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Selectivity of mesotrione and tembotrione to white oat cultivars

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Abstract

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Owing to increased production of oats, research on crop management is needed, especially for weed control. This work aimed to evaluate the selectivity of herbicides mesotrione and tembotrione to white oat. The experiment was conducted in the field (2019 and 2020) in a randomized block split-split plot design. The main plot contains cultivars FAEM-007, IPR-Afrodite, UPFA-Fuerza and URS-Monarca; the split plot, herbicides mesotrione and tembotrione; and the split-split plot, the following doses: mesotrione (0; 42; 84; 168 and 336 g a.i. ha^{-1}) and tembotrione (0; 22.05; 44.1; 88.2 and 176.4 g a.i. ha^{-1}). Yield was reduced by 12.8% (2019) and 6.0% (2020) and industrial yield by 14.5% (2019) and 6.0% (2020) after application of the 336 g of mesotrione, regardless of cultivar. Ther herbicides tembotrione (doses ≤176.4 g a.i. ha^{-1}) and mesotrione (doses ≤168 g a.i. ha^{-1}) are selective for white oat.

Keywords: Avena Sativa L.; carotenoid inhibitors; chemical control

Introduction

White oat (*Avena sativa*) is an annual Poaceae (Leggett, 1992) and are the major winter crops in southern Brazil, for grain production totaling 1.14 million tons of grains in 2021 (Conab, 2022; Pacheco et al., 2021). In addition, white oat has been highlighted in human nutrition owing to the increased demand for food produced from oats, as there is a growing interest in healthy foods (Kim et al., 2021). Despite the increase in production and the improvements in white oat cultivation, there are still limiting factors, i.e., interference of weeds. Although often underestimated, weeds reduce the economic yield of crops (Kadam et al., 2021).

To avoid the damage caused by crop-weed interference, integrated weed management (IWM) is considered to be an efficient method (Kadam et al., 2021). However, preventive, physical, cultural and mechanical management practices are not enough to maintain efficient control throughout the crop cycle. Herbicides also need to be used, as they are an important control method in modern agriculture (Fu et al., 2019).

An analysis of the herbicides available for oat cultivation, shows a lack of herbicides to control monocots (Liliopsida), as well as a small number of registered and crop-selective herbicides – limited to two mechanisms of action: auxin mimics and ALS inhibitors (Agrofit, 2022) – for use at post-emergence, with emphasis on the active ingredients 2,4D, MCPA and metsulfuron-methyl (used for control of Magnoliopsida/Dicots species). The limited use of mechanisms of action may lead to the selection of resistant biotypes, owing to high selection pressure for effective herbicides, resulting from the evolution of one or more resistance mechanisms (Gaines et al., 2020).

To avoid the selection of resistant biotypes and to deal with existing cases, herbicides with different mechanisms of action should be used, but there is a shortage of products with these characteristics in the market. This way, carotenoid biosynthesis inhibitor herbicides can be an alternative for control of non-resistant weeds and biotypes resistant to other mechanisms of action (Bond et al. 2014). Therefore, they are likely tools available for use in winter crops (Schmitz et al. 2015). This group has two major active principles, namely tembotrione and mesotrione, which are classified as selective systemic herbicides (Agrofit, 2022).

Tembotrione and mesotrione belong to the chemical group of tricetones, and according to Beaudegnies et al. (2009) and Godar et al. (2015), they act on the metabolic pathway of plastoquinone biosynthesis by inhibiting the activity of 4-hydroxyphenyl-pyruvatedioxygenase (HPPD) enzyme, blocking the carotenoid biosynthesis pathway.

Herbicides inhibiting carotenoid biosynthesis currently represent the greatest revolution in weed management in the 21st century for winter cereals, owing to high selectivity to crops and efficiency in weed control (Lindell et al., 2015). However, in Brazil, there are few studies on the effects of this group of herbicides on winter crops; information available is mostly restricted to clomazone in wheat (Schmitz et al., 2015; 2018) and mesotrione in black oat (Pedroso et al., 2021). Ahrens et al. (2013) and Ndikuryayo et al. (2017) stressed that HPPD-inhibiting herbicides are an alternative for weed management in winter cereal crops. To provide a safe alternative for weed management in white oat crops, further research is needed on weed selectivity and control, and on the effects of these herbicides on the quality of the harvested product. For oats, there is a lack of research on herbology (Dalazen et al., 2015; Queiroz et al., 2017; Xavier et al., 2022), since production of this crop has been increasing.

Thus, this work aimed to evaluate the selectivity of herbicides mesotrione and tembotrione, when applied at post-emergence to white oat crops, as well as their effects on the industrial grain quality.

Materials and Methods

The experiments were carried out in an experimental area at the State University of Santa Catarina CAV/UDESC, in the city of Lages – SC, under the following geographical coordinates: 27° 52’ South latitude; 50° 18’ West Longitude; and altitude of 930 m, during the 2019 and 2020 growing seasons. The climate of the region, according to the Köppen classification, is Cfb (temperate climate, with mild summers). Fig. 1 shows the meteorological data (maximum, average and minimum temperature and accumulated rainfall) of Lages during the experimental periods.

Both experiments were implemented in an aluminum humic Cambisol (Embrapa, 2017), with the following characteristics: pH in water: 5.0; Ca: 4.7 $cmol_c$ dm^{-3}; Mg: 1.4 $cmol_c$ dm^{-3}; Al: 4.7 $cmol_c$ dm^{-3}; K: 153 mg dm^{-3}; P: 26.8 mg dm^{-3}; CEC: 21.7 $cmol_c$ dm^{-3}; MO: 6.6 % and Clay: 27%.

The oat was sown under a no-tillage system using a randomized block split-split-plot design with four replications per treatment. The four oat cultivars were allocated to the main plot: FAEM 007, IPR Afrodite, UPFA Fuerza and URS Monarca. The herbicides mesotrione (Callisto®) and tembotrione (Soberan®) were allocated to the split-plots, and the doses of each herbicide were evaluated in the split-split-plots: 0 g (control without herbicide application) and the

