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Selectivity of tembotrione + atrazine herbicides for grain sorghum[1]

Weverton Ferreira Santos[2], *João Victor dos Santos Caldas*[3], *Alessandro Guerra da Silva*[3*], *Sergio de Oliveira Procópio*[4], *Guilherme Braga Pereira Braz*[3], *Adriano Jakelaitis*[2]

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[2] Instituto Federal Goiano, Rio Verde, Goiás, Brasil. santoswf1@gmail.com; adriano.jakelaitis@ifgoiano.edu.br

[3] Universidade de Rio Verde, Rio Verde, Goiás, Brasil. jvscaldas@hotmail.com; silvaag@yahoo.com.br; guilhermebrag@gmail.com

[4] Embrapa Meio Ambiente, Jaguariúna, São Paulo, Brasil. procopio.so@gmail.com

*Corresponding author: silvaag@yahoo.com.br

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José Wagner Luiz Melo
Danielle Fabíola Pereira da Silva

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ABSTRACT

The herbicide tembotrione may be seletivity to sorghum, which is of utmost importance in grain production systems. Thus, the present study aimed to evaluate the selectivity of tembotrione + atrazine combinations applied post-emergence at different phenological stages of grain sorghum. Four experiments were carried out in Rio Verde and Montividiu (state of Goiás) in succession to soybean cultivation in 2017 and 2018. The experiments were carried out in randomized block design with six replications, both in a (3x2) + 1 factorial arrangement. The first factor referred to three vegetative stages of application (V_3, V_5 and V_7) associated with two doses of tembotrione (90 and 180 g ha^{-1}) combined with atrazine (1,000 g ha^{-1})and and an additional treatment with no herbicide application. Tembotrione + atrazine applications at the V_7 stage caused less damage to grain yield and dry mass accumulation in relation to V_3 and V_5. The dose of 90 g ha^{-1} tembotrione + atrazine combined with atrazine resulted in higher grain yields compared to 180 g ha^{-1}, although still at lower levels compared to the treatment with no herbicides. Thus, herbicide tembotrione at doses of 90 and 180 g ha^{-1} combined with atrazine did not have selectivity for grain sorghum in applications at V_3, V_5 and V_7 stages.

Keywords: application stage; atrazine; crop sucession; productivity; *Sorghum bicolor*; weeds.

INTRODUCTION

Grain sorghum is grown primarily in the second season after soybeans in Central Brazil. The growing demand for sorghum grains by agribusinesses, mainly for animal feed production, has contributed to the consolidation of this crop (Silva *et al*., 2015). Despite this, the occurrence of weeds, especially monocot species, has become a threat to the economic sustainability of this crop (Machado *et al*., 2016).

The coexistence of weeds with grain sorghum, as in any other crop, can have negative effects on grain yield and quality. This is because sorghum grows slowly in the early stages, making it more susceptible to weed interference. According to Cabral *et al*. (2013), the total period of prevention of weed interference in the sorghum crop is 42 days from its emergence. The potential for reduction in sorghum productivity by coexisting with weeds varies from 20 to 80%, and the intensity depends on the adoption of management practices (Braz *et al*., 2019).

Based on this context, the need to adopt efficient management practices to minimize weed interference in sorghum crop is evident; chemical control is the most widely used method for this purpose (Mota *et al*., 2010). However, the availability of selective herbicides for sorghum is still limited, which limits chemical control of the weed community in sorghum (Braz *et al*., 2019). The most used herbicide in sorghum crops in Brazil is atrazine, whose molecule acts by inhibiting Photosystem II (Dan *et al*., 2011). This herbicide is selective to sorghum (Aladesanwa & Akinbobola, 2008; Archangelo *et al*., 2012) and has a fundamental role in the control of dicotyledonous weeds in the crop (Hamid *et al*., 2011). However, this herbicide is not effective in controlling some grasses infesting sorghum fields, especially in applications carried out on plants at more advanced stages of development. The absence of selective herbicides with a spectrum of action that encompasses the control of grasses for post-emergence applications is the most critical and limiting point for the success of chemical weed control in this crop.

Corn is a crop belonging to the same botanical family of sorghum and has some herbicides registered for use in post-emergence. Among these herbicides, tembotrione is one of the most important (Dan *et al*., 2010), which acts by inhibiting the enzyme 4-hydroxyphenylpyruvate dioxygenase (HPPD), which is essential for carotenoid synthesis (Stephenson *et al*., 2015). Without the production of these substances, chlorophylls are degraded, promoting a typical bleaching on susceptible species, which can evolve to plant necrosis and death (Mançanares *et al*., 2018). Williams *et al*. (2011) found that the combination of tembotrione with atrazine increased the control levels of several weeds, including grasses, compared to the use of isolated atrazine.

