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Selectivity and efficacy of herbicides applied on barley for weed control

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ABSTRACT: Ryegrass and turnip are weeds that cause high yield losses when infesting barley, thus requiring adequate management. In this context, the aim of this study was to evaluate the selectivity of different herbicide treatments and weed control in the barley crop, cultivar BRS Cauê. Two field experiments were conducted in randomized blocks, with four replications. The treatments used were: pendimethalin (800 g·ha^{-1}), sulfentrazone + diuron (175 + 350 g·ha^{-1}), and imazaquim (150 g·ha^{-1} of a. e.) applied pre-emergence; and iodosulfuron (3.5 g·ha^{-1}), pyroxsulam (18 g·ha^{-1}), metsulfuron-methyl (3.96 g·ha^{-1}), 2,4-D (670 g·ha^{-1} of a. e.), clodinafop-propargyl (48 g·ha^{-1}), bentazon + imazamox (600 + 28 g·ha^{-1}), saflufenacil (49 g·ha^{-1}), bentazon (720 g·ha^{-1}), carfentrazone-ethyl (120 g·ha^{-1}), and imazamox (42 g·ha^{-1}) applied post-emergence, with two controls (one weeded and the other infested). The use of the herbicide imazaquim caused high levels of phytotoxicity in barley. Gas exchange was less responsive to herbicide applications in relation to barley phytotoxicity and productivity. Clodinafop-propargil showed the best control of ryegrass, while the herbicides iodosulfuron, pyroxsulam, metsulfurom-methyl, 2,4-D, bentazon + imazamox, saflufenacil, bentazon, carfentrazone-ethyl, and imazaquim showed high efficiency in the control of turnip species. Imazaquim caused reduction of up to 74.7% in barley grain yield. On the other hand, iodosulufuron and piroxsulam allowed the highest grain yields of the barley cultivar, BRS Cauê, by promoting partial control of ryegrass and total control of turnip species, followed by clodinafop-propargyl and metsulfuron-methyl, which controlled ryegrass and turnip, respectively, allowing an increase in yield grain in relation to the infested control.

Key words: *Hordeum vulgare*, *Lolium multiflorum*, *Raphanus raphanistrum*, *Raphanus sativus*.

INTRODUCTION

Barley (*Hordeum vulgare* L.) is a crop that easily adapts to different conditions, growing in regions with subarctic to subtropical climates, and in irrigated or dry land areas. Occupying the fifth position of economic importance, barley stands out among the most produced grains in the world (FAO 2022). Its uses include human and animal food, in addition to being an important raw material for the brewing industry due to the superiority of its malt (Hong and Zhang 2020).

The Brazilian average productivity of barley grains is 3.81 t·ha^{-1}, which is far below those obtained in experimental areas or in crops that adopt high technologies (CONAB 2022). Among the probable causes for this low productivity, we can highlight the interference caused by weeds, which compete with the crop for environmental resources, such as water, light, and nutrients (Pies et al. 2019, Galon et al. 2022). Weed infestation can also cause severe allelopathic effects or host pests and diseases (Tironi et al. 2014, Pies et al. 2019, Nichelati et al. 2020), which can result in a decrease in barley grain yield of up to 78% (Mahajan et al. 2020).

Thus, weed management is one of the cultural practices that need to be used efficiently to achieve high yields and high-quality barley grains. The use of herbicides is the main method of controlling weeds that infest barley crops, such as ryegrass (*Lolium multiflorum* L.) and turnip species (*Raphanus raphanistrum* L. (RAPRA) and *Raphanus sativus* L.), due to their practicality, efficiency and lower cost when compared to other control methods (Tironi et al. 2014, Balem et al. 2021). There are few herbicides registered for the control of weeds in barley, such as 2,4-D, 2,4-D + picloran, and metsulfuron-methyl for post-emergence application (AGROFIT 2022). However, it is known that these herbicides (2,4-D and metsulfuron-methyl) are effective in controlling *R. raphanistrum*, but do not control the incidence of *L. multiflorum*. Thus, alternative strategies to control barley weeds are of paramount importance to minimize the damage caused by competitiveness, especially in barley producing areas that have a ryegrass and turnip seed bank.

Ryegrass is one of the weed species that most affects the productivity and grain quality in crops sown in winter in southern Brazil. This weed has morphophysiological characteristics very close to barley's ones, as they belong to the same botanical family, which indicates possible similar needs for environmental resources (Tironi et al. 2014, Pies et al. 2019, Galon et al. 2022). In addition, ryegrass has many cases of biotypes resistant to herbicide inhibitors of acetolactate synthetase (ALS), acetyl-coenzyme A carboxylase (ACCase), 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS) (Heap 2022).

Similarly, turnip species have caused high productivity losses in winter crops, including barley (Balem et al. 2021). In several countries, including Brazil, turnip species have shown several cases of resistance to herbicides, especially to ALS inhibitors, used for weed control when they are present in winter crops (Costa and Rizzardi 2014, Cechin et al. 2016).

Despite their importance for weed control, herbicides can cause direct and indirect effects on the crop's growth and development (Tironi et al. 2014, Barros and Calado 2020). These products can cause symptoms of intoxication, dysregulation of defense mechanisms, cellular oxidation, and changes in nutrient uptake, which can compromise crop yield components (Singh et al. 2011, Piasecki et al. 2017). Thus, in addition to ensuring effectiveness in controlling weeds, the herbicides used should not cause damage to crops. Also, special attention should be given to the growing cases of resistant biotypes of weeds infesting winter crops (Geier et al. 2011, Heap 2022).

Thus, it is important to evaluate new chemical tools for weed control and barley selectivity to ensure high productivity and enable the expansion of products that can be used in this crop. The objective of this work was to evaluate the selectivity and weed control of the barley cultivar BRS Cauê with the use of 13 different herbicide treatments, under field conditions.

MATERIAL AND METHODS

Field experiments were conducted in the experimental area of the Universidade Federal da Fronteira Sul (UFFS), in Erechim, RS, Brazil, from June to October 2018. The soil of the experimental area is classified as humic Aluminoferric Red Latosol (Santos et al. 2019). The sowing of barley, in both experiments, was carried out in a no-tillage system on June 15, 2018, 15 days after the desiccation of the vegetation with the herbicide glyphosate (1,080 $g{\cdot}ha^{-1}$ of a. e.). The two experiments were carried out in parallel, and the pH correction and soil fertilization were performed according to physical-chemical analysis (Table 1), following the technical recommendations for barley (CQFS 2016). NPK formulation 05-20-20 (330 $kg{\cdot}ha^{-1}$) and urea (120 $kg{\cdot}ha^{-1}$) were applied in the tillering stage and in the elongation, respectively.