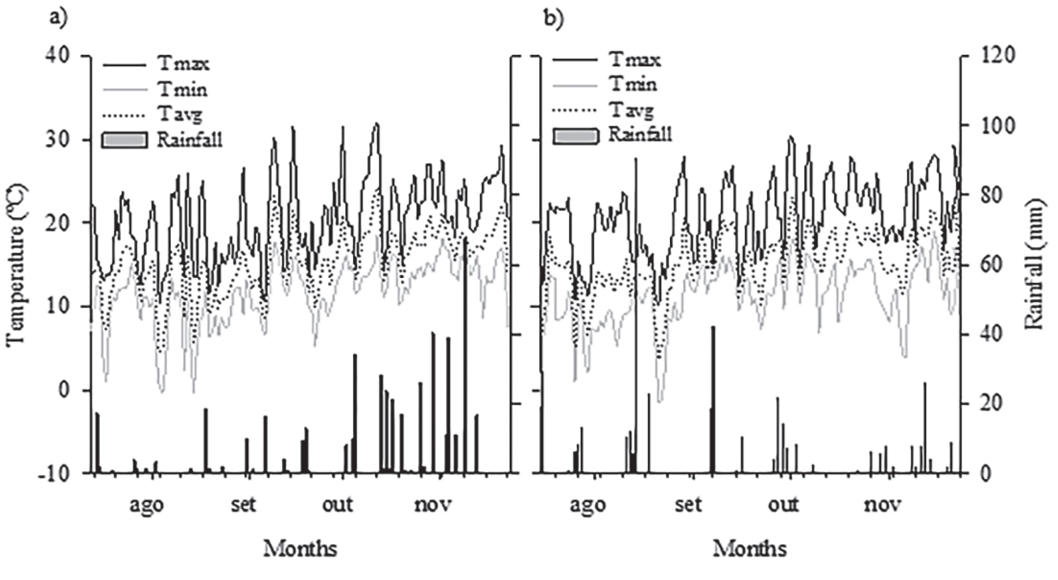

Fig. 1. Rainfall, maximum, minimum and average air temperatures between sowing and harvesting the white oat experiments during 2019 (a) and 2020 (b) growing seasons (T max; Maximum temperature; T min: minimum temperature; T avg: average temperature.)
Source: Authors’ own elaboration

doses to 42 (0.25x); 84 (0.5x); 168 (1x) and 336 (2x) g a.i. ha^{-1} for mesotrione and 22.05 (0.25x); 44.1 (0.5x); 88.2 (1x) and 176.4 (2x) g a.i. ha^{-1} for tembotrione. The "x"correspond a recommended commercial herbicide dose for maize.

The seeds were treated with fipronil+pyraclostrobin+thiophanate-methyl (Standak Top®) and sown mechanically on July 12, 2019 and July 15, 2020, respectively, by depositing sufficient seeds to achieve a desired plant density of 350 plants per square meter. The sowing fertilization was performed using NPK fertilizer blend of 20–80–40 kg ha^{-1} of N-P_2O_5-K_2O, respectively. Later, at the beginning of tillering and stem elongation, topdressing nitrogen fertilization (with 45 kg ha^{-1} of N) was carried out, following the recommendations of the Soil Chemistry and Fertility Commission (CQFS, 2016) for a productive potential of 5 t ha^{-1} of grain. Each split-split-plot consisted of 5 rows of 5.0 m in length, with 0.2 m spacing between rows, spaced 0.5 m apart.

Phytosanitary management of the oat was carried out by applying fungicides and insecticides to ensure the intended yield potential in both seasons, following the technical indications for oat cultivation (Lângaro et al., 2014).

The treatments were applied when 50% of the plants had 3–4 fully expanded leaves (on August 14, 2019 and August 17, 2020, respectively), with the aid of a CO_2 pressurized backpack sprayer (Herbicat, Brazil), with a pressure of 30 KPa, fitted with six 80.02 VS flat jet nozzles (TeeJet®, USA), calibrated for a spray volume of 200 L ha^{-1}. Also, 0.5% v/v of vegetal oil (Áureo®) was added to the spray.

At 7, 14, 21 and 28 days after application of treatments (DAA), plant toxicity symptoms were evaluated using a percentage scale from 0 to 100% (Sbcpd, 1995), where 0% represents the absence of symptoms and 100% the death of all plants.

At the end of the reproductive phase, grain yield was determined by harvesting the total area of each split-split-plot (5m²), followed by correction of water content to 13% and conversion into hectare (kg ha^{-1}). Thousand-grain weight (TGW) was measured by counting 1,000 grains and subsequently weighing them on a semi-analytical scale with a precision of 0.0001 g.

Grain sieve by considering grain thickness higher than 2 mm (G > 2) was determined by weighing and subsequently sieving a 200-g sample of grains in a 40×30 cm rectangular sieve with oblong holes (2×20 mm thickness) and weighing the grains retained on the sieve, thus estimating percentage (%) grains > 2 mm (G > 2).

Hectoliter weight (HW) was measured by weighing a sample of G > 2 contained in a tube with a known volume (0.25 L), using a hectoliter weight scale (Dalle Molle, model 40). Such weight (g) was converted (kg into 100 L) using a specific table for oats (Brasil, 2009).

Dehulled grains (DH) was determined by manually husking a sample of 5 g of grains > 2 mm (husk+caryopsis) previously dried in an oven at 60°C. After husking, the grains were weighed again to determine caryopsis weight.

Industrial yield (AVENACOR) was estimated by calculating the product of Grain Yield (GY) x Grain > 2 mm (G > 2) x dehulled (DH).

Statistical analysis

Data were tested according to the assumptions of analysis of variance (normality and homogeneity), and when the latter were met, the former underwent analysis of variance (ANOVA) using the F-test ($p < 0.05$). Data on toxicity symptoms levels that did not meet the assumptions were arcsine transformed – $(x/100)^{0.5}$ – prior to application of ANOVA. The data, when significant, were further analyzed using Tukey's test ($p < 0.05$) for qualitative treatments through the R software; for quantitative treatments, regression analysis was performed ($p < 0.05$) using the Sigmaplot software (Systat Software, version 10.0, USA).

Results

Selectivity of herbicides mesotrione and tembotrione

The first symptoms of toxicity in oat plants were found at 7 DAA, increasing to 14 and 21 DAA and decreasing to 28 DAA, for both herbicides, four cultivars and two growing seasons (Table 1). The cultivars showed lowest toxicity when they received treatments with tembotrione (ranged 2.1 to 15%), but when treated with mesotrione, the cultivar

Table 1. Toxicity symptoms of four white oat cultivars by herbicides mesotrione and tembotrione at 7 DAA, in the average of doses in the 2019 and 2020 growing seasons

Cultivar	Herbicide	
	Mesotrione	Tembotrione
	2019 season	
FAEM 007	A 11.2 c	B 2.1 a
IPR Afrodite	A 14.9 b	B 3.2 a
UPFA Fuerza	A 23.9 a	B 3.9 a
URS Monarca	A 17.5 b	B 4.8 a
	2020 season	
FAEM 007	A 11.3 d	B 2.8 b
IPR Afrodite	A 16.5 c	B 5.4 b
UPFA Fuerza	A 23.4 b	B 5.6 b
URS Monarca	A 31.9 a	B 15.2 a

Different lowercase letters in the column and uppercase in the row differ from each other by Tukey's test ($p < 0.05$).
Source: Authors' own elaboration

UPFA Fuerza showed the highest levels of toxicity symptoms (23.9 and 23.4%), while FAEM 007 showed the lowest level of toxicity 11.2 and 11.3% for 2019 and 2020 growing seasons, respectively (Table 1).

In 2020, the highest toxicity was found in plants sprayed with mesotrione (Table 2). The treatments with mesotrione resulted in the highest level of toxicity in cultivars UPFA Fuerza (34.5%) and URS Monarca (33.9%), while cultivar FAEM 007 had the lowest level of toxicity (18.1%) (Table 2). The treatments with tembotrione caused the highest level of toxicity in URS Monarca (15.6%) (Table 2).

