Application stages and doses of tembotrione herbicide in grain sorghum (*Sorghum bicolor*) crop

Etapas de aplicación y dosis del herbicida tembotrione en el cultivo del sorgo granífero (*Sorghum bicolor*)

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Abstract

The herbicide tembotrione is effective against grassy weeds constituting an important tool in sorghum crops. However, in Brazil, this herbicide is only registered for corn. This study aimed to evaluate the selectiveness of tembotrione combined with atrazine at different doses and developmental stages of grain sorghum. Two experiments were conducted in Rio Verde and Montividiu, state of Goiás, Brazil, in 2018. A randomized block design with four replications, in a 3x2+1+1 factorial arrangement, tested three developmental stages (V_3, V_5 and V_7), two doses of tembotrione (37.8 and 75.6 g ha^{-1}) combined with the herbicide atrazine (1,000 g ha^{-1}), an additional treatment only with atrazine at V_3 and a control, free of herbicide. Evident phytotoxicity was observed with the combination of tembotrione and atrazine at V_3 and V_5 stages. Symptoms included reductions in plant height, sorghum stem diameter, panicle length, and cumulative dry mass of sorghum plant shoots. However, there was no influence on thousand grains mass, regardless of application stages. Tembotrione at 37.8 g ha^{-1} combined with atrazine at 1,000 g ha^{-1} was selective for grain sorghum when applied at V_7, without affecting grain yield.

Keywords
atrazine • weeds • post-emergence • yield • *Sorghum bicolor*

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Resumen

El herbicida tembotrione tiene un buen control de malezas y puede ser una herramienta importante en el cultivo del sorgo. Sin embargo, este herbicida está registrado en Brasil solo para maíz. Este estudio tuvo como objetivo evaluar la selectividad de la tembotrione asociada a la atrazine en diferentes dosis y etapas de desarrollo del grano de sorgo. Se realizaron dos experimentos en Rio Verde-GO y Montividiu-GO, Brasil en 2018. Se adoptó un diseño de bloques al azar con cuatro repeticiones, en un factorial 3x2+1+1, con tres etapas de desarrollo (V_3, V_5 y V_7), dos dosis de tembotrione (37,8 y 75,6 g ha^{-1}) asociada al herbicida atrazine (1,000 g ha^{-1}), un tratamiento adicional con solo atrazine en V_3 más un testigo sin herbicida. Los resultados permitieron observar síntomas visibles de fitotoxicidad cuando se aplicó la asociación entre los herbicidas tembotrione y atrazine en la etapa V_3 y V_5. Los síntomas incluyeron reducciones en la altura de la planta y el diámetro del tallo del sorgo y reducciones en la longitud de la panícula con la aplicación en la etapa V_5. La aplicación de tembotrione en asociación con atrazine en V_3 y V_5 resultó en una reducción de la acumulación de masa seca en la parte aérea de las plantas de sorgo, pero sin influencia en la masa de mil granos, independientemente de la etapa de aplicación. El herbicida tembotrione en dosis de 37,8 g ha^{-1} en asociación con atrazine en dosis de 1,000 g ha^{-1} fue selectivo para sorgo en grano cuando se aplicó en V_7, sin causar reducción en el rendimiento de grano.

Palabras clave
atrazine • malezas • postemergencia • productividad • *Sorghum bicolor*

Introduction

Under water scarcity and considering food security, sorghum has become an increasingly strategic crop for both animal and human feed (9, 22, 24). In addition, sorghum has a significantly lower production cost than corn (10). Due to these factors, sorghum constitutes an option for second-crop cultivation, mainly in succession to soybean (15, 24).

Like sweet corn, sorghum greater sensitivity to herbicides constitutes one key factor limiting crop expansion (7, 20), especially considering herbicides effective against narrow-leaved weeds (grasses) (21). Evidence of this higher sensitivity refers to sorghum as an indicator plant for herbicide presence in soils (19) and substrates (6). This becomes more evident when analyzing the low number of herbicides registered for sorghum pre or postemergence in Brazil: 2,4-D, atrazine, S-metolachlor, imazethapyr, and imazapic. For imidazolinone herbicides, registers only include tolerant hybrids (17). In Brazil, no selective post-emergence product against weeds can ensure sorghum crops.