Table 1. Chemical and physical traits of the soil.

pH (H_2O)	Organic matter (%)	Base saturation (V, %)	Clay (%)	Cation Exchange Capacity		H + Al ($cmol_c{\cdot}dm^{-3}$)
				t ($cmol_c{\cdot}dm^{-3}$)	pH = 7 ($cmol_c{\cdot}dm^{-3}$)	
5.1	3	53	60	7.4	16.6	7.7
P ($mg{\cdot}dm^{-3}$)	K ($mg{\cdot}dm^{-3}$)	Al^{+3} ($cmol_c{\cdot}dm^{-3}$)	Ca^{+2} ($cmol_c{\cdot}dm^{-3}$)	Mg^{+2} ($cmol_c{\cdot}dm^{-3}$)	Clay (%)	
5.2	118	0.3	5	3	60	

The experiments were carried out in a randomized block design, with four replications. Each experimental unit consisted of an area of 11.05 m^2 (5 × 2.21 m), in which the barley cultivar BRS Cauê was sown with a row spacing of 0.17 m and a final density of 300 plants·m^{-2}. Thirteen herbicide treatments were used, and three were applied pre-emergence: pendimethalin (800 g·ha^{-1}), sulfentrazone + diuron (175+350 g·ha^{-1}), and imazaquim (150 g·ha^{-1} of a. e.), and the others used in post-emergence: iodosulfuron (3.5 g·ha^{-1}), piroxsulam (18 g·ha^{-1}), metsulfuron-methyl (3.96 g·ha^{-1}), 2,4-D (670 g·ha^{-1} of a. e.), clodinafop-propargyl (48 g·ha^{-1}), bentazon + imazamox (600 + 28 g·ha^{-1}), saflufenacil (49 g·ha^{-1}), bentazon (720 g·ha^{-1}), carfentrazone-ethyl (120 g·ha^{-1}), and imazamox (42 g·ha^{-1}). Herbicide application was carried out with a precision backpack sprayer pressurized with CO_2, equipped with four DG 110.02 fan spray nozzles, under the constant pressure of 2 kgf·cm^{-2} and displacement speed of 3.6 km·h^{-1}, with a flow of 150 L·ha^{-1}. The environmental conditions at the time of pre- and post-emergence herbicide application in both experiments are described in Table 2.

Table 2. Environmental conditions at the time of herbicide application pre- and post-emergence of the barley crop, for both barley selectivity and weed control experiments.

Application period	Luminosity (%)	Temperature (°C)	Relative humidity (%)	Soil conditions	Wind speed (km·h^{-1})
Pre-emergence	100	4	80	Wet	4.5
Post-emergence	95	10	78	Wet	5

Experiment I

In the first experiment, the selectivity of barley to different herbicide treatments was verified. The treatments consisted of the application of 13 herbicide treatments mentioned above plus control without the use of herbicides, kept weeded. Pre- and post-emergence herbicides were applied one and 40 days after barley sowing, respectively. Post-emergent herbicides were applied when the barley was at the beginning of tillering, stage 2 of the BBCH scale (Bleiholder et al. 1991). Phytotoxicity, gas exchange, and yield components of the barley crop were evaluated.

The crop phytotoxicity of herbicide treatments was determined by assigning percentage scores from 0 to 100%, at seven, 14, 21, and 28 days after the application of treatments (DAT), according to the methodology described by Sociedade Brasileira da Ciência das Plantas Daninhas (SBCPD 1995). Gas exchange traits were performed at 55 DAT, in the middle third of the barley plants, using an infrared gas analyzer (IRGA, LCA PRO, Analytical Development Co. Ltd, Hoddesdon, UK) to determine the photosynthetic rate (A, μmol·m^{-2}·s^{-1}), stomatal conductance (g_s, mol·m^{-2}·s^{-1}), transpiration (E, mol·m^{-2}·s^{-1}), and internal CO_2 concentration (Ci, μmol·mol^{-1}). From these variables, it was possible to calculate the carboxylation efficiency (CE, A/Ci) and the water use efficiency (WUE, A/E). The evaluations were carried out between 8 and 11 a.m., for four days, with one block being evaluated per day, under ambient conditions of light, temperature, and relative humidity.

Barley yield components were performed at the end of the experiment, 125 days after sowing. The number of ears in a useful area of 0.25 m^2 located at the central point of each experimental unit was determined. Ear length, number of full grains, and number of sterile grains were evaluated on 10 ears of barley, randomly harvested in the center of each experimental unit. The ears were packed in paper bags and sent to the laboratory for Sustainable Management of Agricultural Systems at UFFS, Erechim, for evaluation.

Barley was harvested in a useful area of 4.5 m^2 per experimental unit when the grains reached 15% moisture, and the ears were then threshed with a plot thresher. The 1,000-grain weight (g) was estimated by weighing eight samples of 100 grains each on an analytical balance. To determine yield, grain moisture was adjusted to 13%, and yield data was extrapolated to kg·ha^{-1}. Environmental conditions observed during the experimental periods are shown in Fig. 1.

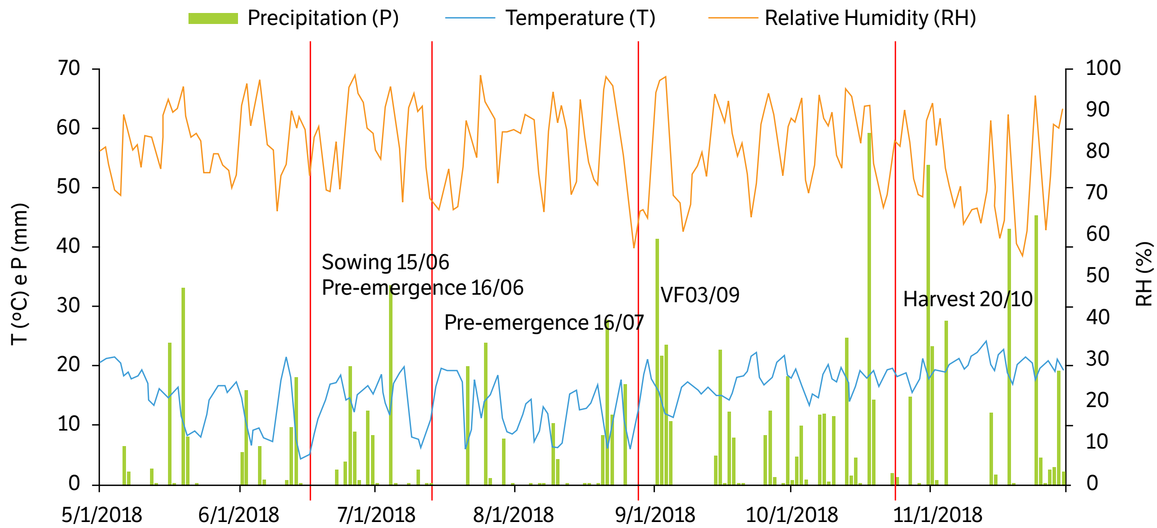

Figure 1. Average temperature (˚C), precipitation (mm), and relative humidity (%) during the experimental period.

Experiment II

In the second experiment, the control of weeds infesting barley was evaluated by the herbicide's application. The application of pre-emergent herbicides occurred one day after sowing the barley and the post-emergent ones, 40 days after sowing the crop, when the barley was at the beginning of tillering, and the turnip weeds (*R. raphanistrum* and *R. sativus*) and ryegrass (*L. multiflorum*) were in the stage of two to four leaves and two leaves and one tiller, respectively. In addition, two control treatments were carried out: one free of weeds (weeded) and another infested. Prior to the application of post-emergence treatments, a population survey was carried out in the experimental area, which showed an average of 50 and 55 plants·m^{-2} of turnip species and ryegrass, respectively, from the soil seed bank.

The percentage of weed control and the yield components of barley plants were evaluated. The percentage of control of turnip and ryegrass was performed at seven, 14, 21, 28, and 35 DAT. Weed control was evaluated using a percentage score, with zero for treatments with no weed control and 100% for weed death, according to the SBCPD (1995). The yield components expressed by the number of ears, ear length, number of full and sterile grains, 1,000-grain weight (TGW), and grain yield were performed at the end of the experimental period, 125 days after sowing, using the same methodology described for the experiment I.

