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Performance of grain sorghum hybrids in soils with low and high aluminum saturation[1]

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ABSTRACT

The presence of aluminum (Al^{3+}) in acidic soils is one of the main causes of low crop yield, since it inhibits the root growth, thus affecting the nutrients and water uptake by plants. An approach to grow crops in areas with high Al^{3+} saturation is the use of tolerant cultivars. This study aimed to evaluate commercial sorghum hybrids in soils with low and high aluminum saturation, in order to select cultivars with high grain yield, even when exposed to abiotic stress. Twenty hybrids were evaluated for characteristics such as plant flowering, plant height and grain yield. All three traits were significantly affected by Al^{3+}, being grain yield the most affected one. Despite the significant genotypes x environments interaction for grain yield, it was possible to select hybrids with yield above the national average in both environments. The hybrids BRS373, 50A50, AS4639, DKB540, AS4625, A9721R, 1167092, DKB550, 1G282 and AG1040 showed a high yield under low and high Al-saturation conditions.

KEYWORDS: *Sorghum bicolor*; abiotic stress; aluminum tolerance; plant breeding.

RESUMO

Desempenho de híbridos de sorgo granífero em solos com baixa e alta saturação por alumínio

A presença de alumínio (Al^{3+}) em solos ácidos é uma das principais causas da baixa produtividade das culturas, pois inibe o crescimento das raízes, afetando a absorção de nutrientes e água pela planta. Uma abordagem para o cultivo em áreas com alta saturação por Al^{3+} é a utilização de cultivares tolerantes. Objetivou-se avaliar híbridos comerciais de sorgo granífero em solos com baixa e alta saturação por Al^{3+}, a fim de selecionar cultivares com alta produtividade de grãos, mesmo quando expostas a estresse abiótico. Avaliaram-se 20 híbridos, quanto às características de florescimento, altura de plantas e produtividade de grãos. As três características foram prejudicadas pelo Al^{3+}, sendo a produtividade de grãos a mais afetada. Apesar de a interação genótipos x ambientes ser significativa para produtividade de grãos, foi possível selecionar híbridos com produtividade acima da média em ambos os ambientes. Os híbridos BRS373, 50A50, AS4639, DKB540, AS4625, A9721R, 1167092, DKB550, 1G282 e AG1040 apresentaram alta produtividade nas condições de baixa e alta saturação por Al^{3+}.

PALAVRAS-CHAVE: *Sorghum bicolor*; estresse abiótico; tolerância a alumínio; melhoramento de plantas.

INTRODUCTION

Sorghum [*Sorghum bicolor* (L.) Moench] is the fifth most produced cereal in the world, after maize, wheat, rice and barley. In 2013, sorghum had an estimated world production of 61.4 million tons, in 42.1 million hectares (FAO 2015).

In Brazil, the acreage of grain sorghum is quite expressive, reaching a crop production of 2.1 million tons in an area of 722,000 hectares (Conab 2015). The consolidation of the sorghum crop in the country is due basically to the increased *per capita* consumption of animal protein, especially from swine, poultry and cattle; seed companies investment in developing hybrids adapted to the off-season; expansion of the no-tillage planting system; and effective actions of sorghum management by research and production agencies.

Over 90 % of the national area of grain sorghum is located in the Brazilian Savannah region, as a succession crop after soybean, in the off-season. The remnants of the Brazilian Savannah vegetation developed on very old soils and are always associated with high acidity. Those soils are characterized by a high acidity, high Al^{3+} saturation and low availability of nitrogen (N), phosphorus (P), potassium (K^+),

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calcium (Ca^{2+}), magnesium (Mg^{2+}), zinc (Zn), boron (B) and copper (Cu). Additionally, most Brazilian Savannah soils have reduced water-holding capacity (Silva & Malavolta 2000).

Aluminum is one of the most abundant metals in the Earth's crust, being released into the soil solution under acidic conditions, taking over phytotoxic forms, like Al^{3+}. The toxicity caused by Al^{3+} affects the development of plants and, in particular, inhibits the root growth, making the roots short and coarse. The root tip is the primary target of Al^{3+} (Kochian et al. 2004).

