Universidade Federal Rural do Semi-Árido
Pró-Reitoria de Pesquisa e Pós-Graduação
http://periodicos.ufersa.edu.br/index.php/sistema

ISSN 0100-316X (impresso)
ISSN 1983-2125 (online)

SOIL EXCHANGEABLE ALUMINUM INFLUENCING THE GROWTH AND LEAF TISSUE MACRONUTRIENTS CONTENT OF CASTOR PLANTS[1]

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ABSTRACT - Three castor (*Ricinus communis*) genotypes were studied regarding tolerance to high exchangeable aluminum in the soil and the changes in macronutrient content in leaf tissue. The treatments consisted of a factorial distribution of five doses of exchangeable aluminum added to the soil (0, 0.15, 0.30, 0.60, and 1.20 $\text{cmol}_c\ \text{dm}^{-3}$) and three castor genotypes (BRS Nordestina, BRS Paraguaçu, and Lyra). The plants were raised in pots in a greenhouse. At 53 days after emergence, data were taken on plant height, leaf area, dry mass of shoot and root, and leaf tissue content of macronutrients. The most sensitive genotype was the cv. BRS Nordestina, in which the shoot and root dry weight in the highest aluminum content were reduced to 12.9% and 16.2% of the control treatment, respectively. The most tolerant genotype was the hybrid Lyra, in which the shoot and root dry weight in the maximum content of aluminum were reduced to 43.5% and 42.7% of the control treatment, respectively.The increased exchangeable aluminum affected the leaf nutrient content, and the intensity of the response was different among cultivars. The aluminum toxicity increased N, Ca, and Mg contents and reduced on P, K, and S contents. The cv. BRS Nordestina had a drastic shoot dry weight reduction associated with an intense increment in the N leaf content. Thus, the N increment was caused by a concentration effect caused by the limited growth.

Keywords: *Ricinus communis*. Acidity. Plant nutrition.

ALUMÍNIO TROCÁVEL NO SOLO INFLUENCIANDO O CRESCIMENTO E O TEOR FOLIAR DE MACRONUTRIENTES DE MAMONEIRAS

RESUMO – Três genótipos de mamona (*Ricinus communis*) foram estudados quanto à tolerância a alumínio trocável no solo e à influência sobre o teor de macronutrientes no tecido foliar. Os tratamentos consistiram em uma combinação fatorial de cinco níveis de alumínio trocável (0; 0,15; 0,30; 0,60 e 1,20 $\text{cmol}_c\ \text{dm}^{-3}$) e três genótipos de mamoneira (BRS Nordestina, BRS Paraguaçu e Lyra). O experimento foi conduzido em vasos em casa de vegetação. Aos 53 dias após a emergência, mediu-se a altura da planta, área foliar, massa seca da parte aérea e das raízes e os teores foliares dos macronutrientes. BRS Nordestina foi o genótipo mais sensível, no qual o peso seco da parte aérea e raízes no teor mais alto de alumínio reduziu-se respectivamente para 12,9% e 16,2% do tratamento controle. O híbrido Lyra foi o genótipo mais tolerante, no qual o peso seco da parte aérea e das raízes foi reduzido respectivamente para 43.5% e 42.7% do tratamento controle. O aumento do teor de alumínio trocável afetou o teor de macronutrientes nas folhas e a intensidade de resposta foi diferente entre as cultivares. A toxidez do alumínio causou aumento dos teores de N, Ca e Mg e redução do P, K e S. A cv. BRS Nordestina sofreu uma redução drástica do peso seco da parte aérea associada com um aumento do teor de N nas folhas. Então, o aumento no teor de N foi causado por efeito de concentração causado pelo crescimento limitado.

Palavras-chave: *Ricinus communis*. Acidez. Nutrição de plantas.

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[1] Recebido para publicação em 10/06/2012; aceito em 21/08/2014.