The data obtained were submitted to analysis of variance by the F test, and, when a significant effect was observed, they were submitted to the Scott-Knott test ($p < 0.05$) to compare the means of the treatments. Statistical analysis was performed using the SISVAR software, version 5.6 (Ferreira 2011).

RESULTS AND DISCUSSION

Herbicides selectivity in barley

In the first experiment, it was possible to verify the differential selectivity of 13 herbicide treatments through barley phytotoxicity, gas exchange, and yield components. The phytotoxicity evaluation performed on seven, 14, 21 and 28 DAT showed that the herbicides metsulfuron-methyl and bentazon presented low symptoms of injury to barley plants (< 3%), with no phytotoxicity at 28 DAT, in relation to the control (Table 3). Metsulfuron-methyl metabolism occurs by hydroxylation followed by conjugation with glucose, and its effect may be related to the herbicide dose (Mancuso et al. 2011) and the affected species (Bedmar and Gianelli 2014). This herbicide acts as an inhibitor of the ALS enzyme and can cause injuries to sensitive crops (Carvalho et al. 2009). Despite having shown phytotoxicity of up to 14% in soybean plants (Silva et al. 2021), the herbicide metsulfuron-methyl did not cause phytotoxic effects in wheat plants (Piasecki et al. 2017), and barley cultivars, such as MN610 and Criola (Galon et al. 2014) and as observed in the present study.

Table 3. Phytotoxicity percentage (%) of 13 herbicide treatments applied to barley plants, cultivar BRS Cauê*.

Treatment	Dose (mL g^{-1}·ha^{-1})	Phytotoxicity (%)			
		7 DAT	14 DAT	21 DAT	28 DAT
Control (weed)	---	0 g	0 d	0 e	0 f
Iodosulfuron	---	0 g	6.50 c	10 c	5 e
Piroxsulam	400	45 b	10.50 c	11.75 b	43.33 c
Metsulfuron-methyl	6.6	0 g	3 d	0 e	0 f
2,4-D	1,000	0 g	9.33 c	6.33 c	2.50 e
Clodinafop-propargyl	200	3.25 f	9 c	8 c	4.33 e
Bentazon + imazamox	1,000	5 f	4.25 d	5.50 d	25 d
Saflufenacil	70	4.75 f	9.25 c	8 c	4.33 e
Bentazon	1,200	0 g	3 d	1.50 e	0 f
Carfentrazone-ethyl	300	3 f	12 c	8.75 c	3 e
Imazamox	60	30 c	7.75 c	14.75 b	50 b
Pendimethalin	2,000	16.25 e	5 d	2.50 e	0 f
Sulfentrazone + diuron	1,000	25 d	47.50 b	12.50 b	6.50 e
Imazaquim	1,000	78.75 a	85 a	80.50 a	61.67 a

*Means followed by the same lowercase letters in the column do not differ from each other by the Scott-Knott test at 5% probability; DAT: days after application of treatments.

The herbicides iodosulfuron, 2,4-D, clodinafop-propargyl, and carfentrazone-ethyl, despite causing phytotoxicity symptoms of up to 12% at 14 DAT in barley plants, had symptoms reduced to less than 5% at 28 DAT (Table 3). An even more expressive recovery was observed after the application of pre-emergence herbicides, pendimethalin and sulfentrazone + diuron, which showed 16 and 25% phytotoxicity at seven DAT, but 0 and 6% at 28 DAT. This may be related to the ability of plants to metabolize herbicides, as reported for tolerant plants exposed to sulfentrazone (Melo et al. 2019, Gehrke et al. 2020), diuron (Sousa et al. 2018), and pendimethalin (Nunes et al. 2018).

In wheat and barley, the metabolism of some herbicides occurs due to rapid hydroxylation followed by conjugation with glucose, or by hydroxylation of the aromatic ring, absorption and differential or limited translocation via phloem and xylem, detoxification, rapidity in P450 metabolism, differences in the sensitivity of herbicides, among others (DeBoer et al. 2011, Mithila et al. 2011, Piasecki et al. 2017). In addition, pre-emergent herbicides are commonly more absorbed by the root system than by leaves (Ribeiro Junior et al. 2018). Pendimethalin, like other dinitroanilines, is subject to photodegradation decomposition, in addition to being highly volatile and, when in soil, has a strong binding coefficient (~KOC = 17,491), which makes it non-motile (Congreve and Cameron 2019). Sulfentrazone, in turn, is a weak acid and, at soil pHs below 6.5, reduces its mobility and availability for plants (Silva et al. 2014).

On the other hand, the herbicide treatments that caused greater phytotoxicity in barley plants at 28 DAT were bentazon + imazamox (25%), piroxsulam (43%), and imazamox (50%) applied post-emergence, and imazaquim (61%) applied pre-emergence; with imazaquim causing phytotoxicity of up to 85% at 14 DAT (Table 3). The commercial mixture of bentazon + imazamox has also been reported to cause phytotoxicity of 48% (Galon et al. 2021) to the death[1] of different wheat cultivars. Imazamox and pyroxsulam act by binding to the ALS enzyme, preventing the production of branched-chain amino acids, which causes the yellowing and purpling of young leaves in sensitive plants (Rodrigues and Almeida 2018).

[1] Oliveira, A. M. (2019). Sensibilidade de trigo do Cerrado a herbicidas e à interferência de plantas daninhas [Trabalho de Conclusão de Curso]. Uberlândia: Universidade Federal de Uberlândia. 33 p.

Imazaquim, in turn, is a systemic herbicide that is highly translocated by the xylem and phloem (Rodrigues and Almeida 2018) and had already been reported as highly phytotoxic to barley, with toxicity ranging from 40 to 92% at 14 and 21 days after application, respectively (Nunes et al. 2007). According to Sondhia (2012), when pendimethalin comes into contact with the soil, it undergoes many effects such as microbial action, soil moisture action, and photodecomposition. These factors can affect the residue levels of this herbicide and its availability to plants, leading to lower phytotoxicity over time, as observed in the present study.

The herbicides iodosulfuron, metsulfuron-methyl, 2,4-D, imazamox, and pendimethalin increased the photosynthetic rate and carboxylation efficiency of barley plants when compared to the control and the other herbicide treatments (Table 4). The carboxylation efficiency indirectly represents the activity of ribulose-1,5 bisphosphate carboxylase/oxygenase (RuBisCO), the enzyme responsible for incorporating the CO_2 absorbed by the stomata into ribulose-1,5-biphosphate (RuBP) in the Calvin cycle (Taiz et al. 2014). Lower stomatal conductance and transpiration rate were observed after the application of the herbicides piroxsulam, clodinafop-propargyl, pendimethalin, and imazaquim, when compared to the control plants. However, the highest values for water use efficiency in barley plants were shown for treatments with piroxsulam, carfentrazone-ethyl, and imazaquin (Table 4).

Table 4. Photosynthetic rate (*A*, μmol·m^{-2}·s^{-1}), stomatal conductance (g_s, mol·m^{-2}·s^{-1}), transpiration (*E*, mol·m^{-2}·s^{-1}), internal CO_2 concentration (Ci, μmol·mol^{-1}), carboxylation efficiency (CE), and water use efficiency (WUE) on barley plants, cultivar BRS Cauê, after the application of 13 different herbicide treatments*.

