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Control of barnyardgrass susceptible and resistant to imidazolinones at different temperature regimes before and after imazethapyr application[1]

Alexandre Pisoni[2], Giliardi Dalazen[3], Rafael Schwalm Rafaeli[2], Catarine Markus[2], Aldo Merotto Júnior[2]

ABSTRACT

Environmental conditions can influence herbicide metabolism and interfere with the evolution of weed resistance. This study aimed to evaluate the effect of thermal regimes on the control of barnyardgrass (*Echinochloa crus-galli*) susceptible and resistant to herbicides of the imidazolinones chemical group. Factor A (biotypes) consisted of one biotype that is susceptible and one that is resistant to imazethapyr; factor B (dose) comprised six imazethapyr doses between 0 and 800 g ha^{-1} for the resistant biotype and between 0 and 100 g ha^{-1} for the susceptible biotype; factor C (temperature) consisted of four thermal regimes (16/16 ºC, 25/25 ºC, 16/25 ºC and 25/16 ºC) to which the plants were submitted before and after the herbicide application. Concerning the resistant biotype, the highest control levels were observed in the thermal regimes with temperature fluctuation, especially at 25/16 ºC. At the recommended imazethapyr dose (100 g ha^{-1}), the herbicide resulted in a control level over 90 % at 25/16 ºC and less than 50 % at 16/16 ºC, in the resistant biotype. The shoot dry mass was reduced by more than 80 % at 25/16 ºC and 16/25 ºC and less than 30 % at 16/16 ºC. The temperature conditions to which the plants are subjected in the pre- and post-application period interfere with the level of imazethapyr resistance in barnyardgrass.

KEYWORDS: *Echinochloa crus-galli*, acetolactate synthase, climate change.

RESUMO

Controle de capim-arroz suscetível e resistente a imidazolinonas em diferentes regimes de temperatura antes e após a aplicação de imazethapyr

As condições ambientais podem influenciar na metabolização de herbicidas e interferir na evolução da resistência de plantas daninhas. Objetivou-se avaliar o efeito de regimes térmicos no controle de capim-arroz (*Echinochloa crus-galli*) suscetível e resistente a herbicidas do grupo químico imidazolinonas. O fator A (biótipos) foi constituído de um biótipo suscetível e um resistente a imazethapyr; o fator B (dose) constou de seis doses de imazethapyr entre 0 e 800 g ha^{-1} para o biótipo resistente e entre 0 e 100 g ha^{-1} para o biótipo suscetível; o fator C (temperatura) foi composto de quatro regimes térmicos (16/16 ºC, 25/25 ºC, 16/25 ºC e 25/16 ºC) aos quais as plantas foram submetidas antes e após a aplicação do herbicida. Considerando-se o biótipo resistente, os maiores índices de controle foram observados nos regimes térmicos com oscilação de temperatura, principalmente para 25/16 ºC. Na dose de imazethayr recomendada (100 g ha^{-1}), o herbicida proporcionou controle superior a 90 % para 25/16 ºC e menos de 50 % para 16/16 ºC, no biótipo resistente. A massa seca da parte aérea teve redução superior a 80 % para 25/16 ºC e 16/25 ºC e inferior a 30 % para 16/16 ºC. As condições de temperatura em que as plantas são submetidas no período pré e pós-aplicação do herbicida interferem no nível de resistência a imazethapyr em capim-arroz.

PALAVRAS-CHAVE: *Echinochloa crus-galli*, acetolactato sintase, mudança climática.

INTRODUCTION

Global climate change has caused several impacts on agriculture, including on weed biology and management (Dalazen et al. 2020, Balbinot et al. 2022). The main agents of climate change are increased atmospheric CO_2 concentration and temperature, which are interrelated, since CO_2 is a greenhouse gas that acts in temperature regulation (Sheppard & Stanley 2014).