Based on this information and given the limitation of herbicides with control spectrum on grasses in sorghum, it is opportune to evaluate the selectivity of tembotrione for this crop. In this sense, one of the steps to be considered in selectivity studies of herbicides used in post-emergence is to define the phenological stages of the crop in which the molecule can be safely applied. Spader & Vidal (2001) observed that the selectivity of nicosulfuron for corn decreases when this herbicide is applied from the six-expanded-leaf stage (V_6). Bunting *et al*. (2004) found that applications of the herbicide foramsulfuron before this stage reduce phytotoxicity and preserve the productive potential of corn.

This study aimed to evaluate the selectivity of tembotrione and atrazine mixtures applied at different phenological stages in post-emergence in grain sorghum.

MATERIAL AND METHODS

The study consisted of four field experiments in the municipalities of Rio Verde, state of Goiás (17°52'55"S; 50°55'43"W; and 740 m altitude) and Montividiu, state of Goiás (17°22'58"S; 51°22'40"W; and 905 m altitude), in the period from March to July 2017 and 2018. All experiments were set up in the second crop after the soybean crop (second season) in areas of notillage.

According to the Köppen classification, the climate in the region where the experiments were conducted is tropical (Aw), with a dry period in winter and rainfall concentrated in the summer (Cardoso *et al*., 2014). The annual averages of rainfall and temperature in the municipalities of Rio Verde and Montividiu are, respectively, 1,493 mm and 23.4°C and 1,512 mm and 23.0°C (Climate-Data, 2021). The meteorological data recorded during the experimental period are illustrated in Figure 1.

The soil of the experimental areas in Montividiu was

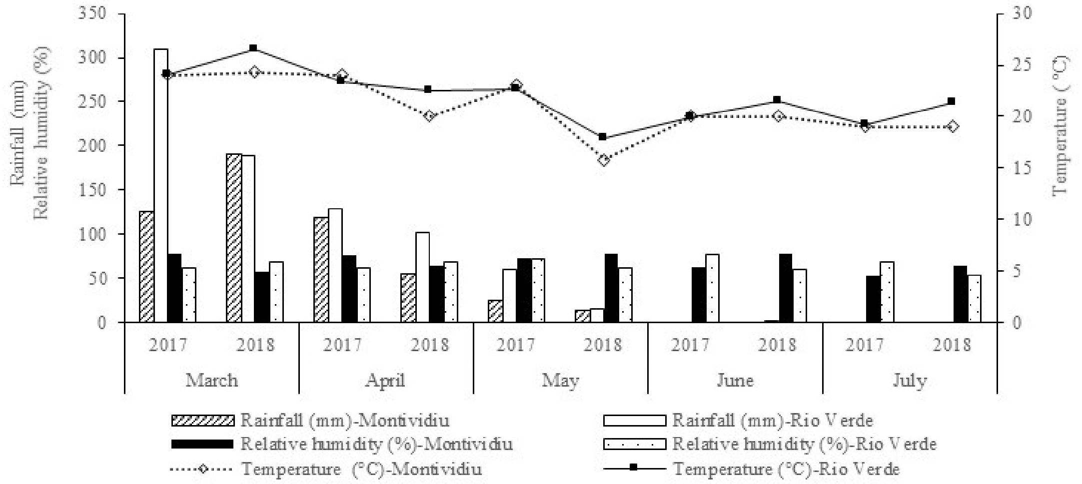

Figure 1: Rainfall data (mm), relative air humidity (%) and average temperature (°C) during the experimental period in Rio Verde and Montividiu, state of Goiás, second season of 2017 and 2018.

classified as a *Latossolo Vermelho amarelo distrófico* and in Rio Verde, *Latossolo Vermelho escuro distrófico* (Santos *et al*., 2018). Before the onset of the experiments, analyses were carried out for physical and chemical characterization of the soil in the 0.0 to 0.20 m layer. The results of the analyses in Rio Verde were pH $CaCl_2$: 4.6 and 5.9; Ca^{2+}, Mg^{2+}, K^+, Al^{3+}, H^++Al^{3+}: 1.8 and 4.2; 0.3 and 1.3; 0.5 and 0.2; 0.2 and 0.1; 7.5 and 4.3 in $cmol_c\ dm^{-3}$; P: 15.9 and 3.8 mg dm^{-3}; Organic matter: 274 and 277 g dm^{-3}; clay, silt and sand: 225 and 393; 78 and 120; 696 and 482 g kg^{-1}, in 2017 and 2018, respectively. In Montividiu, the results of the analyses were: pH $CaCl_2$: 5.7 and 5.6; Ca^{2+}, Mg^{2+}, K^+, Al^{3+}, H^++Al^{3+}: 3.4 and 3.3; 0.8 and 0.9; 0.2 and 0.4, 0.01 and 0.05; 2.1 and 4.5 in $cmol_c\ dm^{-3}$; P: 71.1 and 37.6 mg dm^{-3}; Organic matter: 224 and 226 g dm^{-3}; clay, silt and sand: 348 and 249; 120 and 68; 529 and 683 g kg^{-1}, respectively, in 2017 and 2018.