In 2019, the cultivars FAEM 007, UPFA Fuerza and URS Monarca showed a quadratic response to increasing the dose of the tested herbicides (Fig. 2a). However, cultivar IPR Afrodite showed a linear behavior. But, in 2020, all cultivars showed a quadratic behavior with an increase in the dose of the tested herbicides (Fig. 2b). In both seasons, as doses increased, there was also an increase, following a quadratic behavior, in the levels of toxicity from 39.2% (2019) and 37.9% (2020) for mesotrione and, for tembotrione, the toxicity of 3.2% (2019) and 15.8% (2020) (Fig. 2c and 2d).

Table 2. Toxicity symptoms (%) of four oat cultivars by herbicides mesotrione and tembotrione at 14 DAA, in the average of doses in the 2020 season

Cultivar	Herbicide	
	Mesotrione	Tembotrione
FAEM 007	A 18.1 c	B 4.1 b
IPR Afrodite	A 25.3 b	B 6.0 b
UPFA Fuerza	A 34.5 a	B 7.2 b
URS Monarca	A 33.9 a	B 15.6 a

Different lowercase letters in the column and uppercase in the row differ from each other by Tukey's test ($p < 0.05$).
Source: Authors' own elaboration

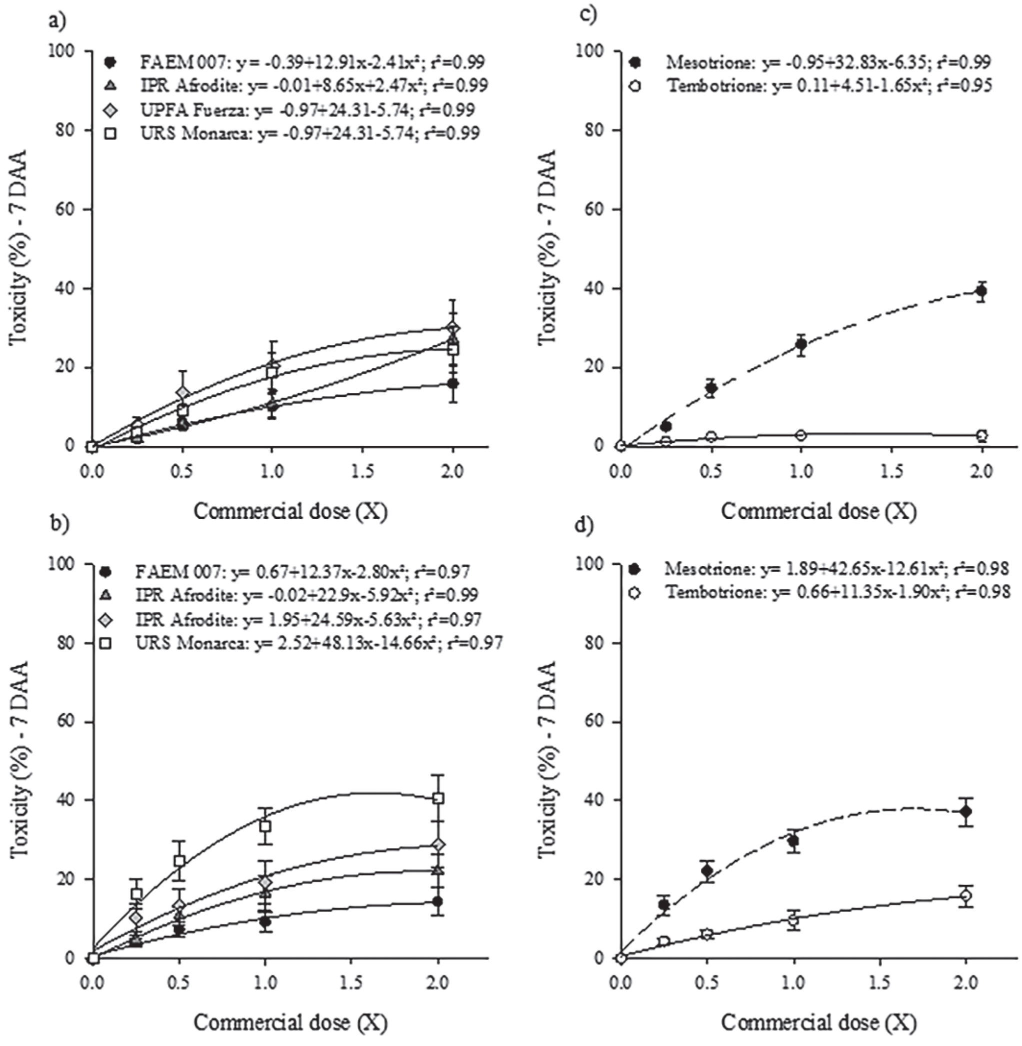

Fig. 2. Toxicity symptoms (%) in white oat cultivars based on herbicide doses in the 2019 (a) and 2020 (b) season and herbicide toxicity as a function of the doses in the 2019 (c) and 2020 (d) season at 7 DAA. Vertical bars represent the standard error of the mean of each treatment
Source: Authors' own elaboration

At 28 DAA in both seasons and all cultivars, tembotrione showed the lowest levels of toxicity than mesotrione (<6%).

In general, in all assessment periods, toxicity levels were lower in treatments with tembotrione compared to mesotrione (Fig. 2c, Fig. 2d, Fig. 3b x 3a, Fig. 4b, Fig. 5c x 5a, Fig. 5d x 5b, Fig 6c x 6a and Fig 6d x 6b). For both herbicides, there was a greater reduction in toxicity at 28 DAA regardless of cultivar and herbicide dose; which indicated plant recovery process.

For the thousand grain weight (TGW) variable in 2019, cultivar FAEM 007 showed the highest value (41.8 g), followed by URS Monarca (37.7 g), UPFA Fuerza (35.2 g) and IPR Afrodite (33.9 g) (Table 3). By comparison, in 2020, cultivars FAEM 007 (39.5 g) and URS Monarca (38.7 g) showed higher TGW when compared to UPFA Fuerza (36.6 g) and IPR Afrodite (34.5 g) (Table 3). In 2019, both herbicides showed the maximum estimation points of TGW at the dose of 52.1 g a.i. ha^{-1} of mesotrione (37.1 g) and 141.1 g a.i. ha^{-1} of tembotrione (38.0 g) (Fig. 7a). In 2020, there was no significant effect (p>0.05) for the herbicide-dose interaction for the TGW (Fig. 7b; TGW around 37 g).

