CHEMICAL WEED MANAGEMENT IN GRAIN SORGHUM AND SELECTIVITY OF ATRAZINE + S-METOLACHLOR TO DIFFERENT HYBRIDS

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ABSTRACT - Grain sorghum (*Sorghum bicolor*) is one cereal crop that faces huge problems with weed interference mostly because the lack of selective herbicides. This study aimed to assess the efficacy and safety of herbicide alternatives for weed control in grain sorghum as well as the selectivity of atrazine + s-metolachlor to different hybrids. Three field trials were designed as a randomized complete block with four replications. All experiments were conducted in Jardinópolis-SP and Mogi Mirim-SP during the 2015/16 growing season. Two trials included acetochlor, flumioxazin, fluroxypyr, mesotrione and s-metolachlor, applied in pre or post-emergence, in association or not with atrazine. A third trial was carried out with rates of the premix containing atrazine + s-metolachlor applied to the following hybrids: 1G100, 1G220, 1G230, 1G244, 1G282, 50A10, 50A40, 50A50 and 50A70. The pre-emergence herbicides that exhibited satisfactory efficacy of weed control and selectivity to sorghum crop were flumioxazin, atrazine + mesotrione and atrazine + s-metolachlor. For post-emergence, atrazine, atrazine + acetochlor, atrazine + s-metolachlor and atrazine + fluroxypyr were the best treatments for both efficacy and selectivity. The application of atrazine + s-metolachlor at the evaluated rates was considered selective to the nine hybrids assessed.
Keywords: acetochlor, fluroxypyr, mesotrione, herbicide tolerance, weed control.

MANEJO QUÍMICO DE PLANTAS DANINHAS EM SORGO GRANÍFERO E SELETIVIDADE DE ATRAZINE + S-METOLACHLOR PARA DIFERENTES HÍBRIDOS

RESUMO – O sorgo granífero (*Sorghum bicolor*) é um dos cereais de verão que mais enfrenta problemas com plantas daninhas em razão da interferência destas espécies e carência de herbicidas para controlá-las. O objetivo deste estudo foi avaliar a eficácia e segurança de herbicidas alternativos no controle de plantas daninhas em sorgo granífero, assim como a seletividade de atrazine + s-metolachlor para diferentes híbridos. Três experimentos foram realizados em campo com delineamento de blocos ao acaso e quatro repetições, sendo conduzidos em Jardinópolis-SP e/ou Mogi Mirim-SP, ao longo da safra 2015/16. Em dois experimentos, acetochlor, flumioxazin, fluroxypyr, mesotrione e s-metolachlor foram avaliados em pré e/ou pós-emergência da cultura, em associação ou não (isolados) com atrazine. O terceiro experimento foi realizado com doses crescentes de atrazine + s-metolachlor e os híbridos de sorgo granífero 1G100, 1G220, 1G230, 1G244, 1G282, 50A10, 50A40, 50A50 e 50A70. Os tratamentos com controle satisfatório de plantas daninhas e seletividade à cultura, em pré-emergência, foram flumioxazin, atrazine + mesotrione e atrazine + s-metolachlor. Em pós-emergência, eles foram atrazine, atrazine + acetochlor, atrazine + s-metolachlor e atrazine + fluroxipyr. A aplicação de atrazine + s-metolachlor nas doses testadas foi seletiva para os nove híbridos avaliados.
Palavras-chave: acetochlor, fluroxypyr, mesotrione, tolerância a herbicidas, controle de plantas daninhas.

Grain sorghum (*Sorghum bicolor*) is one of the five most important cereal crops in Brazil and worldwide especially because its use as an energy source in human and animal nutrition (Mutisyat et al., 2009). World production of this cereal has been around 43 million tons, most in the United States, while Brazil contributes with about 4.5% of production (USDA, 2018). In Brazil, grain sorghum is usually grown with low levels of investment, resulting in low average grain yields (2.8 tons ha^{-1}) (Acompanhamento da Safra Brasileira [de] Grãos, 2018). Yet, in the center-west region, this crop has gained special attention as a second crop, being considered an important alternative in crop rotation with soybean (Fonseca et al., 2008). This is due to the grain sorghum advantages as a wide sowing window and greater resistance to water stress, when compared to corn, which is commonly used as second crop (Borghi et al., 2016).

Among the summer cereals, grain sorghum is one that faces the greatest problems with weeds due to the negative interference of these species and lack of herbicides to control them. Estimates indicate that weeds can reduce up to 97% of the grain yield potential when there is no control (Rodrigues et al., 2010; Tamado et al., 2002). However, even using herbicides the outcome is not always as expected, particularly for grass species (Archangelo et al., 2002; Dan et al., 2010). In fact, only atrazine, simazine and 2,4-D are currently registered herbicides for grain sorghum cropping in Brazil, but the main target of these herbicides are broadleaved species (Brasil, 2003). Although atrazine applications may help in the control of some weeds, its efficacy is variable due to several factors, especially the weed species and its growth stage (Marchesan et al., 2013).