Barnyardgrass [*Echinochloa crus-galli* (L.) P. *Beauv*.] is an important weed with type C4 photosynthetic metabolism, that is present in several crops, though it is of greatest concern in irrigated rice. In recent years, several populations that exhibit resistance to herbicides employing both glyphosate

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[2] Universidade Federal do Rio Grande do Sul, Faculdade de Agronomia, Departamento de Plantas de Lavoura, Porto Alegre, RS, Brasil. *E-mail/ORCID*: ale_pisoni@yahoo.com.br/0000-0003-4210-6156; rafaelsrafaeli@gmail.com/0000-0003-3594-4012; catarine.markus@ufrgs.br/0000-0002-5330-3502; aldo.merotto@ufrgs.br/0000-0002-1581-0669.
[3] Universidade Estadual de Londrina, Centro de Ciências Agrárias, Departamento de Agronomia, Londrina, PR, Brasil. *E-mail/ORCID*: giliardidalazen@gmail.com/0000-0003-2510-8264.

and acetolactate synthase (ALS) inhibitors have been found in Brazil. Resistance to ALS inhibitors, specifically with respect to herbicides belonging to the imidazolinones chemical group like imazethapyr, has arisen particularly after the introduction of rice cultivars that use the clearfield technology (Avila et al. 2021). In recent harvest seasons, the area affected by imidazolinone-resistant barnyardgrass has increased, highlighting the challenge of managing this species in many Brazilian rice-producing regions (Ulguim et al. 2021).

Mechanisms of weed resistance to herbicides are mainly related to the occurrence of mutations or overexpression of the gene encoding the target enzyme, decreased absorption and translocation, and increased herbicide metabolism (Yuan et al. 2007). Studies on barnyardgrass have already shown that resistance occurs both due to mutations in the gene that encodes the ALS enzyme and by increased imidazolinone metabolism (Matzenbacher et al. 2015, Dalazen et al. 2018a). These populations also exhibited the highest expression of genes encoding cytochrome-P450-monooxygenase metabolizing enzymes (Dalazen et al. 2018b).

Some studies have shown that temperature directly affects the ability of weeds to metabolize herbicides. For example, mesotrione metabolism was higher in *Amaranthus palmeri* when plants were subjected to higher temperatures (Godar et al. 2015). Similarly, species of the Poaceae family increased their metabolism rate of amicarbazone by 12 %, when the daytime temperature was raised from 25 to 40 ºC (Yu et al. 2015).

Given the temperature variations expected in the coming decades (IPCC 2014), the effect of temperature variation on the efficacy of imazethapyr needs to be better understood in barnyardgrass with resistance due to increased metabolism. Thus, the present study aimed to evaluate the effect of different temperature scenarios on the control of imazethapyr-resistant and susceptible biotypes of barnyardgrass.

MATERIAL AND METHODS

The study was conducted in a greenhouse and a growth chamber at the Universidade Federal do Rio Grande do Sul, in Porto Alegre, Rio Grande do Sul state (RS), Brazil, during the year 2015. Two biotypes of barnyardgrass (*E. crus-galli*) were used, one from Arroio Grande (RS; ARRGR-01) and the other from Mostardas (RS; MOSTS-01). Both were pre-classified with respect to the resistance level to herbicides belonging to the imidazolinones chemical group according to Matzenbacher et al. (2015). ARRGR-01 is resistant to these herbicides because of the differential metabolism (detoxification) due to increased metabolism caused by cytochrome P450 enzymes. This biotype has no mutations in the ALS gene associated with herbicide resistance (Matzenbacher et al. 2015). In contrast, MOSTS-01 is susceptible to imidazolinone herbicides.

The seeds were placed in Erlenmeyer flasks, submerged in 2 % KNO_3 solution, and kept in an incubation chamber at 25 ºC for five days to overcome dormancy. After germination, the seedlings (one plant per pot) were transplanted to 250 mL pots filled with Gleissolo Háplico Distrófico típico, according to the Brazilian Soil Classification System (SiBCS), corresponding to Eltisol by the Soil Taxonomy (USDA) (Embrapa 2018). The experimental units were placed in trays with a water depth of approximately 10 cm. The plants were kept in a greenhouse with a controlled temperature of around 25 ºC.

The experimental design consisted of completely randomized blocks, with treatments arranged in a factorial scheme (2 x 6 x 4), with four replicates. Factor A comprised two biotypes of barnyardgrass: one susceptible (MOSTS-01) and one resistant to ALS-inhibiting herbicides (ARRGR-01). Factor B was represented by imazethapyr (Pivot, 100 g L^{-1} CS, BASF S. A.) at doses of 0, 50, 100, 200, 400 and 800 g a.i. ha^{-1} for the resistant biotype, and 0, 6.3, 12.5, 25, 50 and 100 g a.i. ha^{-1} for the susceptible biotype, adding non-ionic surfactant at a dose of 0.5 % (v/v). The manufacturer's recommended dose of imazethapyr for the control of barnyardgrass is 100 g a.i. ha^{-1}. Factor C consisted of four temperature regimes to which the plants were subjected, with different pre- and post-treatment temperatures, as it follows: 16/16 ºC; 16/25 ºC; 25/25 ºC; 25/16 ºC. For both the pre- and post-treatments, the plants were subjected to an acclimation period of seven days in the respective thermal regimes.