Treatment	Physiological traits					
	A	g_s	*E*	Ci	CE	WUE
Control (weed)	15.91 c	0.49 a	5.39 a	292.67 a	0.05 b	2.94 b
Iodosulfuron	17.26 b	0.55 a	5.79 a	282.13 b	0.06 a	3.11 b
Piroxsulam	15.94 c	0.40 b	4.30 b	244.50 b	0.06 a	4.47 a
Metsulfuron-methyl	17.59 b	0.53 a	5.10 a	289.85 b	0.06 a	3.42 b
2,4-D	17.04 b	0.59 a	5.04 a	301 a	0.06 a	3.41 b
Clodinafop-propargyl	14.20 c	0.38 b	4.60 b	291.23 a	0.05 b	3.10 b
Bentazon + imazamox	15.14 c	0.56 a	6.60 a	296.65 a	0.05 b	2.39 b
Saflufenacil	15.72 c	0.48 b	5.06 a	288.40 b	0.05 b	3.14 b
Bentazon	15.72 c	0.50 a	5.82 a	282.78 b	0.06 a	2.71 b
Carfentrazone-ethyl	14.64 c	0.62 a	3.85 c	288.70 b	0.05 b	4.26 a
Imazamox	19.16 a	0.57 a	5.82 a	286.68 b	0.07 a	3.39 b
Pendimethalin	17.13 b	0.44 b	4.78 b	285.78 b	0.06 a	3.61 b
Sulfentrazone + diuron	15.31 c	0.58 a	5.30 a	296.45 a	0.05 b	2.89 b
Imazaquim	14.62 c	0.39 b	3.14 c	285.36 b	0.05 b	4.82 a

*Means followed by the same lowercase letters in the column, do not differ from each other by the Scott-Knott test at 5% probability.

The number of ears and TGW increased more significantly in the treatments with bentazon + imazamox and carfentrazone-ethyl when compared to the control plants and the other treatments, which also showed a reduction in the number of sterile grains (Table 5). Ear length and the number of full grains did not differ significantly between treatments. The highest barley grain yields were observed after the application of treatments with clodinafop-propargil and pendimethalin. The use of pendimethalin has also been reported to increase the productivity of rice plants (Baghel et al. 2020), while metsulfuron-methyl and saflufenacil did not affect grain yield. In addition, metsulfuron-methyl did not cause phytotoxicity at 28 DAT either and provided higher photosynthetic rates in barley plants (Tables 3 and 4).

The herbicides metsulfuron-methyl, clodinafop-propagil, saflufenacil, and pendimethalin showed phytotoxicity below 4% in the evaluation carried out at 28 DAT and allowed an increase or maintenance in barley grain yield. It demonstrates the selectivity of the BRS Cauê cultivar towards these herbicides. On the other hand, the lowest grain yield was observed in the treatments with piroxsulam, bentazon + imazamox, imazamox, and imazaquim, with reduction of 22.6, 35.7, 42.5 and

74.7%, respectively. The reduction in productivity by these treatments was accompanied by greater phytotoxicity and, in general, lower TGW of barley (Table 5). In addition to these herbicides, 2,4-D and bentazon caused reduction in the number of ears and, on average, 25% in grain yield, when compared to control plants. The 2,4-D is an auxinic herbicide and, when absorbed by plants, it can interrupt the inducing signals and generate side effects, including abnormal localized growth, twisting of leaves, stems, and curvature of shoots, among others, which can compromise the translocation of nutrients to grains (Ionescu and Penescu 2015) and, consequently, plant productivity.

Table 5. Number of ears per m^{-2} (NE), ear length (EL, cm), number of full grains (NFG), number of sterile grains (NSG), 1,000-grain weight (TGW, g), and grain yield (GY, $kg \cdot ha^{-1}$) in barley plants, cultivar BRS Cauê, after the application of 13 different herbicide treatments*.

Treatment	Yield components					
	NE	EL	NFG	NSG	TGW	GY
Control (weed)	519 c	5.69 a	20.35 a	2.15 a	41.11 b	2,079.18 b
Iodosulfuron	530 c	5.96 a	22.25 a	1.60 b	39.98 c	1,980.97 c
Piroxsulam	602.75 b	5.83 a	21.80 a	1.65 b	39.95 c	1,609.00 d
Metsulfuron-methyl	572 b	5.98 a	23.05 a	1.53 b	40.63 c	2,129.50 b
2,4-D	456 d	5.72 a	20.45 a	2.00 a	40.60 c	1,599.01 d
Clodinafop-propargyl	565.25 b	5.64 a	22.45 a	1.73 b	40.75 c	2,385.61 a
Bentazon + imazamox	688 a	5.05 a	21.40 a	1.60 b	42.72 a	1,337.96 e
Saflufenacil	606.75 b	4.91 a	20.13 a	1.22 b	41.81 b	2,154.03 b
Bentazon	458.75 d	5.41 a	21.00 a	1.95 a	41.72 b	1,563.06 d
Carfentrazone-ethyl	634.75 a	5.54 a	21.73 a	1.35 b	42.90 a	2,034.43 c
Imazamox	570.75 b	6.28 a	20.40 a	2.53 a	37.96 d	1,195.67 f
Pendimethalin	609.25 b	5.13 a	19.95 a	2.33 a	41.47 b	2,424.05 a
Sulfentrazone + diuron	558 b	5.78 a	21.82 a	2.30 a	40.45 c	1,919.70 c
Imazaquim	403 d	7.20 a	23.07 a	2.30 a	40.50 c	526.57 g

*Means followed by the same lowercase letters in the column do not differ from each other by the Scott-Knott test at 5% probability.

The herbicides carfentrazone-ethyl, iodosulfuron, and sulfentrazone + diuron caused reduction in barley yield between 2.2 and 7.7% (Table 5). Barros et al. (2016) found that iodosulfuron (50 $g \cdot L^{-1}$) + metsulfuron-methyl (7.5 $g \cdot L^{-1}$) applied at the beginning of tillering caused reduction in barley productivity.

In the present study, barley plants showed greater selectivity for the herbicides clodinafop-propargil and pendimenthalin, without phototoxicity at 28 DAT, with maintenance of gas exchange and water use efficiency, and higher grain yield (~15.7%), compared to untreated plants. This was followed by the herbicides metsulfuron-methyl and saflufenacil, which showed low phytotoxicity, maintenance in the gas exchange and productivity 3% superior to the control plants. On the other hand, the herbicide imazaquim caused the highest phytotoxicity in barley plants, with a reduced number of ears and 1,000-grain weight (TGW) and the lowest grain yield (74.7%).

The efficiency of ryegrass and turnip weeds control by herbicides in the barley crop

In the second experiment, the efficiency of 13 herbicide treatments in the control of ryegrass and turnip species, and also barley yield components were evaluated. The ryegrass plants were tolerant to the herbicides metsulfuron-methyl, 2,4-D, saflufenacil, bentazon, carfentrazone-ethyl, and imazaquim, with no control at all evaluated times (Table 6). The herbicide pendimethalin promoted control of 26 and 40% at seven and 21 DAT, respectively; but at 35 DAT no control of ryegrass plants was observed. The use of pendimethalin has already been described as having a *L. multiflorum* control greater than 90% with similar doses (500 and 1,000 $g \cdot ha^{-1}$) (Alshallash 2014) to those used in the present study. However, the authors carried out experiments in pots and under controlled conditions of temperature and humidity, with an application of pendimethalin six days after sowing and evaluation performed at 14 DAT. Under these conditions, the herbicide becomes more concentrated in the pot, which may be allowed a greater control of ryegrass when compared to the results obtained in the present study carried out under field conditions.