In recent years, several studies have investigated other herbicide alternatives for use in grain sorghum crops in order to provide new viable weed chemical management strategies. A well-studied and technically viable alternatives are the chloroacetamides, associated or not with atrazine, for post-emergence control (Archangelo et al., 2002; Takano et al., 2016). In a different way, other herbicides such as metsulfuron (Brown et al., 2004), fluroxypyr (Takano et al., 2016), flumioxazin (Galon et al., 2016), mesotrione (Abit et al., 2009) and tembotrione (Dan et al., 2010) have shown potential for use in grain sorghum crops, but they still lack more details regarding crop selectivity and technical positioning. So, additional information on herbicide rate, plant stage and interactions with climate and soil is required for a safe use of these herbicides in grain sorghum.

Other key aspect when one considers other chemical alternatives for the control of weeds in grain sorghum is the selectivity stability to their distinct hybrids. In corn, tolerance of commercial hybrids to sulfonylurea herbicides varies considerably, being high for some hybrids and low for others (Cavalieri et al., 2008). In addition, tolerance of maize hybrids may vary according to the environment, crop management system, herbicide rate and the plant stage during the herbicide application (Cavalieri et al., 2012; Guerra et al., 2010). In a study comparing five grain sorghum hybrids, the hybrid 50A50 was the least sensitive and recovered more rapidly on the evaluation of 18 herbicide treatments (Takano et al., 2016). Despite clearly showing different tolerances for different hybrid, this study was preliminary and did not investigate other variables relating to crop development and performance.

The objectives of the present study were to assess the efficacy and safety of herbicide alternatives for weed control in grain sorghum, applied in pre- or post-emergence of the crop, as well as regarding the selectivity of atrazine + s-metolachlor to different hybrids of this cereal.

Material and Methods

Experimental areas and crop management

Three trials were carried out during the 2015/2016 growth season in the municipalities of Mogi Mirim-SP (22°26’43”S; 47°04’02”W, 690 m altitude) and/or Jardinópolis-SP (20°54’39”S; 47°53’45”W, 560 m altitude), Brazil. The weather conditions during the period are illustrated in Figure 1. Both areas had a history of summer crops, especially soybean and corn, and have used no-till system for at least 10 years. Prior to the installation of the trials, soil samples were collected for physicochemical analysis and recommended fertilization. The soils of the experimental sites were made of 15 and 57% of clay, 73 and 22% of sand, 12 and 21% of silt, with 5.5 and 5.4 pH ($CaCl_2$) values, and 1.6 and 2.6% of organic matter in Mogi Mirim-SP and Jardinópolis-SP, respectively. The spontaneous vegetation grown in the sites was eliminated five days before implementation of the crop with application of 400 g a.i. ha^{-1} of paraquat.

