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Mineral content of sorghum genotypes and the influence of water stress

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ABSTRACT

Sorghum is a source of several minerals whose content may vary depending on the genotype and the production environment. The objective of this study was to screen sorghum genotypes for mineral content and to investigate the effect of water stress on it. A large variability was observed in the mineral content of 100 sorghum genotypes grown in environments without (WoWS) and with water stress (WthWS). The water stress decreased Mn, P, Mg and S contents in 100, 96, 93 and 56% of genotypes, respectively. The genotypes and other factors seemed to have more impact than water stress on K, Ca, Cu, Fe and Zn levels. In 100 sorghum genotypes, 2 were classified as excellent sources of Fe and 25 of Zn, in both environments. The best two genotypes to Fe content were SC21 and SC655 and to Zn were SC320 and SHANQUI-RED which showed great potential for use in biofortification.

1. Introduction

Minerals are inorganic elements widely distributed in nature and essential for growth and proper development of the human organism. The mineral deficiencies in diets may impair mental and physical development, decrease work output and contribute to morbidity from infections, especially among children, pregnant and lactating women (Hussain, Larsson, Kuktaite, & Johansson, 2010; Kayodé, Linnemann, Hounhouigan, Nout, & van Boekel, 2006; Ng'uni, Geleta, Johansson, Fatih, & Bryngelsson, 2011).

An appropriate diet can usually supply minerals. However, the diets of populations subsisting on cereals, or inhabiting regions where soil mineral imbalances occur, often lack some of them. The elements most frequently lacking in human diets are Fe, Zn and I, although other elements, such as Ca, Mg, Cu and Se can be deficient in the diets of some populations (White & Broadley, 2005). In Brazil, a high prevalence of anemia in the early years of life, especially in disadvantaged regions, has been frequently reported (Borges et al., 2007).

Low cost and relatively simple strategies have been proposed and adopted in an attempt to reduce the occurrence of mineral deficiencies such as, provision of medical supplements, fortification of foods and post-harvest change in eating habits (Davidsson & Nestel, 2004; Osendarp, West, & Black, 2003). Several biofortification projects have emerged as an alternative to contribute for the reduction of mineral deficiencies, especially iron and zinc. The objective of these projects is to increase the nutrient density in staple crops, mainly through agronomic intervention and genetic selection (White & Broadley, 2005). There is considerable genetic variation within crop species that is suitable for sustainable biofortification strategies. However, to ensure success in this research and development, a multidisciplinary approach is necessary, and the screening and selection of breeding lines or accesses for higher contents of essential nutrients is a preliminary and basic stage of development.

Cereals grains are the most common foods used in biofortification programs because they have been the major source of calories for human diets (Taylor, Taylor, & Kini, 2012; White & Broadley, 2005). In this sense, several studies have related expressive mineral levels in wheat, rice, maize and sorghum (Bänziger & Long, 2000; Hussain et al., 2010; Kayodé et al., 2006; Martino et al., 2012; Ndukwe, Edeoga, & Omosun, 2015; Ng'uni et al., 2011;

Abbreviations: WthWS, with water stress; WoWS, without water stress; Embrapa, Brazilian Agricultural Research Corporation; IGD, Institute of Genome Development; USDA, United States Department of Agriculture; ANOVA, Analyzes of Variances; ICRISAT, International Crops Research Institute for the Semi-Arid-Tropics.

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Proietti, Mantovani, Mouquet-Rivier, & Guyot, 2013; Queiroz et al., 2011; Zhang et al., 2010). In sorghum, the most usually abundant mineral is K, followed by P and Mg and the most abundant micro-element is Fe (Afify, El-Beltagi, Abd El-Salam, & Omran, 2012; Pontieri et al., 2014).

Sorghum bicolor L. Moench is an important cereal in the world and can grow under adverse environmental conditions, such as very dry, saline and hot areas, where the production of other cereals is uneconomical (Dicko, Gruppen, Traore, van Berkel, & Voragen, 2006). The cereal is used for food in Africa and Asia and for animal feed and ethanol production in the Americas and Australia. There is an increased interest in also using sorghum for human consumption due to the fact that it is gluten-free (Pontieri et al., 2013) and has other health benefit properties, such as cholesterol-lowering, anti-inflammatory, slow digestibility and inhibition of human esophageal and colon cancer cell growth (Awika, Yang, Browning, & Faraj, 2009; Carr et al., 2005; Moraes et al., 2012).