The experiments were carried out in a randomized block design with six replications in the experiments carried out in 2017 and 2018 in a (3x2) + 1 factorial arrangement. The first factor referred to the three stages of sorghum development at the time of application (V_3, V_5 and V_7 with three, five and seven fully developed leaves, respectively). The second referred to two doses of the herbicide tembotrione (Soberan™, Bayer) (90 and 180 g ha^{-1}) combined with atrazine (Atrazina™, Nortox) (1,000 g ha^{-1}), and an additional treatment without herbicide. In the preparation of the mixture for all treatments with herbicide application, adjuvant based on soybean oil methyl ester was added at a concentration of 0.1%. The experimental plots consisted of four rows spaced 0.5 m apart, 6.0 m long, making a total area of 12.0 m^2 and a useful area of 5.0 m^2, which was formed by the two central rows, disregarding 0.5 m from the ends.

In all experiments, the grain sorghum hybrid BRS 380 was used (simple, early hybrid, with red grains and without tannin), which is widely cultivated in the Southwest region of the state of Goiás, in an area grown under no-tillage, after the soybean harvest, in the first half of March in both second season. A seed density was adopted to obtain a final population of 200,000 plants per hectare. Fertilization was not carried out during the experiments, either basal or top-dressing, since this practice was carried out upon planting the soybean crop.

Herbicides were applied with a CO_2 pressurized back sprayer fitted with a bar with four double fan spray nozzles, 110.02, with air induction, spaced 0.5 m apart. The working pressure used was 2 kgf cm^{-2}, resulting in a spray volume equivalent to 150 L ha^{-1}. In the municipality of Rio Verde, the average climatological data recorded at the time of applications (V_3, V_5 and V_7 stages) in 2017 and 2018, respectively, were: 22.5 and 23.0; 19.0 and 23.8; and 24.5 and 28.3°C; relative air humidity: 49 and 65; 67 and 56; and 53% in both years; and wind speed: 1.9 and 2.8; 3.8 and

2.4; and 2.9 and 2.5 m s^{-2}. In Montividiu, state of Goiás, the data recorded for both second season were: temperature: 25.4 and 27.0; 23.0 and 28.8; and 26.0 and 29.6°C; relative air humidity: 53.0 and 55.0; 68.0 and 58.6; and 62.1 and 39.0%; and wind speed: 2.3 and 3.2; 3.2 and 1.2; and 2.2 and 2.1 m s^{-2}.

Regardless of the action of the herbicide treatments used, the plots of all experiments were maintained without weed interference by manual weeding. This was done in order to leave the sorghum plants exposed only to the effect of herbicide treatments. There was no need for pesticide applications to control pests or diseases in the experiments.

To evaluate the response of sorghum plants to herbicide application, crop injury was evaluated visually at 2, 7, 14 and 28 days after application (DAA) in the respective treatments. For this, the index of the European Weed Research Council (EWRC, 1964) was used, with assignment of scores from 1 to 9, according to the intensity of the symptoms observed.

At harvest, the following evaluations were carried out on five plants randomly chosen from the useful area of the plots: plant height (from the ground to the upper end of the panicle); panicle length (from the base to the apex of the panicle); stem diameter (measurement using a digital caliper, located at the first node above the soil surface); and dry mass of the aerial part (weighing the plant material on a precision scale, after the complete drying of the aerial part of the plants in a forced air oven at 65°C).

In addition, also in the useful area of the plots, grain yield (panicle harvest and thresh, with subsequent cleaning and weighing of the grains) and one thousand grain mass were evaluated according to the methodology proposed in the Rules for Seed Analysis (Brasil, 2009). For both variables, moisture was corrected to 13%.

Data were tested by analysis of variance by F-test at 5% significance. Initially, the crop injury data were transformed, using the expression ($\sqrt{x+1}$), following the assumptions of the analysis of variance for data homogenization. When significant effect of the stages of application and doses of herbicides were found, Tukey's test was applied to compare the means. Dunnett's test was used to compare the means of the herbicide treatments with the control, both at 5% probability. For statistical analysis, the Assistat statistical software was used (Silva & Azevedo, 2009).

RESULTS AND DISCUSSION

Herbicide treatments caused crop injuries in sorghum plants in all experiments and in all evaluations carried out (Table 1). In general, more intense injuries were observed in experiments conducted in 2017, characterized by higher rainfall in the period of germination and vegetative growth of sorghum compared to 2018 (Figure 1). Greater soil moisture in 2017 may have resulted in greater absorption and translocation of herbicides, especially tembotrione, thus causing the appearance of more intense injuries.

In general, the highest level of injuries of sorghum, taking into account the stages of application, was found when herbicides were applied at V_3 (Table 1), highlighting the following situations in both of years: Rio Verde: at 7 and 28 DAA; Montividiu: in all stages of application. In some of these evaluations, the highest injuries, assigned at V_3, did not differ from those observed in other stages of application. The use of herbicides at V_7 caused less injuries compared to V_5 in some evaluations: Rio Verde: in 2018 at 7 and 14 DAA; Montividiu: in 2017 at 7 and 28 DAA; and in 2018 at 7 DAA (Table 1).

