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Physiological quality of oat seeds produced by plants treated with mesotrione or tembotrione

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Abstract

Selective herbicides may cause plant stresses as a result of changes in plant physiology or seed formation and development processes, thus affecting the quality of seeds. Thus, the aim of this study was to assess the effect of application of increasing doses of mesotrione or tembotrione on the physiological quality of white oat seeds from different cultivars. It is a field experiment carried out in two crop years (2019 and 2020), in a split split-plot randomized block design. The main plots consisted of the cultivars: FAEM 007, IPR Afrodite, UPFA Fuerza and URS Monarca. The subplots were mesotrione and tembotrione; and sub-subplots were doses of each herbicide: 0x;1/4x; 1/2x, 1x and 2 x (x= recommended commercial doses for maize, equivalent to 168.0 g a.i. ha^{-1} for mesotrione and 88.2 g a.i. ha^{-1} for tembotrione). Seed germination was 1% lower after application of the 2x dose of the herbicides, compared with control, i.e., there was a slight reduction in the germination of seeds produced in 2019. There was a significant effect of cultivar on germination and vigor. The cultivar UPFA Fuerza showed better performance than the other cultivars, with 96% germination index (GI) and 94% accelerated aging (AA) in 2019, while the best performance in 2020 was achieved by URS Monarca, with 98% GI and 97% AA. It was concluded that the oat seeds had high physiological quality in all treatments tested. The germination and vigor of oat seeds depended on the genotype being used, especially UPFA Fuerza (2019) and URS Monarca (2020), but they were not affected by the herbicides and doses tested.

Keywords: *Avena sativa* L; carotenoids; germination; herbicide; vigor.

Abbreviations: 2,4D_2,4-dichlorophenoxyacetic acid; AA_accelerated aging; a.i._active ingredient; Al_aluminum; ANOVA_analysis of variance; GI_germination index; ABRASEM_Associação Brasileira de Sementes e Mudas; AGROFIT_Informações sobre agrotóxicos fitossanitários registrados no Ministério da Agricultura, Pecuária e Abastecimento; ALS_acetolactate synthase enzyme; C1_seed category 1; C2_seed category 2; Ca_calcium; CEC_cation exchange capacity; CFB_Clima temperado com verão ameno e falta de estação seca; CONAB_Companhia Nacional de Abastecimento; CQFS_Comissão de Química e Fertilidade do Solo; CT_cold test; DEM_days from emergence to maturation; DSW_dry shoot weight; EC_electrical conductivity; EMBRAPA_Empresa Brasileira de Pesquisa Agropecuária; FAEM_Faculdade de Agronomia e Medicina Veterinária Eliseu Maciel; GSI_germination speed index; IPR_Instituto Agronômico do Paraná; ISTA_International Seed Testing Association; IWM_integrated weed management; K_potassium; MAPA_Ministério da Agricultura, Pecuária e Abastecimento; MCPA_2-methyl-4-chlorophenoxyacetic acid; Mg_magnesium; NI_Normative Instruction; OM_organic matter; P_phosphorus; RAS_Regras de Análises de Sementes; UFGRS-URS_Universidade Federal do Rio Grande do Sul; SL_seedling length; SDW_seedling dry weight; VI_vigor index.

Introduction

White oats (*Avena sativa* L.) are one of the major winter crops grown in southern Brazil, and they are widely used by the food industry for human nutrition (Pacheco et al., 2021). Oat production in Brazil increased in the 2020 crop year, yielding 850 thousand tons, while a total of 1080 thousand tons were expected in 2021 (Conab, 2021). In turn, the production of certified seeds in the country in 2020 reached approximately 27.2 thousand tons, with a rate of only 38% of certified seed use (Abrasem, 2021). However, to cultivate the Brazilian area, which corresponds to 400 thousand hectares (Conab, 2021), 40 thousand tons of seeds are required just to sow this area for production of oats.

Weed plants are among the factors that negatively affect the production of certified seeds and ultimately cause the exclusion of field areas from activities such as seed production or trading of white oat seeds (Normative Instruction no. 45 of Sept. 17, 2013). Therefore, weeds in oat crops are controlled by integrated weed management (IWM), combined with herbicide application (Fu et al., 2020; Kadam et al., 2021). Nevertheless, there is a small number of selective herbicides available for use in oat crops, owing to the absence of active ingredients for control of Liliopsida (Monocots); for Magnoliopsida (Dicots), only two mechanisms of action have been registered: one of ALS inhibitors (metsulfuron-methyl) and one of auxin-mimic herbicides (2,4 D and MCPA) (Agrofit, 2021). However, the successive use of few mechanisms of action is conducive to the selection of resistant biotypes (Gaines et al., 2020); for this reason, there is a need to identify new mechanisms of action selective to white oat crops. Carotenoid biosynthesis inhibitor herbicides offer a possible alternative (Bond et al., 2014; Schmitz et al., 2015); tembotrione and mesotrione, for example, were reported as being potential selective herbicides for winter cereals (Ahrens et al., 2013; Lindell et al. 2015; Schmitz et al., 2015; Ndikuryayo et al. 2017; Schmitz et al., 2018).