Tembotrione is registered in Brazil for post-emergence applications in corn (17). This herbicide is a triketone that inhibits the enzyme 4-hydroxyphenylpyruvate dioxygenase (HPPD), essential for carotenoid synthesis, causing leaf discoloration, necrosis, and plant death (12, 26). This highly selective herbicide for corn (11, 28) could be evaluated for sorghum, a taxonomically related species (Poaceae).

Studies on post-emergence herbicide selectivity should consider adequate dosages and application stages. According to Negrisoli *et al.* (2004), selectivity cannot solely be determined by isolated assessments of visual intoxication symptoms. These authors state that several herbicides reduce crop yield without causing visual injuries.

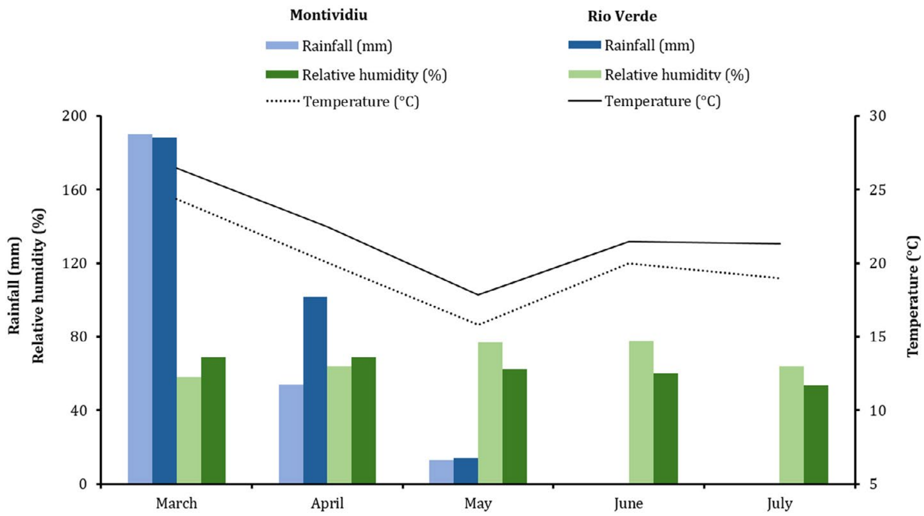
Complementing tembotrione with atrazine seeks sorghum selective improvement in weed control (8). In this sense, this research hypothesized that selectivity of the herbicide tembotrione in association with atrazine may vary depending on sorghum phenological stage and dose. The objective was to evaluate herbicide selectivity of tembotrione combined with atrazine, at post-emergence of sorghum in different doses and developmental stages.

Material and methods

Two field experiments were conducted in the southwest region of the state of Goiás, an important sorghum-producing region in Brasil, in the municipalities of Rio Verde (17°52'55" S; 50°55'43" W, 740 m altitude) and Montividiu (17°22'58" S; 51°22'40" W, 905 m altitude). The experiments were installed in the second crop after soybean in a no-till system, from March to July 2018.

Soils were classified as *Latossolo Vermelho-Amarelo Distrófico* and *Latossolo Vermelho distrófico* in Montividiu and Rio Verde, respectively (23). Soil analysis was performed for chemical and physical characterization at the 0.0 - 0.20 m layer. Results for Rio Verde were: pH in $CaCl_2$: 5.9; Ca, Mg, K, Al, H+Al: 4.2; 1.3; 0.2; 0.1; 4.3 in $cmol_c\ dm^{-3}$, respectively; P: 3.8 mg dm^{-3}; Organic matter (OM): 277 g dm^{-3}; clay, silt, and sand: 393; 125 and 482 in g kg^{-1}, respectively. In Montividiu results were: pH in $CaCl_2$: 5.6; Ca, Mg, K, Al, H+Al: 3.3; 0.9; 0.4, 0.05; 4.5 in $cmol_c\ dm^{-3}$, respectively; P: 37.6 mg dm^{-3}; OM: 226 g dm^{-3}; clay, silt, and sand: 249; 68 and 683 in g kg^{-1}, respectively.