Each plant group was maintained under artificial conditions in a growth chamber, according to the respective temperature regime. The photoperiod was the same for all thermal regimes, with 14 h of light followed by 10 h of darkness.

Herbicides were applied when the plants reached the growth stage between three and four

leaves. The herbicide application was carried out in an automated chamber (Greenhouse Spray Chamber, Generation III model), with an aTJ8002E tip, at a constant pressure of 200 kPa, and calibrated for a spray volume equivalent to 200 L ha^{-1}. Immediately after the application, each treatment group was submitted to the second step of the thermal regime.

Phytotoxicity assessments were performed at 7, 14 and 21 days after treatment (DAT) with imazethapyr. The phytotoxicity analysis was performed through visual evaluations on a percentage scale where zero corresponds to the absence of damage and 100 % to the death of the plant (Frans et al. 1986). At the end of the experiment, the shoot dry mass (SDM) was measured. The results obtained from the control and SDM were submitted to analysis of variance and, when significant, a complementary analysis was performed employing adjustment with the following equations, with three parameters, using the Sigma Plot version 10.0: 1) log-logistic: $Y = A/[1 + (X/Xa_{50})^b]$, where: Y is the dependent variable (% control or SDM); X the independent variable (herbicide dose; g ha^{-1}); A the maximum asymptote; b the curve slope; and Xa_{50} the herbicide dose (g ha^{-1}) responsible for reducing the dependent variable to the level corresponding to 50 % of the maximum asymptote value (a); or 2) sigmoid: $Y = A/\{1 + \exp[-(X - Xa_{50})/b]\}$, where: Y is the dependent variable (control or SDM); X the independent variable [herbicide dose (g ha^{-1})]; A the difference between maximum and minimum asymptotes; b the curve slope; and Xa_{50} the herbicide dose (g ha^{-1}) responsible for reducing the dependent variable to the level corresponding to 50 % of the maximum asymptote value (a). The dose value responsible for reducing the control (C_{50}) or the SDM (GR_{50}) by 50 % was calculated as proposed by Ritz et al. (2015). The resistance factor was calculated using the $C_{50}R/C_{50}S$ and $GR_{50}R/GR_{50}S$ for the control and the SDM variables, respectively. For the qualitative factors (barnyardgrass biotype and thermal regime), the treatments were compared using the Tukey test ($p < 0.05$) within each imazethapyr dose.

RESULTS AND DISCUSSION

The analysis of variance indicated that the factors evaluated for all analyzed variables were significant ($p < 0.05$). This shows a differentiated effect of the imazethapyr doses on the relative tolerance of barnyardgrass plants as a function of the different temperature conditions. Table 1 shows the parameters of the adjusted equations for each biotype and thermal regime.

At 7 DAT, significant differences were observed in the percentage of plant control across different temperature regimes (Figure 1). For the susceptible biotype (Figure 1A), the highest control level was detected when the plants were exposed to 25/16 ºC. In this condition, with the dose of only 25 g ha^{-1} of imazethapyr (25 % of the recommended dose), a control greater than 80 % was reached, resulting in a low C_{50} (1.68 g ha^{-1}). In the 16/16 ºC thermal regime, regardless of the herbicide dose, the control did not exceed 40 % at 7 DAT, being this the thermal regime with the lowest control efficiency