Besides being harmful to the growth of the root system, Al^{3+} interferes with the uptake of P, Ca and Mg by plants, also contributing to the adsorption of P in the soil. High levels of Al^{3+} in soil with water deficiency reduce yield drastically, making cultivation impractical in areas of high acidity (Kochian et at. 2015).

An approach to the cultivation in areas with high Al^{3+} saturation is the use of tolerant cultivars. Plant breeding enables the increase of yield without the expansion of the area, resulting in economic and environmental benefits. The selection of sorghum hybrids with this characteristic would be an efficient alternative to facilitate the exploitation of areas with high Al^{3+} saturation (Caniato et al. 2007 and 2014).

There are already Al^{3+} tolerant hybrids in the market, but further studies continue to be developed to search for new sources of tolerance and better understand the effect of these genes in grain yield under Al^{3+} stress. Thus, this study aimed to evaluate commercial hybrids of grain sorghum in soils with low and high Al^{3+} saturation, in order to identify those with high grain yield, even when exposed to Al^{3+} stress. The selected genotypes have no previous information about Al^{3+} tolerance.

MATERIAL AND METHODS

The trials were carried out at the aluminum-phenotyping site of the Embrapa Milho e Sorgo, in Sete Lagoas, Minas Gerais state, Brazil, being sown on 23 March 2015 and harvested on 15 August 2015. The site is located at 767 m above the sea level and has an average annual rainfall of 1,400 mm, as well as temperatures ranging from 17 ºC to 25 ºC.

Nineteen commercial hybrids of grain sorghum (BRS 373, BRS 330, BRS 332, 1G 100, 1G 282, 50A50, 50A70, AG 1040, AG 1060, AS 4625, AS 4639, DKB 540, DKB 550, Jade, 80G80, BM 737, Buster, FOX and A 9721R) and one experimental hybrid (1167092) were grown under two aluminum (Al^{3+}) saturation conditions (0 % and 40 %). BRS 330 was used as the control.

The experimental design was a randomized complete block, in a 2 x 20 factorial scheme (Al^{+3} saturation x hybrids), with three replications. Plots consisted of 4 rows of 5 m, with 0.5 m between rows. Plots were thinned to 12 cm between plants (180,000 plants ha^{-1}).

The experimental area, with different levels of Al^{3+} saturation, was set according to Menezes et al. (2014). Dolomite limestone with 33 % of CaO and 14 % of MgO was broadcasted over the entire area and disked to a depth of 20 cm, in order to achieve an exchangeable Al^{3+} saturation of 0 %. No limestone was needed in the area with 40 % of Al^{3+} saturation. Two months after liming, the area was divided into rectangular 10 m x 10 m and 5 m x 5 m grids, for the control and Al^{3+} toxicity site, respectively. A total of 51 and 169 points were sampled in the control and Al^{3+} toxicity site, respectively. Three subsamples located in a maximum radius of 1.0 m from each sampling grid point were collected and the compound samples were used for the soil analysis. The measurements of soil exchangeable aluminum (Al^{3+}) and exchangeable cations (Ca^{+2}, Mg^{+2}) were performed with KCl 1 mol L^{-1} as extractor (Donagema et al. 2011), using inductively-coupled argon plasma (ICP) emission spectrometry. Percent values of Al^{3+} saturation were calculated as the ratio of exchangeable Al^{3+} divided by the sum of basic cations plus Al^{3+}. The two areas presented means of Al^{3+} saturation of 0 % and 40 %. In the area with 0 % of Al^{3+} saturation, the soil analysis presented pH of 5.7, 23 mg dm^{-3} of P ($Mehlich^{-1}$) and 223 mg dm^{-3} of K ($Mehlich^{-1}$), while a pH of 4.8, 15 mg dm^{-3} of P ($Mehlich^{-1}$) and 51 mg dm^{-3} of K ($Mehlich^{-1}$) were observed in the area with 40 % of Al^{3+} saturation. Starter fertilizers were applied using 400 kg ha^{-1} of 08-28-16 ($N-P_2O_5-K_2O$) + Zn. At the sixth-leaf stage, 250 kg ha^{-1} of urea (44 % of N) were side dressed in all the area.