Selectivity depends on the physicochemical characteristics of the product being used, the soil and climate conditions at the time of application, genotype susceptibility, dose in use and plant development stage (Harrison et al., 1995; Oliveira Jr et al., 2011). It is noteworthy that a selective herbicide may cause direct and indirect effects on the growth and development of a crop (Agostinetto et al., 2016; Marchezan et al., 2017; Marchi et al., 2021).

Herbicides can interfere in the formation and development of seeds, affecting their germination and vigor (Albretcht et al., 2012). In this regard, Albrecht et al. (2010) found a negative effect on the vigor of wheat seeds after application of increasing doses of metsulfuron-methyl; Marchi et al. (2021) also reported negative outcomes in soybean after application of flumioxazin. But there is lack of information available on the effect of application of mesotrione or tembotrione on the physiological quality of white oat seeds produced. Thus, the aim of this study was to assess the effect of mesotrione or tembotrione applied at postemergence of white oat cultivars on the physiological quality of the oat seeds produced.

Results

Seed moisture and germination

There was a significant effect (P<0.05) for the interaction between cultivar, herbicide and dose for the variable seed moisture at harvest in the 2019 crop year, while for 2020, there was an effect only for cultivar. In 2019, the increasing doses of mesotrione resulted in a quadratic behavior for cultivar FAEM 007, and the maximum seed moisture at harvest estimated for the 1.35x dose of this herbicide was 18.5% (Figure 1a). The cultivars IPR Afrodite, UPFA Fuerza and URS Monarca, after application of increasing doses of mesotrione, exhibited an increasingly linear behavior, i.e., seed moisture at harvest was increased by 1.4%, 2.4% and 0.2%, respectively, for each gram of active ingredient (g a.i. ha^{-1}) applied (Figure 1a). The increased doses of tembotrione resulted in an average seed moisture of 13.9% for cultivar UFFA Fuerza, but for the other species, they exhibited a quadratic trend (Figure 1b). Cultivar FAEM 007 reached the minimum seed moisture at harvest estimated for the 1.6x dose (16%), while cultivars IPR Afrodite and URS Monarca exhibited the maximum moisture estimated for the 1.3x (17.3%) and 0.8x (15.3%) doses (Figure 1b). In 2019, for seed moisture at harvest, considering the simple effect of cultivar, FAEM 007 and IPR Afrodite exhibited a higher value, namely 17.1%, when compared with UPFA Fuerza and URS Monarca, which showed about 15% (Table 1). However, in 2020, cultivar IPR Afrodite exhibited a higher moisture percentage, i.e., 15.8%, when compared with the other cultivars, which had approximately 13% of moisture (Table 1).

There was a significant effect (P<0.05) of cultivar on the variables relating to the germination in the 2019 and 2020 crop years, and an effect of dose in the 2019 crop year. In 2019, UPFA Fuerza exhibited the highest seed germination (96%), while the other cultivars achieved 94% (Table 2). However, in 2020, the highest seed germination was found for URS Monarca (98%), and the lowest germination rate, for UPFA Fuerza (95%), while FAEM 007 and IPR Afrodite did not differ significantly from the other two cultivars, with 96% (Table 1). Seed germination was also influenced by the herbicide doses applied in the 2019 crop year, and the maximum estimated seed germination was 95% for the 0.5x dose for both herbicides tested (Figure 2a). There was a 1% reduction in comparison to control for application of the 2x dose (Figure 2a), but this percentage did not adversely affect seed quality. In 2020, seed germination was not affected by the different doses of herbicides being used, indicating a germination rate of 96% (Figure 2b).

Seed vigor

There was a significant effect (P<0.05) of cultivar, as shown by the accelerated aging (AA) in both crop years. In 2019, AA was divided into two vigor classes: the highest for UPFA Fuerza (94%), and the lowest for IPR Afrodite (91%) (Table 1). Cultivars FAEM 007 and URS Monarca, with 92%, did not exhibit a significant difference from the previous classes (Table 1). Similarly, in 2020, AA provided two vigor classes: the highest for URS Monarca and IPR Afrodite, with 97%, and the lowest for FAEM 007, with 94% (Table 1). In contrast, the cultivar UPFA Fuerza, with 95%, did not show a significant difference from the classes previously cited (Table 1).