In 2019, the cultivar UPFA Fuerza showed a higher yield compared to the others: 6845 kg ha^{-1} (Table 3). In 2020, there was no significant difference ($p > 0.05$) among cultivars, which had an average yield of 6541 kg ha^{-1} (Table 3; Fig. 8a and 8c). There was a significant effect ($p < 0.05$) of the herbicide-dose interaction for the yield variable in both seasons. In 2020 (Fig. 8c), the average yield of all treatments was higher than in 2019 season (Fig. 8a) – a fact associated with lower rainfall (cumulative number and

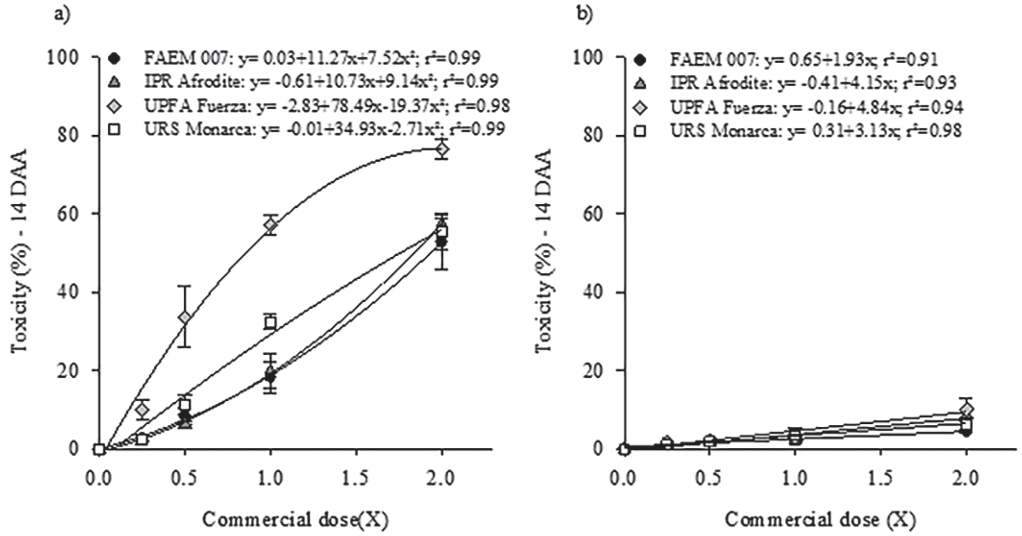

Fig. 3. Toxicity symptoms (%) in oat cultivars as a function of the doses of herbicides mesotrione (a) and tembotrione (b) at 14 DAA in the 2019 season. Vertical bars represent the standard error of the mean of each treatment
Source: Authors' own elaboration

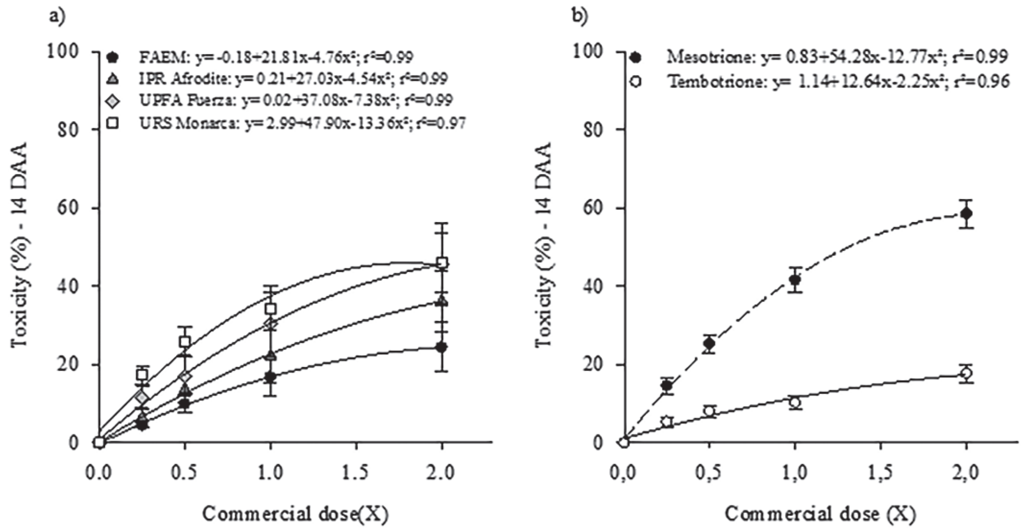

Fig. 4. Toxicity symptoms in white oat cultivars based on herbicide doses (a) and toxicity by herbicides as a function of doses for the average of cultivars (b) 14 DAA in the 2020 season. Vertical bars represent the standard error of the mean of each treatment
Source: Authors' own elaboration

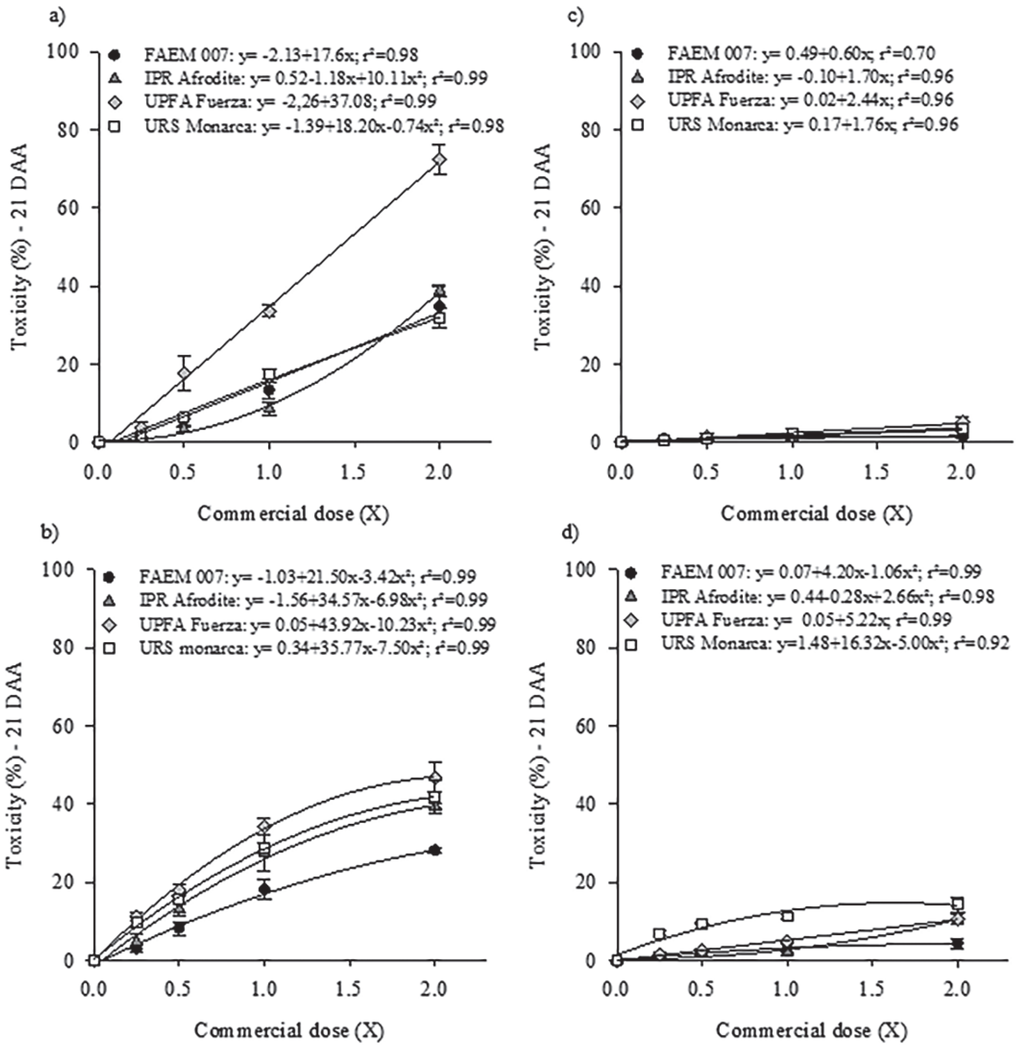

Fig. 5. Toxicity symptoms in white oat cultivars based on mesotrione doses in the 2019 (a) and 2020 (b) seasons and tembotrione in the 2019 (c) and 2020 (d) seasons at 21 DAA. Vertical bars represent the standard error of the mean of each treatment
Source: Authors' own elaboration

