 35 DAT, it can be seen that TBIO Duque is more tolerant to the herbicides tested, especially at the higher doses, with an exception at 35 DAT where TBio Sossego showed less phytotoxicity than TBio Duque when S-metolachlor + pinoxaden (1440 + 40 g ha^{-1}) was applied. This differentiation in selectivity is usually found in wheat cultivars, and is related to the distinct genetic and morphophysiological characteristics they have (El-Sobki et al., 2021; Islam et al., 2023), as explained above.

The highest dose of the herbicide S-metolachlor, together with pinoxaden or applied alone, showed the greatest phytotoxicity to the wheat crop, even in the last evaluations, at 28 and 35 DAT (Table 3). This dose makes it unfeasible to use this herbicide on wheat in this application method, as phytotoxicity was 31.25% for the cultivar TBIO Sossego and 27.50% for TBIO Duque, which is considered high for the crop.

Higher doses of S-metolachlor are being tested in order to increase the spectrum of control and the residual effect on crops of agronomic interest, such as rice and wheat. This is only possible due to the protective effect of some chemical compounds that inactivate the herbicide in question, called safeners (Tang et al., 2014; Deng et al., 2021).

For the grain yield components, the cultivars were not compared with each other, because genetically they differ, making it difficult to separate what is the effect of the treatments applied or the genetic characteristics of the plants themselves. For the number of ears m^{-2} (NE), there was a decrease of approximately 18% when ryegrass infestation occurred compared to the weeded control and the treatments containing herbicides that showed control and were selective to the crop (pinoxaden applied in isolation and the combined use of S-metolachlor + pinoxaden at doses of 480+40 and 720+40 g ha^{-1}), for both wheat cultivars studied (Tables 4 and 5). This increase directly favors the productivity of the wheat crop, given the importance of this variable. The NE of the two wheat cultivars decreased when the highest dose of S-metolachlor (1440 g ha^{-1}) was applied, both on its own and in a mixture with pinoxaden (40 g ha^{-1}), compared to the control without herbicide application. This can be explained by the fact that the crop, regardless of cultivar, showed greater phytotoxicity when the 1440 g ha^{-1} dose of S-metolachlor was used, with a probable reduction in plant stand (due to the death or reduced tillering of the wheat plants), i.e. the crop had difficulty metabolizing or getting rid of the herbicide damage in the detoxification process (Samota et al., 2024; Schaeffer et al., 2024).

The thousand-grain weight (TGW) was affected by the treatments applied to both cultivars (Tables 4 and 5). The cultivars TBio Duque and TBio Sossego showed a reduction in TGW as a result of the increase in the dose of the herbicide S-metolachlor, as can be seen in Tables 4 and 5. This response may be associated with the oxidative stress that S-metolachlor causes in wheat plants, inhibiting the growth of the root system, which reduces the absorption of water and nutrients, as well as the development of the plant, reflecting in the lower TGW. It is important to note that S-metolachlor markedly alters the composition of rhizosphere microorganisms and the abundance of root exudates of wheat seedlings (Qu et al., 2021).

The herbicides also influenced the hectolitre weight (HW) of both wheat cultivars (Tables 4 and 5). As a result of the competition between wheat and ryegrass, together with less selective herbicides, the HW of the cultivars decreased. In general, this reduction occurred on average by 3.3 and 4.2%, respectively, for TBio Duque and TBio Sossego. The most likely hypothesis for this decrease in HW is the occurrence of high phytotoxicity, especially when applying the highest doses of S-metolachlor alone or in combination with pinoxaden (Table 3).

For the yield components of the wheat crop, pinoxaden showed excellent results, being superior to the use of S-metolachlor alone or in combination. This may be linked to the low phytotoxicity that pinoxaden causes to wheat, the

Table 4. Effect of herbicides on grain yield components, number of ears (NE), thousand-grain weight (TGW), hectolitre weight (HW) and grain yield (YIE) of the TBio Duque wheat cultivar. UFFS, Erechim-RS, Brazil.