Regarding electrical conductivity (EC), there was a significant effect (P<0.05) of cultivar in both crop years. In 2019, four levels of vigor resulted from the EC test: the highest for IPR Afrodite (33.1 µS cm^{-1} g^{-1}), followed by URS Monarca (43.8 µS cm^{-1} g^{-1}), UPFA Fuerza (62.6 µS cm^{-1} g^{-1}) and FAEM 007 (85.8 µS cm^{-1} g^{-1}) (Table 1). However, in 2020, three levels of vigor were found: the highest one for URS Monarca (43.7 µS cm^{-1} g^{-1}), followed by FAEM 007 (54.8 µS cm^{-1} g^{-1}) and IPR Afrodite and UPFA Fuerza, which did not differ from one another, with 71 µS cm^{-1} g^{-1} (Table 1).

For the vigor tests, namely cold test (CT), germination speed index (GSI), seedling length (SL), there was a significant effect (P<0.05) of cultivar only in the 2019 crop year (Table 2). The cold test was efficient in segregating oat cultivars into two groups of vigor in 2019: the highest one was found for FAEM 007 (95%) and UPFA Fuerza (95%), and the lowest one. for IPR Afrodite (93%), while URS Monarca (94%) showed no significant difference from the other groups (Table 2).

With the result of the germination speed index in 2019, two groups of vigor could be formed: the first group (higher vigor) was made up of IPR Afrodite (11.3), UPFA Fuerza (10.9) and URS Monarca (10.5) while the second group (lower vigor) was composed of FAEM 007 (9.5) (Table 2).

As for the seedling performance tests in 2019, two groups of vigor were formed for seedling length (SL): the group with greater vigor was formed by FAEM 007 (23.8 cm), IPR Afrodite (24.1 cm) and UPFA Fuerza (24.8 cm) and the group with lower vigor included UPFA Fuerza (21.5 cm) (Table 2). For SDW, however, there was a significant effect (P<0.05) in 2019 and 2020 crop years (Table 2). The SDW in 2019 provided two levels of vigor: the highest one was formed by cultivars FAEM 007 (22.5 mg), UPFA Fuerza (21.6 mg), and URS Monarca (23.5 mg) while the group with the lowest vigor was formed by IPR Afrodite (19.3 mg). Similarly, in 2020, two levels of vigor were found: the highest one was formed by FAEM 007 (21.3 mg) and URS Monarca (19.6 mg), and the group with the lowest vigor was formed by IPR Afrodite (14.6 mg), but UPFA Fuerza (18.1 mg) did not differ from the others (Table 2).

There was a significant effect (P<0.05) of cultivar on vigor index (VI) of seeds produced in both crop years. In 2019, UPFA Fuerza exhibited the highest VI (1231), while the VI of the other cultivars tested did not differ from one another (Table 3). In 2020, however, URS Monarca achieved the highest VI (2430), while FAEM 007 (2288) and UPFA Fuerza (2322) exhibited the lowest VI (Table 3).

Discussion

Seed moisture and germination

In both crop years, seed moisture levels at harvest were within the recommended limits (13 to 18%) for oat crops, ranging from 13.5% to 18.0% in 2019 (Figure 1) and between 12.5 and 15% in 2020 (Table 1). Harvesting oat seeds with the ideal moisture content is crucial to prevent mechanical damage caused by excess of moisture (crushing) or excessive drying (impacts and abrasion). Mechanical injuries caused by seed moisture may affect the physiological potential, physical purity and health of seed lots (Marcos Filho, 2015).

The application of herbicides caused injuries to the plants' leaves. The injuries increased as the herbicide doses increased, and they were greater in the treatments with mesotrione. Nonetheless, the plants started to recover at 14 days after application of the treatments, exhibiting new tissues without signs and symptoms of injury. The plants' life cycle continued as usual and enabled the use of seeds in the present study (data not shown).

In this regard, Negrisoli et al. (2004) underlined that while there are herbicides that affect yields and the final quality of crop products without causing visible injury symptoms, others cause injuries that are recoverable and do not affect yields or the quality of grains and seeds. Therefore, herbicide selectivity should be assessed not only on the basis of visible injuries and yields, but also by considering the quality of the harvested product, including the physiological quality of the seeds produced.

During observations of the climate conditions in the growing seasons when the seeds were produced and harvested, there was a higher cumulative rainfall rate in 2019, compared with 2020 (Figure 3), particularly during the plant reproductive stage. Such climatic factors, combined with strong winds occurring in 2019, resulted in oat plant lodging – an outcome which did not occur in 2020. Several factors can influence the physiological quality of seeds, e.g., genotype, climate conditions, nutrition, diseases and pests, crop growing practices, mechanical damage, deterioration and seed size (Pádua et al., 2010; Carvalho et al., 2012; Zucareli et al., 2014). Lodging affects plants by limiting their access to sunlight, thus impairing photosynthesis and increasing the likelihood of diseases (Ingver et al., 2010; Packa et al., 2015); also, it leads to uneven seed moisture contents at harvest, as found in 2019. Seed moisture levels were influenced by the cultivar, herbicide and doses tested (Figure 1). Orthodox seeds that remained in the field after physiological maturity may show marked variations in moisture levels as result of climate fluctuations at the end of the cycle (Marcos Filho, 2015), especially when plants are lodged. In contrast, in 2020, only the effect of cultivar was found to occur on seed moisture at the time of harvest (Table 1).