Importantly, increasing the dose of tembotrione from 90 to 180 g ha^{-1} resulted in higher crop injuries phytotoxicity in some evaluations: Rio Verde: in 2017 at V_5 at 14 and 28 DAA; and at V_7 at 2, 7 and 28 DAA; Montividiu: in 2017 at V_5 at 2 DAA; Montividiu: in 2018 at V_5 at 7 and 14 DAA (Table 1). When herbicides were applied at V_3, no increase in crop injuries was detected by increasing the dose of tembotrione in any experiment and in any evaluation period. High levels of injuries in forage sorghum plants were also observed by Teixeira *et al*. (2017) at 40 days after application of tembotrione (100 g ha^{-1}) at 11 days after seedling emergence.

Crop injurie symptoms can be described by an initial slight discoloration of the leaves (bleaching), evolving to a reddish hue, and causing, in some cases, necrosis of the affected tissues. This symptomatology occurs due to inhibition of the enzyme 4-hydroxyphenylpyruvate dioxygenase (HPPD), which is essential for the conversion of 4-hydroxyphenylpyruvate into homogentisate, an intermediate compound for the biosynthesis of plastoquinone and tocopherol (Lee *et al*., 1998). Importantly, plastoquinone is essential for the biosynthesis of carotenoids, compounds protecting chlorophyll from photooxidative damage

(Pandian *et al*., 2020).

Both herbicide treatments and application stages influenced the final height of grain sorghum plants. However, interaction between these factors was only found in the Rio Verde experiment in 2018 (Table 2). In general, in all experiments, it was observed that the treatment tembotrione + atrazine (180 + 1,000 g ha^{-1}) caused a reduction in plant height compared to the treatment with half the dose of tembotrione (tembotrione + atrazine - 90 + 1,000 g ha^{-1}). Such reduction ranged from approximately 4 to 9 cm in the final height of grain sorghum plants.

Lesser effects on the development of sorghum plants by herbicides can be seen when applying tembotrione and atrazine at V_7. In this situation, a greater height of sorghum plants was observed in relation to the other phenological stages, only not differing from the application at V_5 in the experiment conducted in Montividiu (2018), as well as from stage V_3 in the experiment in Montividiu (2017) (Table 2).

Table 1: Visual phytointoxication after application of tembotrione and atrazine at different doses and development stages of grain sorghum grown in Rio Verde and Montividiu, state of Goiás, second seasons of 2017 and 2018

Development stages	Herbicides (g ha^{-1})	2 DAA*	7 DAA	14 DAA	28 DAA
		Scores from 1 to 9 (EWRC)			
Rio Verde (2017)					
V_3	tembotrione + atrazine (90 + 1,000)	2	5	4	4
V_3	tembotrione + atrazine (180 + 1,000)	2	5	4	4
V_5	tembotrione + atrazine (90 + 1,000)	3	3	3	2
V_5	tembotrione + atrazine (180 + 1,000)	3	3	4	4
V_7	tembotrione + atrazine (90 + 1,000)	2	2	3	2
V_7	tembotrione + atrazine (180 + 1,000)	3	3	3	3
	Control	1	1	1	1
Rio Verde (2018)					
V_3	tembotrione + atrazine (90 + 1,000)	2	3	3	2
V_3	tembotrione + atrazine (180 + 1,000)	2	3	3	2
V_5	tembotrione + atrazine (90 + 1,000)	2	3	5	2
V_5	tembotrione + atrazine (180 + 1,000)	2	3	5	2
V_7	tembotrione + atrazine (90 + 1,000)	2	2	2	2
V_7	tembotrione + atrazine (180 + 1,000)	2	2	2	2
	Control	1	1	1	1
Montividiu (2017)					
V_3	tembotrione + atrazine (90 + 1,000)	4	5	5	4
V_3	tembotrione + atrazine (180 + 1,000)	4	5	5	4
V_5	tembotrione + atrazine (90 + 1,000)	2	3	3	3
V_5	tembotrione + atrazine (180 + 1,000)	3	3	3	3
V_7	tembotrione + atrazine (90 + 1,000)	2	2	3	2
V_7	tembotrione + atrazine (180 + 1,000)	2	2	3	2
	Control	1	1	1	1
Montividiu (2018)					
V_3	tembotrione + atrazine (90 + 1,000)	3	5	5	2
V_3	tembotrione + atrazine (180 + 1,000)	3	5	5	2
V_5	tembotrione + atrazine (90 + 1,000)	2	3	2	2
V_5	tembotrione + atrazine (180 + 1,000)	2	4	3	2
V_7	tembotrione + atrazine (90 + 1,000)	2	2	2	2
V_7	tembotrione + atrazine (180 + 1,000)	2	2	2	2
	Control	1	1	1	1

*DAA: days after application.

These results corroborate Dan *et al*. (2010), who reported that tembotrione caused a greater reduction in plant growth when the application occurred at V_3 of grain sorghum.