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INTRODUCTION

Castor (*Ricinus communis*) is an industrial oilseed crop that is often considered to be cultivated in less fertile land in order to avoid competition with food crops (NASCIMENTO et al., 2012a; BRITO NETO et al., 2014). This crop is sensitive to soil acidity (JOSHI et al., 2012), salinity (SEVERINO et al., 2014), cold air temperatures (SEVERINO et al., 2014), soil compaction (NASCIMENTO et al., 2012b), and other environmental stresses (LIMA et al., 2007; LI et al., 2010). Therefore, cultivation of castor on marginal land depends on the use of adequate agronomical practices and on the selection of genotypes better suited for such harsh conditions. High exchangeable aluminum content in acid soil is regarded as a major problem for castor cultivation.

Aluminum toxicity occurs when the soil has a pH below 5.5, low exchangeable bases, and low organic matter content. Under those conditions, toxic forms of aluminum are solubilized into the soil solution affecting root growth and function. Worldwide, Al toxicity is an important limitation to crop production because it has been estimated that over 50%of the world's potentially arable lands are acidic (KOCHIAN et al., 2005; ABATE et al., 2013).

The most important consequence of aluminum toxicity is the reduction on the root growth, specially the root tips, but to some extent the uptake of some nutrients can also be directly or indirectly impaired (DOGAN et al., 2014; MATSUMOTO, 2002; KOCHIAN et al., 2005; GEORGE et al., 2012). The direct effect occurs because the Al^{+3} competes with other cations such as Ca^{2+} and Mg^{2+} for binding sites in the apoplasm, and it may also inhibit Ca^{2+} uptake by blocking Ca^{2+} channels in the plasma membrane and Mg^{2+} binding sites of transport proteins (GEORGE et al., 2012; GUPTA et al., 2013). The indirect effect occurs because the reduced root system disposes of a smaller volume of soil, and the nutrients and water uptake is impaired. Thus, the shoot growth reduction is a consequence of the diminished water and nutrients uptake (SALVADOR et al., 2000; CUSTODIO et al., 2002; LIAO et al., 2006; LANA et al., 2009; ROY; BHADRA, 2014).

The mechanisms that some plant species developed to tolerate high levels of exchangeable aluminum include the capacity to keep adequate nutrient content in the root and shoot tissue, the ability to increase the pH to precipitate the aluminum outside the root, the chelation of the element in organic molecules, and its compartmentalization on the vacuole (BRUNNER; SPERISEN, 2013; MARSCHNER, 2012; MENDONÇA et al., 2003; POSCHENREIDER et al., 2008; BROWN et al., 2008).

Castor plants were observed to be very sensitive to exchangeable aluminum content higher than 1 $cmol_c\ dm^{-3}$ in the soil, and the toxic effect was alleviated by increasing soil organic matter content (HUE et al., 2011; LIMA et al., 2007). As the addition of high doses of organic matter is not feasible for cultivation in large areas, the options are the management of the soil acidity (liming, gypsum) and the development of castor genotypes more tolerant to high aluminum content.

This experiment had the objective to assess the tolerance to aluminum among three castor genotypes and how high aluminum content influences the macronutrient content in the leaf tissue.

MATERIAL AND METHODS

An experiment was run in the greenhouse of Embrapa Algodão (Campina Grande, Paraíba, Brazil) in a completely randomized block design with four replications. The treatments were a factorial distribution of five aluminum levels (0, 0.15, 0.30, 0.60, and 1.20 $cmol_c\ dm^{-3}$) and three genotypes (BRS Nordestina, BRS Paraguaçu, and Lyra). Each plot was a 10 L pot with one plant.

The initial characteristics of the soil were: pH 6.6, 88.5 mg dm^{-3} of phosphorus, 10 $mmol_c\ dm^{-3}$ of potassium, 18.3 $mmol_c\ dm^{-3}$ of calcium, 15.8 $mmol_c\ dm^{-3}$ of magnesium, 3.9 $mmol_c\ dm^{-3}$ of sodium, no detectable aluminum, 85% of bases saturation, 7.9 g kg^{-1} of organic matter, and 96% of sand. Hexahydrated aluminum chloride was added to the soil in the amount to reach the target content. It was thoroughly homogenized, irrigated to reach field capacity, and incubated for 15 days. Before planting, each pot was fertilized with 4 g of ammonium sulfate, 6 g of triple superphosphate, and 4 g of potassium chloride.