The effect of cultivar on harvest seed moisture is directly related to cultivar life cycle, as can be seen for IPR Afrodite, with a total cycle of 126.1 days from emergence to maturation (DEM); UFPA Fuerza, with 125.2 days; FAEM 007, with 124 days; and URS Monarca, with 116.5 days (Danielowski et al., 2021). DEM have an impact on the speed of development and maturation of seeds at the end of the cycle.

The physiological attributes that determine seed quality include germination and vigor (Peske et al., 2012). Concerning the germination of white oat seeds, the Normative Instruction no. 45 of Sept 17, 2013 establishes a minimum germination rate of 80% for trading oat seed lots (Brasil, 2013). Thus, regardless of cultivar, herbicide and dose, the seeds had a high germination rate (G>94%) and met the quality standards defined by NI 45/2013 in both crop years, i.e., a germination rate equal to or over 80% for seeds of categories C1 and C2 (Table 1).

Spraying the 2x dose of the herbicides mesotrione or tembotrione reduced seed germination by 1% compared with the control treatment (95%) (Figure 2), in 2019; this response was not found in 2020, when only the cultivar effect (P>0.05) (Table 1) occurred. The slight reduction in germination reported in 2019 did not compromise the germination of seeds, whose rate was 94% (Table 1).

These results corroborate the ones reported by Albrecht et al. (2010), who found that increasing doses of metsulfuron-methyl (0 to 12 g ha^{-1}) sprayed on wheat crops at the vegetative and reproductive phases did not affect seed germination. Similarly, soybean seeds from plants treated with flumioxazin did not exhibit changes in germination rates (Marchi et al., 2021). Soybean seeds from plants treated with glyphosate alone and combined with clethodin, lactofem, chlorimuron, fluazifop and cloransulam also showed no significant difference in seed germination (Silva et al., 2018). In contrast, in a study conducted by Albrecht et al. (2012), increasing doses of glyphosate (0, 1440 and 2880 g ha^{-1} acid equivalent) applied on soybean crops at the developmental stages V6 and R2 linearly reduced seed germination.

Considering the oats assessed, cultivars UPFA Fuerza (96%) and URS Monarca (98%) exhibited a higher germination rate in 2019 and 2020, respectively (Table 1). However, it should be noted that the other cultivars achieved germination rates between 94% and 96% in both crop years (Table 1). Such white oat cultivars have an aptitude to produce grains - a fact that indirectly favors the production of quality seeds. After all, modern white oat cultivars developed by plant breeding provided an increase of grain yield ant quality, resulting in higher industrial yields. One of the characteristics appreciated by the industry of oat flakes is the high percentage of grains>2mm-sized, combined with the dehull index.

Seed size and weight may affect germination and vigor (Araújo Neto et al., 2014). According to Carvalho et al. (2012), larger seeds may have had good nutrition during their development, and probably have well-formed embryos with greater amount of reserve substances, resulting in better germination and vigor. Padilha et al. (2020) and Ehrhardt-Brocardo et al. (2022) argued that seeds with greater vigor have higher mobilization and use of seed reserves for the seedlings, which favors the development of vigorous seedlings.

Seed vigor

Seed vigor is also associated with physiological attributes. Vigor is measured by several tests which are aimed at

Table 1. Seed moisture (SM) percentage at harvest, germination index (G), Accelerated aging (AA) and Electrical Conductivity (EC) of white oats for the cultivars assessed at the average spray rate of mesotrione and tembotrione, in the 2019 and 2020 crop years, in Lages, SC.

	2019 crop year						
Cultivar	SM	G		AA		EC	
	(%)	(%)		(%)		(µS $cm^{-1}g^{-1}$)	
FAEM 007	17.1 a	94	b	92	ab	85.8	d
IPR Afrodite	17.1 a	94	b	91	b	33.1	a
UPFA Fuerza	14.8 b	96	a	94	a	62.6	c
URS Monarca	15.0 b	94	b	92	ab	43.8	b
	2020 crop year						
FAEM 007	12.7 b	96	ab	94	b	54.8	b
IPR Afrodite	15.8 a	96	ab	97	a	71.0	c
UPFA Fuerza	13.7 b	95	b	95	ab	71.0	c
URS Monarca	12.5 b	98	a	97	a	43.7	a

The same letters in the column do not differ from one another by Tukey's test at 5% probability.