According to the Köppen classification, the climate is tropical (Aw), with dry winter and rainfall concentrated in summer (2). Annual rainfall and temperature averages in Rio Verde and Montividiu are, 1,493 mm and 23.4°C and 1,512 mm and 23.0°C, respectively (3). Figure 1 shows meteorological data recorded during the experiments.



Source/Fuente: INMET - *Instituto Nacional de Meteorologia*. Collection station: Rio Verde (Goiás State).

Figure 1. Rainfall (mm), relative humidity (%) and average temperature (°C) in Rio Verde and Montividiu (Brazil), 2018 second crop.

Figura 1. Datos de precipitación (mm), humedad relativa del aire (%) y temperatura media (°C) durante los experimentos realizados en Rio Verde y Montividiu (Brasil), 2018 fuera de temporada.

The experiments were conducted in a randomized block design with four replications, in a 3x2+1+1 factorial arrangement, with three developmental stages (V_3, V_5 and V_7; with three, five and seven fully developed leaves, respectively), two doses of the herbicide tembotrione (37.8 and 75.6 g ha^{-1}) combined with the herbicide atrazine (1,000 g ha^{-1}), an additional treatment with only atrazine applied at V_3 stage and a herbicide-free control. Experimental units consisted of four 6.0 m long rows spaced 0.5 m, constituting a total area of 12.0 m^2 and a useful area of 5.0 m^2, with two central rows, ignoring the last 0.5 m.

In both locations, the grain sorghum hybrid BRS 330 (simple, early hybrid with red grains and no tannin) was used. This genotype is widely cultivated in the Southwest region of Goiás State. Mechanical sowing at 3 cm depth was carried out in March, with 200,000 plants per hectare. According to the regional cultivation system, no fertilization was carried out after the preceding soybean crop.

Herbicides were applied using a CO_2-pressurized backpack sprayer equipped with a bar with four double-fan nozzles, 110.02, with air induction, spaced 0.5 m apart. The working pressure was 2 kgf cm^{-2}, resulting in a spray volume of 150 L ha^{-1}. Mixture preparation included herbicide and an adjuvant based on soybean oil methyl ester at 0.1% v v^{-1}. Climate data during application (development stages V_3, V_5 and V_7, respectively) in Rio Verde were: temperature: 23.0; 23.8 and 28.3°C, relative humidity: 65; 56 and 53% and wind speed: 2.8; 2.4 and 2.5 m s^{-2} at V_3, V_5 and V_7, respectively. In Montividiu, the recorded data were temperature: 27.0; 28.8 and 29.6°C, relative humidity: 55; 59 and 39% and wind speed: 3.2; 1.2 and 2.1 m s^{-2}. Regardless of herbicide action, all plots were hand-weeded, leaving sorghum plants exposed to herbicide treatments. No pest or disease control was necessary.

Responses of sorghum plants to herbicide application, *i.e.* phytotoxicity, were visually evaluated at 2, 7, 14 and 28 days after application (DAA). According to the SBCPD scale (27), percentage scores were assigned where zero is symptoms absence and 100 is plant death. At harvest, five plants randomly chosen were evaluated for plant height (from neck to the upper end of the panicle); panicle length (between base and panicle tip); stem diameter (using a digital caliper, at the first node above the ground); and shoot dry mass (weighing oven-dried shoots, after forced air circulation at 65°C). In addition, evaluations were carried out for grain yield (harvesting and threshing panicles, with subsequent cleaning and weighing of grains) and thousand-grain mass, evaluated according to the Rules for Seed Analysis (1). For both variables, moisture was corrected to 13%.

Data were tested by ANOVA at 5% significance. Initially, phytotoxicity data were transformed by the expression ($\sqrt{x}+1$), for homoscedasticity and normality followed by Tukey test ($p \leq 0.05$) and Dunnet test ($p \leq 0.05$) for means comparison. Statistical tests were run using the Assistant statistical software (25).

Results and discussion

Treatments containing tembotrione and atrazine caused phytotoxicity symptoms in grain sorghum plants in both locations (table 1, page 98 and table 2, page 99). Observed symptoms included leaf discoloration (whitening), with a slightly reddish tint, and in most severe cases, necrosis, in accordance with Karam *et al.* (2009). At 2, 7 and 14 DAA and in both locations, the use of 75.6 g ha^{-1} tembotrione + atrazine, caused stronger effects compared to the lowest dose (37.8 g ha^{-1}) of tembotrione, also combined with atrazine. Furthermore, later applications (V_7 stage) resulted in lower phytotoxicity comparing V_3 and V_5 applications (table 1, page 98 and table 2, page 99).