Three seeds were sowed 2 cm deep, and emerged plants were thinned 10 days later. The plants were irrigated daily. At 53 days after emergence (DAE), data were taken on plant vegetative growth (height, leaf area, and shoot and root dry weight). The leaf area was estimated from the leaf dimensions using the equation $S = 0.24 \times (W + L)^{1.93}$, in which S is the leaf area, W is the leaf width, and L is the length of the main vein (SEVERINO et al., 2004). The relative growth was calculated considering the control treatment as 100%. All leaves were used in the sample for measuring the macronutrients content. The nutrients were measured by the methods described by Braga and Defelipo (1974) for phosphorus, Blanchar (1963) for sulfur, and Le Poidevinand (1964) for the other nutrients. The K/(Ca + Mg) ratio in the leaf tissue was calculated.

The data were submitted to Linear Regression Analysis, and the significance of the regression coefficient was tested with t test ($p < 0.10$). The hypothesis that the regression lines of genotypes were not parallel (i.e., the response to aluminum is different among genotypes) was tested in the F test ($p < 0.10$) of the aluminum doses vs. genotypes interaction using the GLM procedure of SAS (SAS, 1990). When the lines were parallel, one equation was calculated including all the genotypes; otherwise, one equation was calculated for each genotype.

RESULTS AND DISCUSSION

The increments in the aluminum soil content caused reduction in all the growth characteristics considered in this study (Table 1). The effect of aluminum on leaf area and root dry weight was similar among genotypes, but plant height and shoot dry weight were influenced in different intensity according to the genotype. The shoot/root dry weight ratio was not influenced as both characteristics were reduced at similar rates. The aluminum effect on relative growth was inconsistent in the doses of 0.15 and 0.3 cmol$_c$ dm^{-3}, but the relative growth reduction was intense in the doses of 0.6 and 1.2 cmol$_c$ dm^{-3}, particularly on shoot and root dry weight (Figure 1).

Table 1. Vegetative growth (y) of three castor genotypes at 53 days after emergence influenced by the dose of aluminum added to the soil (x).

Genotype	Regression equation	R^2
	Plant height (cm)	
BRS Nordestina	y = -24.0*x +44.1	0.720
BRS Paraguaçu	y = -8.9*x +35.6	0.304
Lyra	y = -9.2*x +35.9	0.598
	Leaf area (cm^2)	
All	y = -981.0*x +1950.5	0.513
	Shoot dry weight (g plant^{-1})	
BRS Nordestina	y = -17.6*x +23.3	0.736
BRS Paraguaçu	y = -11.2*x +20.5	0.597
Lyra	y = -6.5*x +13.8	0.712
	Root dry weight (g plant^{-1})	
All	y =-4.5*x +7.8	0.528
	Shoot/root dry weight ratio	
All	y = -0.07^{ns}x +2.5	0.002

* and^{ns}: significant and not significant by t test ($p < 0.10$), respectively.