In Brazil, Embrapa Milho e Sorgo (Brazilian Agricultural Research Corporation) and partner institutions have been conducting breeding programs seeking the selection of sorghum genotypes with improved quality for human consumption. There is a large collection of sorghum accessions that have not been characterized for food quality characteristics at Embrapa. Thus, there is a great potential to be explored for the use of some of these genotypes to develop biofortified sorghum cultivars. Furthermore, there has been no investigation about the effect of water stress on the mineral levels of these genotypes.

It is widely known that grain mineral contents are influenced by genotype, environment and interactions between genotype and environment (Hussain et al., 2010; Ng'uni et al., 2011; Ray, Shipe, & Bridges, 2008; Zhang et al., 2010). In this context, plants exposed to some kind of stress may show a wide range of mechanisms that involve morphological, physiological, and biochemical changes that are dependent on the inherent sensitivity of the particular genotype to stress (Cramer, Urano, Delrot, Pezzotti, & Shinozaki, 2011; Jogaiah, Govind, & Tran, 2013). According to Singh, Gupta, and Kaur (2012), wheat grain grown under water stress showed lower levels of Fe, but in relation to Zn, other factors also affected mineral content.

The main objective of this study was to screen sorghum genotypes for mineral content and to investigate the effect of water stress on content. In addition, this research aimed to identify superior genotypes to use in breeding programs to successfully develop biofortified cultivars with high iron and zinc density and availability.

2. Material and methods

One hundred sorghum accessions from the IGD (Institute of Genome Development) association panel (Casa et al., 2008) with high genetic variability were used in this study (Supplementary Table 1). Trials were planted at the Embrapa Milho e Sorgo research station, located in Nova Porteirinha, MG, at latitude 15°47′S, longitude 43°18′W and 516 m above sea level, in June 2010. The climate of this region is semi-arid, with regular rainfall and is used for drought tolerance tests evaluation. The soil was classified as dystrophic Red-Yellow Latosol. The genotypes were evaluated in two environments; without water stress (WoWS) and with post-flowering water stress (WthWS) in order to evaluate the effect of water stress on mineral content of sorghum grain. The experimental plots consisted of two rows three meters long, spaced 0.50 m between rows. Three hundred kg/ha of the NPK (nitrogen, phosphorus and potassium) formula 08-28-16 was applied at planting and twenty-five days after planting, 150 kg/ha of urea was applied. This is the recommended fertilizer rate for the grain sorghum production system in this region. Supplemental water was applied by sprinkler irrigation for two hours once a week. In the WoWS environment, the irrigation remained until the grain-filling phase was complete and in the WthWS irrigation was suspended 50 days after planting, at the boot stage, that is just prior to the emergence of the panicle where the panicle is extended into flag leaf sheath. At maturity, in October 2010, the panicles were harvested and transported to Embrapa Milho e Sorgo in Sete Lagoas, Minas Gerais, where they were threshed and the grain was stored in a cold chamber at 10 °C until analysis.

2.1. Pericarp color, origin and race of the genotypes

The pericarp color of the genotypes was determined visually and the origin and race (Supplementary Table 1) was based on Casa et al. (2008), Morris et al. (2013), Sukumaran et al. (2012) and USDA (2013).

2.2. Levels of minerals in sorghum grain genotypes

The Long, Bänziger, and Smith (2004) methodology was used to remove any mineral contaminants from the field. The grain was washed for 10 s with running deionized water in a plastic sieve and was thoroughly dried with paper towel. After washing, the samples were transferred to paper bags and placed immediately in an oven with forced air circulation at 80 °C for 4 days. Following drying, the grain samples were ground in a cyclone mill (Marconi, Piracicaba, São Paulo, Brazil) to a particle size of 0.5 mm and the flour was packaged in polyethylene bottles until mineral analysis in the Laboratory of the Embrapa Milho e Sorgo, between April and May 2012.

The analyses of minerals P, K, Ca, Mg, S, Cu, Fe, Mn and Zn were determined according to the methodology proposed by Silva (1999). Acids and other chemicals were obtained from Sigma for use in the digestion process. All glassware and plastic ware were washed with deionized water, soaked in 2% HNO_3 overnight, rinsed with deionized water, and air-dried before use.