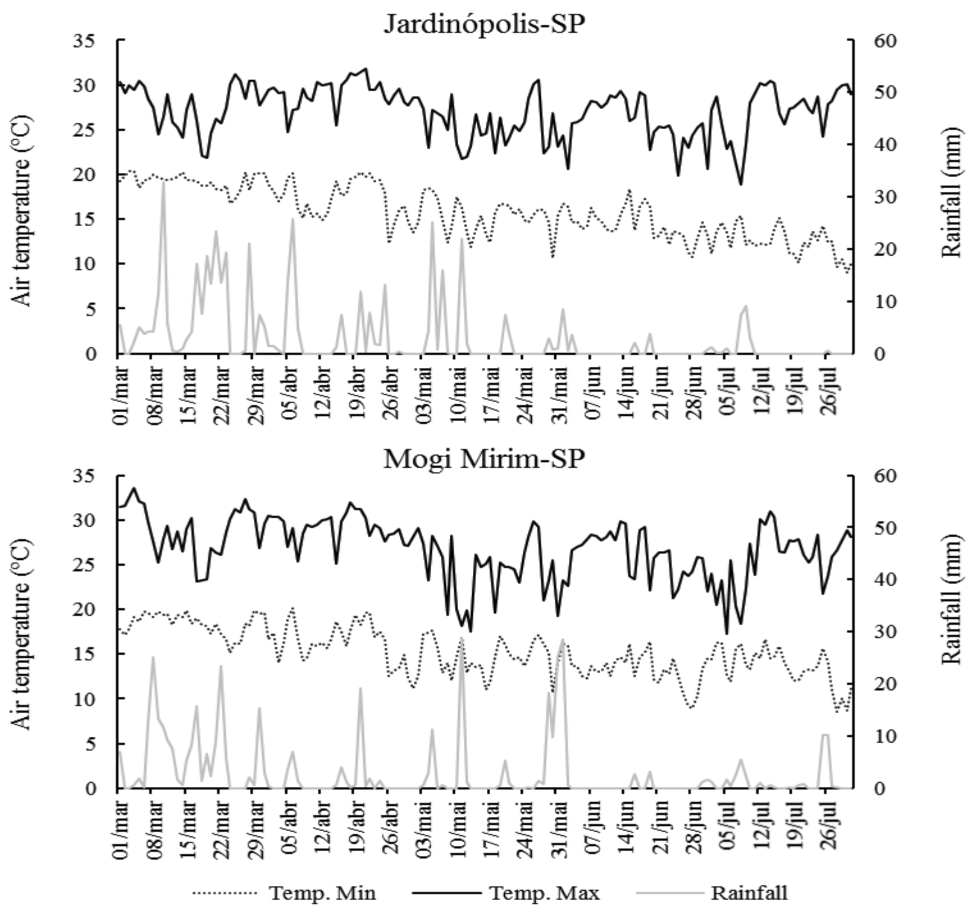

Figure 1 - Climate data collected during the conduction of the studies in Jardinópolis-SP and Mogi Mirim-SP, 2016.

The experimental sites were sowed from March 15 to 27, 2016, using a seeder-fertilizer machine, simulating a conventional second-crop planting in Brazil. The hybrid 50A40 of grain sorghum was sowed with 18 seeds m^{-1} in rows, spaced 0.5 m, aiming to reach a population of 320,000 plants ha^{-1}. The agricultural practices used were those recommended for the region, with investment for high grain yield (Borghi et al., 2016). The experimental sites were spray-irrigated to a water level of 10 mm when occurred drought for a period longer than seven days. The experimental units consisted of field plots measuring 3 x 4 m (12 m^2) of useful land, containing six crop lines.

Efficacy and selectivity of pre-emergence herbicides (first trial)

The experimental design consisted of randomized blocks with four replications, and was replicated in two sites, Jardinópolis-SP and Mogi Mirim-SP. Treatments consisted of distinct herbicides applications during crop pre-emergence ("plant and spray"), as follows (g ai ha^{-1}): atrazine (2,000), flumioxazin (60), atrazine + flumioxazin (2,000 + 60), mesotrione (100), atrazine + mesotrione (2,000 + 100), s-metolachlor (576, 770 and 1,150) and atrazine + s-metolachlor (2,000 + 576, 770 and 1,150). There was also an untreated check-plot (without application of herbicides) for comparison, where weeds were not controlled during the crop cycle. The same hybrids used for the post emergence experiment were employed in this experiment.

The herbicides were applied using a CO_2 backpack sprayer equipped with 3-m long boom and six nozzles (AIXR 110.015) and calibrated for 100-L ha^{-1} of spray volume. The weeds assessed were *Amaranthus* spp., *Bidens pilosa* and *Portulaca oleraceae* in Jardinópolis-SP and *Amaranthus* spp., *Euphorbia heterophylla* and *Raphanus raphanistrum* in Mogi Mirim-SP.

Efficacy and selectivity of post-emergence herbicides (second trial)

The experimental design, number of replications and locations were identical to the pre-emergence trial. Treatments consisted of distinct herbicides applied at the crop post-emergence (3-4 leaves stage) as follows (g a.i. ha^{-1}): atrazine (2,000), acetochlor (1,150 and 2,300), atrazine + acetochlor (2,000 + 1,150 and 2,300), fluroxypyr (100 and 120), atrazine + fluroxypyr (2,000 + 100 and 120), mesotrione (50 and 100), atrazine + mesotrione (2,000 + 50 and 100), s-metolachlor (576 and 770) and atrazine + s-metolachlor (2,000 + 576 and 770). In this experiment, it was also added an untreated check-plot without herbicides application. The herbicides were applied as described in the previous experiment.

On the day of the herbicides application, the following weed species were visually evaluated: *Amaranthus viridis* (13 plants m^{-2}) and *Raphanus raphanistrum* (32 plants m^{-2}), staged at 2 to 4 leaves, in Mogi Mirim-SP; *Amaranthus viridis* (33 plants m^{-2}) and *Portulaca oleracea* (5 plants m^{-2}), staged at 2 to 4 leaves, in Jardinópolis-SP.

Selectivity of atrazine + S-metolachlor to sorghum hybrids (third trial)

The experimental design and number of replicates were identical to the previous experiments; however, in this case, the experiment was conducted only in Jardinópolis-SP. The experiments were arranged in factorial design with subdivided plots (A = 3 x B = 9), with Factor A being allocated to the plots, and Factor B to the sub-plots. Factor A consisted of three rates of the pre-mixture atrazine + s-metolachlor applied in the crop post-emergence (3 to 4 leaves) (g a.i. ha^{-1}): 0, 1,480 + 1,160 and 2,960 + 2,320. In this case, besides serving as a comparison pattern for the herbicides treatments, the untreated check-plot was also one of the levels of treatments tested for Factor A. Factor B consisted of nine sorghum hybrids with different levels of sensitivity to herbicides (Takano et al., 2016): 1G100, 1G220, 1G230, 1G244, 1G282, 50A10, 50A40, 50A50 and 50A70. Application of the treatments was carried out as described for the other experiments, and *Amaranthus* spp. (33 plants m^{-2}) was the only weed evaluated.