Treatments	Doses (g ha^{-1})	Wheat grain yield components			
		NE (m^2)	TGW (g)	HW (kg hl^{-1})	YIE (kg ha^{-1})
Weeded control	---	476.0 a[1]	29.4 a	72.0 a	2093.0 a
Infested control	---	435.0 b	29.1 a	70.0 b	1563.1 c
S-metolachlor	480	484.0 a	29.0 a	69.0 b	1586.4 c
S-metolachlor	720	432.0 b	28.4 a	69.5 b	1629.2 c
S-metolachlor	960	484.0 a	28.2 a	69.3 b	1507.0 d
S-metolachlor	1440	432.0 b	27.5 b	69.8 b	1595.1 c
S-metolachlor +pinoxaden	480+40	443.0 b	28.6 b	71.3 a	1819.7 b
S-metolachlor +pinoxaden	720+40	481.0 a	27.6 b	71.0 a	1476.6 d
S-metolachlor +pinoxaden	960+40	515.0 a	28.3 a	70.0 b	1417.7 e
S-metolachlor+pinoxaden	1440+40	444.0 b	27.1 b	68.0 b	1117.1 f
Pinoxaden	40	467.0 a	28.9 a	73.0 a	2068.1 a
Overall average	---	463.00	28.35	70.25	1572.20
CV (%)	---	4.81	3.08	1.87	2.05

[1] Averages followed by different lowercase letters in the column differ by the Scott-Knott test ($p < 0.05$).

Table 5. Effect of herbicides on grain yield components, number of ears (NE), thousand-grain weight (TGW), hectolitre weight (HW) and grain yield (YIE) of the TBio Sossego wheat cultivar. UFFS, Erechim-RS, Brazil.

Treatments	Doses (g ha^{-1})	Wheat grain yield components			
		NE (m^2)	TGW (g)	HW (kg hl^{-1})	YIE (kg ha^{-1})
Weeded control	---	529.0 a[1]	28.1 a	70.3 b	1774.3 d
Infested control	---	468.0 c	24.1 c	67.0 f	1630.2 e
S-metolachlor	480	485.0 c	26.5 a	71.0 a	2018.7 b
S-metolachlor	720	479.0 c	24.5 c	69.0 d	1420.2 f
S-metolachlor	960	488.0 c	27.5 a	68.3 e	1711.7 d
S-metolachlor	1440	424.0 d	24.1 c	68.0 e	1610.9 e
S-metolachlor +pinoxaden	480+40	508.0 b	24.9 c	69.0 d	2231.9 a
S-metolachlor +pinoxaden	720+40	535.0 a	25.8 b	69.0 d	2065.1 b
S-metolachlor +pinoxaden	960+40	508.0 b	25.8 b	69.8 c	1996.9 b
S-metolachlor+pinoxaden	1440+40	491.0 c	25.0 c	69.0 d	1871.0 c
Pinoxaden	40	551.0 a	25.8 b	71.1 a	2180.5 a
Overall average	---	496.91	25.64	68.90	1812.86
CV (%)	---	3.10	3.78	0.37	2.56

[1] Averages followed by different lowercase letters in the column differ by the Scott-Knott test ($p < 0.05$).

improvement in weed control, enabling the crop to express its productive potential. When there is selectivity and adequate weed control, wheat grain yield is maintained (Saif & Bashar, 2024). Wheat grain yield was better when pinoxaden was applied, both for the TBio Duque and TBio Sossego cultivars (Tables 4 and 5). This is probably due to the fact that this treatment showed no phytotoxicity to the wheat cultivars, equaling the weeded control in all the seasons evaluated (Table 3). For the TBio Duque cultivar, the application of pinoxaden alone resulted in the best grain yield compared to the other herbicides, statistically equal to the weeded control (Table 4). For the TBio Sossego cultivar, S-metolachlor + pinoxaden (480 + 40 g ha^{-1}), applied in combination, and pinoxaden (40 g ha^{-1}) alone were statistically better than all the other treatments, even the weeded control. All the other treatments, for both cultivars, had lower grain yields. Grain productivity is closely linked to the use of herbicides that are efficient at controlling weeds and selective to the crop. And this depends on factors such as the application method, dose, formulation, type of herbicide, tank mixes, crops sown, climate and soil characteristics, among others. According to the study by Samota et al. (2024), the use of herbicides in the pre- and/or post-emergence of wheat, as long as they are selective, provided the highest net returns, highlighting the importance of efficient weed management and at the same time maintaining selectivity to the crop.