Moreover, all applications of the herbicides tembotrione and atrazine at V_3 in all experiments, regardless of the dose used, resulted in smaller sorghum plants than the control without herbicides (Table 2). On the other hand, the application of the treatment tembotrione + atrazine (90 + 1,000 g ha^{-1}) at V_7 did not differ from the control without herbicides in all the experiments carried out, indicating greater selectivity to grain sorghum.

The timing of application of the combination tembotrione + atrazine was decisive in preventing the grain sorghum from a reduction in stem diameter. For this, applications at V_3 should be avoided, which resulted in smaller stem diameter in all experiments carried out in Southwestern state of Goiás, compared to applications at in V_5 and V_7 (Table 3). On the other hand, probably due to greater tolerance, Maia *et al*. (2019) found no differences in stem diameter of popcorn plants after the application of tembotrione combined with atrazine (76 + 2,000 g ha^{-1}) at V_2, V_4 and V_6.

The application of tembotrione at V_3 in all experiments resulted in smaller sorghum stem diameters compared to the control without application, except for the tembotrione + atrazine treatment (90 + 1,000 g ha^{-1}) in Montividiu in the 2017 second season (Table 3). The application at V_5 of this combination of herbicides resulted in stems with smaller diameter in the experiment carried out in Rio Verde (2018) and in the treatment tembotrione + atrazine (180 + 1,000 g ha^{-1}) evaluated in the experiment by Montividiu (2018). For all experiments, applications of tembotrione + atrazine at V_7 did not reduce in the diameter of the grain sorghum culm.

Table 2: Final plant height (cm) after application of tembotrione and atrazine at different doses and development stages of grain sorghum grown in Rio Verde and Montividiu state of Goiás, second season of 2017 and 2018

Herbicides (g ha^{-1})	**Development stages**			**Means**
	V_3	**V_5**	**V_7**	
		Rio Verde (2017)		
tembotrione + atrazine (90 + 1,000)	113.2*	121.6*	129.2	121.3 a
tembotrione + atrazine (180 + 1,000)	105.7*	105.9*	124.9*	112.1 b
Means	109.5 B	113.7 B	127.0 A	
Control		138.5		
Coefficient of variation (%)		6.18		
		Rio Verde (2018)		
tembotrione + atrazine (90 + 1,000)	96.8* Ba	100.6* Ba	129.4 Aa	108.9 a
tembotrione + atrazine (180 + 1,000)	97.9* Ba	97.9* Ba	117.2 Ab	104.3 b
Means	97.3 B	99.2 B	123.3 A	
Control		122.3		
Coefficient of variation (%)		4.73		
		Montividiu (2017)		
tembotrione + atrazine (90 + 1,000)	119.2*	110.9*	124.5	118.2 a
tembotrione + atrazine (180 + 1,000)	109.5*	104.4*	116.9*	110.2 b
Means	114.3 AB	107.6 B	120.7 A	
Control		133.6		
Coefficient of variation (%)		6.94		
		Montividiu (2018)		
tembotrione + atrazine (90 + 1,000)	108.2*	111.6	121.2	113.6 a
tembotrione + atrazine (180 + 1,000)	96.7*	115.3	112.0	108.0 b
Means	102.4 B	113.4 A	116.6 A	
Control		122.1		
Coefficient of variation (%)		5.83		

Means followed by different letters, uppercase in the same row and lowercase in the same column, are significantly different by Tukey's test, at 5% probability. *Significant difference from the control by Dunnett's test, at 5% probability.

Table 3: Final stem diameter (mm) of plants after application of tembotrione and atrazine at different doses and development stages of grain sorghum grown in Rio Verde and Montividiu state of Goiás, second season of 2017 and 2018

Herbicides (g ha^{-1})	Development stages			Means
	V_3	V_5	V_7	
		Rio Verde (2017)		
tembotrione + atrazine (90 + 1,000)	12.5*	15.4	15.2	14.4 a
tembotrione + atrazine (180 + 1,000)	11.7*	15.0	15.0	13.9 b
Means	12.1 B	15.2 A	15.1 A	
Control		15.4		
Coefficient of variation (%)		2.67		
		Rio Verde (2018)		
tembotrione + atrazine (90 + 1,000)	13.0 Ca*	15.0 Ba*	15.7 Aa	14.6 a
tembotrione + atrazine (180 + 1,000)	11.9 Bb*	14.9 Aa*	15.2 Aa	14.0 b
Means	12.5 C	14.9 B	15.4 A	
Control		15.9		
Coefficient of variation (%)		2.51		
		Montividiu (2017)		
tembotrione + atrazine (90 + 1,000)	12.5	15.8	13.5	13.9 a
tembotrione + atrazine (180 + 1,000)	11.5*	15.1	14.9	13.8 a
Means	12.0 B	15.5 A	14.2 A	
Control		14.8		
Coefficient of variation (%)		12.31		
		Montividiu (2018)		
tembotrione + atrazine (90 + 1,000)	11.9*	13.4	13.6	13.0 a
tembotrione + atrazine (180 + 1,000)	11.4*	13.1*	13.3	12.6 b
Means	11.6 B	13.2 A	13.4 A	
Control		14.0		
Coefficient of variation (%)		2.87		

Means followed by different letters, uppercase in the same row and lowercase in the same column, are significantly different by Tukey's test, at 5% probability. *Significant difference from the control by Dunnett's test, at 5% probability.