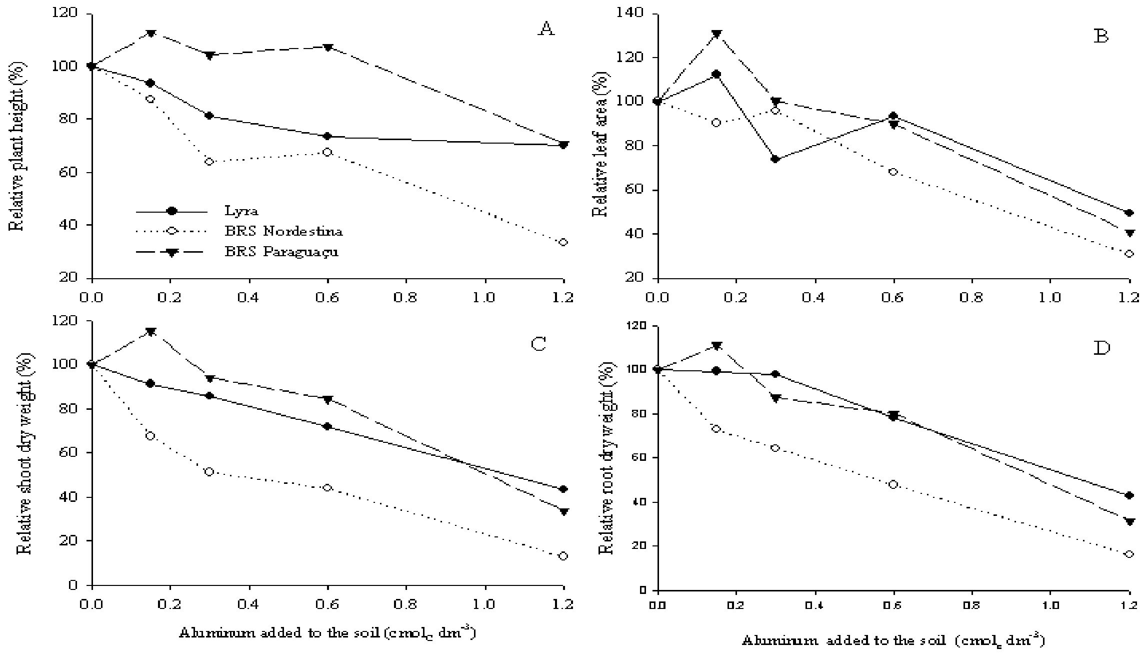

Figure 1. Relative growth of plant height (A), leaf area (B), shoot dry weight (C), and root dry weight (D) of three castor genotypes at 53 days after emergence influenced by doses of aluminum added to the soil.

The effect of aluminum on plant height was the most intense on BRS Nordestina. The relative plant height was reduced to 33.3% at 1.2 $cmol_cdm^{-3}$, while BRS Paraguaçu and Lyra were reduced to 70.9 and 70%, respectively (Figure 1). The leaf area was estimated to be reduced by 981 cm^2 for each 1 $cmol_cdm^{-3}$ of aluminum added to the soil, and this rate was similar among genotypes (Table 1).

Confirming its high sensitiveness, the shoot and root relative dry weight in the cv. BRS Nordestina were respectively reduced to 12.9 and 16.2% in response to the maximum dose of aluminum (Figure 1). The relative growth of the other two genotypes was reduced with less intensity.

The content of all macronutrients on leaf tissue was influenced by the aluminum added to the soil (Table 2). The increasing doses of aluminum caused increments in the nitrogen content in the cv. BRS Nordestina and in the hybrid Lyra, but not in the cv. BRS Paraguaçu. Nitrogen fertilization promotes an expressive growth of castor plants (LIMA et al., 2011). Usually, aluminum has not a direct effect on the N uptake and metabolism, but it is likely that the increments were caused by a concentration effect, as the shoot biomass was strongly reduced. The more intensive N-concentration effect on cv. BRS Nordestina is coherent with its steep shoot dry weight reduction.

Table 2. Macronutrient content on the leaf tissue (y) of three castor genotypes influenced by the aluminum content in the soil (x).