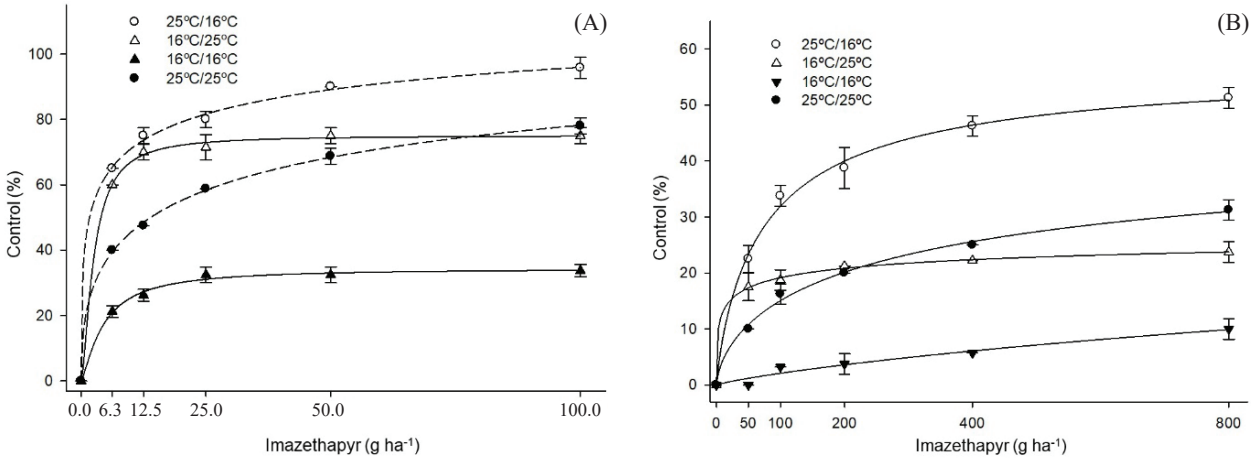

Figure 1. Control of susceptible (A) and resistant (B) barnyardgrass biotypes at 7 days after the treatment with imazethapyr doses under different thermal regimes. Vertical bars indicate a 95 % confidence interval.

Table 1. Parameters of the equation adjusted to estimate the dose required to obtain 50 % control (C_{50}) or 50 % growth reduction (GR_{50}) of plants of the barnyardgrass biotypes resistant and susceptible to imazethapyr under different thermal regimes.

Biotype/thermal regime	A	b	Xa_{50}	C_{50}	R^{2a}	RF[b]
			7 DAT[c]			
Susceptible/ 25/16 ºC	130.13	-0.37	6.07	1.68	0.99	-
Susceptible/ 16/25 ºC	75.12	1.53	2.52	1.61	0.98	-
Susceptible/ 16/16 ºC	34.47	-1.29	4.46	> 100.00	0.98	-
Susceptible/ 25/25 ºC	126.90	-0.46	35.52	13.88	0.99	-
Resistant/ 25/16 ºC	57.72	-0.86	78.20	678.26	0.99	402.48
Resistant/ 16/25 ºC	30.35	-0.36	22.22	> 800.00	0.99	> 497.10
Resistant/ 16/16 ºC	51.90	-0.83	4,579.66	> 800.00	0.95	-
Resistant/ 25/25 ºC	48.71	-0.65	341.67	> 800.00	0.98	> 57.65
			14 DAT			
Susceptible/ 25/16 ºC	100.29	-1.72	1.48	1.48	0.99	-
Susceptible/ 16/25 ºC	111.19	-0.69	3.94	2.94	0.98	-
Susceptible/ 16/16 ºC	101.89	-1.12	0.80	0.78	0.99	-
Susceptible/ 25/25 ºC	102.45	-0.81	0.97	0.92	0.99	-
Resistant/ 25/16 ºC	74.34	-0.71	11.03	30.50	0.99	20.62
Resistant/ 16/25 ºC	122.11	-0.22	231.46	42.49	0.98	14.44
Resistant/ 16/16 ºC	42.13	-0.25	1,007.24	> 800.00	0.98	> 1,027.22
Resistant/ 25/25 ºC	55.03	-1.17	60.44	429.85	0.98	469.16
			21 DAT			
Susceptible/ 25/16 ºC	100.06	-2.44	1.92	1.92	0.99	-
Susceptible/ 16/25 ºC	100.03	-3.63	3.77	3.77	0.99	-
Susceptible/ 16/16 ºC	118.11	-0.62	5.01	3.04	0.99	-
Susceptible/ 25/25 ºC	100.08	-3.37	4.24	4.24	0.99	-
Resistant/ 25/16 ºC	101.75	-0.84	5.83	5.60	0.99	2.91
Resistant/ 16/25 ºC	145.16	-0.20	202.23	8.10	0.99	2.15
Resistant/ 16/16 ºC	100.08	-0.66	102.01	101.77	0.98	33.46
Resistant/ 25/25 ºC	184.33	-0.36	626.82	41.49	0.99	9.78
			Shoot dry mass			
Susceptible/ 25/16 ºC	99.99	0.22	0.00	0.00	0.99	-
Susceptible/ 16/25 ºC	100.02	0.80	0.32	0.32	0.98	-
Susceptible/ 16/16 ºC	99.97	0.85	2.44	2.44	0.98	-
Susceptible/ 25/25 ºC	100.09	1.01	0.22	0.22	0.99	-
Resistant/ 25/16 ºC	99.99	0.22	0.02	0.02	0.98	9.11
Resistant/ 16/25 ºC	100.00	0.63	6.27	6.27	0.99	19.63
Resistant/ 16/16 ºC	102.29	1.45	73.26	75.49	0.90	30.91
Resistant/ 25/25 ºC	99.86	0.79	33.17	33.05	0.99	152.02

[a] Coefficient of determination; [b] resistance factor = C_{50} resistant/C_{50} susceptible within the same thermal regime; [c] days after the treatment.

by 7 DAT, with a C_{50} of over 100 g ha^{-1} (Table 1; Figure 1A).