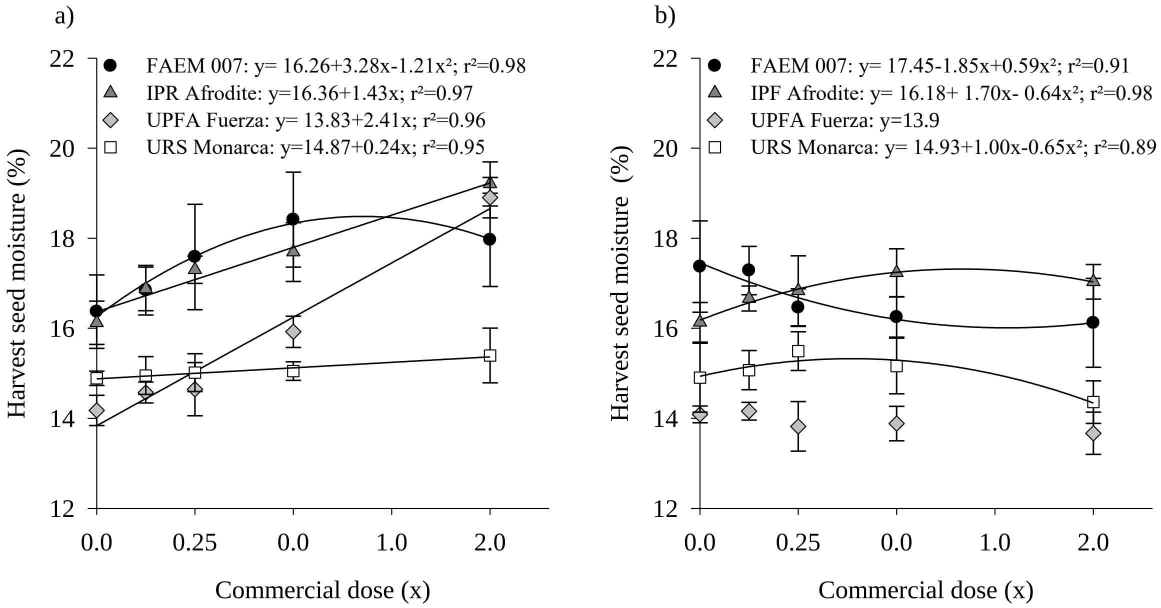

Fig 1. Seed moisture of oat cultivars at harvest as a result of doses of mesotrione (a) and tembotrione (b) sprayed in the 2019 crop year in Lages, SC. The vertical bars represent the standard error of the mean of each treatment.

Table 2. Cold test (CT), germination speed index (GSI), seedling length (SL) and shoot dry weight (SDW) of white oat cultivars, at the average spray rate of mesotrione and tembotrione, in the 2019 and 2020 crop years, in Lages, SC.

	2019 crop year							
Cultivar	CT		GSI		SL		SDW	
	(%)				(cm)		(mg)	
FAEM 007	95	a	9.5	b	23.8	a	22.5	a
IPR Afrodite	93	b	11.3	a	24.1	a	19.3	b
UPFA Fuerza	95	a	10.9	a	24.8	a	21.6	a
URS Monarca	94	ab	10.5	a	21.5	b	23.5	a
	2020 crop year							
FAEM 007	97	ns	10.9	ns	23.9	ns	21.3	a
IPR Afrodite	96		11.3		24.6		14.2	b
UPFA Fuerza	96		10.7		24.4		18.1	ab
URS Monarca	96		10.2		24.8		19.6	a

The same letters in the column do not differ from one another by Tukey's test at 5% of probability.

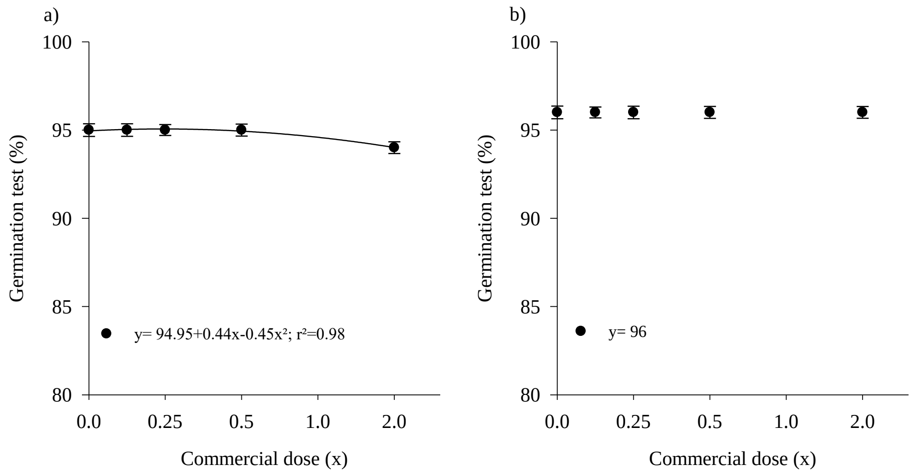

Fig 2. Germination (%) as a result of the herbicides doses sprayed, considering the average value of the oat cultivars, in the 2019 crop year (a) and the 2020 crop year (b), in Lages, SC. The vertical bars represent the standard error of the mean value of each treatment.