It should also be noted that the combination of S-metolachlor + pinoxaden (480 + 40 g ha^{-1}) appears to be a promising treatment for weed control in wheat, second only to the weeded control and pinoxaden when applied to the cultivar TBio Duque and statistically equal to pinoxaden when used on TBio Sossego (Tables 4 and 5). The combination of herbicides applied pre- or post-emergence, with different mechanisms of action, helps to increase the spectrum of control, minimize problems related to interference and avoid or manage biotypes of resistant weed species (Chen et al., 2023; Galon et al., 2023).

Herbicide efficacy test for ryegrass control

Table 6 evaluates the control of ryegrass infesting wheat, with an interaction between the factors tested (cultivars × herbicides) in the evaluations carried out at 14, 21, 28 and 35 DAT.

It was observed at 14, 21, 28 and 35 DAT that the best ryegrass control occurred with the highest doses of S-metolachlor applied alone or in combination with pinoxaden, in both wheat cultivars (Table 6). These same comparisons also showed that the application of pinoxaden alone was statistically equal to the use of the highest doses of S-metolachlor applied in combination or only in the pre-emergence of the wheat cultivars TBio Duque and TBio Sossego. Pinoxaden showed satisfactory results, even when applied alone. As a relatively new herbicide, the efficiency of pinoxaden on grasses is high, both in wheat and barley, and it is the only product belonging to the phenylpyrazoline chemical group (Tang et al., 2014; Leon, 2019).

The results show that there was an increase in control from 14 to 35 DAT, particularly when pinoxaden was applied alone or in a mixture, especially at the highest doses of S-metolachlor applied to the two wheat cultivars evaluated (Table 6). This control effectiveness is justified by the fact that it is a grass-specific herbicide with an ACCase mechanism of action. However, it is important to note that these new chemical control strategies must be preserved to avoid resistance to this new herbicide, as has already been reported in other countries in *Digitaria ciliaris* (Basak et al., 2020).

Table 6 shows that as the dose of the herbicide S-metolachlor increased, ryegrass control was greater, with similar results in all evaluations (14, 21, 28 and 35 DAT) and for the cultivars TBio Duque and TBio Sossego. It can be inferred that the pre-emergence herbicide alone was not enough to control ryegrass up to the dose of 960 g ha^{-1}, so some post-emergence control strategy for the crop and the weed is needed to prevent matocompetition.

Table 6. Control (%) of ryegrass (*Lolium multiflorum*) as a function of herbicide application to wheat cultivars TBio Duque and TBio Sossego. UFFS, Erechim-RS, Brazil.