Evaluations and statistical analysis

The efficacy of weed control was assessed 21 and 42 days after application (daa) and crop injury 14, 21 and 42 daa, using a visual scale ranging from 0 to 100%. In addition, the number of days between the plants emergence and 50% flowering (F_{50}), the crop population and height during full blossom were also evaluated. Finally, crop grain yield was assessed by harvesting the four central lines of the plot, and normalizing the values found to the standard grain moisture of 13%. The data were subjected to analysis of variance by the F-test for significant effects ($p<0.05$) and Tukey's pairwise comparison test for mean separation of the tested treatments. When the effect of sites and its interactions was not significant, the locations were considered as a random variable because there was homogeneity of error variances (Zimmermann, 2004).

Results and Discussion

A joint analysis of the data of Jardinópolis-SP and Mogi Mirim-SP was made for the majority of the variables, except for efficacy of control, where significant differences were found at the sites ($p<0.05$). So, the treatments values for this variable are shown in separate by location, while for the other variables are considered the means derived from the means of both places.

Efficacy and selectivity of pre-emergence herbicides (first trial)

In general, the efficacy of weed control in the treatments had mean values of at least 90%, especially when atrazine was associated with other residual herbicides (Table 1). In fact, these associations provided a high control of all species examined, except *Portulaca oleraceae*, which indicated 83-86% of control with atrazine and mesotrione. However, when applied alone the effect of the herbicides was not always satisfactory, such as of atrazine applied in both sites, and s-metolachlor in the experimental site in Mogi Mirim-SP. Control was higher than 90% only with flumioxazin applied alone, for most of the weeds in both assessments.

Regarding crop injury, a great variability of response was found in the treatments tested, atrazine being the only herbicide that caused less than 5% of injury in the three assessments (Table 2). Mesotrione, flumioxazin and their mixtures with atrazine caused maximum injury levels of 20%, which declined over time and remained below 10% at 42 daa. In the case of s-metolachlor, an effect of the dose-response was observed for the magnitude of this variable since the grain sorghum injury increased as the rate of the

Table 1. Efficacy of weed control after application of pre-emergence herbicides on grain sorghum (50A40). Jardinópolis-SP and Mogi Mirim-SP, 2016.

Treatment	Dose (g ai ha^{-1})	Jardinópolis-SP						Mogi Mirim-SP					
		AMASS[1/]		BIDPI		POROL		AMASS		EPHHL		RAPRA	
		21 daa[2/]	42 daa	21 daa	42 daa	21 daa	42 daa	21 daa	42 daa	21 daa	42 daa	21 daa	42 daa
Untreated	0	0	0.0	0	0	0	0	0	0	0	0	0	0
Mesotrione	100	97A[3/]	96a	98a	97a	82c	68b	95	97a	94a	92	96a	96a
S-metolachlor	576	93a	86a	93a	90a	93ab	92a	94	82b	67b	90	61b	52b
S-metolachlor	770	94a	90a	95a	91a	97a	95a	94	85b	79ab	92	74ab	68ab
S-metolachlor	1150	96a	93a	97a	96a	98a	97a	95	85b	93a	91	88a	84a
Flumioxazin	60	100a	100a	100a	100a	100a	100b	98	98a	97a	97	96a	88a
Atrazine	2000	70b	64b	81b	74b	84c	80ab	91	91ab	95a	91	87a	88a
Atrazine + mesotrione	(2,000 + 100)	98a	96a	99a	98a	86bc	83ab	99	100a	99a	100	98a	98a
Atrazine + s-metolachlor	(2,000 + 576)	96a	96a	95a	96a	98a	99a	99	98a	96a	96	96a	94a
Atrazine + s-metolachlor	(2,000 + 770)	97a	95a	98a	97a	97a	97a	98	98a	99a	98	91a	88a
Atrazine + s-metolachlor	(2,000 + 1150)	99a	96a	98a	96a	99a	97a	98	99a	98a	98	94a	89a
Atrazine + flumioxazin	(2,000 + 60)	100a	100a	100a	100a	100a	100A	98	98a	99a	99	93a	94a
F		24.6	7.3	2.5	2.1	6.4	5.6	1.3^{ns}	1.6	14.0	1.2^{ns}	13.2	14.4
CV (%)		3.6	8.3	10.7	12.6	5.7	10.6	21.0	11.4	47.9	46.7	58.8	52.6
DMS		8.4	18.8	20.9	21.8	13.3	22.8	41.2	15.3	21.8	27.9	22.5	21.2

[1/]AMASS: *Amaranthus* spp., BIDPI: *Bidens pilosa*, POROL: *Portulaca oleraceae*, RAPRA: *Raphanus raphanistrum* and EPHHL: *Euphorbia heterophylla*.