Table 6. Control of ryegrass (*Lolium multiflorum* L.) weed in barley, cultivar BRS Cauê, after the application of 13 different herbicide treatments*.

Treatment	Ryegrass control (%)				
	7 DAT	14 DAT	21 DAT	28 DAT	35 DAT
Control (weed)	100 a	100 a	100 a	100 a	100 a
Infested	0 e	0 e	0 e	0 e	0 f
Iodosulfuron	42.50 c	25 d	35 c	35 d	55 c
Piroxsulam	70 b	36.25 c	58.75 b	61.25 b	63.75 b
Metsulfurom-methyl	0 e	0 e	0 e	0 e	0 f
2,4-D	0 e	0 e	0 e	0 e	0 f
Clodinafop-propargyl	100 a	100 a	100 a	100 a	94.25 a
Bentazon + imazamox	35 c	41.25 c	40 c	43.75 c	21.25 e
Saflufenacil	0 e	0 e	0 e	0 e	0 f
Bentazon	0 e	10 e	0 e	0 e	0 f
Carfentrazone-ethyl	0 e	0 e	0 e	0 e	0 f
Imazamox	40 c	26.25 d	18.75 d	42.50 c	15 d
Pendimethalin	26.25 d	0 e	40 c	0 e	0 f
Sulfentrazone + diuron	66.25 b	56.25 b	45 c	0 e	30 d
Imazaquim	0 e	0 e	0 e	0 e	0 e

*Means followed by the same lowercase letters in the column do not differ from each other by the Scott-Knott test at 5% probability; DAT: days after application of treatments.

Partial control of ryegrass plants was also observed with the application of imazamox (15%), bentazon + imazamox (21%), sulfentrazone + diuron (30%), iodosulfuron (55%), and piroxsulam (63%), at 35 DAT (Table 6). However, these percentages are still not considered effective weed control. On the other hand, the herbicide clodinafop-propargyl showed, from seven DAT onwards, 100% ryegrass control, with 94% at 35 DAT (Table 5). Clodinafop-propargyl has also been reported to efficiently control wild oat (*Avena fatua* L.) in wheat and barley cultivation in Argentina (Scursoni et al. 2011), and ryegrass in wheat in Brazil (Galon et al. 2021).

Percentage values of weed control greater than 80% were, for a period, considered effective to be recommended when applying herbicides when they infested the crops (SBCPD 1995). However, ryegrass is a very competitive weed with proven resistance to several mechanisms of action such as ALS-inhibiting herbicides (Mariani et al. 2015), ACCase (Kaundun et al. 2013), EPSPS (Roman et al. 2004, Holkem et al. 2022), and more recently Very Long-Chain Fatty Acid Synthesis inhibitors (VLCFA) (Brunton et al. 2019, Dücker et al. 2019). Therefore, for the herbicide to be recommended for the management of a particular weed, it must have a control greater than 80% (Roman et al. 2004, Vargas et al. 2013, Mariani et al. 2015).

Regarding the control of turnip species, it was observed that most herbicide treatments showed high efficacy level. Although the herbicides clodinafop-propargil and pendimethalin did not show control over turnip, as they were not registered for this purpose (AGROFIT 2022), and imazamox and imazaquim showed control of 76 and 90%, respectively at 35 DAT, and the other herbicide treatments evaluated (iodosulfuron, piroxsulam, metsulfuron-methyl, 2,4-D, bentazon + imazamox, saflufenacil, bentazon, carfentrazone-ethyl, and sulfentrazone + diuron) showed a turnip control superior to 96% (Table 7). In previous studies, Pandolfo et al. (2013) and Costa and Rizzardi (2014) found a high degree of resistance to groups of herbicides belonging to ALS inhibitors in *R. sativus* and *R. raphanistrum* biotypes. Therefore, the herbicides' control efficiency of the ALS inhibitors' mechanism of action in the present study is because we have a susceptible biotype in the area of the present study. Turnip was also sensitive to the herbicides imazaquim (Nunes et al. 2007) and iodosulfuron (Barros et al. 2016), corroborating the results found in this study.

Table 7. Control of turnip species (*Raphanus raphanistrum* L. (RAPRA) and *Raphanus sativus* L.) weed in barley, cultivar BRS Cauê, after the application of 13 different herbicide treatments*.

Treatment	Turnip species control (%)				
	7 DAT	14 DAT	21 DAT	28 DAT	35 DAT
Control (weed)	100 a	100 a	100 a	100 a	100 a
Infested	0 d	0 g	0 g	0 f	0 e
Iodosulfuron	98.50 a	82.50 d	82.50 b	98 b	96 a
Piroxsulam	100 a	87.25 c	87.25 b	99.50 a	98.75 a
Metsulfuron-methyl	100 a	88.50 c	88.50 b	100 a	98.75 a
2,4-D	100 a	85.75 c	92.75 a	100 a	99 a
Clodinafop-propargyl	0 d	0 g	0 g	0 f	0 e
Bentazon + imazamox	99.50 a	87 c	96.75 a	97.50 b	99.50 a
Saflufenacil	100 a	98 a	100 a	100 a	99.25 a
Bentazon	97.25 a	90 c	94.50 a	94.50 c	97.50 a
Carfentrazone-ethyl	100 a	93.25 b	99 a	100 a	98.75 a
Imazamox	86.50 b	75 e	75 c	83 d	76.26 c
Pendimethalin	0 d	0 g	15 f	0 f	0 e
Sulfentrazone + diuron	20 c	43.75 f	32.50 d	16.25 e	5 d
Imazaquim	95.50 a	98.75 a	95.50 a	95 c	90.75 b

*Means followed by the same lowercase letters in the column do not differ from each other by the Scott-Knott test at 5% probability; DAT: days after application of treatments.

For yield components, it can be observed that the highest value for the number of ears was observed when bentazon + imazamox was applied (Table 8). Iodosulfuron, metsulfuron-methyl, carfentrazone-ethyl, imazamox, pendimethalin, and sulfentrazone + diuron herbicide treatments allowed the highest values for the length of the ears, which were higher than the infested control, but did not differ statistically from the weed control (Table 8). The number of full grains was reduced in barley plants treated with clodinafop-propargil, bentazon + imazamox, imazamox, and imazaquim when compared to the weed control, and they were similar to the infested control (Table 8), while sterile grains did not differ significantly between the treatments. These herbicides are described as changing the content of important amino acids in proteins and enzyme formation (Zhou et al. 2018, El-Sobki et al. 2021). According to these authors, the decline in protein formation can reduce plant development and affect yield components.

The number of grains is determined in the period before anthesis, making it a critical period for grain establishment (Magrin et al. 1993). In this way, it is important that the culture is free of weeds during the initial stages of development in order to uptake more environmental resources (light, water, and nutrients, among others) and, thus, obtain the maximum ear growth rate and numbers of grains (Scursoni et al. 2011). In addition, herbicide application during the early stages of weed development is also indicated for greater management efficiency, due to the greater sensitivity to herbicide treatments and even the possibility of using lower doses.

The TGW was higher for most of the herbicides' treatments in relation to the weed and infested controls, except the ones with bentazon + imazamox and imazaquim (Table 7). The highest results for TGW were observed for treatments with metsulfuron-methyl, saflufenacil, pendimenthalin, and sulfentrazone + diuron.

The highest productivity of the barley crop was verified after the application of iodosulfuron (14.9%) and pyroxsulam (7.5%), when compared to the weed control (Table 7). On the other hand, treatments with the herbicides bentazon and imazaquim caused the greatest reductions in grain yield, 36.1 and 45%, respectively, in relation to the weed control.