Genotype	Regression equation	R^2
	Nitrogen ($g\ kg^{-1}$)	
BRS Nordestina	$y = 7.26^{*}x + 17.70$	0.533
BRS Paraguaçu	$y = 0.69^{ns}x + 20.51$	0.033
Lyra	$y = 1.94^{*}x + 19.10$	0.459
	Phosphorus ($g\ kg^{-1}$)	
BRS Nordestina	$y = -0.57^{ns}x + 7.76$	0.137
BRS Paraguaçu	$y = 0.33^{ns}x + 6.75$	0.028
Lyra	$y = -2.43^{*}x + 9.16$	0.650
	Potassium ($g\ kg^{-1}$)	
BRS Nordestina	$y = -10.88^{*}x + 37.79$	0.608
BRS Paraguaçu	$y = -20.67^{*}x + 46.95$	0.885
Lyra	$y = -19.33^{*}x + 46.05$	0.939
	Calcium ($g\ kg^{-1}$)	
BRS Nordestina	$y = 7.88^{*}x + 2.03$	0.879
BRS Paraguaçu	$y = 5.05^{*}x + 2.73$	0.871
Lyra	$y = 7.77^{*}x + 1.01$	0.906
	Magnesium ($g\ kg^{-1}$)	
BRS Nordestina	$y = 7.49^{*}x + 6.05$	0.892
BRS Paraguaçu	$y = 9.34^{*}x + 6.99$	0.969
Lyra	$y = 6.67^{*}x + 6.69$	0.917
	Sulfur ($g\ kg^{-1}$)	
BRS Nordestina	$y = -0.15^{ns}x + 6.68$	0.014
BRS Paraguaçu	$y = -2.60^{*}x + 8.09$	0.893
Lyra	$y = -1.05^{*}x + 4.80$	0.499
	Ratio Potassium/(Calcium + Magnesium)	
All	$y = -2.93^{*}x + 4.22$	0.846

* and^{ns}: significant and not significant by t test ($p < 0.10$), respectively.

The phosphorus content was not influenced in BRS Nordestina and BRS Paraguaçu, but it was reduced in the hybrid Lyra in response to doses of Al^{+3}. Because the concentration effect observed on N was not verified on P, it is reasonable to assume that the total P uptake was considerably impaired by aluminum toxicity in all genotypes. As P has low mobility in the soil, it depends on a vigorous root system for an adequate uptake. Thus, the aluminum toxicity indirectly played a role on P uptake by reducing the root growth.

Usually, potassium content is not negatively influenced by the aluminum content in the soil (GEORGE et al., 2012). However, a sharp reduction on K^+ content was observed in the three genotypes, although the intensity of reduction was not the same for all of them. The Ca^{2+} and Mg^{2+} uptake is frequently impaired by aluminum toxicity, but in this study it was increased in the higher doses of Al^{+3}. The reduction in K^+ and increase in Ca^{2+} and Mg^{2+} resulted in a reduced $K^+/(Ca^{2+} + Mg^{2+})$ ratio. The effect of aluminum on P, K^+, Ca^{2+}, and Mg^{2+} content was atypical (DOGAN et al., 2014; MATSUMOTO, 2002; GEORGE et al., 2012), and a more detailed study would be necessary to detect the exact reason for this effect. It is likely that the root-soil interaction in a pot experiment influenced the nutrients uptake differently of what would be expected under field conditions.

There are multiple and complex mechanism of aluminum tolerance (POSCHENRIEDER et al., 2008; BRUNNER; SPERISEN, 2013), and the differences in vegetative growth and nutrients uptake are evidences of genotypic variability on castor that can be explored for breeding for aluminum tolerance. Tolerant genotypes should be able to keep adequate nutrient content, particularly of Ca^{2+} and Mg^{2+}, in order to sustain an adequate seed production.

It is common in many tropical species that despite a large difference in yield caused by soil acidity, the mineral nutrient concentration in leaves remains about the same (MARSCHNER, 2012). However, the effects of aluminum toxicity are not the same if evaluated in field, pot, or hydroponic solution, and results obtained on those different conditions are not satisfactorily correlated (MARSCHNER, 2012; MATSUMOTO, 2002). For instance, in an experiment with wheat (*Triticum aestivum*) in field conditions, Valle et al. (2011) found that the aluminum had little influence on the macronutrients content, but as the shoot biomass was reduced the total amount of nutrients was proportionally reduced. Using hydroponic solution for studying aluminum toxicity on pineapple (*Ananas comosus*), Lin (2010) observed no influence on P content, but more K^{+}, Ca^{2+}, and Mg^{2+} uptake was found in the genotypes with higher tolerance to aluminum. Souza (2001), however, found a good correlation of the effect of aluminum between hydroponic solution and soil experiments with soybean (*Glycine max*) and suggested that those two techniques could be complementary in the selection of genotypes tolerant to this stress.