[2/]daa: days after application

[3/]Means followed by the same letter do not differ from each other by the Tukey's test ($p<0.05$).

herbicide increased. Less than 20% of injury was observed in the plots treated with 576 g ha^{-1}, while in the plots with 770 and 1,150 g ha^{-1} injury levels were higher than 50%.

The population of grain sorghum was reduced only in the plots treated with s-metolachlor at 770 and 1,150 g ha^{-1}, which were statistically different from the untreated check-plot (Table 2). The crop height was only lower with application of s-metolachlor at 1,150 g ha^{-1}, associated or not with atrazine, when compared to the control. The number of days between the plants emergence and 50% of flowered sorghum plants (F_{50}) was smaller for the treatment with atrazine only and for the untreated check-plot, when compared to the s-metolachlor (1,150 g ha^{-1}) alone or mixed with atrazine. The crop grain yield was only reduced with application of s-metolachlor (1,150 g ha^{-1}), associated or not with atrazine, while the yields in the other treatments were not reduced.

Efficacy and selectivity of post-emergence herbicides (second trial)

In most cases, the efficacy of control values was higher than 95% in the plots treated with atrazine and its associations with other herbicides, in both assessments (Table 3). However, when applied alone (not associated with other herbicides), the effect was unsatisfactory (<90%), although no significant statistical difference was always found. In fact, acetochlor, s-metolachlor and fluroxypyr did not achieve a satisfactory efficacy for *Amaranthus* spp., *P. oleracea* and *R. raphanistrum*, regardless of herbicide rate and experimental site. For mesotrione, the effect was satisfactory for *Amaranthus* spp., in both sites, and for *R. raphanistrum* in Jardinópolis-SP, but not for *P. oleracea* in Jardinópolis-SP.

Concerning crop injury, most of the treatments indicated high selectivity to the grain sorghum hybrid 50A40, with mean values lower than 5%, in the three assessment dates (Table 4). Acetochlor associated with atrazine with the highest rate tested caused injuries ranging from 6 to 10%, but did not differ statistically from the other treatments with the herbicides tested. Mesotrione and its associations with atrazine caused the greatest injury levels to the crop, either at 50 g ha^{-1} or 100 g ha^{-1}, in the three dates of visual assessment of the symptoms. While with the exclusive application of mesotrione the injury levels ranged from 12 to 27%, the magnitude of the effect of its association with atrazine was greater, with values ranging from 40 to 55%.

The crop population and height did not vary as a result of the treatments studied (data not presented). The F_{50} value was higher for the association of the atrazine + mesotrione (2,000 + 100 g ha^{-1}) herbicides than for the untreated check-plot, as described in Table 4. Crop grain yield was lower only for the treatment with atrazine + mesotrione (2,000 + 100 g ha^{-1}), when compared with the untreated check-plot. Therefore, in the plots treated with atrazine + mesotrione (2000 + 50 g ha^{-1}), as well as with the other herbicides tested, there was not a decrease in yields that might be caused by the treatments.

Selectivity of atrazine + s-metolachor to sorghum hybrids (third trial)

The efficacy of control of *Amaranthus* spp. at 28 daa varied only as a function of the rate of the atrazine + s-metolachor, applied in a pre-formulated mixture, as shown in Figure 2. It can be seen that the efficacy of control provided by both dosages of herbicide was over 98%, and the control obtained

Table 2. Visual injury, crop height, crop stand, flowering time of 50% of the plants (F_{50}) and crop grain yield after application of pre-emergence herbicides on grain sorghum (50A40). Jardinópolis-SP and Mogi Mirim-SP, 2016.