Variations in the control, in response to the thermal regimes, were similar in the resistant and susceptible biotypes (Figure 1B). The highest control level in resistant plants at 7 DAT occurred under the 25/16 ºC temperature regime, though the control did not exceed 50 %, even at the highest dose used (800 g ha^{-1} of imazethapyr). The 16/16 ºC temperature regime provided the lowest control, with no dose exceeding 20 % at 7 DAT (Figure 1B). In this temperature regime, there was practically no visual effect of the herbicide action on resistant plants. The level of plant control was only 10 % higher than at the control treatment at eight times the recommended herbicide dose.

At 14 DAT, the susceptible biotype exhibited control levels of over 80 % for most the thermal regimes, even at the lowest imazethapyr dose (6.3 g ha^{-1}), except for the 16/25 ºC temperature regime, in which the control level was approximately 65 % (Figure 2A). This response can be observed in the C_{50} results, where the condition of 16/25 ºC provided the highest C_{50} value (2.94 g ha^{-1}) among all the evaluated temperature conditions (Table 1). These results demonstrate this biotype's high sensitivity

to imazethapyr. The resistant biotype showed more contrasting differences at 14 DAT, in terms of the different thermal regimes to which the plants were subjected (Figure 2B). Even at the maximum herbicide dose used, none of the treatments provided over 80 % control. The 25/16 ºC and 16/25 ºC regimes provided the highest control values and were the only ones to provide approximately 50 % control using only 50 % of the recommended herbicide dose. In the 14 DAT evaluation, the treatments in which there was a change in temperature during the experiment (25/16 ºC and 16/25 ºC) more clearly demonstrated higher control levels than the thermal regimes with constant pre- and post-treatment temperatures (Figure 2B).

At 21 DAT, all the thermal regimes resulted in control close to 100 % for the doses of 12.5 g ha^{-1} and over, with the sole exception of the 16/16 ºC regime (Figure 3A). The latter treatment showed a lower control than the other thermal regimes at the lowest imazethapyr doses (6.3-25 g ha^{-1}). At doses of 50 g ha^{-1} and up, the control was 100 % under all thermal regimes.

For the evaluation carried out at 21 DAT, the effect of the thermal regime on the control of imazethapyr-resistant barnyardgrass was remarkable (Figure 3B). As observed in previous evaluations, the 25/16 ºC thermal regime provided the highest control levels, reaching values close to 100 % when the recommended herbicide dose (100 g ha^{-1}) was used. These results were reflected in the low resistance factor (2.91 g ha^{-1}) (Table 1). This treatment presented a control level higher than the other thermal regimes