For quantitative analyses, the working standard solutions used for calibration were prepared by diluting a monoelement stock solution of 1000 mg mL^{-1} Ca, Cu, Fe, K, Mg, Mn, P, S and Zn (Specsol, Jacareí, São Paulo, Brazil) and used to prepare multielement analytical calibration solutions to desired concentration in 0.25 mol L^{-1} HNO_3. The ranges of the calibration curves (5 points) were selected to match the expected concentrations for all the elements of the sample studied by ICP-OES. High purity water (i.e., with conductivity approximately 18 MΩ cm^{-1}) was used in all sample preparation and analysis steps.

The Inductively coupled plasma-optical emission spectrometer (ICP-OES) used was a Varian 720 ES (Varian, Santa Clara, CA, USA) with axial viewing configuration. The ICP-OES instrument was initialized and allowed to achieve thermal equilibrium over 30 min. Details of the operating conditions are summarized in Table 1. Emission lines utilized were shown in Table 2.

Table 1
Operational conditions adopted for the elemental analysis of samples by ICP OES.

Operational conditions	
RF power (kW)	1.2
Gas	Argon
Plasma gas (L.min^{-1})	15.0
Auxiliary gas (L.min^{-1})	1.5
Nebulizer pressure (Kpa)	200.0
Pump rate (rpm)	15
View	Axial
Number of replicates	1
Nebulizer spray chamber	Sturman Master
Nebulizer type	V-Groove

Table 2
Lines used for determination of the elements with ICP-OES and accuracy assessment through the analysis of the corn bran SRM 8433.

Analyte	λ (nm)	Certified[a] (mg/kg)	Found[b] (mg/kg)
P	213.618	171 ± 11	166 ± 1.7
K	766.491	566 ± 75	578 ± 26.6
Ca	317.933	420 ± 38	410 ± 6.3
Mg	285.213	818 ± 59	805 ± 10.4
S	181.972	860 ± 150	807 ± 10.0
Cu	327.395	2.47 ± 0.40	2.30 ± 0.03
Fe	238.204	14.8 ± 1.8	13.84 ± 0.15
Mn	257.610	2.55 ± 0.29	2.39 ± 0.04
Zn	206.200	18.6 ± 2.2	17.40 ± 0.14

[a] Results for SRM 8433 represented as mean ± confidence interval, informative value.
[b] Mean ± standard error of mean. Average of three determinations.

The sorghum flour (0.200 g) was weighed and placed into 100 mL glass tube, 4 mL of nitropercloric solution in the ratio 2:1 (HNO_3:$HClO_4$) was added. After five hours, the tubes were heated on an electric hot block at 150 °C for 40 min. The mixture was heated again after the release of brown fumes at 200 °C for 30 min until complete digestion. At this point, the residual solution was totally clear and was increased in volume to 75 mL with 0.25 mol L^{-1} HNO_3. The blank digestion experiments were also conducted in the same way.

The accuracy of analytical procedure was verified by analyzing the Standard Reference Material corn bran (SRM 8433). The results were found to be in good agreement with the certified values (Table 2).

All results were expressed on a dry weight basis, which was determined by the gravimetric method in a 2 g sample, using a forced-air oven at 105 °C for 6 h. Samples were analyzed in duplicate (two independent analyses). The results between two replicates did not differ by more than 2%.

2.3. Statistical analysis

Analysis of variances (ANOVA) was performed for the content of each mineral, considering a completely randomized design, in a factorial scheme (100 genotypes × 2 environments). The averages were compared by the Scott-Knott test, at 5% probability. Pearson correlation coefficients were obtained between all minerals and between each mineral and protein, fiber and carbohydrate of these 100 sorghum genotypes. Queiroz et al., 2015, published these nutritional values. The significance of the correlation estimates were assessed by the *t*-test. These statistical analyses were performed using the statistical software GENES VS 2009 7.0 (Cruz, 2006).

The average mineral content of each genotype was plotted on scatterplots, the WoWS environment averages were plotted on the y-axis, and the WthWS environment averages were plotted on the x-axis as proposed by Guimarães, Machado, and Guimarães (2009).