Treatments	Doses (g ha^{-1})	Ryegrass control (%)			
		Duque	Sossego	Duque	Sossego
		14 DAT		21 DAT	
Weeded control	---	100.00 Aa[1]	100.00 Aa	100.00 Aa	100.00 Aa
Infested control	---	0.00 Ae	0.00 Af	0.00 Ae	0.00 Ae
S-metolachlor	480	48.75 Ad	36.25 Be	60.00 Ad	61.25 Ad
S-metolachlor	720	66.25 Ac	43.75 Be	70.00 Ac	70.00 Ac
S-metolachlor	960	61.25 Ac	52.50 Bd	75.00 Ac	76.25 Ab
S-metolachlor	1440	81.25 Ab	65.00 Bc	81.25 Ab	78.75 Ab
S-metolachlor +pinoxaden	480+40	75.00 Ab	50.00 Bd	63.75 Ad	68.75 Ac
S-metolachlor +pinoxaden	720+40	65.00 Ac	51.25 Bd	70.00 Ac	72.50 Ab
S-metolachlor +pinoxaden	960+40	58.75 Ac	56.25 Ad	73.75 Ac	76.25 Ab
S-metolachlor+pinoxaden	1440+40	78.75 Ab	72.50 Ab	82.50 Ab	81.25 Ab
Pinoxaden	40	75.00 Ab	68.00 Ab	78.75 Ab	75.50 Ab
Overall average		53.84		61.88	
CV (%)		10.74		7.08	
		28 DAT[1]		35 DAT	
Weeded control	---	100.00 Aa[2]	100.00 Aa	100.00 Aa	100.00 Aa
Infested control	---	0.00 Ae	0.00 Ad	0.00 Af	0.00 Ae
S-metolachlor	480	56.25 Ad	56.25 Ac	66.25 Ad	58.75 Bd
S-metolachlor	720	68.25 Ac	68.75 Ab	71.25 Ad	71.25 Ac
S-metolachlor	960	76.25 Ab	73.75 Ab	78.75 Ac	78.75 Ab
S-metolachlor	1440	77.50 Ab	81.25 Ab	84.25 Ab	82.75 Ab
S-metolachlor +pinoxaden	480+40	70.00 Ac	63.75 Ac	81.25 Ac	74.00 Bc
S-metolachlor +pinoxaden	720+40	68.25 Ac	73.75 b	72.50 Bd	79.50 Ab
S-metolachlor +pinoxaden	960+40	63.75 Ac	70.00 Ab	77.50 Ac	80.75 Ab
S-metolachlor+pinoxaden	1440+40	82.50 Ab	75.00 Ab	85.00 Ab	85.00 Ab
Pinoxaden	40	81.50 Ab	72.00 Ab	80.00 Ab	83.25 Ab
Overall average	---	60.24		74.19	
CV (%)	---	9.37		5.89	

[1] Averages followed by the same uppercase letters in the row (for the same DAT) and lowercase letters in the column do not differ according to the Scott-Knott test ($p < 0.05$).

Results in the literature show the potential for reducing the dose of herbicides when different management strategies are involved in the integration of the control system. For example, for the *Avena fatua* species, the density of the crop contributes to a lower dose of the herbicide and lower seed production for the species. In the less competitive scenario, with a lower density of crop plants, greater efficacy was required to avoid seed return and an increase in the herbicide dose (Jäck et al., 2017). Galon et al. (2023) also found an increase in ryegrass control when they combined pre- and post-emergence herbicides, especially clodinafop-propargyl, which is also an ACCase inhibitor, like the pinoxaden used in this study.

The effect of cultivars on ryegrass control was very similar, especially after 14 DAT (Table 6). However, it was observed at 14 DAT that ryegrass control in the TBio Duque cultivar was superior to TBio Sossego for all doses of S-metolachlor applied pre-emergence to wheat and the doses of 480 and 720 g ha^{-1} associated with pinoxaden. For the other treatments used, there was no difference between the wheat cultivars in relation to ryegrass control. This may be associated with the difference in ryegrass control in relation to the products used at 14 DAT and the cultivars ability to compete with the weed. TBio Duque probably showed faster and more vigorous initial growth, mainly related to greater height, leaf area index and tillering compared to the cultivar TBio Sossego, which contributes to greater soil coverage and thus better control of ryegrass by the herbicides. Lamego et al. (2013) also observed differentiation between wheat cultivars (BRS Guamirim, Fundacep Cristalino, Fundacep Raízes and BRS 296) when they coexisted with ryegrass and turnip. In addition to this variation, pinoxadem can directly interfere in the concentration of nutrients in the plant and also in the concentration of amino acids in the wheat crop, reducing the competitive capacity and thus obtaining different responses in weed control (El-Sobki et al., 2021).