Weeds were managed with atrazine (2-chloro-4-ethylamine-6-isopropylamine-s-triazine) at 3.0 kg ha^{-1}, and hand hoeing was used as needed, in order to control additional weeds during the study.

The other crop managements were carried out according to recommendations for sorghum crop

(Menezes et al. 2015b). After the grain filling stage, panicles were protected with polyethylene bags, to prevent bird damage. Harvest was carried out mechanically, after the grains reached physiological maturity.

The following traits were measured: days to flowering (estimated by counting the number of days between sowing and the moment when more than 50 % of the plants achieved anthesis), plant height (obtained by measuring the distance between the ground and the apex of the panicle after the physiological maturity) and grain yield (estimated by weighing the grain mass, corrected to 13 % of moisture, transforming the results to t ha^{-1}).

Data were submitted to the individual variance analysis, considering the effect of the hybrids and Al^{3+} saturation as fixed. As the ratio between the greatest and the smallest mean square of the individual variance analysis did not exceed the 7:1 ratio, the joint analysis of the trials was performed (Banzatto & Kronka 2006). Statistical analyses were performed using the Genes software (Cruz 2006), and the Scott-Knott test ($p > 0.05$) was used to group the hybrids.

RESULTS AND DISCUSSION

The effects of hybrids and environments were significant for all three traits evaluated, indicating a differential performance of the hybrids in both conditions of low and high Al^{3+} saturation (Table 1). The effect of Al^{3+} (environments) is expected, since the Al^{3+} saturation changes the plant physiology, affecting the root development (Kochian et al. 2004) and, consequently, grain yield. The hybrids x environments interaction was non-significant, what implies that the relative performance of the genotypes is not affected by Al^{+3}. Therefore, genotypes selected under low Al^{3+} saturation also have a superior performance under high Al^{3+}.

The coefficients of variation were low for days to flowering (3.7 %) and plant height (5.4 %), and intermediate for grain yield (19.3 %). This last trait, due to its polygenic control, is more influenced by environment and usually presents higher coefficients of variation. Despite this, the value is within the range recommended for plant breeding trials.

The average of days to flowering were 67 and 69, respectively under 0 % and 40 % of Al^{3+} saturation. Even though this difference was low, it was significant. The flowering of the hybrids ranged from 60 to 72 days after sowing under low Al^{3+} saturation, and from 61 to 78 under high saturation (Table 2). Most of the hybrids reached flowering earlier than 70 days, which is an intermediate cycle. The characteristic days to flowering neither drops nor selects the hybrid, because it is important that the grower has cultivars with different cycles, in order to allow the scheduling of sowing and harvesting, thus optimizing his machinery and labor. However, hybrids with flowering later than 75 days must be avoided. In general, it is recommended that the grower starts sowing late maturity hybrids in the beginning of the season and finalize planting those earlier ones. The former have a higher yield potential and the latter, even yielding less, are indicated to finish the season, once they will spend less time in the field and suffer less risk of water stress, a recurrent fact at the end of the off-season (Menezes et al. 2015a).

Despite the significant hybrids x environments interaction for days to flowering, the earliest hybrids were common in both environments (Table 2). The average grouping test ranked the hybrids in three and four flowering groups, respectively under low and

Table 1. Summary of the joint variance analysis (Anova) for days to flowering, plant height and grain yield of twenty sorghum hybrids evaluated under low and high aluminum saturation.

Source of variation	D.F.	Flowering (days)	Plant height (cm)	Yield (t ha^{-1})
		Mean squares		
Hybrids (H)	19	89.47**	551.80**	3.44**
Environments (E)	1	58.80**	4,183.10**	30.82**
H x E	19	10.69*	88.26**	0.48^{ns}
Error	76	6.34	39.38	0.43
Mean control^1		67.10 a	122.00 b	3.90 b
Mean stress^2		68.50 b	110.15 a	2.89 a
CV (%)		3.71	5.41	19.34

**,* Significant at 1 % and 5 %, respectively, by the F-test; ^{ns} non-significant; ^{1} 0 % of Al^{+3} saturation; ^{2} 40 % of Al^{+3} saturation.

high Al^{3+} saturation. The hybrids FOX, Buster and 1G100 were the earliest ones, with flowering up to 62 days, in both conditions. BRS373 was also among the earliest in high Al^{3+} saturation. Only three hybrids showed differences for flowering between the two Al^{3+} saturations: the hybrid 1G282 was earlier under low Al^{3+} saturation, while DKB550 and 80G80 were earlier under high Al^{3+} saturation.