3. Results and discussion

3.1. Mineral content in sorghum grain genotypes

The ANOVA showed significant differences ($p < 0.05$) for genotypes, environment and the genotype × environment interaction for mineral content. There was high variability in the content of the minerals among the genotypes in both environments (WoWS and WthW) (Table 3, Supplementary Tables 2 and 3). The maximum levels were about 2–3 times higher than the minimum levels of P (2.48–5.69 and 1.33–3.42 g/kg), K (2.93–5.87 and 2.71–5.63 g/kg), Mg (1.28–2.43 and 0.88–1.84 g/kg) and S (0.79–1.60 and 0.7–1.54 g/kg) Mn (13.11–32.27 and 7.68–22.20 mg/kg) and Zn (16.21–45.78 and 12.81–38.98 mg/kg) in the WoWS and WthWs environments, respectively. The largest variation was observed in the Ca (0.09–0.36 and 0.09–0.28 g/kg in the WoWS and WthWs environments, respectively), Cu (1.36–6.90 mg/kg and 1.67–8.02 mg/kg in the WoWS and WthWs environments, respectively) and Fe contents (12.50–76.64 mg/kg in the WthWs environments), whose maximum levels were, respectively, 4, 5 and 6 times higher than the minimum. According to Teixeira et al. (2013) traditional plant breeding involves recombination and selection of genotypes with different genetic background and depends on exploiting natural variation. Consequently, the knowledge of variation in nutrient concentration of different groups of genotypes is important to support plant breeding programs to develop grain cultivars with high nutrient value. Thus, the results of this study revealed that there is great potential for use of some of these genotypes in sorghum improvement programs for nutritional quality as in the biofortification programs.

Table 3
Range, mean and standard deviation (SD) values of 100 sorghum genotypes grown in environments with and without water stress.

Mineral	WoWS		WthWS		% *	% **
	Range	Mean ± SD	Range	Mean ± SD		
P[a]	2.48–5.69	3.67 ± 0.54	1.33–3.42	2.17 ± 0.39	96	96
K[a]	2.93–5.87	4.08 ± 0.64	2.71–5.63	3.72 ± 0.55	60	50
Ca[a]	0.09–0.36	0.17 ± 0.04	0.09–0.28	0.17 ± 0.04	30	17
Mg[a]	1.28–2.43	1.76 ± 0.22	0.88–1.84	1.26 ± 0.43	94	93
S[a]	0.79–1.60	1.10 ± 0.17	0.70–1.54	1.09 ± 0.16	84	56
Cu[b]	1.36–6.90	3.25 ± 1.08	1.67–8.02	3.08 ± 1.02	27	18
Fe[b]	19.54–54.57	31.94 ± 6.62	12.50–76.64	29.54 ± 7.32	45	35
Mn[b]	13.11–32.27	19.75 ± 4.01	7.68–22.20	12.56 ± 2.89	100	100
Zn[b]	16.21–45.78	26.59 ± 4.45	12.81–38.98	22.41 ± 5.11	51	43

[a] Values expressed in g/kg.
[b] Values expressed in mg/kg.
* Percentage of samples that showed statistical difference ($p < 0.05$) in mineral level between genotype grown in WoWS and WthWS environments.
** Percentage of samples that showed significant decrease ($p < 0.05$) in mineral level when grown in WthWS environment.

Martino et al. (2012) also quantified the mineral contents of eight sorghum genotypes cultivated in Brazil and found lower values than those presented in this study for Cu (0.33–1.01 mg/kg), Fe (4.7–14.9 mg/kg), Mn (not detected-0.6 mg/kg), Mg (0.79–1.47 g/kg), Ca (0.06–0.19 g/kg), P (1.79–2.78 g/kg), S (0.67–1.01 g/kg) and Zn content (13.2–27.0 mg/kg). Genetic, soil and climate variations may influence the concentration of minerals and may have been one of the causes of the differences between these two studies. Additionally, the present study evaluated 100 sorghum lines of a panel with high genetic variability, so Martino et al. (2012), which evaluated four sorghum hybrids and four lines, expected less variation than in this study.