Treatment	Dose (g ai ha^{-1})	Visual injury (%)			Height (cm)	Stand (pl. m^{-1})	F_{50} (dias)	Yield (kg ha^{-1})[2/]
		14 daa[1/]	21 daa	42 daa				
Untreated	0	0	0	0	132a	18a	69bc	5,529abc
Mesotrione	100	8d[2/]	7e	3cd	131a	16ab	70abc	6,505a
S-metolachlor	576	16bcd	14de	9bcd	128ab	16ab	70abc	5,850ab
S-metolachlor	770	33bc	29cd	13bc	128ab	14b	70abc	5,221abc
S-metolachlor	1150	59a	55a	43a	125b	14b	72ab	4,199c
Flumioxazin	60	20bcd	15de	9bcd	130ab	15ab	70abc	6,044ab
Atrazine	2000	4d	4e	1d	131a	17ab	68c	6,367ab
Atrazine + mesotrione	(2000 + 100)	15cd	15de	4cd	130ab	16ab	70abc	6,061ab
Atrazine + s-metolachlor	(2000 + 576)	17bcd	14de	6cd	130ab	15ab	70abc	5,820ab
Atrazine + s-metolachlor	(2000 + 770)	38ab	36bc	20b	127ab	15ab	71abc	5,717ab
Atrazine + s-metolachlor	(2000 + 1150)	59a	54ab	43a	125b	15ab	73a	5,016bc
Atrazine + flumioxazin	(2000 + 60)	17bcd	17cde	7.1cd	130ab	15ab	70abc	5,440abc
F		15.6	18.9	35.2	4.5	2.5	3.6	14.7
CV (%)		52.1	48.5	49.6	1.7	9.6	1.8	14.5
DMS		22.7	19.3	11.7	3.2	2.2	3.1	1,387.2

[1/]daa: days after application;

[2/]Mean values of both sites by the joint analysis. Means followed by the same letter do not differ from each other by the Tukey's test ($p<0.05$).

Table 3. Efficacy of weed control after application of post-emergence herbicides on grain sorghum (50A40). Jardinópolis-SP and Mogi Mirim-SP, 2016.

Treatment	Dose ($g\ ai\ ha^{-1}$)	Jardinópolis-SP				Mogi Mirim-SP			
		AMASS[1/]		POROL		AMASS		RAPRA	
		7 daa[2/]	28 daa	7 daa	28 daa	7 daa	28 daa	7 daa	28 daa
Untreated	0	0	0	0	0	0	0	0	0
Acetochlor	1150	76abc[3/]	71ab	73bcd	67b	26e	66d	24fg	65b
Acetochlor	2300	73abc	77ab	82abc	80ab	26e	60d	22g	59b
Mesotrione	50	60cd	97a	43d	61b	85b	97bc	82b	95a
Mesotrione	100	86ab	98a	73bcd	69ab	85b	99abc	84b	96a
S-metolachlor	576	50d	48b	50cd	54b	28e	35e	25fg	31c
S-metolachlor	770	58cd	66ab	54cd	63b	35de	59d	34e	59b
Fluroxypyr	100	65bcd	77ab	68cd	81ab	43c	65d	42d	64b
Fluroxypyr	120	73abc	75ab	85abc	82ab	32de	66d	31ef	66b
Atrazine	2000	95a	96a	97ab	97a	98a	97bc	96a	95a
Atrazine + acetochlor	(2000+1150)	99a	99a	99a	100a	94a	99ab	93a	98a
Atrazine + acetochlor	(2000+2300)	86ab	98a	96ab	99a	97a	99abc	96a	98a
Atrazine + mesotrione	(2000+50)	100a	100a	100a	100a	97a	100a	94a	98a
Atrazine + mesotrione	(2000+100)	100a	100a	100a	100a	98a	100a	98a	98a
Atrazine + s-metolachlor	(2000+576)	100a	100a	100a	100a	97a	100a	97a	99a
Atrazine + s-metolachlor	(2000+770)	100a	100a	100a	100a	99a	100a	97a	98a
Atrazine + fluroxypyr	(2000+100)	95a	98a	98ab	98a	97a	98abc	96a	97a
Atrazine + fluroxypyr	(2000+120)	100a	100a	100a	100a	98a	100a	96a	98a
F		17.1	11.7	17.6	14.5	247.2	169.6	215.9	186.6
CV (%)		14.4	16.3	15.4	15.2	5.8	4.9	6.3	4.7
DMS		16.7	19.9	15.3	17.9	5.9	2.1	6.4	5.5

[1/]AMASS: *Amaranthus* spp.. POROL: *Portulaca oleraceae*, RAPHA: *Raphanus raphanistrum*.

[2/]daa: days after application.

[3/]Means followed by the same letter do not differ from each other by the Tukey's test ($p<0.05$)

Table 4. Visual injury, flowering time of 50% of the plants (F_{50}) and crop grain yield after application of post-emergence herbicides on grain sorghum (50A40). Jardinópolis-SP and Mogi Mirim-SP. 2016.