In the 21 and 28 DAT evaluations, there was no difference between the TBio Duque and TBio Sossego cultivars for all the treatments applied to control ryegrass (Table 6). At 35 DAT, there was less ryegrass control in the TBio Duque cultivar when S-metolachlor + pinoxaden was applied at a dose of 720 + 40 g ha^{-1} and for TBio Sossego when the lowest dose of S-metolachlor (480 g ha^{-1}) was used, either alone or in combination with pinoxaden. The other treatments used to control ryegrass showed equality when comparing the wheat cultivars with each other. These results may be associated with the different competitive abilities of the cultivars. As explained above, or even if there has been a variation in control in some of the evaluation seasons, this is important for choosing a cultivar that will have a competitive

advantage over the weeds, thus avoiding matocompetition. With regard to the grain yield components of wheat cultivar TBio Duque, it was found that the application of S-metolachlor (960 g ha^{-1}) had the highest NE (number of ears), statistically equal to pinoxaden and the weeded control (Table 7). Studies by Piasecki et al. (2017), Raj et al. (2020) and Galon et al. (2023) using herbicides with different mechanisms of action found similar results for grain yield components, including higher number of ears, thousand-grain weight, hectolitre weight and grain yield.

For the two wheat cultivars, TBio Duque and TBio Sossego, the highest doses of S-metolachlor (960 and 1440 g ha^{-1}) associated with pinoxaden resulted in lower NE when compared to the weeded control and the use of pinoxaden alone (Tables 7 and 8). This is probably due to the cultivars being susceptible to high doses of the herbicide S-metolachlor, which stresses the plant. When the crop suffers damage, as a defence mechanism and in order to metabolize the herbicide in the plant, it expends more energy carrying out photosynthesis and issuing new leaves free of phytotoxicity (Raj et al., 2020). The ALS, ACCase and Photosystem II inhibitor herbicides did not have a negative effect on the number of ears in the TBio Pioneiro and TBio Quartzo wheat cultivars (Galon et al., 2015). Some studies have reported differences in the number of ears in wheat due to the application of herbicides, suggesting that this is mainly due to the genetic characteristics of the cultivars that show different selectivity, doses and herbicides used (Van Der Meulen & Chauhan, 2017; Zakariyya et al., 2022).

In the TBio Sossego cultivar, the application of S-metolachlor (480 g ha^{-1}) provided the lowest NE, statistically equal to the infested control (Table 8). This is due to the high infestation of ryegrass and the lack of control or low effectiveness, resulting in competition for resources in the environment, which can negatively affect all wheat yield components. Wheat grain yield losses when no weed control is adopted can exceed 80% (Gharde et al., 2018; Galon et al., 2019; Balem et al., 2021).

Table 7. Effect of herbicides on grain yield components, number of ears (NE), thousand-grain weight (TGW), hectolitre weight (HW) and grain yield (YIE) of the TBio Duque wheat cultivar. UFFS, Erechim-RS, Brazil.

Treatments	Doses (g ha^{-1})	Wheat grain yield components			
		NE (m²)	TGW (g)	HW (kg hl^{-1})	YIE (kg ha^{-1})
Weeded control	---	497.0 a[1]	30.3 b	74.0 a	1735.6 b
Infested control	---	407.0 c	30.4 b	71.0 b	1595.8 c
S-metolachlor	480	423.0 c	28.9 c	69.3 b	1774.0 b
S-metolachlor	720	448.0 b	28.9 c	68.8 b	1452.6 d
S-metolachlor	960	496.0 a	29.5 c	70.0 b	1258.8 e
S-metolachlor	1440	395.0 c	28.2 d	70.0 b	992.2 f
S-metolachlor +pinoxaden	480+40	361.0 b	29.6 c	73.0 a	1819.5 b
S-metolachlor +pinoxaden	720+40	458.0 b	27.4 d	70.0 b	1178.4 e
S-metolachlor +pinoxaden	960+40	472.0 b	30.5 b	72.3 a	1537.4 c
S-metolachlor+pinoxaden	1440+40	416.0 c	31.6 a	71.0 b	1531.4 c
Pinoxaden	40	493.0 a	31.2 a	73.0 a	2315.3 a
Overall average	---	445.09	29.71	71.11	1563.74
CV (%)	---	5.78	1.81	2.00	4.03

[1] Averages followed by different lowercase letters in the column differ by the Scott-Knott test ($p < 0.05$).