Table 3. Vigor index (VI) of white oats of different cultivars at the average spray rate of mesotrione and tembotrione, in the 2019 and 2020 crop years, in Lages, SC.

Cultivar	2019 crop year	2020 crop year
	VI	VI
FAEM 007	1074 b	2288 b
IPR Afrodite	1090 b	2370 ab
UPFA Fuerza	1231 a	2322 b
URS Monarca	1005 b	2430 a

The same letters in the column do not differ from one another by Tukey's test at 5% of probability.

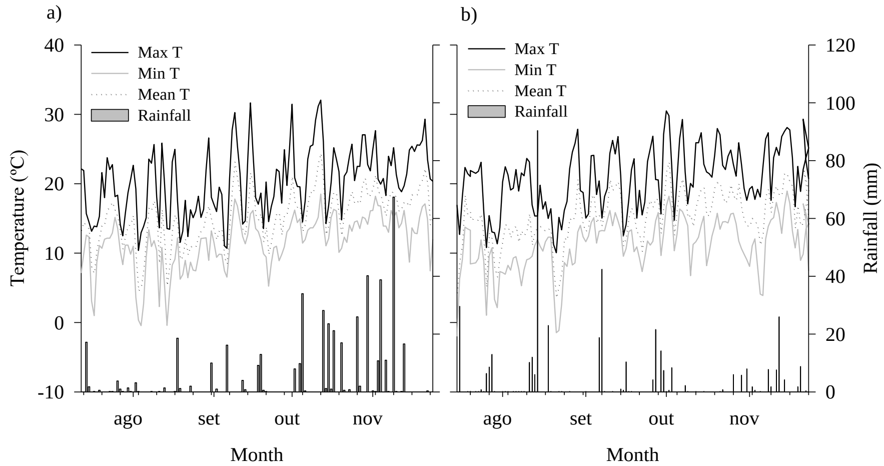

Fig 3. Rainfall, maximum, minimum and mean air temperature (daily) in the period from oat sowing to harvest for the experiment in the 2019 (a) and 2020 (b) crop years. Source: *Inmet (2019 and 2020).*

assessing the performance of seed lots under environmental conditions that are not ideally suitable for the germination of the species (Ista, 2014). Moreover, such tests may reveal significant differences in the physiological potential of seed lots with similar germination (Marcos Filho, 2015).

There were no changes to seed vigor on the basis of the doses and herbicides tested; it was only influenced by oat cultivar (Tables 1, 2 and 3). Contrary to the findings of the present study, a previous study reported that the application of different doses of glyphosate on soybean crop linearly reduced seed vigor (Albrecht et al., 2012). Similar results were found in the study by Marchin et al. (2021), in which flumioxazin sprayed on the mother plant resulted in soybean seeds with the lowest vigor, as shown by the tetrazolium and the electrical conductivity test. However, Silva et al. (2018) did not find alterations in the vigor of soybean seeds from plants treated with glyphosate and combinations (clethodin, lactofen, chlorimuron, fluazifop and cloransulam), based on the first germination count of seeds produced in two consecutive years. Albrecht et al. (2010) found reduced vigor (first count) in wheat seeds from plants treated with increasing doses of metsulfuron-methyl in the plant reproductive phase in 2008 - a fact that did not occur again in 2009. According to the authors, this seed behavior is related to the prevailing environmental conditions in the crop area and growing seasons.

The vigor tests used in the present study, e.g., accelerated aging (AA), electrical conductivity (EC) and vigor index (VI) were efficient in segregating white oat cultivars in 2019 and 2020 (Table 1). The cold test (CT), germination speed index (GSI), seedling length (SL) and dry shoot weight (DSW) tests segregated cultivars into different groups of vigor only in 2019 (Table 2). The AA test measures the tolerance of seeds to high air humidity and temperature (41 to 45 ºC), and such exposure enhances seed deterioration in several species (Marcos Filho, 2015). Thus, seeds that exhibit higher vigor achieve superior germination after this procedure (Vieira et