The selection of castor genotypes with enhanced tolerance to acidic soils with toxic levels of exchangeable aluminum is promising. The variability on the response to this stressing factor suggests that the plant possesses mechanisms for coping with toxic aluminum. However, the selection should preferably be performed under field conditions, while studies in pots or hydroponic solution should be limited to preliminary screenings of genotypes.

CONCLUSION

The increment of aluminum content in the soil reduced vegetative growth of castor plants, but the cv. BRS Nordestina was found more sensitive than the cv. BRS Paraguaçu and the hybrid Lyra. The effect of aluminum on macronutrients leaf content was different among genotypes. There was an increase on nitrogen (except on BRS Paraguaçu), calcium, and magnesium leaf content, and a reduction on phosphorus (Lyra), potassium, and sulfur (except on BRS Nordestina).

REFERENCES

ABATE, E. et al. Aluminum toxicity tolerance in cereals: Mechanisms, genetic control and breeding methods. **African Journal of Agricultural Research**, Lagos, v. 8, p. 711-722, 2013.

BLANCHAR, R.W et al. Sulfur in plant material by digestion with nitric and perchloric acid. **Proceedings of the Soil Science Society of America**, Madison, v. 29, p. 71-72, 1963.

BRAGA, J. M. et al. Determinação espectrofotométrica de P em extratos de solo e material vegetal. **Revista Ceres**, Viçosa, v. 21, n. 113, p. 73-85, 1974.

BRITO NETO, J. F. et al. Absorption and critical levels of phosphorus in castor bean shoots grown in diferente soil classes. **Semina**, Londrina, v. 35, n. 1, p. 239-250, 2014.

BROWN, T. T. et al. Lime effects on soil acidity, crop yield, and aluminum chemistry in direct-seeded cropping systems. **Soil Science Society America Journal**, Madison, v. 72, n. 3, p. 634-640, 2008.

BRUNNER, I. et al. Aluminum exclusion and aluminum tolerance in wood plants. **Frontiers in Plant Science**, Lausanne, v. 4, p. 1-12, 2013.

CUSTÓDIO, C. C. et al. Estresse por alumínio e por acidez em cultivares de soja. **ScientiaAgricola**, Piracicaba, v. 59, n. 1, p. 145-153, 2002.

DOGAN, I. et al. Influence of aluminum on mineral nutrient uptake and accumulation in *Urtica pilulifera* L. **Journal of Plant Nutrition**, London, v. 37, p. 469-481, 2014.

GEORGE, E. et al. Adaptation of plants to adverse chemical soil conditions. In: MARSCHNER, P. **Mineral nutrition of higher plants**. London: Academic Press, 2012, p. 409-472.

MARSCHNER, P. **Mineral nutrition of higher plants**. London: Academic Press, 2012, p. 409-472.

GUPTA, N. et al. Molecular basis of aluminum toxicity in plants: A review. **American Journal of Plant Science**, Irvine, v. 4, p. 21-37, 2013.

HUE, N. V. Alleviating soil acidity with crop residues. **Soil Science**, Riverwoods, v. 176, n. 10, p. 543 -549, 2011.

KOCHIAN, L. V. et al. The physiology, genetics and molecular biology of plant aluminum resistance and toxicity. **Plant and Soil**, Berlin, v. 274, n. 1-2, p. 175 -195, 2005.

LANA, M. C. et al. Tolerância de plântulas de pinhão manso a toxicidade de alumínio em solução nutritiva. I: Desenvolvimento da parte aérea e sistema radicular. **Synergismus Scyentifica UTFPR**, Pato Branco, v. 4, n. 1, p. 1–3, 2009.

LE POIDEVIN, N. et al. Métodos de diagnósticos foliares utilizados nas plantações do grupo Booken na Guiana inglesa: amostragem e técnica de análises. **Fertilité**, v. 21, n. 21, p. 3-11, 1964.

LI, G. et al. Leaf chlorophyll fluorescence, hyperspectral reflectance, pigments content, malondialdehyde and proline accumulation responses of castor bean (*Ricinus communis* L.) seedlings to salt stress levels. **Industrial Crops and Products**, Amsterdam, v. 31, n. 1, p. 13-19, 2010.