mm) during grain filling (Fig. 1). In 2019, increasing doses of mesotrione influenced white oat grain yield (Fig. 8a), with a maximum yield estimate of 5861 kg ha^{-1} after application of 33.6 g a.i. ha^{-1} of mesotrione. The application of a 336 g a.i. ha^{-1} of mesotrione decreased 12.8% in yield compared to the control treatment, while the application of increasing doses of tembotrione resulted in maximum yield at the 39.7 g a.i. ha^{-1} with 6186 kg ha^{-1}. For tembotrione (both seasons), there was no reduction in comparison to the control treatment when the other doses were applied (Fig. 8a and 8c). In the 2020 season (Fig. 8c), the herbicides showed a maximum yield estimate at the dose of 105.8 g a.i. ha^{-1} (6990 kg ha^{-1}) for tembotrione and at a dose of 84 g a.i. ha^{-1} (6787 kg ha^{-1}) for mesotrione. The application of 336 g a.i. ha^{-1} mesotrione led to a 6.0% reduction in yield when compared to the control treatment (Fig. 8c).

The cultivar URS Monarca had the highest G > 2 (94.3% and 96.2%) and FAEM 007 the lowest G > 2 (88.9 and 86.7%) in both seasons (Table 4). In 2020, there was a significant effect ($p < 0.05$) of dose, with the estimated maximum G > 2 of 91.5% at the dose of 302.4 g a.i. ha^{-1} of mesotrione and 158.8 g a.i. ha^{-1} of tembotrione (Fig. 9a). The highest HW values were found in 2020, regardless of cultivar, compared to 2019 (Table 4). In 2019 and 2020, the highest HW values were measured in the cultivar URS Monarca (53.2 and 54.2 kg hL^{-1}) and the lowest for UPFA Fuerza (45.2 and 48.2 kg hL^{-1}) (Table 4).

The herbicide-dose interaction for the HW variable (in average of cultivars during 2019 season) showed a quadratic behavior with increasing doses, with a maximum estimate of HW = 48.7 kg hL^{-1} at a dose of 158.8 g a.i. ha^{-1} of tembotrione and a minimum estimate of HW = 46.9 kg hL^{-1} at the 268.8 g a.i. ha^{-1} of mesotrione (Fig. 9b).

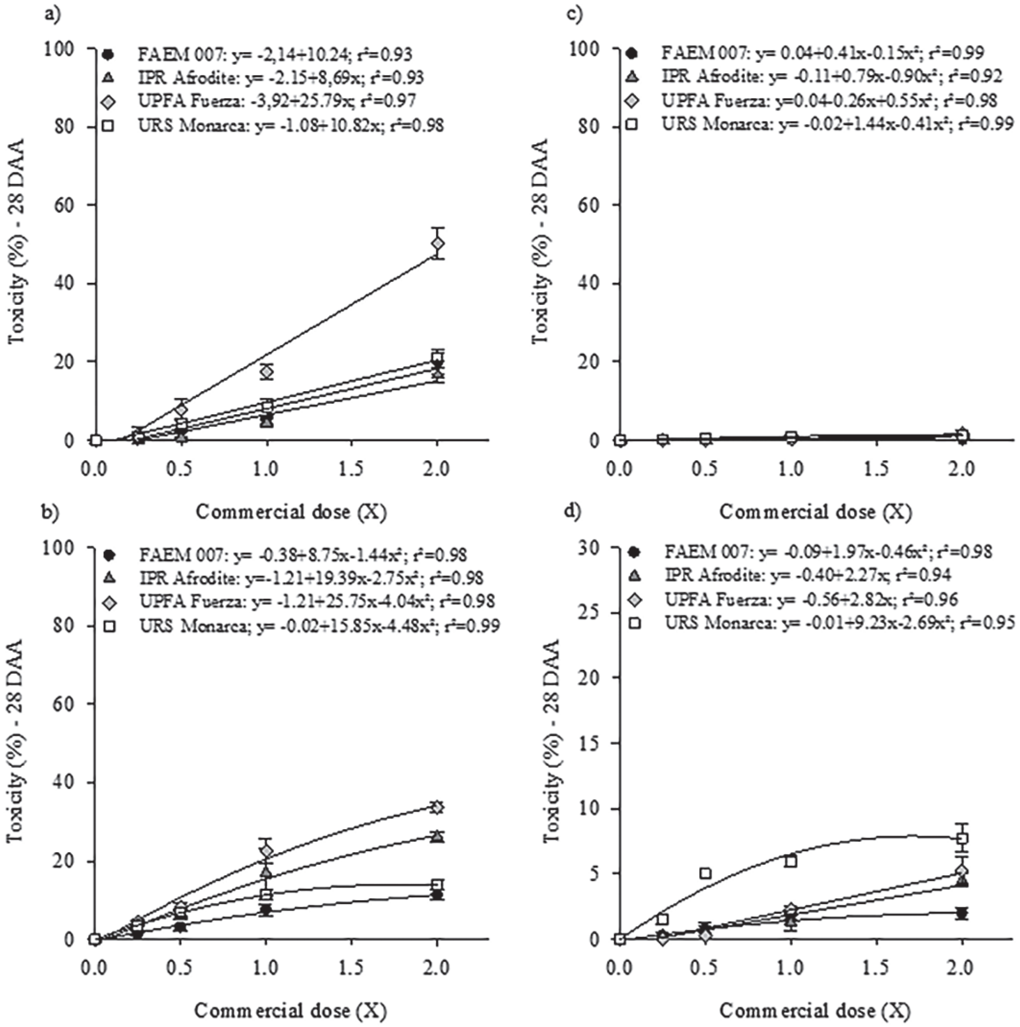

Fig. 6. Toxicity symptoms in oat cultivars based on mesotrione doses in the 2019 (a) and 2020 (b) season and tembotrione doses in the 2019 (c) and 2020 (d) season at 28 DAA. Vertical bars represent the standard error of the mean of each treatment
Source: Authors' own elaboration

For the dehulled index (DH), in 2019 and 2020 seasons, respectively, the cultivar URS Monarca had the highest DH (80.6% and 78.2%) and the lowest were FAEM 007 (72.9% and 73.4%) (Table 4).