In three of the four experiments carried out in Southwestern state of Goiás, the use of the highest dose of tembotrione (180 g ha^{-1}) combined with atrazine (1,000 g ha^{-1}) resulted in smaller diameters of grain sorghum stem compared to the lowest evaluated dose (90 g ha^{-1}) (Table 3). Silva *et al*. (2012) reported that the application of tembotrione (110.8 g ha^{-1}) in post-emergence of cassava (20 cm tall plants) did not lead to a reduction in stem diameter.

Applications of the combination of tembotrione + atrazine at V_7 provided, in general, larger panicles compared to applications of these herbicides at V_3 or V_5, not differing only from the application at V_3 in the experiment conducted in Montividiu in the 2017 second season (Table 4). It is noteworthy that only the application of this herbicide combination at V_7 resulted in a reduction in the length of sorghum panicles in Rio Verde in the 2018 second season, with no effects in the other experiments when compared to the treatment without herbicide. The application at V_5 of this herbicide combination caused panicle deformation. The deformation of this reproductive structure in sorghum plants can be explained by the differentiation of the apical meristem, not forming the panicle primordia.

In general, in the experiments conducted in the 2017 second season, the use of the highest dose of tembotrione (180 g ha^{-1}) combined with atrazine caused a reduction in the sorghum panicle length compared to the lowest dose of tembotrione (90 g ha^{-1}), which was not found in the experiments in 2018. Again, the greater soil moisture in 2017, due to the greater volume of rainfall after the application of herbicides, may explain the stronger effects of tembotrione in inhibiting sorghum panicle elongation compared to the results obtained in 2018. The effectiveness of herbicides

Table 4: Panicle length (cm) after application of tembotrione and atrazine at different doses and development stages of grain sorghum grown in Rio Verde and Montividiu state of Goiás, second season of 2017 and 2018

Herbicides (g ha^{-1})	**Development stages**			**Means**
	V_3	**V_5**	**V_7**	
		Rio Verde (2017)		
tembotrione + atrazine (90 + 1,000)	18.9* Ba	20.8* ABa	21.5 Aa	20.5 a
tembotrione + atrazine (180 + 1,000)	16.2* Bb	17.8* Bb	22.8 Aa	19.0 b
Means	17.6 C	19.3 B	22.1 A	
Control		23.5		
Coefficient of variation (%)		8.07		
		Rio Verde (2018)		
tembotrione + atrazine (90 + 1,000)	19.1*	18.3*	28.4*	21.9 a
tembotrione + atrazine (180 + 1,000)	17.6*	18.8*	26.7*	21.0 a
Means	18.3 B	18.5 B	27.5 A	
Control		26.5		
Coefficient of variation (%)		7.88		
		Montividiu (2017)		
tembotrione + atrazine (90 + 1,000)	29.2	24.2*	30.2	27.9 a
tembotrione + atrazine (180 + 1,000)	27.6	20.9*	27.6	25.4 b
Means	28.4 A	22.6 B	28.9 A	
Control		29.4		
Coefficient of variation (%)		8.62		
		Montividiu (2018)		
tembotrione + atrazine (90 + 1,000)	23.2* ABa	20.8* Ba	25.2 Aa	23.1 a
tembotrione + atrazine (180 + 1,000)	19.8* Bb	19.7* Ba	26.9 Aa	22.1 a
Means	21.5 B	20.2 B	26.0 A	
Control		27.4		
Coefficient of variation (%)		6.59		

Means followed by different letters, uppercase in the same row and lowercase in the same column, are significantly different by Tukey's test, at 5% probability. *Significant difference from the control by Dunnett's test, at 5% probability.

applied to plants that develop under water deficit is usually reduced, due to the limited uptake and translocation (Zanatta *et al*., 2008).

In general, sorghum shoot dry mass accumulation was reduced as the application of herbicides tembotrione and atrazine was anticipated (Table 5). In all experiments and for applications at V_7, no differences were detected between tembotrione doses (90 and 180 g ha^{-1}). On the other hand, effects of herbicide doses were more evident in the application at V_3. At this stage, there was a greater reduction in shoot dry mass of sorghum using a dose of 180 g ha^{-1} tembotrione combined with atrazine.

Only applications at V_7 in the experiment conducted in Montividiu in the 2017 second season caused a reduction in shoot dry mass of grain sorghum compared to the control without herbicides (Table 5). Thus, these results indicate the safest time to apply this herbicide combination in the crop. In pearl millet, tembotrione (75.5 g ha^{-1}) applied at the stage of four developed leaves caused reductions from 6 to 8% in shoot dry mass accumulation (Dan *et al*., 2009).