Table 8. Effect of herbicides on grain yield components, number of ears (NE), thousand-grain weight (TGW), hectolitre weight (HW) and grain yield (YIE) of the TBIO Sossego wheat cultivar. UFFS, Erechim-RS, Brazil.

Treatments	Doses (g ha^{-1})	Wheat grain yield components			
		NE (m²)	TGW (g)	HW (kg hl^{-1})	YIE (kg ha^{-1})
Weeded control	---	461.0 a[1]	25.8 a	69.0 b	1993.8 a
Infested control	---	407.0 c	26.3 a	67.0 c	847.5 f
S-metolachlor	480	411.0 c	25.7 a	65.3 d	1416.5 e
S-metolachlor	720	484.0 a	24.2 b	65.0 d	1358.8 e
S-metolachlor	960	487.0 a	24.0 b	67.3 c	1600.8 d
S-metolachlor	1440	491.0 a	24.0 b	67.8 c	1762.8 c
S-metolachlor +pinoxaden	480+40	504.0 a	25.1 b	70.0 a	1915.9 b
S-metolachlor +pinoxaden	720+40	492.0 a	27.1 a	68.8 b	1928.1 b
S-metolachlor +pinoxaden	960+40	452.0 b	24.8 b	67.0 c	1760.5 c
S-metolachlor+pinoxaden	1440+40	432.0 b	26.3 a	66.5 c	1710.7 c
Pinoxaden	40	483.0 a	26.1 a	70.0 a	1912.3 b
Overall average	---	464.00	25.04	67.59	1618.46
CV (%)	---	5.15	3.78	0.87	2.63

[1] Averages followed by different lowercase letters in the column differ by the Scott-Knott test ($p < 0.05$).

The TGW showed a difference depending on the treatments, for the wheat cultivar TBio Duque (Table 7) and TBio Sossego (Table 8). The highest averages were found when pinoxaden was applied alone or in a mixture with S-metolachlor at the highest dose, with an average of 31.40 and 26.20 g, approximately 6.70 and 3.80% higher than the average of the other treatments (Tables 7 and 8), for the TBio Duque and TBio Sossego cultivars, respectively. Balem et al. (2021) obtained similar results regarding yield components with the application of pinoxaden to wheat. The same authors attributed the result to less interspecific competition, since greater weed control results in a greater amount of photoassimilates accumulated in the wheat grains.

When the crop is selective, it may suffer damage as a result of the application of herbicides, but its metabolism is able, over time, to overcome the phytotoxicity of the product and return to its initial metabolism, with no negative effect on plant growth and development or even on yield components, such as the thousand-grain weight (Piasecki et al., 2017; Zakariyya et al., 2022).

The HW of the wheat cultivars showed similarity, both for the effects of the herbicides (selectivity experiment) and in relation to ryegrass control (efficacy experiment), i.e. treatments that obtained lower phytotoxicity (Table 3) and higher control (Table 4) were superior. Particularly noteworthy was the treatment containing S-metolachlor at a dose of 480 g ha^{-1} + pinoxaden 40 g ha^{-1} and pinoxaden alone, whose average HW was 73 kg hl^{-1}, equal to the weeded control, and 70 kg hl^{-1}, respectively for the TBio Duque and TBio Sossego cultivars (Tables 7 and 8). Karpinski et al. (2018), when studying the combination of the herbicides iodosulfuron-methyl + fenoxaprop-p-ethyl, also found lower HW in the Campeiro wheat cultivar, which is partly similar to the results found in this study.