Plants under low Al^{3+} saturation were taller than under high Al^{3+} saturation. The mean grouping test divided the hybrids into three and four groups, with plants varying 99.2-142.5 cm and 87.5-130 cm tall, respectively under low and high Al^{3+} saturation (Table 3). All the hybrids presented plant height within the limits recommended for grain sorghum. Plant height is positively correlated with grain yield in sorghum. Nevertheless, the seed market demands a plant between 100 cm and 150 cm tall, because harvest is done using the same machine for soybean, which performs between these ranges. In addition, plants taller than 150 cm are more susceptible to lodging, causing losses in grain quality, besides increasing labor to harvest and time waste (Santos et al. 2005). Some hybrids presented shorter plants under the stress condition, but, in general, almost all stayed within the standard accepted by the national market.

The trait most affected by high Al^{3+} saturation was grain yield, with a reduction of 26 %, when comparing the environment of high and low Al^{3+} saturation (Figure 1). The grain yield averages were 3.9 t ha^{-1} and 2.9 t ha^{-1}, respectively in the environments with low and high Al^{3+} saturation (Figure 1 and Table 4). That reduction corroborates previous studies carried out under field conditions. Menezes et al. (2014) observed a reduction of 29.5 % in grain yield, in an environment with 40 % of Al^{3+} saturation, in relation to another with 0 % of Al^{3+}. Baligar et al. (1989) found a reduction of 24 %, in comparison to environments with low (2 %) and high (41 %) Al^{3+} saturation.

The mean grouping test divided the hybrids into three and two groups, with yield ranging 2.1-5.1 t ha^{-1} and 1.2-4.0 t ha^{-1}, respectively in the environments with low and high Al^{3+} saturation (Table 4). Considering the national sorghum yield average of 2.8 t ha^{-1} (Conab 2015), 94 % of the hybrids under low Al^{3+} saturation and 64 % of the

Table 2. Averages of days to flowering of twenty hybrids of grain sorghum evaluated under low and high Al^{3+} saturation.

Hybrids		Flowering (days)	
		0 % Al	40 % Al
1	BRS 373	64.3 bA*	63.3 aA
2	BRS 330	70.7 cA	70.7 cA
3	BRS 332	70.3 cA	72.0 cA
4	1G 100	61.0 aA	61.0 aA
5	1G 282	72.3 cB	65.7 bA
6	50A50	67.0 cA	67.3 cA
7	50A70	70.3 cA	70.0 cA
8	AG 1040	68.0 cA	71.3 cA
9	AG 1060	69.7 cA	70.7 cA
10	AS 4625	70.7 cA	70.7 cA
11	AS 4639	70.0 cA	72.7 cA
12	DKB 540	70.0 cA	71.0 cA
13	DKB 550	71.7 cA	77.7 dB
14	Jade	64.0 bA	66.3 bA
15	80G80	64.0 bA	68.7 cB
16	BM 737	65.3 bA	69.3 cA
17	Buster	60.7 aA	62.0 aA
18	FOX	60.0 aA	60.7 aA
19	A 9721 R	65.0 bA	68.7 cA
20	1167092	67.7 cA	71.0 cA

* Means followed by the same lowercase letter in the column and capital letter in the row do not differ from each other by the Scott-Knott test at 5 %.

Table 3. Average plant height of twenty hybrids of grain sorghum evaluated under low and high Al^{3+} saturation.