The AVENACOR corresponds to the industrial yield of oat grains (IY) in oat flakes, and it was influenced by the cultivar and by the herbicide-dose interaction in both seasons (2019 and 2020). In 2019 and 2020 seasons, cultivar URS Monarca (4288 and 5124 kg ha^{-1} of caryopsis) and UPFA Fuerza (4669 kg ha^{-1} of caryopsis, only 2019) showed higher IY compared to other cultivars (Table 4). But, in both seasons was observed the herbicide-dose interaction for IY; in 2019, the maximum IY of 2911 kg ha^{-1} of caryopsis was achieved with 35.3 g a.i. ha^{-1} of mesotrione (Fig. 8b) and 3883 kg ha^{-1} of caryopsis with 53.8 g a.i. ha^{-1} of tembotrione. However, the reductions in comparison to the control treat-

Table 3. Thousand grain weight (TGW) and yield of four white oat cultivars in the average doses of mesotrione and tembotrione, for the 2019 and 2020 seasons

	2019 season		2020 season	
Cultivar	TGW	Yield	TGW	Yield
	(g)	(kg ha^{-1})	(g)	(kg ha^{-1})
FAEM 007	41.8 a	5276.1 b	39.5 a	6157.6 ^{ns}
IPR Afrodite	33.9 d	5362.6 b	34.5 c	6457.7
UPFA Fuerza	35.2 c	6844.9 a	36.6 b	6737.7
URS Monarca	37.7 b	5636.4 b	38.7 a	6812.3

Different lowercase letters differ from each other by Tukey's test ($p<0.05$); ns: non-significant ($p > 0.05$).
Source: Authors' own elaboration

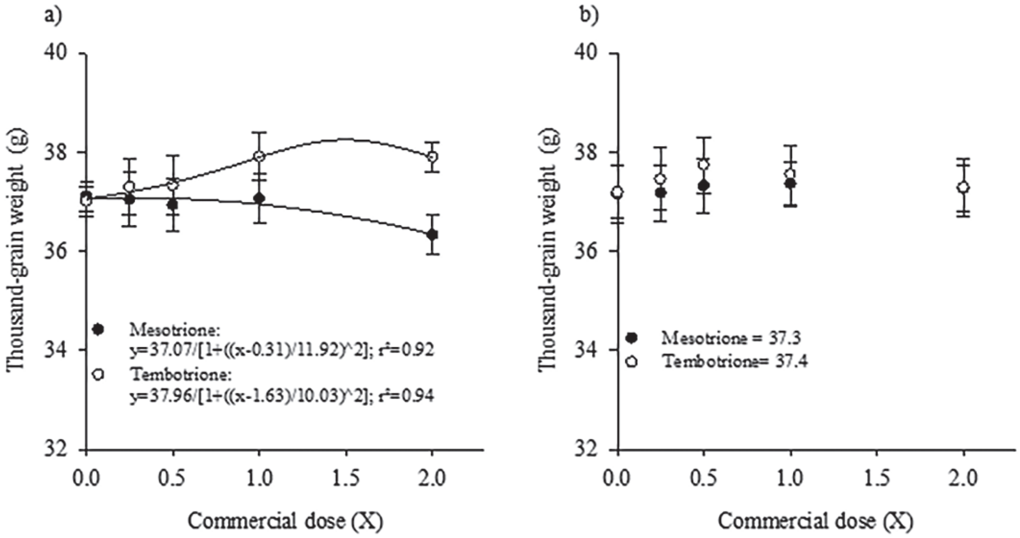

Fig. 7. Thousand grain weight (g) of white oat at the average doses of herbicides tembotrione and mesotrione in the 2019 (a) and 2020 (b) seasons. Vertical bars represent the standard error of the mean of each treatment
Source: Authors' own elaboration

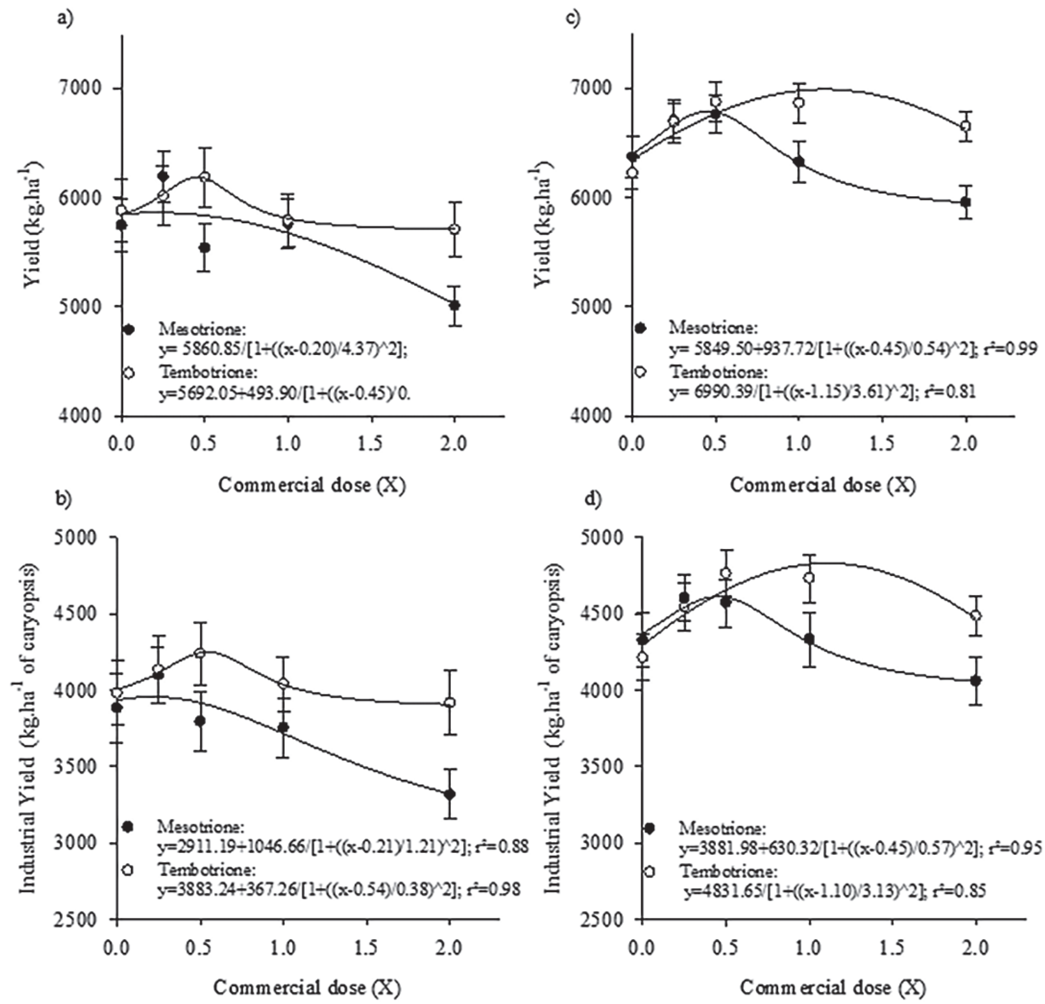

Fig. 8. Yield (kg ha^{-1}) of white oat based on herbicide doses, in the average of the cultivars in the 2019 (a) and 2020 (c) growing seasons and industrial yield – IY (kg ha^{-1} of caryopsis) of white oat on the basis of the doses of herbicides mesotrione and tembotrione in 2019 (b) and 2020 seasons (d), Lages-SC. Vertical bars represent the standard error of the mean of each treatment
Source: Authors' own elaboration