Analyzing the data together, it was observed that the herbicide clodinafop-propargil, despite not controlling the turnip plants–and has no indication for this weed–, showed the greatest effectiveness for ryegrass (94%), promoting a higher TGW and barley grain yield (47.1%), in relation to the infested control. Likewise, as it is not indicated for the control of ryegrass, the herbicide metsulfuron-methyl did not control this weed (0%). However, it allowed the control of turnip plants (98%) and, as a consequence, promoted greater ear length, number of full grains and TGW, allowing to obtain a productivity 69.2% higher than the infested control plants. The highest productivity values, on average 99% higher than the infested control, were observed for plants treated with iodosulfuron and pyroxsulam, which showed partial control of ryegrass (~ 59%) and almost total control of turnip species (~97%), with an increase in the number of grains, and TGW.

Table 8. Number of ears per m^{-2} (NE), ear length (EL, cm), number of full grains (NFG), number of sterile grains (NSG), 1,000-grain weight (TGW, g), and grain yield (GY, $kg \cdot ha^{-1}$) in barley plants, cultivar BRS Cauê, with voluntary infestation of ryegrass (*Lolium multiflorum* L.) and turnip species (*Raphanus raphanistrum* L. (RAPRA) and *Raphanus sativus* L.) after the application of 13 different herbicide treatments*.

Treatment	Yield components					
	NE	EL	NFG	NSG	TGW	GY
Control (weed)	519 e	5.08 a	15.75 a	3.10 a	32.20 c	2021.61 b
Infested	646.75 b	4.58 b	12.63 b	3.60 a	28.20 c	1132.39 d
Iodosulfuron	530 e	5.51 a	19.40 a	2.30 a	33.84 b	2322.27 a
Pyroxsulam	647.75 b	4.55 b	14.10 a	3.15 a	32.26 b	2184.67 a
Metsulfuron-methyl	598.50 c	5.41 a	16.75 a	4.95 a	37.58 a	1916.08 b
2,4-D	436 f	4.75 b	15.31 a	4.60 a	32.26 b	1506.06 c
Clodinafop-propargyl	589.75 c	4.71 b	12.50 b	5 a	31.50 b	1666.01 c
Bentazon + imazamox	720 a	4.72 b	9.20 b	5 a	26.52 c	1486.56 c
Saflufenacil	606.75 c	4.85 b	13.70 a	4.70 a	36.07 a	1512.12 c
Bentazon	458.75 f	4.74 b	14.05 a	4 a	32.37 b	1292.64 d
Carfentrazone-ethyl	650.25 b	5.13 a	14.49 a	5.30 a	32.14 b	1573.57 c
Imazamox	570.75 d	4.98 a	12.10 b	6.65 a	33.92 b	1558.81 c
Pendimethalin	623 c	5.11 a	14.55 a	4.85 a	37.39 a	1894.31 b
Sulfentrazone + diuron	558 d	5.23 a	16.35 a	4.50 a	35.27 a	1559.59 c
Imazaquim	412 f	3.93 b	8.30 b	6.40 a	25.24 c	1111.49 d

*Means followed by the same lowercase letters in the column do not differ from each other by the Scott-Knott test at 5% probability; DAT: days after application of treatments.

Moreover, barley yield is dependent both on the herbicides' selectivity and on the adequate weed management. Efficient field activities and crop yields profoundly affect systems, so management practice and high yield are the predominant processes to focus on (Lovarelli et al. 2020). Thus, the search for alternatives that improve yield, as well as the control of weeds voluntarily present in crops, becomes constant.

CONCLUSION

The herbicides pendimethalin, clodinafop-propagil, saflufenacil, and metsulfuron-methyl were more selective for the barley cultivar BRS Cauê, less than 4% when present, in addition to allowing an increase or maintenance in the crop's grain yield. The gas exchange variables were not responsive in the study of barley selectivity to different herbicide treatments.

The herbicide imazaquim caused the highest phytotoxicity in barley plants, associated with 74.7% reduction in grain yield compared to the weed control. In addition, this herbicide was not effective in the ryegrass control and also caused the most expressive reduction in barley yield components, in relation to the other treatments.

The herbicide clodinafop-propargil showed the best control of ryegrass in barley cultivation.

The herbicides iodosulufuron and piroxsulam allowed the highest grain yields of the barley cultivar BRS Cauê, by promoting partial control of ryegrass and total control of turnip species, followed by clodinafop-propargyl and metsulfuron-methyl, which controlled ryegrass and turnip, respectively, allowing an increase in yield grain in relation to the infested control.

AUTHORS' CONTRIBUTION STATEMENT

Conceptualization: Galon, L.; **Funding acquisition:** Galon, L.; **Supervision:** Galon, L.; **Data curation:** Silva, A. M. L., Franceschetti, M. B., Weirich, S. N., Toso, J. O. and Tonin, R. J.; **Investigation:** Silva, A. M. L., Franceschetti, M. B., Weirich, S. N., Toso, J. O. and Tonin, R. J.; **Validation:** Silva, A. M. L., Franceschetti, M. B., Weirich, S. N., Toso, J. O. and Tonin, R. J.; **Formal analysis:** Perin, G. F.; **Writing – original draft:** Silva, A. M. L.; **Writing – review & editing:** Galon, L. and Müller, C.

DATA AVAILABILITY STATEMENT

All data generated or analysed during this study are included in this published article. The raw datasets are available from the corresponding author on reasonable request.

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REFERENCES

[AGROFIT]. (2022). Sistemas Agrotóxicos Fitossanitários. Available at: http://agrofit.agricultura.gov.br/agrofit_cons/principal_agrofit_cons. Accessed on: Jul 13, 2022.

Alshallash, K. S. (2014). Effect of pendimethalin, trifluralin and terbutryn on *Lolium multiflorum* growing with barley during pre-emergence stage. Annals of Agricultural Sciences, 59, 239-242. https://doi.org/10.1016/j.aoas.2014.11.012

Baghel, J. K., Das, T. K., Pankaj, Mukherjee, I., Nath, C. P., Bhattacharyya, R. and Raj, R. (2020). Impacts of conservation agriculture and herbicides on weeds, nematodes, herbicide residue and productivity in direct-seeded rice. Soil and Tillage Research, 201, 104634. https://doi.org/10.1016/j.still.2020.104634

Balem, R., Rodrigues Padilha, L., Michelon, C. J. and Costa, L. (2021). Controle de nabo e azevém em trigo com herbicidas pós-emergentes. Revista de Ciência e Inovação, 6, 45-56. https://doi.org/10.26669/2448-4091251

Barros, J. and Calado, J. (2020). Rotação de herbicidas em trigo para prevenir a resistência das infestantes em condições Mediterrânicas. Revista de Ciências Agrárias, 43, 3-13.

Barros, J., Calado, J., Carvalho, M. and Basch, G. (2016). Eficácia e seletividade do iodossulfurão-metilo-sódio+mesossulfurão-metilo na cevada dística (*Hordeum distichum* L.). Revista de Ciências Agrárias, 39, 161-169. https://doi.org/10.19084/rca15005

Bedmar, F. and Gianelli, V. R. (2014). Comportamiento de herbicidas en el suelo. In O. A. Fernández, E. S. Leguizamón and H. A. Acciaresi (Eds.). Malezas e Invasoras de la Argentina: (p. 361-390). Argentina: Ecologia y Manejo.