At 28 DAA, the highest dose of tembotrione (75.6 g ha^{-1}) still showed the highest phytotoxicity (table 1, page 98 and table 2, page 99). However, a tendency towards recovery of sorghum plants was observed mainly in Rio Verde, compared to the previous evaluation at 14 DAA (table 1, page 98). In this evaluation, applications at V_3 caused greater phytotoxicity in sorghum than those at V_5 and V_7. Therefore, early applications of the combination of tembotrione and atrazine cause greater toxicity to sorghum plants, in accordance with Dan *et al.* (2010b), who reported that sorghum plants receiving tembotrione at three-leaf stage showed higher phytotoxicity than at five-leaf stage. This leads to the conclusion that, at more advanced stages, sorghum better tolerates tembotrione.

Atrazine alone (1,000 g ha^{-1} at V_3) did not cause any phytotoxicity in sorghum plants (table 1, page 98 and table 2, page 99), demonstrating its high selectivity when used at the said dose. Takano *et al.* (2018) found high selectivity even at higher doses (2,000 g ha^{-1}) when applied to grain sorghum plants with three to four leaves.

Increasing the dose of tembotrione from 37.8 to 75.6 g ha^{-1-} in combination with atrazine did not reduce plant height, regardless of the experimental location (table 3, page 100). Applications of tembotrione and atrazine herbicides at V_3 and V_5, in Rio Verde, induced lower growth rates, yielding smaller plants compared to the application at V_7. In Montividiu, V_3 application resulted in the highest occurrence of smaller plants. In agreement with Dan *et al.* (2010b), who concluded that tembotrione reduced growth when applied at V_3 stage.

Table 1. Visual phytotoxicity after application of tembotrione and atrazine herbicides at different doses and developmental stages of grain sorghum. Rio Verde (Brazil), 2018.

Tabla 1. Fitotoxicidad visual después de la aplicación de los herbicidas tembotriona y atrazina en diferentes dosis y estados de desarrollo de sorgo en grano. Rio Verde (Brasil), 2018.

Herbicides (g ha^{-1})	Developmental stages							
	V_3		V_5		V_7		Mean	
Phytotoxicity 2 DAA (%)								
Tembotrione + atrazine (37.8 + 1,000)	5.0	*	7.5	*	4.2	*	5.5	a
Tembotrione + atrazine (75.6 + 1,000)	8.5	*	11.3	*	4.0	*	7.9	b
Means	6.7	B	9.3	C	4.1	A		
Atrazine (1,000) at V_3	0.0							
Control	0.0							
Coefficient of variation (%)	15.0							
Phytotoxicity 7 DAA (%)								
Tembotrione + atrazine (37.8 + 1,000)	14.7	*	10.5	*	5.2	*	10.1	a
Tembotrione + atrazine (75.6 + 1,000)	17.5	*	15.0	*	9.0	*	13.8	b
Means	16.1	C	12.7	B	7.1	A		
Atrazine (1,000) at V_3	0.0							
Control	0.0							
Coefficient of variation (%)	5.2							
Phytotoxicity 14 DAA (%)								
Tembotrione + atrazine (37.8 + 1,000)	11.2	*	16.2	*	6.5	*	11.3	a
Tembotrione + atrazine (75.6 + 1,000)	15.0	*	18.7	*	6.7	*	13.5	b
Means	13.1	B	17.5	C	6.6	A		
Atrazine (1,000) at V_3	0.0							
Control	0.0							
Coefficient of variation (%)	10.7							
Phytotoxicity 28 DAA (%)								
Tembotrione + atrazine (37.8 + 1,000)	4.0*	Aa	4.5*	Aa	4.0*	Aa	4.1	a
Tembotrione + atrazine (75.6 + 1,000)	10.0*	Bb	5.2*	Aa	4.2*	Aa	6.5	b
Means	7.0	B	4.8	A	4.1	A		
Atrazine (1,000) at V_3	0.0							
Control	0.0							
Coefficient of variation (%)	8.4							

DAA: days after application. Means followed by different uppercases, in the same row, and lowercases, in the same column, are significantly different by Tukey's test (p≤0.05). * Significant difference from the control by Dunnett test (p≤0.05).