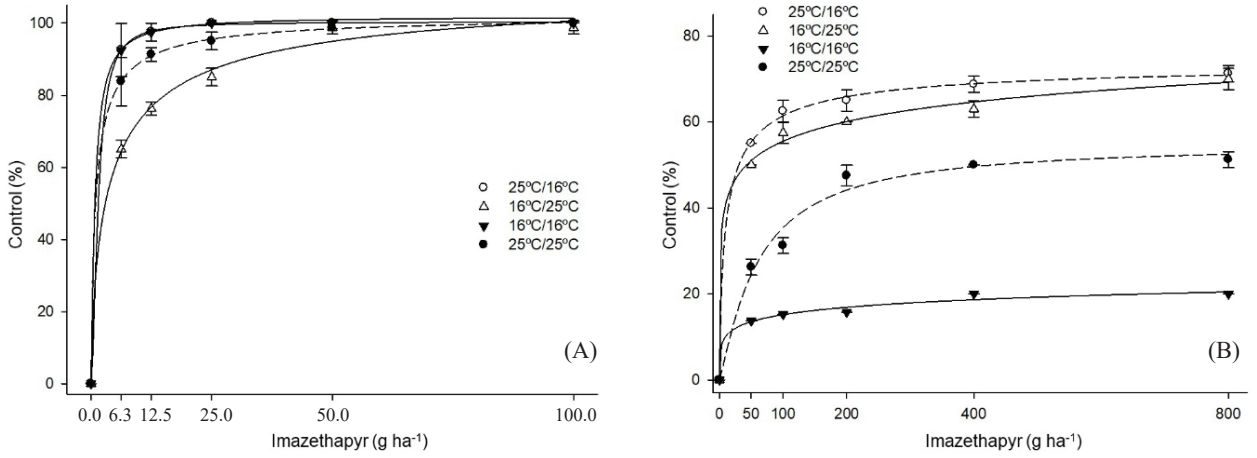

Figure 2. Control of susceptible (A) and resistant (B) barnyardgrass biotypes at 14 days after the treatment with imazethapyr doses under different thermal regimes. Vertical bars indicate a 95 % confidence interval.

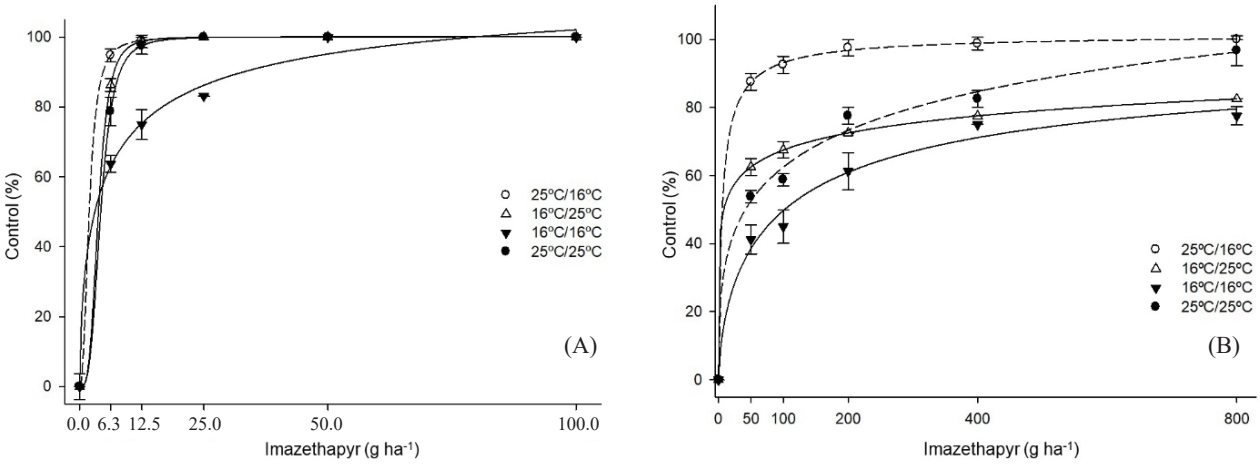

Figure 3. Control of susceptible (A) and resistant (B) barnyardgrass biotypes at 21 days after the treatment with imazethapyr doses under different thermal regimes. Vertical bars indicate a 95 % confidence interval.

evaluated in the experiment, when considering the recommended herbicide dose (100 g ha^{-1}). The lowest control levels were observed for the 16/16 ºC thermal regime, regardless of the dose. Control was below 80 % under this temperature regime, even at the highest evaluated dose. Similar results were observed for the other temperature regime with pre-treatment at 16 ºC (16/25 ºC).

The results observed in the control efficiency assessments were reflected in the plant growth and, consequently, in the accumulation of SDM (Figure 4A). The lowest SDM reduction for both biotypes was observed at 16/16 ºC, with reductions of 60 % in the susceptible and only 20 % in the resistant biotype at the lowest herbicide dose used (6.3 g ha^{-1} for the susceptible and 50 g ha^{-1} for the resistant biotype). The SDM evaluation in the susceptible biotype confirms the control efficiency results, since, at 14 DAT, a control higher than 90 % was observed in the thermal regimes of 16/25 ºC and 25/16 ºC (Figure 3A), resulting in greater reductions for SDM (Figure 4).