Seeds that are less vigorous (or more deteriorated) according to the EC test, have lower speed of restoration of cell membrane integrity during imbibition; consequently, they release a greater number of solutes to the exterior, which results in a higher electric conductivity value (Vieira et al., 1999). Sponchiado et al. (2014) indicated that EC is efficient for use in white oats, and it can be used for assessing the physiological potential of oat seeds. The cultivar UPFA Fuerza exhibited greater vigor compared with other cultivars for AA, VI, CT, GSI, SL and DSW in 2019 (Table 1 and 2), while URS Monarca exhibited higher vigor according to the VI, AA, EC and DSW in 2020 (Table 1). For oats, no test to date is considered as entirely standardized to assess vigor, for example, for soybean (Marcos Filho, 2015). However, there are various tests that enable consistent differentiation between high- and low-vigor lots of oat seeds (Sponchiado et al., 2014). The present results show the high physiological quality achieved by the seeds in the experiments (Table 1 and 2), which results from: (i) lack of interference from the herbicides; (ii) use of seeds from genetic category obtained directly from breeders; (iii) adoption of crop growing practices that are suitable for in-field cultivation of oats (Lângaro et al., 2014); (iv) standardization of moisture levels immediately at harvest and (v) use of an adequate process breaking for seed dormancy prior to the seed evaluations.

So far, few studies have assessed the physiological quality of seeds produced from herbicide-treated plants. However, selective herbicides, when applied on the mother plant, are considered to be plant stressors (Agostinetto et al., 2016; Marchezan et al., 2017; Marchi et al., 2021). Although they may not affect a given crop, they can affect the processes of formation and development of seeds (Albrecht et al., 2012; Marchi et al., 2021). Taken together, the results point to a reduction in seed quality around 1% on germination, when compared to the control, owing to the herbicides doses applied. The treatments may minimally affect the physiological quality of the seeds, but they do not affect the performance of seed lots. This suggests that both active ingredients can be indicated as safe for use in white oat crops, considering the target weed plants and their development stage; in addition, the application method and doses previously considered as efficient in weed control in maize crops can also be used in white oat crops.

Materials and methods

Characterization of the experiment site

The seeds were produced under field conditions in the municipality of Lages-SC, at coordinates 27° 52’ South latitude, 50° 18' West longitude, and mean altitude of 930 m, during the 2019 and 2020 crop years. The climate in the region, according to the Köppen classification, is Cfb (temperate climate with mild summers). Figure 3 shows the climate data (maximum, medium and minimum temperatures, and rainfall) in Lages during the periods of conduction of the study.

The soil in the experimental area is classified as 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 $cmol_c\ dm^{-3}$; O.M.= 6.6% and Clay = 27%.

Conduction of study and experimental design

Prior to sowing, the seeds (C1 category) were treated with fipronil + pyraclostrobin + thiophanate-methyl (Standak Top®), and sowed mechanically in a non-tillage system (the previous crop was soybean) on July 12, 2019 and July 15, 2020, using 350 suitable seeds per m². Each plot consisted of five 5.0-m long rows with inter-row spacing of 0.2 m and spaced 0.5 m apart from each other plot. A total of 400 kg ha^{-1} of NPK (N-P_2O_5-K_2O) formulation 5-20-10 was used for fertilization. After emergence, side-dressing nitrogen fertilization (45 kg ha^{-1} of N) was performed twice, split at the plant stages of tillering (first) and stalk elongation (second), as recommended by the Soil Chemical and Fertility Commission (“*Comissão de Química e Fertilidade do Solo*” - CQFS, 2016) for a production potential of 5 t ha^{-1} of grains.

The experiment was conducted in a randomized block design (RBD) arranged in split-split-plots with four replications per treatment. The main plot consisted of four oat cultivars: FAEM 007, IPR Afrodite, UPFA Fuerza and URS Monarca. The split-plots consisted of the herbicides mesotrione (Callisto®) and tembotrione (Soberan®), and the split-split-plot contained the herbicide doses applied, as follows: 0x (control, without herbicide application); 1/4x, 1/2x, 1x and 2x, where x corresponds to the commercial dose recommended for maize crops. Mesotrione doses corresponded to 0; 42; 84; 168 and 336 g a.i. ha^{-1} and tembotrione doses were 0.0; 22.1; 44.1; 88.2 and 176.4 g a.i. ha^{-1}.

Application of the herbicides was conducted when 50% of the plants exhibited 3-4 fully expanded leaves (on Aug 14, 2019 and Aug 17, 2020, respectively), using a CO_2-pressurized backpack sprayer (Herbicat, Brazil). The other phytosanitary managements (fungicide and insecticide applications) were carried out following the technical recommendations for cultivation of white oats (Lângaro et al., 2014).

Traits measured

At harvest (Nov 25, 2019 and Nov 23, 2020), seed moisture content (on a wet basis) was determined by using a sample collected from the split-split-plot area (5 m²), following the oven method proposed by the Brazilian Rules for Seed Testing (*Regras de Análises de Sementes-RAS*) (Brasil, 2009).