DAA: días después aplicación. Medias seguidas de diferentes letras mayúsculas, en la misma fila, y minúsculas, en la misma columna, son significativamente diferentes mediante prueba de Tukey (p≤0,05). * Diferencia significativa respecto al control mediante prueta de Dunnett (p≤0,05).

Table 2. Visual phytotoxicity after application of tembotrione and atrazine herbicides at different doses and developmental stages of grain sorghum. Montividiu (Brazil), 2018.

Tabla 2. Fitotoxicidad visual después de la aplicación de los herbicidas tembotriona y atrazina en diferentes dosis y estados de desarrollo de sorgo en grano. Montividiu (Brasil), 2018.

Herbicides (g ha^{-1})	**Developmental stages**							
	V_3		**V_5**		**V_7**		**Means**	
Phytotoxicity 2 DAA (%)								
Tembotrione + atrazine (37.8 + 1,000)	8.7	*	6.2	*	3.2	*	6.0	a
Tembotrione + atrazine (75.6 + 1,000)	11.2	*	9.5	*	4.0	*	8.2	b
Means	10.0	B	7.8	B	3.6	A		
Atrazine (1,000) at V_3	0.0							
Control	0.0							
Coefficient of variation (%)	14.6							
Phytotoxicity 7 DAA (%)								
Tembotrione + atrazine (37.8 + 1,000)	12.2	*	9.5	*	4.5	*	8.7	a
Tembotrione + atrazine (75.6 + 1,000)	16.2	*	13.7	*	6.0	*	12.0	b
Means	14.2	B	11.6	B	5.2	A		
Atrazine (1,000) at V_3	0.0							
Control	0.0							
Coefficient of variation (%)	11.2							
Phytotoxicity 14 DAA (%)								
Tembotrione + atrazine (37.8 + 1,000)	22.5*	Ba	9.0*	Aa	7.7*	Aa	13.0	a
Tembotrione + atrazine (75.6 + 1,000)	31.2*	Cb	13.7*	Bb	7.7*	Aa	17.5	b
Means	26.8	C	11.3	B	7.7	A		
Atrazine (1,000) at V_3	0.0							
Control	0.0							
Coefficient of variation (%)	8.2							
Phytotoxicity 28 DAA (%)								
Tembotrione + atrazine (37.8 + 1,000)	11.2*	Ba	3.7*	Aa	2.7*	Aa	5.9	a
Tembotrione + atrazine (75.6 + 1,000)	20.0*	Cb	6.2*	Bb	3.0*	Aa	9.7	b
Means	15.6	B	5.0	A	2.8	A		
Atrazine (1,000) at V_3	0.0							
Control	0.0							
Coefficient of variation (%)	9.3							

DAA: days after application. Means followed by different uppercases, in the same row, and lowercases, in the same column, are significantly different by Tukey's test (p≤0.05). * Significant difference from the control by Dunnett test (p≤0.05).

DAA: días después aplicación. Medias seguidas de diferentes letras mayúsculas, en la misma fila, y minúsculas, en la misma columna, son significativamente diferentes mediante prueba de Tukey (p≤0,05). * Diferencia significativa respecto al control mediante prueta de Dunnett (p≤0,05).

Table 3. Plant height and stem diameter after application of tembotrione and atrazine at different doses and developmental stages of grain sorghum. Rio Verde and Montividiu (Brazil), 2018.

Tabla 3. Altura de planta y diámetro de tallo después de la aplicación de tembotriona y atrazina en diferentes dosis y estados de desarrollo de sorgo en grano. Rio Verde y Montividiu (Brasil), 2018.