Bleiholder, H., Kirfel, H., Langelüddeke, P. and Stauss, R. (1991). Codificação unificada dos estádios fenológicos de culturas e ervas daninhas. Pesquisa Agropecuária Brasileira, 26, 1423-1429.

Brunton, D. J., Boutsalis, P., Gill, G. and Preston, C. (2019). Resistance to very-long-chain fatty-acid (VLCFA)-inhibiting herbicides in multiple field-selected rigid ryegrass (*Lolium rigidum*) populations. Weed Science, 67, 267-272. https://doi.org/10.1017/wsc.2018.93

Carvalho, S. J. P., Nicolai, M., Ferreira, R. R., Oliveira Figueira, A. V. and Christoffoleti, P. J. (2009). Herbicide selectivity by differential metabolism: Considerations for reducing crop damages. Scientia Agricola, 66, 136-142. https://doi.org/10.1590/s0103-90162009000100020

Cechin, J., Vargas, L., Agostinetto, D., Zimmer, V., Pertile, M. and Garcia, J. R. (2016). Resistência de biótipos de nabo ao herbicida iodosulfurom e controle alternativo. Planta Daninha, 34, 151-160. https://doi.org/10.1590/S0100-83582016340100016

[CONAB] Companhia Nacional de Abastecimento. (2022). Acompanhamento da safra brasileira. Available at: http://www.conab.gov.br. Accessed on: Jan 26, 2022.

Congreve, M. and Cameron, J. (2019). Soil behaviour of pre-emergent herbicides in Australian farming systems: A reference manual for agronomic advisers (2nd ed.). Australia: GRDC publication. Available at: https://grdc.com.au/resources-and-publications/all-publications/publications/2018/soil-behaviour-of-pre-emergent-herbicides/10751-Pre-emergent-manual-2019.pdf?utm_source=website&utm_medium=download_link&utm_campaign=pdf_download&utm_term=National&utm_cont. Accessed on: Sep 12, 2022.

Costa, L. O. and Rizzardi, M. A. (2014). Resistance of *Raphanus raphanistrum* to the herbicide metsulfuron-methyl. Planta Daninha, 32, 181-187. https://doi.org/10.1590/S0100-83582014000100020

[CQFS] Comissão de Química e Fertilidade do Solo. (2016). Manual de calagem e adubação para os Estados do Rio Grande do Sul e de Santa Catarina (11th ed.). Porto Alegre: Sociedade Brasileira de Ciência do Solo - Núcleo Regional Sul.

DeBoer, G. J., Thornburgh, S., Gilbert, J. and Gast, R. E. (2011). The impact of uptake, translocation and metabolism on the differential selectivity between blackgrass and wheat for the herbicide pyroxsulam. Pest Management Science, 67, 279-286. https://doi.org/10.1002/ps.2062

Dücker, R., Zöllner, P., Lümmen, P., Ries, S., Collavo, A. and Beffa, R. (2019). Glutathione transferase plays a major role in flufenacet resistance of ryegrass (*Lolium* spp.) field populations. Pest Management Science, 75, 3084-3092. https://doi.org/10.1002/ps.5425

El-Sobki, A. E., Saad, A. M., El-Saadony, M. T., El-Tahan, A. M., Taha, A. E., Aljuaid, B. S. and Salem, R. E. M. E. (2021). Fluctuation in amino acids content in *Triticum aestivum* L. cultivars as an indicator on the impact of post-emergence herbicides in controlling weeds. Saudi Journal of Biological Sciences, 28, 6332-6338. https://doi.org/10.1016/j.sjbs.2021.06.097

[FAO] Food and Agriculture Organization. (2022). Available at: http://www.fao.org/statistics/en/. Accessed on: Mar 31, 2022.

Ferreira, D. F. (2011). Sisvar: a computer statistical analysis system. Ciência e Agrotecnologia, 35, 1039-1042. https://doi.org/10.1590/S1413-70542011000600001

Galon, L., Basso, F. J. M., Forte, C. T., Bagnara, M. A. M., Gallina, A., Aspiazú, I. and Brunetto, L. (2022). Weed interference period and economic threshold level in barley. Journal of Plant Protection Research, 62, 33-48. https://doi.org/10.24425/jppr.2022.140295

Galon, L., Forte, C. T., Kujawiski, R., Radunz, A. L., David, F. A., Perin, G. F. and Radunz, L. L. (2014). Eficácia e fitotoxicidade de herbicidas aplicados para o manejo de plantas daninhas em cevada. Revista Brasileira de Herbicidas, 13, 105-116. https://doi.org/10.7824/rbh.v13i2.274

Galon, L., Ulkovski, C., Oliveira Rossetto, E. R., Cavaletti, D. C., Weirich, S. N., Brandler, D. and Perin, G. F. (2021). Selectivity and efficacy of herbicides applied to the wheat crop. Revista de Ciencias Agroveterinarias, 20, 199-212. https://doi.org/10.5965/223811712032021199

Gehrke, V. R., Camargo, E. R. and Avila, L. A. (2020). Sulfentrazone: Environmental dynamics and selectivity. Planta Daninha, 38, e020215663. https://doi.org/10.1590/S0100-83582020380100032

Geier, P. W., Stahlman, P. W., Peterson, D. E. and Claassen, M. M. (2011). Pyroxsulam compared with competitive standards for efficacy in winter wheat. Weed Technology, 25, 316-321. https://doi.org/10.1614/wt-d-10-00055.1

Heap, I. (2022). The international survey of herbicide resistant weeds. Available at: http://www.weedscience.org. Accessed on: Mar 29, 2022.

Holkem, A. S., Anelise, L., Bianchi, M. A., Corassa, G. and Ulguim, A. R. (2022). Weed management in Roundup Ready® corn and soybean in Southern Brazil: survey of consultants' perception. Advances in Weed Science, 40, e020220111. https://doi.org/10.51694/AdvWeedSci/2022;40:00003

Hong, Y. and Zhang, G.-P. (2020). The influence of drought stress on malt quality traits of the wild and cultivated barleys. Journal of Integrative Agriculture, 19, 2009-2015. https://doi.org/10.1016/S2095-3119(19)62794-2

Ionescu, N. and Penescu, A. (2015). Aspects of winter wheat physiology treated with herbicides. Agriculture and Agricultural Science Procedia, 6, 52-57. https://doi.org/10.1016/j.aaspro.2015.08.037

Kaundun, S. S., Hutchings, S. J., Dale, R. P. and McIndoe, E. (2013). Role of a novel I1781T mutation and other mechanisms in conferring resistance to acetyl-CoA carboxylase inhibiting herbicides in a black-grass population. PLoS One, 8, e69568. https://doi.org/10.1371/journal.pone.0069568

Lovarelli, D., Garcia, L. R., Sánchez-Girón, V. and Bacenetti, J. (2020). Barley production in Spain and Italy: Environmental comparison between different cultivation practices. Science of the Total Environment, 707, 135982. https://doi.org/10.1016/j.scitotenv.2019.135982

Magrin, G. O., Hall, A. J., Baldy, C. and Grondona, M. O. (1993). Spatial and interannual variations in the photothermal quotient: implications for the potential kernel number of wheat crops in Argentina. Agricultural and Forest Meteorology, 67, 29-41. https://doi.org/10.1016/0168-1923(93)90048-M

Mahajan, G., Hickey, L. and Chauhan, B. S. (2020). Response of barley genotypes to weed interference in Australia. Agronomy, 10, 99. https://doi.org/10.3390/agronomy10010099