Treatment	Dose ($g\ ai\ ha^{-1}$)	Visual injury (%)			F_{50} (days)	Grain yield ($kg\ ha^{-1}$)[2/]
		7 daa[1/]	14 daa	28 daa		
Untreated	0	0	0	0	68b	4,907ab
Acetochlor	1150	2c[2/]	2c	0b	68b	6,057ab
Acetochlor	2300	3bc	2c	3b	68b	6,384ab
Mesotrione	50	12bc	16bc	17ab	69ab	6,311ab
Mesotrione	100	25b	18bc	26ab	69ab	5,532ab
S-metolachlor	576	1c	1c	2b	68b	5,747ab
S-metolachlor	770	1c	1c	2b	69ab	5,712ab
Fluroxypyr	100	1c	0c	1b	69ab	5,646ab
Fluroxypyr	120	1c	1c	1b	70ab	5,425ab
Atrazine	2000	1c	2c	1b	72a	6,489a
Atrazine + acetochlor	(2.000 + 1.150)	4bc	4c	3b	68b	6,585a
Atrazine + acetochlor	(2.000 + 2.300)	6bc	7c	9b	70ab	6,163ab
Atrazine + mesotrione	(2.000 + 50)	51a	43ab	40a	69ab	4,537ab
Atrazine + mesotrione	(2.000 + 100)	49a	55a	41a	72a	4,320b
Atrazine + s-metolachlor	(2.000 + 576)	2c	1c	0b	69ab	5,988ab
Atrazine + s-metolachlor	(2.000 + 770)	2c	1c	1b	69ab	6,490a
Atrazine + fluroxypyr	(2.000 + 100)	0c	1c	0b	68b	6,626a
Atrazine + fluroxypyr	(2.000 + 120)	2c	1c	4b	69ab	6,479a
F		14.0	5.8	5.9	2.9	12.6
CV (%)		126.1	195.8	172.8	1.4	18.9
DMS		22.4	33.9	28.9	2.5	2.076.9

[1/]daa: days after application;

[2/]Mean values of both sites by the joint analysis. Means followed by the same letter do not differ from each other by the Tukey's test ($p<0.05$).

with the greater rate was significantly higher than that of the lower rate.

Regarding crop injury, there was a variation resulting from the interaction between the factors related to the rate of atrazine + s-metolachor and sorghum hybrids (Table 5). Higher levels of injuries were observed with increased herbicide rate in all hybrids except for 50A10 and 50A40, whose tolerance level was not affected by the treatment. The hybrid 1G220 exhibited higher levels of visual injury, with values in the range of 8 to 28%, and was statistically different from the other hybrids tested in this work. The other hybrids tested always indicated injury levels lower than 11%, especially 1G233, 50A10 and 50A40, whose injury level never exceeded the mean value of 5%.

Grain yields also varied as a function of the interaction between the factors relating to rate of atrazine + s-metolachor herbicide and grain sorghum hybrids, as shown in Table 5. In general, the increased herbicide rate caused an increase in this variable magnitude, since the highest values were found for rate of 2960 + 2320 g ha^{-1}. However, the rate effect could only be observed in four of the nine possible comparisons, since there was no statistical difference between the herbicide rates in most of the cases. Despite the potential yield of the different grain sorghum hybrids in Jardinópolis-SP, hybrid 1G220 and 1G282 varieties had the highest yields compared to the other hybrids.

Weed interference constrains sorghum grain yields in Brazil and is exacerbated by lack of effective

Table 5. Visual injury[1/] and crop grain yield as a result of different hybrids and [atrazine + S-metolachlor] rates on grain sorghum crop. Jardinópolis-SP, 2016.

Hybrid*	Visual injury (%)								Grain yield (kg ha^{-1})								
	Atrazine + S-metolachlor [g i.a. ha^{-1}]																
	0		[1480+1160]			[2960+2320]			0			[1480+1160]			[2960+2320]		
1G100	0[2/]	C	3	bc	B	6	c	A	3,992	ab	AB	3,191	ab	B	5,271	abc	A
1G220	0	C	8	a	B	28	a	A	3,760	ab	A	3,050	c	A	4,476	c	A
1G233	0	B	1	bc	B	4	cd	A	5,819	a	AB	4,652	ab	B	7,317	a	A
1G244	0	B	0	c	B	5	cd	A	4,240	ab	A	3,656	ab	A	4,907	bc	A
1G282	0	B	2	bc	B	11	b	A	3,370	c	B	4,573	ab	AB	4,608	c	A
50A10	0	A	1	bc	A	1	d	A	3,941	ab	A	4,754	ab	A	5,960	abc	A
50A40	0	A	1	bc	A	4	cd	A	5,528	a	AB	5,060	ab	B	6,860	ab	A
50A50	0	C	3	bc	B	7	bc	A	5,398	ab	A	5,072	ab	A	5,119	bc	A
50A70	0	B	1	bc	B	7	bc	A	4,842	ab	A	5,245	a	A	6,251	abc	A
DMS row	2.6								1587.7								
DMS colum	4.2								2129.2								
CV	30.3								16.6								
F	25.9								1.6								

[1/] Means followed by the same lowercase letter in the column and uppercase in the row not differ from each ot.

herbicide options. Furthermore, even with the use of registered herbicides, the outcome is not always as expected, especially for grass weeds (Archangelo et al., 2002; Dan et al., 2010). Prospection of new herbicide alternatives is necessary to overcome this problem, either with products already available in the market or those under development. The present work contributes with alternatives for use in pre-emergence (Tables 1 and 2) and post-emergence (Tables 3 and 4) crops, both with good results in weed control and crop selectivity. In addition, the study shows that the pre-mix atrazine + s-metolachlor has a high level of selectivity to the most hybrid varieties of sorghum (Table 5, Figure 2).