Hybrids		Plant height (cm)	
		0 % Al	40 % Al
1	BRS 373	122.5 cA*	115.0 cA
2	BRS 330	123.3 cA	120.0 dA
3	BRS 332	117.5 cB	100.8 bA
4	1G 100	118.3 cB	100.0 bA
5	1G 282	142.5 dB	130.0 dA
6	50A50	120.8 cA	115.0 cA
7	50A70	107.5 aA	101.7 bA
8	AG 1040	128.3 cB	115.0 cA
9	AG 1060	99.2 aB	87.5 aA
10	AS 4625	125.0 cA	125.0 dA
11	AS 4639	125.8 cB	110.0 cA
12	DKB 540	127.5 cA	120.8 dA
13	DKB 550	121.7 cB	102.2 bA
14	Jade	126.7 cB	114.2 cA
15	80G80	111.7 bB	90.8 aA
16	BM 737	120.8 cA	113.3 cA
17	Buster	130.0 cB	98.3 bA
18	FOX	130.0 cB	113.3 cA
19	A 9721 R	128.3 cA	119.2 dA
20	1167092	111.7 bA	110.8 cA

* Means followed by the same lowercase letter in the column and capital letter in the row do not differ from each other by the Scott-Knott test at 5 %.

hybrids under high Al^{3+} saturation presented yield above the average.

Despite the significant hybrids x environments interaction for grain yield, it was possible to find hybrids with yield above the average in both environments. Grain yield is graphically depicted in Figure 2, in which the x axis shows the yield under low Al^{3+} saturation and the y axis the yield under high Al^{3+} saturation. The graphic is divided into four quadrants, according to the methodology proposed by Fageria & Baligar (1993). In the upper left quadrant (A) are the tolerant hybrids that are non-responsive to environment improvement; in the upper right quadrant (B) the most promising hybrids, i.e., those that are tolerant and responsive to environment improvement; in the lower left quadrant (C) the susceptible and non-responsive hybrids; and in the lower right quadrant (D) the hybrids susceptible and responsive to the environment.

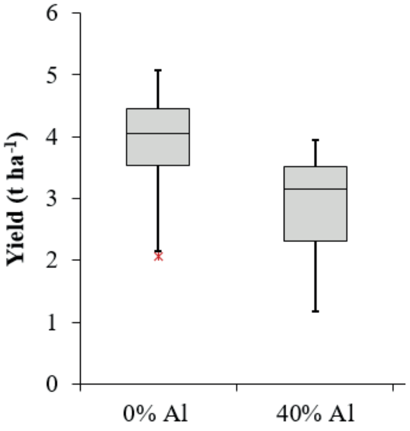

Figure 1. Box plot of grain yield for twenty sorghum hybrids evaluated under low and high Al^{3+} saturation. * Minimum outlier.

Table 4. Average grain yield of twenty hybrids of grain sorghum evaluated under low and high Al^{3+} saturation.

	Hybrids	Grain yield (kg ha^{-1})	
		0 % Al	40 % Al
1	BRS 373	4,519 aA*	3,952 aA
2	BRS 330	3,368 bA	3,216 aA
3	BRS 332	3,242 bA	2,635 aA
4	1G 100	4,178 aA	2,294 bB
5	1G 282	4,099 aA	3,108 aA
6	50A50	4,838 aA	3,879 aA
7	50A70	2,072 cA	1,279 bA
8	AG 1040	4,487 aB	3,065 aA
9	AG 1060	4,077 aA	2,846 aB
10	AS 4625	3,930 aA	3,533 aA
11	AS 4639	4,950 aA	3,804 aB
12	DKB 540	4,092 aA	3,657 aA
13	DKB 550	5,069 aA	3,275 aB
14	Jade	3,200 bA	2,068 bB
15	80G80	3,654 bA	2,325 bB
16	BM 737	2,559 cA	1,593 bA
17	Buster	3,585 bA	1,168 bB
18	FOX	3,679 bA	3,280 aA
19	A 9721 R	4,438 aA	3,521 aA
20	1167092	4,028 aA	3,292 aA

* Means followed by the same lowercase letter in the column and capital letter in the row do not differ from each other by the Scott-Knott test at 5 %.

In the quadrant A, two tolerant hybrids non-responsive to the improvement of the environment were found. Six hybrids were classified in the quadrant C as susceptible and non-responsive. In the quadrant D, two hybrids proved to be susceptible and responsive to the environment improvement.