Herbicides (g ha^{-1})	Developmental stages							
	V_3		V_5		V_7		Means	
Plant height (cm)								
--- Rio Verde ---								
Tembotrione + atrazine (37.8 + 1,000)	108.2	*	111.1	*	119.1		112.8	a
Tembotrione + atrazine (75.6 + 1,000)	103.2	*	102.8	*	123.5		109.8	a
Means	105.7	B	106.9	B	121.3	A		
Atrazine (1,000) at V_3	124.3							
Control	126.9							
Coefficient of variation (%)	6.8							
--- Montividiu ---								
Tembotrione + atrazine (37.8 + 1,000)	113.4	*	120.5		119.9		117.9	a
Tembotrione + atrazine (75.6 + 1,000)	111.5	*	120.8		120.6		117.6	a
Means	112.4	B	120.6	A	120.2	A		
Atrazine (1,000) at V_3	123.2							
Control	122.3							
Coefficient of variation (%)	2.5							
Stem diameter (mm)								
--- Rio Verde ---								
Tembotrione + atrazine (37.8 + 1,000)	13.0		13.3		13.5		13.2	a
Tembotrione + atrazine (75.6 + 1,000)	11.9	*	13.3		13.3		12.8	a
Means	12.4	A	13.3	A	13.4	A		
Atrazine (1,000) at V_3	14.6							
Control	14.9							
Coefficient of variation (%)	9.5							
--- Montividiu ---								
Tembotrione + atrazine (37.8 + 1,000)	9.9	*	12.2		12.8		11.6	a
Tembotrione + atrazine (75.6 + 1,000)	9.7	*	13.0		12.6		11.8	a
Means	9.8	B	12.6	A	12.7	A		
Atrazine (1,000) at V_3	12.3							
Control	13.0							
Coefficient of variation (%)	11.3							

Means followed by different uppercases, in the same row, and lowercases, in the same column, are significantly different by Tukey's test ($p \leq 0.05$). * Significant difference from the control by Dunnett test ($p \leq 0.05$).

Medias seguidas de diferentes letras mayúsculas, en la misma fila, y minúsculas, en la misma columna, son significativamente diferentes mediante prueba de Tukey (p≤0,05). * Diferencia significativa respecto al control mediante prueta de Dunnett (p≤0,05).

In Rio Verde, only the treatment tembotrione + atrazine (75.6 + 1,000 g ha^{-1}) applied at V_3 reduced stem diameter of sorghum plants compared to the control without application and the treatment containing only atrazine (1,000 g ha^{-1}) (table 3). This was also observed in Montividiu, independently of the dose of tembotrione and atrazine applied at V_3. The reduction in stem diameter may cause lodging and consequent losses during mechanized harvesting.

In contrast, applications of tembotrione combined with atrazine at V_5 or V_7 did not change stem diameter (table 3). In popcorn, regardless of stage (V_2, V_4 or V_6), Maia *et al.* (2019) detected no differences in stem diameter after application of tembotrione + atrazine (76 + 2,000 g ha^{-1}).

Tembotrione affected panicle development in grain sorghum plants. In Rio Verde, tembotrione + atrazine (37.8 + 1,000 g ha^{-1}) applied at V_5, and tembotrione + atrazine (75.6 + 1,000 g ha^{-1}) at V_3 and V_5 reduced panicle length compared to atrazine alone (1,000 g ha^{-1}) and the control without herbicide (table 4). In Montividiu, this was observed only when sorghum plants were subjected to the combination of tembotrione + atrazine (75.6 + 1,000 g ha^{-1}) at the V_5, demonstrating that applications with these two herbicides at V_5 are not recommended.

Table 4. Panicle length and shoot dry mass after application of tembotrione and atrazine at different doses and developmental stages of grain sorghum. Rio Verde and Montividiu (Brazil), 2018.

Tabla 4. Longitud de panícula y masa seca de brotes después de la aplicación de tembotriona y atrazina en diferentes dosis y estados de desarrollo de sorgo en grano. Rio Verde y Montividiu (Brasil), 2018.