Table 4. Sieve grains (G > 2), hectoliter weight (HW), dehulled (DH) and industrial yield (IY) of four white oat cultivars according to the application of mesotrione and tembotrione in the 2019 and 2020 seasons

Cultivar	G>2 (%)	HW (kg hL^{-1})	DH (%)	IY (kg ha^{-1} of caryopsis)
	2019 season			
FAEM 007	88.9 c	46.3 b	72.9 c	3447.4 b
IPR Afrodite	82.0 d	46.9 b	75.5 b	3301.0 b
UPFA Fuerza	90.3 b	45.2 c	75.6 b	4669.3 a
URS Monarca	94.3 a	53.2 a	80.6 a	4288.1 a
	2020 season			
FAEM 007	86.7 c	50.9 b	73.4 c	3925.3 b
IPR Afrodite	91.2 b	52.1 b	74.7 b	4369.7 b
UPFA Fuerza	90.3 b	48.2 c	72.7 c	4435.9 b
URS Monarca	96.2 a	54.2 a	78.2 a	5123.7 a

Different lowercase letters in the column and uppercase in the row differ from each other by Tukey's test ($p < 0.05$).
Source: Authors' own elaboration

ment were due to the application of doses greater than 168 g a.i. ha^{-1} of mesotrione and 176 g a.i. ha^{-1} of tembotrione (Fig. 8b). The average IY values were higher in 2020 compared to 2019 season (Fig. 8b and 8d). In this season, the application of increasing doses of mesotrione resulted in a maximum estimate of IY at the dose of 75.6 g a.i. ha^{-1} with 4612 kg ha^{-1} of caryopsis, while the application of tembotrione resulted in an estimated maximum IY of 4832 kg ha^{-1} of caryopsis at a dose of 97 g a.i. ha^{-1} (Fig. 8d).

The variables related to yield and industrial quality of oat grains (G>2, HW, DH and IY) showed a similar behavior in both seasons, but with higher average values of treatments in 2020, when compared to 2019. Tembotrione showed lower levels of toxicity in oat cultivars and, consequently, a better performance in variables related to yield and industrial quality, when compared to mesotrione. The tested doses of both herbicides did not reduce the yield and industrial quality of oat grains in comparison to the control treatment, except for the 336 g a.i. ha^{-1} dose of mesotrione. Among the cultivars, URS Monarca stands out in the industrial quality-related variables, compared to the other cultivars tested.

Discussions

The symptoms of bleaching or albinism result from the application of the herbicides mesotrione and tembotrione, which inhibit HPPD – a key enzyme in the biosynthesis of tocopherol and plastoquinone (Beaudegnies et al., 2009; Godar et al., 2015). The application of these herbicides reduces the levels of tocopherol and plastoquinone, depleting carotenoids and, consequently, causing leaf bleaching and plant death by oxidative stress (Beaudegnies et al., 2009; Dankov et al., 2009; Wang et al., 2020).

The symptoms found at 7 DAA worsened at 14 DAA in all cultivars and herbicide doses tested in both seasons (Fig. 4 and 5). This behavior is due to the mechanism of herbicidal action, which inhibits the synthesis of new carotenoids after application, but without affecting previously formed

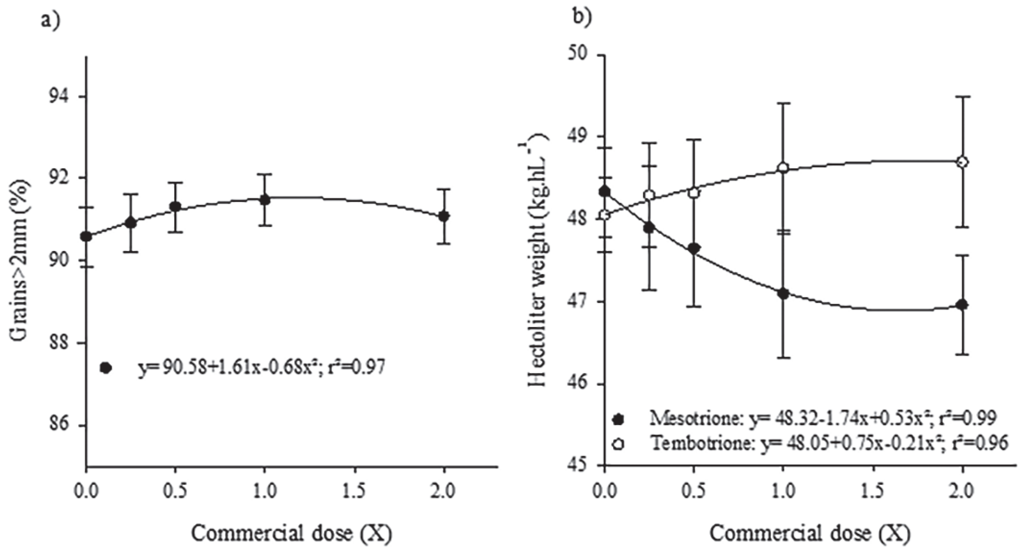

Fig. 9. Sieve grains (G>2) (%) based on the average herbicide doses in the 2020 season (a) and hectoliter weight (kg hL^{-1}) of white oat as a function of mesotrione and tembotrione doses (b) in the average of the cultivars in the 2019 season. Vertical bars represent the standard error of the mean of each treatment
Source: Authors' own elaboration

carotenoids (Dan Hess et al., 2000; Grossman and Ehrhardt, 2007; Hawkes, 2007). These data corroborate those reported by Teixeira et al. (2017) on sweet sorghum under increasing doses of tembotrione.

Unlike previous periods, at 21 DAA there was a reduction in herbicide toxicity symptoms for all doses of both herbicides in all cultivars (Fig. 6). This effect was intensified at 28 DAA (Fig. 7). Such detoxification effect is due to the production of new tissues without the presence of symptoms.

The production of new tissues without symptoms is an indication that the herbicides are not inhibiting the site of action. The pathway is reestablished and starts producing carotenoids again. This study has not evaluated the likely mechanisms of selectivity; however, the non-inhibition of the herbicidal site of action on the plant may be due to reduced translocation, and/or increased metabolism and/or compartmentalization of the herbicide by the plant (Délye et al., 2013). Mitchell et al. (2001) reported that this group of herbicides has a great capacity to recover the signals they cause in plants, owing to the rapid metabolism of HPPD through hydroxylation. The selectivity of HPPD-inhibiting herbicides in most crops is related to detoxification mechanisms by the action of cytochrome P450 (Ahrens et al., 2013). Lu et al. (2020), when investigating the resistance of wild radish (*Raphanus raphanistrum*) to HPPD inhibitors, used maize as a positive control to evaluate herbicide metabolism, and they found that tembotrione was rapidly and efficiently metabolized in non-toxic compounds, as opposed to what occurred in tembotrione-susceptible biotypes of wild radish, a fact previously reported by Karam et al. (2010).