The treatments with the greatest reduction in SDM of barnyardgrass were the thermal regimes with the greatest variation in pre- and post-treatment temperatures (16/25 ºC and 25/16 ºC). Under these conditions, at the lowest herbicide dose, there was a reduction of over 90 % in the SDM of the susceptible biotype (Figure 4A). Similarly, the greatest reduction in SDM for the resistant biotype was observed under the 16/25 ºC and 25/16 ºC temperature regimes, which resulted in SDM reductions above 70 % for 16/25 ºC and 80 % for 25/16 ºC at the lowest herbicide doses (Figure 4B). These results were reflected in the resistance factor values, which were low for the 25/16 ºC and 16/25 ºC treatments in the SDM evaluation (9.11 g ha^{-1} for 25/16 ºC and 19.63 g ha^{-1} for 16/25 ºC), when compared to the other thermal regimes evaluated (Table 1). The thermal regimes had a greater effect on SDM for the lowest imazethapyr doses in both the evaluated biotypes (Figure 4). At lower doses, temperature effects on the tolerance of barnyardgrass to imazethapyr were observed. These effects may have gone unnoticed at higher doses due to the greater effect of the herbicide on plant growth.

The mechanism of tolerance to imazethapyr in *E. crus-galli* plants involves, at least in part, herbicide degradation by the action of cytochrome P450 enzymes (Matzenbacher et al. 2015, Dalazen et al. 2018a). It is speculated that the temperature conditions to which the plants were subjected in the period before and after the herbicide application alter the plants' metabolic capacity to degrade the herbicide. According to the results observed in the present study, the lowest control values in the resistant biotype (ARRGR-01) were observed for the 16/16 ºC thermal regime and the highest control values for the 25/16 ºC thermal regime, followed by the 16/25 ºC treatment.

Two hypotheses may explain the low control rates observed for the 16/16 ºC temperature regime, which simulates stress conditions due to low temperature. The first is that low-temperature conditions impair the absorption and translocation

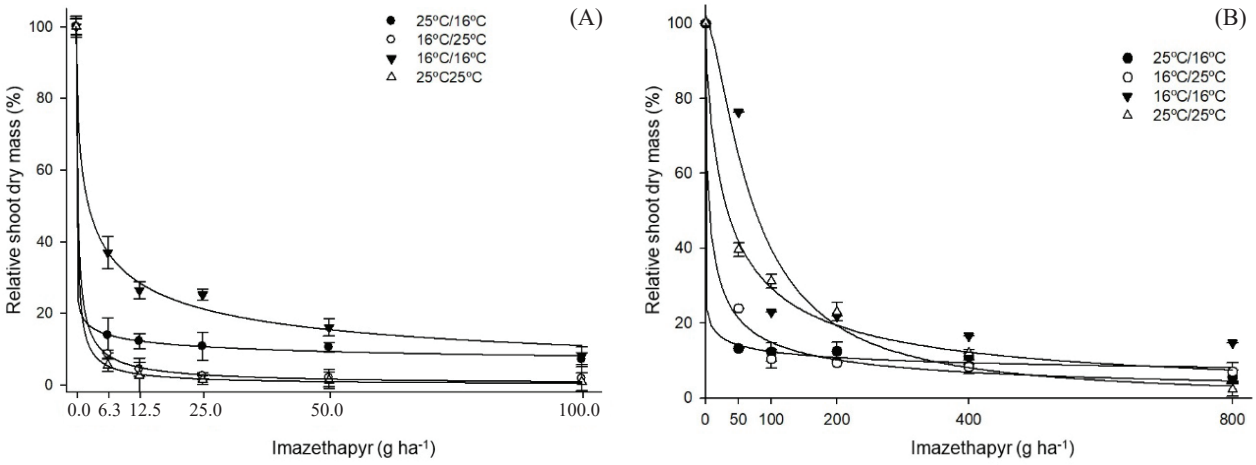

Figure 4. Relative shoot dry mass of susceptible (A) and resistant (B) barnyardgrass biotypes at 21 days after the treatment with imazethapyr doses under different thermal regimes. Vertical bars indicate a 95 % confidence interval.

of the herbicide. Similar results were observed when evaluating the efficacy of the penoxsulam herbicide (ALS inhibitor) on the control of *Alternanthera philoxeroides*, where the control in a temperature range between 21/11 ºC and 30/25 ºC (day/night) was inversely proportional to the temperature (Willingham et al. 2008). In *Avena fatua*, for example, the absorption and translocation of fenoxaprop-ethyl (ACCase inhibitor) and imazamethabenz-methyl (ALS inhibitor) were reduced when the plants were subjected to low-temperature conditions (5/10 ºC), while the opposite was observed under higher temperature conditions (30/20 ºC) (Xie et al. 1996).