The seeds were then placed in an air circulation oven at 35 ºC to standardize their moisture content to 13%, and then they were kept for 30 days in a cold chamber (10±2 ºC and RH 50%) to prevent accelerated aging (Coelho et al., 2007) until the conduction of the tests. The oat seeds underwent a treatment for seed dormancy breaking, using the preheating method (Brasil, 2009). The seeds were subjected to the following tests:

Germination test

Carried out with four replicates of 100 seeds arranged in Germitest® paper rolls moistened with distilled water at the rate of 2.5 times the dry paper weight. The paper rolls were placed vertically in a germinator set at 20±1 °C. Normal seedlings were counted at the 10th day after sowing, following the Brazilian Rules for Seed Testing (“*Regras de Análises de Sementes-RAS* ”) (Brasil, 2009).

Cold test

Carried out with four replicates of 100 seeds per treatment, arranged in Germitest® paper rolls moistened with a quantity of water equivalent to 2.5 times the dry weight of the substrate. The rolls were placed into plastic bags to prevent moisture loss and maintained in a BOD chamber at 10 °C for seven days (Krzyzanowski et al., 1999). After this period, the seeds were transferred to a germinator and maintained at 20±1 °C for seven days. After that, vigor was determined by the cold test for quantification of normal seedling percentage.

Accelerated aging

The test used transparent germination boxes with a lid (11x11x3.5 cm), containing an aluminum wire mesh suspended inside, on whose surface the seeds were arranged to form a single layer. A total of 40 mL of distilled water was poured onto the bottom of the container, which was then covered and maintained in a BOD chamber at 41 ºC for 48 h (Tunes et al., 2008). After the aging period, seed moisture content was determined by the oven method at 105±3 ºC for 24 h (Brasil, 2009). Afterwards, the seeds were arranged in Germitest® paper moistened with a quantity of water equivalent to 2.5 times the dry weight of the substrate and kept in a germinator at 20±1 °C. At the fifth and tenth days after assembling the test, normal seedling percentage was determined to measure seed vigor by the accelerated aging test.

Electrical conductivity

Measured using the mass system with four replicates of 50 seeds per treatment. Seed mass was determined by placing the seeds in plastic cups with 75 mL of distilled water and maintained them at a temperature of 25 ºC. After 24 h of soaking, the electrical conductivity of this solution was determined by using a conductivity meter, and the results were expressed in $\mu S\ cm^{-1}\ g^{-1}$ (Vieira et al., 1999).

Emergence Speed Index (in sand)

the index was determined in a greenhouse environment with four replicates of 50 seeds per treatment, sown at a depth of 3 cm. The sand was previously washed and placed in plastic trays. Moisture was maintained with irrigations as needed. The number of emerged seedlings was assessed on a daily basis after sowing until the number of emerged plants remained stable. The index was calculated according to the formula proposed by Maguire (1962): $GSI = G1/N1 + G2/N2 + ... + Gn/Nn$, where: GSI = Germination Speed Index; G1, G2, Gn = number of seedlings emerged in the first, second and last count and N1, N2, Nn = number of days since the first, second, etc. until the last count.

Seedling length

Four replicates of 20 seeds were sowed in the upper third portion of Germitest® paper moistened with distilled water at the rate of 2.5 times the weight of dry paper. The paper rolls containing the seeds were kept in a germinator for seven days at 20±1 °C. With the aid of a millimeter rule, ten randomly chosen normal seedlings were measured, and the results were expressed in centimeters (Nakagawa, 1999).

Shoot dry weight

Ten normal seedlings were used for measuring seedling length. They were placed in a paper bag and dried in an oven at 60±3 ºC to constant weight; afterwards, they were weighed on a semi-analytical balance (precision of 0.001 g), and the results were expressed in mg $plant^{-1}$ (Nakagawa, 1999).

Vigor index

Calculated according to the method of Abdul-Baki et al. (1973), through the equation: VI = germination (%) x seedling length (cm).

Statistical analysis

Data were tested according to the assumptions of the analysis of variance (normality and homogeneity); when these assumptions were met, the data underwent the ANOVA F-test ($P<0.05$). When significant, they were split by Tukey’s test ($P<0.05$) for qualitative treatments, and regression analysis was performed for the quantitative treatments ($P<0.05$).

Conclusions

The application of increasing doses of mesotrione or tembotrione herbicides did not affect the germination and vigor of white oat seeds, but the safe dose for post-emergence application is 168 g a.i. ha^{-1} for mesotrione or 88.2 g a.i. ha^{-1} for tembotrione in production fields of white oat seeds. Of the four study cultivars, better seed physiological performance was achieved with UPFA Fuerza and URS Monarca in the 2019 and 2020 crop years, respectively.

The sampled oat seeds exhibited high germination and vigor rates, namely over 94%, regardless of herbicide or dose applied on the plants, cultivars or crop years.

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