Another factor that may increase tolerance to these herbicides is the rusticity and genetic diversity of the species. Matringe et al. (2005), Hawkes et al. (2016) and Dreesen et al., (2018) stressed that modified HPPD-resistant genes of *Pseudomonas fluorescens* and *Avena sativa* were used for developing HPPD inhibitor-resistant transgenic soybean (*Glycine max*). According to Kramer et al. (2014), the *avhppd-03* gene from oat encodes the p-hydroxyphenylpyruvate dioxygenase isoenzyme (*AvHPPD-03*), which has 99.7% sequence identity with the HPPD isoenzyme from *A. sativa*. This isoenzyme has reduced binding affinity for mesotrione; therefore, plants may have mild toxicity symptoms with subsequent recovery from injuries through their antioxidant mechanisms.

In both growing seasons, regardless of evaluation periods, doses and cultivars used, toxicity symptoms levels were higher in treatments with mesotrione compared to tembotrione. The application of tembotrione resulted in toxicity symptoms of less than 20% for doses in the tested cultivars, while mesotrione reached toxicity between 50 and 80% in the dose of 2x in the same cultivars. The lower levels of tembotrione toxicity may be a result of the addition of safener isoxadifen-ethyl in its commercial formulation, but the same did not occur for mesotrione. Ahrens et al. (2013) stressed that adding safeners to HPPD-inhibiting herbicides reduces crop toxicity symptoms without affecting weed control. These authors also pointed out that adding isoxadifen-ethyl to tembotrione in a 2:1 ratio can reduce by up to 55% the injury caused in maize, compared to tembotrione alone.

The tested white oat cultivars showed linear and quadratic responses to increasing doses of both herbicides in the 2019 and 2020 seasons, and their maximum estimate point of toxicity symptoms occurred at doses greater than 1x; they predominantly showed higher levels of toxicity symptoms at the tested dose of 2x – especially mesotrione. Wang et al. (2020) found that when the proposed dose of bipyrazone (HPPD inhibitor) was applied in sixteen wheat cultivars, there was a reduction of dry matter by 1 to 4%. When using twice as much this dose, dry matter was reduced from 6 to 14% in comparison to the control treatment. However, yerba mate under 0.0; 50.4; 100.8 and 201.4 g a.i. ha^{-1} of tembotrione showed no significant differences between levels of toxicity symptoms (De David et al., 2017). Therefore, dose is a key factor for selectivity.

Oat cultivars show differential toxicity symptoms at the doses of the study herbicides. Such a reaction can be attributed to the genetic diversity and intrinsic capacity of each cultivar to tolerate herbicides, since they come from different breeding programs. In Brazil, breeding programs for oats are recent when compared to other crops, which provides this species with wide genetic diversity and rusticity (Castro et al., 2012; Federizzi, 2014).

The high levels of toxicity symptoms resulting from herbicide application, particularly, the 2x dose of mesotrione, reduce the photosynthetically active area of the plant in the initial stages of development. This fact can affect the biological yield and the efficiency of the plant to convert photoassimilates into grains, thus reducing thousand grain weight (Fig. 8) and yield (Fig. 9). It is reported that when wheat is under shading, the photosynthetic dose is decreased; therefore, there are limitations in cell division and elongation, as well as decreased dry matter accumulation and grain filling (Fageria et al., 2006).

Yield was reduced by 12.8% and 6.0% compared to the control at the 2x mesotrione dose in 2019 and 2020, respectively, while treatments with tembotrione showed no reduction compared to the control (Fig. 8a, 8c). These results show that selectivity is dose and herbicide dependent. Tembotrione was tolerated at a higher dose, probably owing to the addition of safener isoxadifen-ethyl in its commercial formulation (Ahrens et al., 2013).

Cultivar URS Monarca stands out in terms of industrial grain quality in both seasons, regardless of treatment (Table 4). However, the herbicide-dose interaction affected hectoliter weight in the 2019 season (Fig. 9b). This variable is of paramount importance, because the higher it is, the better the classification of the product and the higher the market price because there is higher yield in the industry (Nunes et al., 2011).

HW was reduced by 3% when applying a 2x dose, compared to the control, but there was no significant difference for the other treatments (Fig. 9b) and in the 2020 season. High toxicity symptoms (greater than 20%), together with plant lodging at the end of the crop cycle, in 2019, may have reduced the photosynthetic dose of plants. In the study conducted by Torres et al. (2012), the application of tembotrione on sugarcane resulted in a lower photosynthetic dose and reduced water use efficiency for two cultivars, while there was no significant effect for the third cultivar when compared to the control. The reduction of the photosynthetic dose consequently leads to changes in the source-sink relationship of the plants (Asseng et al., 2017), thus reducing HW.

The AVENACOR corresponds to the industrial yield (IY) of flaked oat grains, and it was reduced by 14.5% (2019) and 6.1% (2020) at the 336 g a.i ha^{-1} (2x) dose of mesotrione in both seasons (Fig. 8b and 8d). This occurs because IY is estimated by a calculation that involves grain thickness, dehulled and yield. Yield was changed as a result of the treatments, and it is a very important component for industrial yield because, combined with the high percentage of caryopsis and husking efficiency, it results in a high industrial yield dose (Doehlert et al., 2009).

Based on the present results, the herbicides present selectivity to the white oat crop up to doses of 1x (168 g a.i. ha^{-1}) of mesotrione and 2x (176.4 g a.i. ha^{-1}) of tembotrione, respectively, without compromising the yield and industrial quality of grains of the tested cultivars. A similar dose (150 g a.i. ha^{-1}) of a new herbicide molecule called Pyrazole – Quinazoline-2,4-dione, belonging to the group of HPPD inhibitors, was considered as selective to wheat and maize by He et al. (2020). However, Wang et al. (2020) reported that pyrazole was tolerated by 16 wheat cultivars at a dose of 375 g a.i. ha^{-1} and 750 g a.i. ha^{-1}, which indicates selectivity of this herbicide to the wheat. The selectivity of HPPD inhibitors in winter crops at doses between 90 and 180 g a.i. ha^{-1} had previously been reported by Wang et al. (2015) and by Zhang et al. (2019), when testing new herbicide molecules developed in the laboratory.

Conclusions

Tembotrione up to 176.4 g a.i. ha^{-1} (2x the recommended dose for maize) and mesotrione up to 168 g a.i. ha^{-1} (1x) – applied at post-emergence of the crop – are selective to white oat; therefore, they do not change the yield and industrial quality of the grains.

Yield and industrial quality were dependent on the cultivar being used, especially UPFA Fuerza and URS Monarca, respectively.

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Author contributions

GPB and CAS planned the experiments, GPB, CAS, FFF and CC interpreted the results, GPB, CA and EFC made the write up and FFF and GPB statistically analyzed the data and made illustrations.

Conflict of interest

All authors declare no conflict of interest.

Data availability

Data presented in this study will be available on a fair request to the corresponding author.

Ethics approval

Not applicable to this paper.

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