For the TBio Sossego cultivar, all the treatments did not reach the minimum HW of 72 kg hl^{-1} (Table 8), so they are classified as off-type and are destined for feed production and other purposes. There are several factors that may have limited the HW quality of both cultivars, from factors such as growing conditions, harvesting operations, drying and storage that directly influence the quality characteristics of wheat grains (Dias et al., 2015).

The effect of ryegrass control is directly related to wheat HW, i.e. when herbicides are effective against weeds, the crop shows a better value in this variable, due to less competition between plants (Galon et al., 2023). Raj et al. (2020) also found a better response of grain yield components for herbicides that demonstrated greater weed efficacy, thus corroborating the results of this study.

Wheat grain yield was influenced by ryegrass competition for both cultivars, with an average reduction of 33%, i.e. a significant loss due to the interference caused by the weed (Tables 7 and 8). These results corroborate those found by Lamego et al. (2015) when they highlighted the high competitive capacity of ryegrass when in competition with wheat. Another major problem, when this weed is not controlled, concerns the increase in the seed bank, increasing the chance of herbicide-resistant biotypes emerging and thus perpetuating themselves longer in crops (Galon et al., 2019; Balem et al., 2021).

The application of pinoxaden alone or in combination with S-metolachlor (480 g ha^{-1}) showed the highest grain yields for both the TBio Duque and TBio Sossego wheat cultivars (Tables 7 and 8). This is due to the selectivity that these herbicides have shown to wheat cultivars and the good control they have caused to ryegrass. It should also be noted that the use of pre-emergent herbicides helps the crop to germinate and grow free from weed competition, thus avoiding losses in grain yield as a result.

Management with the herbicide pinoxaden, for both cultivars and associated with lower doses of S-metolachlor (480 g ha^{-1}), were the most promising treatments for safe ryegrass control. This combination of active ingredients delays the likelihood of resistance occurring and reduces the ryegrass seed bank in the soil, making it easier to implement and control for future production cycles. Increasing doses of S-metolachlor, above 720 g ha^{-1}, delay the establishment of the wheat crop, reduce productivity and should be avoided, regardless of the wheat cultivar studied, the behavior was similar (Tables 7 and 8).

In this study, the average reduction in grain yield for the two cultivars, when comparing the infested control with the best treatment, was 565.8 kg ha^{-1} of grain, i.e. an average of 26% in yield loss as a result of ryegrass interference in wheat. These average losses can be even higher, depending on the density of the weed and the crop, management and cultivation, soil fertility, competitiveness of the cultivars, among other factors (Jäck et al., 2017; Galon et al., 2019; Tavares et al, 2019).

Given the difficulties of weed management in wheat growing, the results of this study made it possible to establish that each application method or herbicide behaves differently in terms of weed control or crop selectivity. It is important to note that each cultivar can express different characteristics in the environment as a result of herbicide applications and the combination of products applied pre- and post-emergence, which is one of the alternatives for delaying the emergence of weed resistance to herbicides. It should be emphasized that the use of herbicides is just one of the methods used for control. For greater effectiveness, it is necessary to combine more than one management strategy in different crops, including wheat.

Conclusions

The herbicide pinoxaden stood out in terms of crop selectivity, ryegrass control and yield gain compared to the other treatments, making it an alternative for weed control in wheat.

Doses above 960 g ha^{-1} of S-metolachlor applied alone or in combination with pinoxaden cause increased phytotoxicity to wheat cultivars, with a negative effect on the crop's grain yield components.

The herbicides S-metolachlor and pinoxaden, applied pre- and post-emergence respectively, are an important strategy for managing ryegrass weeds in wheat.

Ryegrass caused wheat grain yield losses of approximately 30% when no control method was adopted on the crop.

When using S-metolachlor, care must be taken with the dose used on wheat, as applications of more than 720 g ha^{-1} can compromise the development of the crop, and even then there is no good ryegrass control in the situation of the experiment.

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