The second explanation for the lower control observed in the 16/16 ºC thermal regime is the reduction of the plants growth rate, resulting in a lower need for amino acid production and, consequently, a reduction of ALS activity. This reduces the number of binding sites for the herbicide molecule, meaning that cytochrome P450 enzymes have more time to perform the detoxification process. A previous study showed that temperature was able to change the kinetics of ALS inhibition by herbicides (Light et al. 1999). The authors found differences in the activity and changes in the ALS inhibition by the pyrithiobac-sodium herbicide in *Amaranthus palmeri* between the temperatures of 15 and 50 ºC.

Temperature does not equally affect all metabolic processes of the plant at the time of stress, as it also has an effect on enzymatic kinetics, and the functions of the herbicide's target enzyme (ALS) and the enzymes involved in degrading it (P450) could both have their activity modified as a function of temperature (Mahan et al. 2004). In this sense, optimal temperatures for the activity of detoxifying enzymes (P450 in the case of the biotype used in the present study) could be sub-optimal for the ALS activity, favoring resistance.

On the other hand, the thermal regimes of 25/16 ºC and 16/25 ºC simulate a thermal shock effect in the plants through a change in temperature immediately following the herbicide application in the plants. The results obtained under these treatments may be due to the thermal shock (abiotic stress) that generally triggers physiological defense processes in plants, with an increase in the expression of genes linked to the production of compounds responsible for minimizing the stress effects, such as chaperones, compatible solutes and heat shock proteins (HSPs) (Bowler et al. 1992, Xu et al. 2010). These plant responses, when subjected to exposure to sudden changes in temperature, result in changes in membrane lipid content, increased levels of soluble proteins and sugars, as well as changes in the expression of various genes related to protein processing, redox cascades, photosynthesis and nitrogen synthesis (Timperio et al. 2008).

The metabolic changes in plants subjected to these thermal shock conditions (25/16 ºC and 16/25 ºC) are triggered very quickly and may demonstrate effects on the interaction with the applied herbicide in a short period. These results corroborate the study carried out with *Amaranthus palmeri*, where the temperature one hour after the application of pyrithiobac-sodium proved to be a determinant of the herbicide efficacy (Light et al. 1999). Similarly, the temperature extremes used in the experiment may represent different responses, depending on the temperature ranges affecting the plants in the period before and after the herbicide application. The sulfosulfuron herbicide, when applied in two temperature ranges (5/10 ºC and 7/21 ºC), had a greater phytotoxic effect on wheat at the higher temperature (7/21 ºC), regardless of the dose used (Geier et al. 1999, Olson et al. 2000).

The metabolism of ALS-inhibiting herbicides in plants is temperature-dependent. This was observed for the chlorsulfuron treatment in wheat (*Triticum aestivum*), where conditions of wide diurnal temperature variation or low after-treatment temperatures delayed metabolism and increased the potential for lesions (Ferreira et al. 1990). That is, the decrease in air temperature and the presence of temperature extremes immediately following the treatment decreased the herbicide detoxification in plants, increasing the risk of injury even for tolerant species.

At high temperatures, herbicides are more readily absorbed, since the permeability of the cuticle and membranes is higher (Los & Murata 2004). Dalazen et al. (2020) observed that imazethapyr was more effective in susceptible barnyardgrass biotypes when plants were kept at temperatures of 30/26 ºC (day/night), if compared to 24/20 ºC. However, in resistant biotypes, the efficacy of imazethapyr was lower at the highest temperature. However, unlike in the present study, the study by Dalazen and colleagues involved no change in temperature before and after the treatment.

The aforementioned results highlight the need for further studies related to the physiological

activity of barnyardgrass in the face of climate change scenarios, especially as they relate to temperature variation. Analyses of gene expression and enzyme activity related to metabolic processes of activity and detoxification of herbicides, or even related to tolerance to abiotic stresses, may offer insights to the physiological and genetic processes involved in the weed response when exposed to the application of imazethapyr under different thermal regimes.

CONCLUSIONS

1. The temperature conditions to which plants are subjected in the pre- and post-application periods of imazethapyr interfere with the level of sensitivity of barnyardgrass to the herbicide;
2. Conditions of 16/16 ºC reduce the sensitivity of barnyardgrass to imazethapyr, while temperature variations simulating a thermal shock (16/25 ºC and 25/16 ºC) increase the sensitivity to this herbicide;
3. The effect of the temperature regime on the change in sensitivity of the resistant barnyardgrass biotype, which increases metabolism by cytochrome P450 enzymes, indicates a strong relationship between temperature and this resistance mechanism.

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