Herbicides (g ha^{-1})	**Developmental stages**							
	V_3		**V_5**		**V_7**		**Means**	
Panicle length (cm)								
--- Rio Verde ---								
Tembotrione + atrazine (37.8 + 1,000)	22.3		18.7	*	22.6		21.2	a
Tembotrione + atrazine (75.6 + 1,000)	20.9	*	17.7	*	23.0		20.5	a
Means	21.6	A	18.2	B	22.8	A		
Atrazine (1,000) at V_3	24.0							
Control	24.3							
Coefficient of variation (%)	5.8							
	--- Montividiu ---							
Tembotrione + atrazine (37.8 + 1,000)	21.0		20.9		21.4		21.1	a
Tembotrione + atrazine (75.6 + 1,000)	20.4		19.6	*	21.5		20.5	a
Means	20.7	A	20.2	A	21.4	A		
Atrazine (1,000) at V_3	22.1							
Control	22.5							
Coefficient of variation (%)	5.1							
Shoot dry mass (g $plant^{-1}$)								
--- Rio Verde ---								
Tembotrione + atrazine (37.8 + 1,000)	96.7	*	107.5	*	129.2		111.1	a
Tembotrione + atrazine (75.6 + 1,000)	91.5	*	103.0	*	124.5		106.3	b
Means	94.1	C	105.2	B	126.8	A		
Atrazine (1,000) at V_3	128.7							
Control	128.6							
Coefficient of variation (%)	2.30							
--- Montividiu ---								
Tembotrione + atrazine (37.8 + 1,000)	85.7	*	93.0	*	107.0		95.2	a
Tembotrione + atrazine (75.6 + 1,000)	82.7	*	91.2	*	106.7		93.5	a
Means	84.2	C	92.12	B	106.8	A		
Atrazine (1,000) at V_3	107.2							
Control	107.3							
Coefficient of variation (%)	6.20							

Means followed by different uppercases, in the same row, and lowercases, in the same column, are significantly different by Tukey's test ($p \leq 0.05$). * Significant difference from the control by Dunnett test ($p \leq 0.05$).

Medias seguidas de diferentes letras mayúsculas, en la misma fila, y minúsculas, en la misma columna, son significativamente diferentes mediante prueba de Tukey ($p \leq 0,05$). * Diferencia significativa respecto al control mediante prueta de Dunnett ($p \leq 0,05$).

Negative effects of tembotrione and atrazine herbicides at V_3 and V_5 include significant reductions in shoot dry mass in both locations (table 4, page 101). However, effects observed at V_3 were stronger than at V_5. On the other hand, applications of this mixture of herbicides at V_7 did not influence shoot dry mass. Thus, applications at more advanced stages result safer for sorghum plants. Dan *et al.* (2010a) found that tembotrione doses equal to or less than 118 g ha^{-1} applied to millet plants with seven leaves reduced shoot dry mass by less than 10%. Even focusing on grain yield, dry mass production is important for straw mulch, and the consequent no-till sustainability. Due to biomass production, the crop becomes an excellent option for crop rotation systems (16).

No dose of tembotrione (37.8 and 75.6 g ha^{-1}) + atrazine (1,000 g ha^{-1}), nor application stage (V_3, V_5 and V_7) affected the thousand-grain mass in either location (table 5, page 102-103). This yield component was hardly influenced by herbicides. Similarly, in corn, tembotrione at 100.8 g ha^{-1} at V_2, V_4, V_7 and V_{10}, did not affect thousand-grain mass (14).

In both locations, sorghum grain yield was significantly reduced with the application of tembotrione at V_3 or V_5, either at 37.8 or 75.6 g ha^{-1} combined with atrazine (table 5, page 102-103). On the other hand, applications of these herbicides at V_7 did not reduce grain yield, except for the treatment tembotrione at 75.6 + atrazine 1,000 g ha^{-1}, in Rio Verde. In this case, yield reduction was approximately 234 kg ha^{-1}.

Tembotrione selectivity is related to the cytochrome P-450 complex, majorly responsible for the metabolism of HPPD-inhibiting herbicides in species tolerant to active ingredients. In this study, sorghum grain yields indicated that tembotrione at 37.8 g ha^{-1}, in combination with atrazine at V_7, was selective when applied in the second crop in Southwestern Goiás.

The application of atrazine alone at V_3 did not reduce grain yield compared to the control without herbicide (table 5, page 102-103). Previous research states that post-emergence application of 2,000 g ha^{-1} atrazine is selective for sorghum, without affecting grain yield (21). Given reductions in grain yield after tembotrione doses over 75.6 g ha^{-1} combined with atrazine regardless of stage, using these herbicides becomes unfeasible. After lower reductions in yield when applying tembotrione to the most developed sorghum plants (five and seven developed leaves) (6), lower doses should be considered.