In the experiments carried out in Montividiu, no effects were detected either from the doses of tembotrione or from the stage of application on the one thousand grain mass of sorghum (Table 6). However, reductions in sorghum grain mass in relation to the control without application were observed when the experiments were conducted in Rio Verde for the treatments tembotrione + atrazine (90 + 1,000 g ha^{-1}) applied at V_3 in 2017 and at V_5 in 2018, in

Table 5: Plant shoot dry mass (g plant^{-1}) after application of tembotrione and atrazine at different doses and development stages of grain sorghum grown in Rio Verde and Montividiu state of Goiás, second season of 2017 and 2018

Herbicides (g ha^{-1})	Development stages V_3	V_5	V_7	Means
		Rio Verde (2017)		
tembotrione + atrazine (90 + 1,000)	90.7 Ba*	113.2 Aa	114.3 Aa	106.0 a
tembotrione + atrazine (180 + 1,000)	83.0 Bb*	111.2 Aa	113.2 Aa	102.5 b
Means	86.9 B	112.2 A	113.7 A	
Control		114.5		
Coefficient of variation (%)		2.17		
		Rio Verde (2018)		
tembotrione + atrazine (90 + 1,000)	74.5*	84.5*	113.8	90.9 a
tembotrione + atrazine (180 + 1,000)	72.0*	82.3*	111.3	88.5 a
Means	73.2 C	83.4 B	112.5 A	
Control		116.2		
Coefficient of variation (%)		3.12		
		Montividiu (2017)		
tembotrione + atrazine (90 + 1,000)	65.3 Ca*	89.5 Ba*	150.5 Aa*	101.8 a
tembotrione + atrazine (180 + 1,000)	48.3 Cb*	79.7 Bb*	148.5 Aa*	92.2 b
Means	56.8 C	84.6 B	149.5 A	
Control		162.5		
Coefficient of variation (%)		4.05		
		Montividiu (2018)		
tembotrione + atrazine (90 + 1,000)	97.8 Ca*	112.5 Ba*	135.0 Aa	115.1 a
tembotrione + atrazine (180 + 1,000)	84.5 Cb*	109.0 Ba*	133.8 Aa	109.1 b
Means	91.1 C	110.8 B	134.4 A	
Control		140.5		
Coefficient of variation (%)		3.64		

Means followed by different letters, uppercase in the same row and lowercase in the same column, are significantly different by Tukey's test, at 5% probability. *Significant difference from the control by Dunnett's test, at 5% probability.

addition to the treatments tembotrione + atrazine (180 + 1,000 g ha^{-1}) applied at V_3 and V_5, in 2017 and 2018. The application of tembotrione (100.8 g ha^{-1}), at V_2, V_4, V_7 or V_{10}, in the RB 9006 corn hybrid, used for grain and silage production, probably due to the greater tolerance of the crop to the herbicide, does not cause a reduction in the one thousand grain mass (Mançanares *et al*., 2018).

Grain yield was significantly affected by the application of tembotrione and atrazine. In all experiments, regardless of the dose of tembotrione, the values of this variable were lower compared to controls without herbicides (Table 7). The only exception was observed for the application of tembotrione + atrazine (90 + 1,000 g ha^{-1}) at V_7 in Rio Verde (2018), whose result was similar to the control. These results demonstrate the importance of grain yield assessments in field studies aimed at evaluating herbicide selectivity. Often, the effects observed on the agronomic characteristics of the plant, or even on the isolated yield components, can indicate a "false selectivity" of the evaluated product. Thus, crop grain yield analysis should be considered mandatory in herbicide selectivity studies (Fernandes *et al*., 2012).

Regarding the evaluated doses of tembotrione, the application of 180 g ha^{-1} provided, in all experiments, lower sorghum grain yields compared to the lowest dose (90 g ha^{-1}) (Table 7). The only exception was observed in the application at V_3 in Montividiu in the 2018 second season, with no significant differences between the doses.

In the two experiments carried out in Rio Verde and in

Table 6: One thousand grain mass (grams) after application of tembotrione and atrazine at different doses and development stages of sorghum grown in Rio Verde and Montividiu state of Goiás, second season of 2017 and 2018

Herbicides (g ha^{-1})	**Development stages** V_3	V_5	V_7	**Means**
		Rio Verde (2017)		
tembotrione + atrazine (90 + 1,000)	21.2*	23.7	24.5	23.1 a
tembotrione + atrazine (180 + 1,000)	20.9*	22.3*	24.2	22.5 a
Means	21.0 B	23.0 A	24.3 A	
Control		25.2		
Coefficient of variation (%)		6.47		
		Rio Verde (2018)		
tembotrione + atrazine (90 + 1,000)	26.6	25.8*	26.7	26.4 a
tembotrione + atrazine (180 + 1,000)	24.4*	24.7*	26.8	25.3 a
Means	25.5 A	25.2 A	26.8 A	
Control		29.1		
Coefficient of variation (%)		5.73		
		Montividiu (2017)		
tembotrione + atrazine (90 + 1,000)	24.5	23.6	23.0	23.7 a
tembotrione + atrazine (180 + 1,000)	23.7	23.5	23.6	23.6 a
Means	24.1 A	23.5 A	23.3 A	
Control		25.9		
Coefficient of variation (%)		7.99		
		Montividiu (2018)		
tembotrione + atrazine (90 + 1,000)	24.9	27.6	28.5	27.0 a
tembotrione + atrazine (180 + 1,000)	23.9	26.1	25.4	25.1 a
Means	24.4 A	26.8 A	26.9 A	
Control		27.4		
Coefficient of variation (%)		11.64		