The hybrids of the quadrant B (BRS373, 50A50, AS4639, DKB540, AS4625, A9721R, 1167092, DKB550, 1G282 and AG1040) are the most important ones, due to the fact that they showed yield above the average in both environments, and can be considered as tolerant and responsive to the environment improvement. No hybrid of the quadrant B is among the earliest flowering ones. Only BRS 373 presented flowering earlier than the general average in both Al^{3+} conditions

Comparing the two Al^{3+} saturation environments, BRS330 and AS4625 presented a

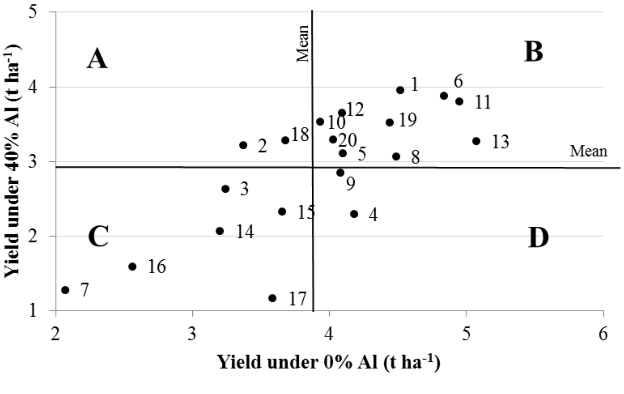

Figure 2. Dispersion diagram for grain yield of twenty sorghum hybrids evaluated under 0 % (x axis) and 40 % (y axis) of Al^{3+} saturation. Quadrant A: identifies hybrids that had low yield at 0 % and high yield at 40 % of Al^{3+} saturation; B: hybrids with high yield at both 0 % and 40 % of Al^{3+} saturation; C: hybrids with low yield at both 0 % and 40 % of Al^{3+} saturation; D: hybrids with high yield at 0 % and low yield at 40 % of Al^{3+} saturation. See number legends in Table 2.

reduction lesser than 10 % (Table 4). On the other hand, Buster and 1G100 presented a reduction above 40 %. The hybrids in quadrant B had less than 25 % of yield reduction, except for AG1040 (32 %). The hybrids BRS330, DKB550 and AG1040 were classified as Al^{3+} tolerant in a previous study (Menezes et al. 2014), and all hybrids from the quadrant B have a yield statistically similar to it.

In sorghum, the major Al^{3+} tolerance locus (Alt_{SB}) was mapped to the end of sorghum chromosome 3, what explains a large proportion of the phenotypic variation for the Al^{3+} tolerance assessed in hydroponics (Magalhães et al. 2004). Alt_{SB} is a major gene of the Multidrug and Toxic Compound Extrusion (MATE) family that confers tolerance to aluminum in sorghum (Magalhães et al. 2007). Al^{3+} tolerance involves the release of organic acids as malate and citrate, which form stable and non-toxic complexes with Al^{3+}, thereby providing a means for plants to withstand Al^{3+} toxicity (Kochian et al. 2004). Studies have confirmed that the Alt_{SB} gene in sorghum cultivars used in regions with acid soils or subsoils contributes to the development of better and deeper root systems and promotes a greater and sustainable yield. Carvalho Júnior et al. (2015), evaluating isogenic hybrids, found a stronger effect of Alt_{SB} with a yield advantage of 0.5 t ha^{-1} in hybrids arising from one Al^{3+} tolerance Alt_{SB} allele.

In the present study, comparing the two environments (low and high Al^{3+} saturation), the reduction in the yield average, considering the hybrids from quadrants A and B, was of 0.72 t ha^{-1}, while, for the hybrids from quadrants C and D, it was of 1.51 t h^{-1}. Therefore, high Al^{3+} saturation reduces the grain yield in sorghum, but tolerant hybrids have lower losses, when compared to susceptible ones.

CONCLUSION

Ten hybrids (BRS373, 50A50, AS4639, DKB540, AS4625, A9721R, 1167092, DKB550, 1G282 and AG1040) outperformed the check cultivar under low and high aluminum conditions.

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