These evaluations should always be done in combination with atrazine, due to greater efficiency in weed control, even when used with higher doses (8). As grain sorghum is planted soon after soybean harvest, and grain losses are inevitable, atrazine becomes a fundamental herbicide for the control of volunteer plants of the legume when applied post-emergence (4).

Table 5. Thousand-grain mass and grain yield after application of tembotrione and atrazine at different doses and developmental stages of grain sorghum. Rio Verde and Montividiu (Brazil), 2018.

Tabla 5. Masa de mil granos y rendimiento de grano después de la aplicación de tembotriona y atrazina en diferentes dosis y estados de desarrollo de sorgo granífero. Rio Verde y Montividiu (Brasil), 2018.

Herbicides (g ha^{-1})	**Developmental stages**							
	V_3		**V_5**		**V_7**		**Means**	
Thousand grain mass (g)								
--- Rio Verde ---								
Tembotrione + atrazine (37.8 + 1,000)	23.6		23.3		24.7		23.9	a
Tembotrione + atrazine (75.6 + 1,000)	23.2		22.5		24.4		23.4	a
Means	23.4	A	22.9	A	24.5	A		
Atrazine (1,000) at V_3	24.2							
Control	24.4							
Coefficient of variation (%)	5.69							

Herbicides (g ha^{-1})	Developmental stages							
	V_3		V_5		V_7		Means	
--- Montividiu ---								
Tembotrione + atrazine (37.8 + 1,000)	25.1		25.0		25.1		25.1	a
Tembotrione + atrazine (75.6 + 1,000)	24.9		24.1		25.0		24.7	a
Means	24.0	A	24.6	A	25.1	A		
Atrazine (1,000) at V_3	25.5							
Control	25.7							
Coefficient of variation (%)	5.72							
Grain yield (kg ha^{-1})								
--- Rio Verde ---								
Tembotrione + atrazine (37.8 + 1,000)	2,765	*	2,644	*	3,456		2,955	a
Tembotrione + atrazine (75.6 + 1,000)	2,420	*	2,506	*	3,261	*	2,729	b
Means	2,592	B	2,575	B	3,358	A		
Atrazine (1,000) at V_3	3,478							
Control	3,495							
Coefficient of variation (%)	3.65							
--- Montividiu ---								
Tembotrione + atrazine (37.8 + 1,000)	2,232	*	2,573	*	3,192		2,666	a
Tembotrione + atrazine (75.6 + 1,000)	2,132	*	2,284	*	3,120		2,512	a
Means	2,182	C	2,428	B	3,156	A		
Atrazine (1,000) at V_3	3,350							
Control	3,381							
Coefficient of variation (%)	6.72							

Means followed by different uppercases, in the same row, and lowercases, in the same column, are significantly different by Tukey's test ($p \leq 0.05$). * Significant difference from the control by Dunnett test ($p \leq 0.05$).

Medias seguidas de diferentes letras mayúsculas, en la misma fila, y minúsculas, en la misma columna, son significativamente diferentes mediante prueba de Tukey ($p \leq 0,05$). * Diferencia significativa respecto al control mediante prueta de Dunnett ($p \leq 0,05$).

Conclusions

Phytotoxicity symptoms are more noticeable in grain sorghum plants when combinations of tembotrione and atrazine are applied at V_3 stage.

Reductions in plant height and stem diameter of grain sorghum plants are observed when tembotrione (37.8 and 75.6 g ha^{-1}) and atrazine (1,000 g ha^{-1}) are applied in combination at V_3 stage, while panicle reduction is evidenced when applications are at V_5.

Application of tembotrione (37.8 and 75.6 g ha^{-1}) and atrazine (1,000 g ha^{-1}) at V_3 and V_5 leads to a reduction in cumulative shoot dry mass of grain sorghum plants; with no effects on thousand-grain mass, regardless of application stage.

Tembotrione at 37.8 g ha^{-1} with atrazine at 1,000 g ha^{-1} is selective for grain sorghum (hybrid BRS 330) when applied at the V_7 stage, not reducing grain yield.

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