Flumioxazin and mesotrione, applied alone or in combination with atrazine, achieved satisfactory levels of efficacy and selectivity (Tables 1 and 2). In other studies, the use of flumioxazin (50 g ha^{-1}) and mesotrione (105 g ha^{-1}) in this condition was also promising (Abit et al., 2009; Galon et al., 2016). Added to these herbicides, s-metolachlor (576 g ha^{-1}) was also another selective alternative to the crop, although its efficacy has not always been satisfactory, being required its association with atrazine (Tables 1 and 2). However, with rates of 770 g ha^{-1} and 1,150 g ha^{-1}, the use of this herbicide should not be recommended because of the high levels of injury caused to the crop, especially in sandy soils. In contrast, atrazine + s-metolachlor with rates of 1,120 + 1,400 g ha^{-1} (Geier et al., 2009) or 1,000 + 800 g ha^{-1} (Takano et al., 2016) exhibited selectivity to grain in pre-emergence condition.

In the case of application of post-emergence herbicides, diverse combinations with atrazine and acetochlor, s-metolachlor and fluroxypyr indicated satisfactory efficacy of control and selectivity to the crop (Tables 3 and 4). These combinations also exhibited promising results in preliminary studies (Takano et al., 2016), and their use prevents the selection of triazine-resistant weed biotypes (Geier et al., 2009). In addition to these herbicides, mesotrione (50 g ha^{-1}) was also an interesting option, even causing low-to-moderate injuries, which however did not affect the crop development and crop grain yield. These results corroborate those found by Hugie et al. (2008) and Abit et al. (2009), where mesotrione was a major option for the control of *Amaranthus* spp. Furthermore, this herbicide exhibited a high level of control of grass weeds such as *Brachiaria* spp., *Digitaria* spp., among others, and can be used with this purpose in grain sorghum crops.

The results obtained in the study with different grain sorghum hybrids showed that there is a special tolerance to atrazine + s-metolachlor, and that selectivity is associated with the herbicide rate (Table 5). These differences were also found in a preliminary study with grain sorghum (Takano et al., 2016) and have been widely known and studied for different maize hybrid (Cavalieri et al., 2008, 2012). Therefore, the choice of the herbicide and rate to be applied, the hybrid variety to be planted and the crop management system should be taken into account in the strategy of weed control. For the particular case of the pre-formulated mixture of atrazine + s-metolachlor, with dose of 1,480 + 1,160 g a.i ha^{-1}, there is high selectivity stability among the commercial hybrids of this crop. This ensures the safe use of this new option for weed chemical control, and the effect of these herbicides will be a high level of control of a wide range of species (Table 4, Figure 2).

Although it is the most used herbicide for weed control in grain sorghum crops in Brazil, atrazine applied alone did not indicate good control of part of the weeds under evaluation in this study (Table 2). This shows the importance of its association with other residual herbicides in pre-and post-emergence conditions, which benefits the effect obtained with the use of chemical control. The herbicides combinations that exhibited satisfactory weed control and selectivity to grain sorghum in the crop pre-emergence were: atrazine + flumioxazin (2,000 + 60 g ha^{-1}), atrazine + mesotrione (2,000 + 100 g ha^{-1}) and atrazine + S-metolachlor (2,000 + 576 g ha^{-1}). In the crop post-emergence, the best herbicide combinations were: atrazine + acetochlor (2,000 + 1150 and 2300 g ha^{-1}), atrazine + s-metolachlor (2,000 + 576 and 770 g ha^{-1}) and atrazine + fluroxipyr (2,000 + 100 and 120 g ha^{-1}). These management strategies would provide benefits such as the rotation of herbicides action mechanisms, an increased range of weeds control, especially grasses, in the case of acetochlor, s-metolachlor and mesotrione.

Conclusion

The pre emergence herbicide alternatives that best optimized weed control and crop selectivity were flumioxazin (60 g ha^{-1}), atrazine + flumioxazin (2,000 + 60 g ha^{-1}), atrazine + mesotrione (2,000+100 g ha^{-1}) and atrazine + S-metolachlor (2,000 + 576 g ha^{-1}). The best post emergence herbicide alternatives were atrazine (2,000 g ha^{-1}), atrazine + acetochlor (2,000 + 1,150 and 2,300 g ha^{-1}), atrazine + s-metolachlor (2,000 + 576 and 770 g ha^{-1}) and atrazine + fluroxypyr (2,000 + 100 and 120 g ha^{-1}). The application of atrazine + s-metolachlor at the evaluated rates was selective to the nine hybrids assessed.

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