Means followed by different letters, uppercase in the same row and lowercase in the same column, are significantly different by Tukey's test, at 5% probability. *Significant difference from the control by Dunnett's test, at 5% probability.

Montividiu in 2017, in general, the applications of tembotrione and atrazine at V_3 and V_5 resulted in lower grain yields compared to applications at V_7 (Table 7). This was not observed only in the experiment conducted in Montividiu in 2018. In this case, applications at V_7 resulted in grain yield similar to that in V_5, however higher than the application at V_3.

Due to the magnitude of reductions in grain yield, the use of the combination of tembotrione and atrazine at V_3, V_5 and V_7, at tembotrione doses equal to or greater than 90 g ha^{-1}, is unfeasible due to the lack of selectivity presented by the grain sorghum crop. The continuity of studies aiming to make the use of tembotrione herbicide viable in the crop should focus on the evaluation of doses lower than those tested herein. In this context, Dan *et al*. (2010) found that tembotrione at 75.6 g ha^{-1} caused a reduction in grain sorghum grain yield of 11.4% when applications were carried out at the three-leaf stage, and of 7.3 and 6.1% with plants containing five and eight leaves, respectively. Therefore, it is clear that these values are lower than those found in the present study.

It is of fundamental importance that the selectivity of the herbicide tembotrione is always evaluated in combination with atrazine. This is attributed to the fact that tembotrione, when applied alone, is less efficient in controlling weeds compared to the application combined with atrazine, even though it is used in higher doses (Dourado Neto *et al*., 2013). Besides that, the use of this herbicide in post-emergence in sorghum crop helps controlling soybean volunteer plants from previous crops (Dan *et al*., 2009), since the crop is planted soon after the legume harvest in the Central Brazil region.

Table 7: Grain yield (kg ha^{-1}) after application of tembotrione and atrazine at different doses and development stages of grain sorghum grown in Rio Verde and Montividiu state of Goiás, second season of 2017 and 2018

Herbicides (g ha^{-1})	**Development stages** V_3	V_5	V_7	**Means**
		Rio Verde (2017)		
tembotrione + atrazine (90 + 1,000)	2,801*	2,608*	3,298*	2,902 a
tembotrione + atrazine (180 + 1,000)	1,869*	1,850*	2,684*	2,134 b
Means	2,335 B	2,229 B	2,991 A	
Control		4,447		
Coefficient of variation (%)		20.05		
		Rio Verde (2018)		
tembotrione + atrazine (90 + 1,000)	2,783*	2,138*	3,473	2,798 a
tembotrione + atrazine (180 + 1,000)	1,892*	1,801*	2,834*	2,176 b
Means	2,338 B	1,969 B	3,154 A	
Control		3,555		
Coefficient of variation (%)		15.16		
		Montividiu (2017)		
tembotrione + atrazine (90 + 1,000)	2,689 Ba*	2,579 Ca*	3,189 Aa*	2,819 a
tembotrione + atrazine (180 + 1,000)	2,194 Cb*	2,322 Bb*	2,654 Ab*	2,390 b
Means	2,441 B	2,450 B	2,921 A	
Control		4,164		
Coefficient of variation (%)		2,58		
		Montividiu (2018)		
tembotrione + atrazine (90 + 1,000)	2,234* Ba	3,008* Aa	3,220* Aa	2,821 a
tembotrione + atrazine (180 + 1,000)	2,000* Aa	1,868* Ab	2,195* Ab	2,021 b
Means	2,117 B	2,438 AB	2,708 A	
Control		4,022		
Coefficient of variation (%)		12.55		

Means followed by different letters, uppercase in the same row and lowercase in the same column, are significantly different by Tukey's test, at 5% probability. *Significant difference from the control by Dunnett's test, at 5% probability.

CONCLUSIONS

Tembotrione applications at the V_7 stage cause less damage in relation to grain yield and dry mass accumulation in the grain sorghum when compared to applications at V_3 and V_5. The application of 90 g ha^{-1} tembotrione combined with atrazine leads to higher grain yields of grain sorghum compared to the dose of 180 g ha^{-1}, however still at lower levels compared to the treatment without the use of herbicides (control). Tembotrione applied at doses of 90 and 180 g ha^{-1} combined with atrazine is not selective for use in grain sorghum in applications at V_3, V_5 and V_7 stages.

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