Mancuso, M. A. C., Negrisoli, E. and Perim, L. (2011). Efeito residual de herbicidas no solo ("carryover"). Revista Brasileira de Herbicidas, 10, 151. https://doi.org/10.7824/rbh.v10i2.106

Mariani, F., Vargas, L., Agostinetto, D., Silva, D. R. O., Fraga, D. S. and Silva, B. M. (2015). Inheritance of resistance of *Lolium multiflorum* to iodosulfuron-methyl sodium. Planta Daninha, 33, 351-356. https://doi.org/10.1590/0100-83582015000200021

Melo, C. A. D., Passos, A. B. R. J., Madalão, J. C., Silva, D. V., Massenssini, A. M., Silva, A. A. and Souza, M. F. (2019). Bioaugmentation as an associated technology for bioremediation of soil contaminated with sulfentrazone. Ecological Indicators, 99, 343-348. https://doi.org/10.1016/j.ecolind.2018.12.034

Mithila, J., Hall, J. C., Johnson, W. G., Kelley, K. B. and Riechers, D. E. (2011). Evolution of resistance to auxinic herbicides: Historical perspectives, mechanisms of resistance, and implications for broadleaf weed management in agronomic crops. Weed Science, 59, 445-457. https://doi.org/10.1614/ws-d-11-00062.1

Nichelati, F. D., Bottega, E. L., Guerra, N., Fioreze, S. L., Oliveira Neto, A. M. and Oliveira, Z. B. (2020). Interferência de plantas daninhas na cultura da canola (*Brassica napus* L.). Revista Ciência Agrícola, 18, 39-47. https://doi.org/10.28998/rca.v18i1.7807

Nunes, A. L., Lorenset, J., Gubiani, J. E. and Santos, F. M. (2018). A multy-year study reveals the importance of residual herbicides on weed control in glyphosate-resistant soybean. Planta Daninha, 36, e018176135. https://doi.org/10.1590/s0100-83582018360100039

Nunes, A. L., Vidal, R. A., Goulart, I. C. G. R. and Kalsing, A. (2007). Tolerance of winter crops to residual herbicides. Scientia Agraria, 8, 443-448. https://doi.org/10.5380/rsa.v8i4.9895

Pandolfo, C. E., Presotto, A., Poverene, M. and Cantamutto, M. (2013). Limited occurrence of resistant radish (*Raphanus sativus*). Planta Daninha, 31, 657-666. https://doi.org/10.1590/S0100-83582013000300017

Piasecki, C., Bilibio, M. I., Fries, H., Cechin, J., Schmitz, M. F., Henckes, J. R. and Gazola, J. (2017). Seletividade de associações e doses de herbicidas em pós emergência do trigo. Revista Brasileira de Herbicidas, 16, 286-295. https://doi.org/10.7824/rbh.v16i4.562

Pies, W., Werlang, T., Pereira da Luz, A. C., Galon, L. and Tironi, S. P. (2019). Competitive barley ability coexisting with ryegrass densities. Revista Brasileira de Ciências Agrárias, 14, 1-6. https://doi.org/10.5039/AGRARIA.V14I2A5630

Ribeiro Junior, L. F., Gonçalo, T. P., Sousa, B. F. and Costa, J. L. B. (2018). Tolerância inicial de feijão-caupi a herbicidas aplicados em pré-emergência. Revista Brasileira de Herbicidas, 17, e603. https://doi.org/10.7824/rbh.v17i3.603

Rodrigues, B. N. and Almeida, F. S. (2018). Guia de Herbicidas (7th ed.). Londrina: Produção Independente.

Roman, E. S., Vargas, L., Rizzardi, M. A. and Mattei, R. W. (2004). Resistance of Italian ryegrass (*Lolium multiflorum*) to glyphosate. Planta Daninha, 22, 301-306. https://doi.org/https://doi.org/10.1590/S0100-83582004000200018

Santos, H. G., Jacomine, P. K. T., Anjos, L. H. C., Oliveira, V. A., Lumbreras, J. F., Coelho, M. R. and Cunha, T. J. F. (2019). Sistema brasileiro de classificação de solos (5th ed.). Brasília: Embrapa.

[SBCPD] Sociedade Brasileira da Ciência das Plantas Daninhas. (1995). Procedimentos para instalação, avaliação e análise de experimentos com herbicidas. Londrina: SBCPD.

Scursoni, J. A., Martín, A., Catanzaro, M. P., Quiroga, J. and Goldar, F. (2011). Evaluation of post-emergence herbicides for the control of wild oat (*Avena fatua* L.) in wheat and barley in Argentina. Crop Protection, 30, 18-23. https://doi.org/10.1016/j.cropro.2010.09.003

Silva, G. S., Melo, C. A. D., Fialho, C. M. T., Santos, L. D. T., Costa, M. D. and Silva, A. A. (2014). Impacto de sulfentrazona, isoxaflutol e oxyfluorfem sobre a microbiota de dois solos florestais. Bragantia, 73, 292-299. https://doi.org/10.1590/1678-4499.0061

Silva, J. D. G., Müller, C., Galon, L., Pawelkiewicz, R., Menegat, A. D., Brandler, D., Toso, J. O. and Perin, G. F. (2021). Selectivity of metsulfuron applied to soybean before sowing in different intervals and soils. Journal of Environmental Science and Health - Part B, 56, 623-633. https://doi.org/10.1080/03601234.2021.1929004

Singh, S., Punia, S. S., Yadav, A. and Hooda, V. S. (2011). Evaluation of carfentrazone-ethyl+metsulfuron-methyl against broadleaf weeds of wheat. Indian Journal of Weed Science, 43, 12-22.

Sondhia, S. (2012). Dissipation of pendimethalin in soil and its residues in chickpea (*Cicer arietinum* L.) under field conditions. Bulletin of Environmental Contamination and Toxicology, 89, 1032-1036. https://doi.org/10.1007/s00128-012-0804-7

Sousa, G. V., Pereira, G. A. M., Teixeira, M. F. F., Faria, A. T., Paiva, M. C. G. and Silva, A. A. (2018). Sorption and desorption of diuron, hexazinone and mix (Diuron + hexazinone) in soils with different attributes. Planta Daninha, 36, e018176803. https://doi.org/10.1590/S0100-83582018360100097

Taiz, L., Zeiger, E., Møller, I. M. and Murphy, A. (2014). Plant Physiology and Development (6th ed.). Sinauer Associates.

Tironi, S. P., Galon, L., Silva, A. F., Fialho, C. M. T., Rocha, P. R. R., Faria, A. T., Aspiazú, I., Forte, C. T., Silva, A. A. and Radünz, A. L. (2014). Época de emergência de azevém e nabo sobre a habilidade competitiva da cultura da cevada. Ciência Rural, 44, 1527-1533. https://doi.org/10.1590/0103-8478cr20131633

Vargas, L., Fraga, D. S., Agostinetto, D., Mariani, F., Duarte, T. V. and Silva, B. M. (2013). Dose-response curves of *Lolium multiflorum* biotypes resistant and susceptible to clethodim. Planta Daninha, 31, 887-892. https://doi.org/10.1590/s0100-83582013000400015

Zhou, C., Huang, Y., Jia, B., Wang, Y., Wang, Y., Xu, Q., Li, R., Wang, S. and Dou, F. (2018). Effects of cultivar, nitrogen rate, and planting density on rice-grain quality. Agronomy, 8, 246. https://doi.org/10.3390/agronomy8110246