LIAO, H. et al. Phosphorus and aluminum interaction in soybean in relation to aluminum tolerance: exudation of specific organic acids from different regions of the intact root system. **Plant Physiology**, Rockville, v. 141, n. 2, p. 674-684, 2006.

LIMA, R. L. S. et al.Crescimento da mamoneira em solo com alto teor de alumínio na presença e ausência de matéria orgânica. **Revista Brasileira de Oleaginosas e Fibrosas,** Campina Grande, v. 11, n. 1, p. 15-21, 2007.

LIMA, R. L. S. et al. Blends of castor meal and castor husks for optimized use as organic fertilizer. **Industrial Crops and Products**, Amsterdam, v. 33, n. 2, p. 364-368, 2011.

LIN, Y. H. Effects of aluminum on root growth and absorption of nutrients by two pineapple cultivars [*Ananas comosus* (L.) Merr.]. **African Journal of Biotechnology**, Lagos, v. 9, n. 26, p. 4034-4041, 2010.

MARSCHNER, H. Mineral nutrition of higher plants. 3 ed. London Academic Press, 2012. 651 p.

MATSUMOTO, H. Plant roots under aluminum stress: toxicity and tolerance. In: WAISEL, Y.; ESHEL, A.; KAFKAFI, U. **Plant roots: the hidden half**. New York, CRC Press, 2002, p. 821-838.

MENDONÇA, R. J. et al.Efeito do alumínio na absorção e na utilização de macronutrientes em duas cultivares de arroz. **Pesquisa Agropecuária Brasileira**, Brasília, v. 38, n. 7, p. 843-848, 2003.

NASCIMENTO, M. S. et al. Nutrient extraction and exportation by castor bean hybrid Lyra. **Revista Brasileira de Ciência do Solo**, Viçosa, v. 36, n. 1, p. 113-124, 2012a.

NASCIMENTO, A. H. C. et al. Desenvolvimento da mamoneira com diferentes níveis de calagem em um Latossolo Vermelho-Amarelo compactado. **Revista Brasileira de Ciências Agrárias**, Recife, v. 5, n. 2, p. 163-169, 2010a.

POSCHENRIEDER, C. et al. A glance into aluminum toxicity and resistance in plants. **Science of the Total Environment**, Amsterdam, v. 400, n. 1-3, p. 356-368, 2008.

ROY, B. et al. Effects of toxic levels of aluminum on seedling parameters of rice under hydroponic culture. **Rice Science**, Amsterdam, v. 21, n. 4, p. 217-223, 2014.

SALVADOR, J. O. et al. Influência do alumínio no crescimento e na acumulação de nutrientes em mudas de goiabeira. **Revista Brasileira de Ciência do Solo**, Viçosa, v. 24, n. 4, p. 787-796, 2000.

SAS Institute. **SAS/STAT user's guide**. Cary, SAS Institute, 1990.

SEVERINO, L. S. et al. Método para determinação da área foliar da mamoneira. **Revista Brasileira de Oleaginosas e Fibrosas**, Campina Grande, v. 8, n. 1., p. 753-762, 2004.

SEVERINO, L. S. et al. Study on the effect of air temperature on seed development and determination of the base temperature for seed growth in castor (*Ricinus communis* L.). **Australian Journal of Crop Science**, v. 8, p. 290-295, 2014.

SEVERINO, L. S. et al. Calcium and magnesium do not alleviate the toxic effect of sodium on the emergence and initial growth of castor, cotton, and safflower. **Industrial Crops and Products**, Amsterdam, v. 57, p. 90-97, 2014.

SOUZA, L. A. C. Relação de genótipos de soja ao alumínio em hidroponia e no solo. **Pesquisa Agropecuária Brasileira**, Brasília, v. 36, n. 10, p. 1255-1260, 2001.

VALLE, S. R. et al. Uptake and use efficiency of N, P, K, Ca, and Al by Al-sensitive and Al-tolerant cultivars of wheat under a wide range of soil Al concentrations. **Field Crop Research**, Amsterdam, v. 121, n. 3, p. 392-400, 2011.