Ng'uni et al. (2011) reported similar average levels of P (3.44 g/kg), K (4.37 g/kg), Ca (0.15 g/kg), Mg (1.64 g/kg), S (1.49 g/kg), Mn (20.6 mg/kg) and Zn (29.7 mg/kg) of sorghum genotypes from Africa and higher Cu (4.6 mg/kg) and Fe contents (41.1 mg/kg) than that found in the present sorghum germplasm grown in the without water stress environment (Table 3). The means of Fe reported by Kayodé et al. (2006) in sorghum genotypes from Benin/West Africa (58 mg/kg), by Proietti et al. (2013) in sorghum cultivars from Africa (76 mg/kg) and by Pontieri et al. (2014) in sorghum hybrids from Italy (53.4 mg/kg) also were higher than the contents found in the present work.

As shown in Table 3, water stress had more influence on Mn, P, Mg and S levels with a reduction of the contents, respectively, in 100, 96, 93 and 56% of the genotypes. In relation to K, Zn, Fe, Ca

and Cu, which only 60, 51, 45, 30 and 27% of the genotypes showed significant difference between the two environments, other factors may have influenced the levels of these elements. According to Ferreira, Magalhaes, Durães, Vasconcellos, and Araújo Neto (2008) the amount of nutrients present in crop tissue of a certain species, at a certain time, is a result of the interaction between environmental conditions and genotype. These authors (Ferreira et al., 2008) evaluated the influence of drought stress on the levels of macrominerals in different tissues of two maize hybrids and concluded that the suppression of irrigation caused greater reduction of macronutrients in the vegetative tissues of the hybrid BR 205, while in the hybrid BRS 2121, this reduction was higher in grains, indicating that water stress affected the transport of nutrients in this hybrid.

Considering the Fe daily intake recommendation for adult females (19–30 years), and the Zn daily intake recommendation for adult males (19–30 years), 2% of the sorghum genotypes grown in both environment may be classified as excellent sources of Fe (genotypes 40 and 95) and 25% as excellent sources of Zn (genotypes 3, 6, 8, 20, 21, 24, 30, 32, 36, 37, 40, 42, 43, 46, 64, 65, 66, 69, 78, 79, 84, 85, 93, 94, 96) because they can supply 20% or more of these recommendation in 100 g of sorghum grain, in wet weight (Institute of Medicine U.S., 2003). Taking into account that the sorghum is one of the cereals most resistant to drought stress and that in West Africa countries, as well as some other countries, the daily diet is often 100% sorghum, this data is relevant, especially for this population.

3.2. Correlation among sorghum minerals

The Pearson correlation of grain minerals are presented in Table 4. The highest magnitude of correlation was observed between Mg and P in both environments (0.89 and 0.86).

Among the 100 sorghum genotypes grown in the WoWS and WthWS environments, other significant positive correlations (above 0.60) were found between Mg and S (r = 0.63), S and Fe (r = 0.67), Zn and S (r = 0.61), Zn and Cu (r = 0.61) and Zn and Fe (0.64) in the WoWS environment and to S and P (r = 0.62), and Zn and P (r = 0.64) in WthWS environment. No negative correlations among minerals were observed in either environment. These results indicated that when there is an increase in one mineral content, the other also increases, making it possible to select for increased mineral content of several elements simultaneously. This finding is consistent with other sorghum minerals studies (Ng'uni et al., 2011).

3.3. Correlation among sorghum minerals and protein, fiber and carbohydrate

Queiroz et al. (2015) measured the nutritional composition (protein, lipids, ash, fiber and carbohydrate) of these 100 genotypes of sorghum cultivated without and with water stress. Comparing these results with the mineral contents, higher correlations between minerals and protein could be found, as compared with carbohydrates and fiber (Table 5).

In agreement with these results, Zhao et al. (2009) evaluated 150 lines of bread wheat and found high correlation between both Fe and Zn concentration and protein content in grains. The mineral content was highly correlated to protein content, since they are involved in protein biosynthesis (Cramer et al., 2011). In addition, Fe, Zn, Mn and protein are translocated from the leaves to the seeds during maturation of cereal plants (Brinch-Pedersen, Borg, Tauris, & Holm, 2007).

Under drought stress, there is a reduction of minerals, once the protein synthesis decreases in this condition (Queiroz et al., 2015). On the other hand, in response to water stress many minerals are necessary for the synthesis of proteins responsible for antioxidant activity (Jogaiah et al., 2013). The secretion of the peroxidases and

Table 5
Estimates of Pearson correlations between minerals and protein, fiber and carbohydrate content in sorghum grown in environments without water stress (WoWS) and with water stress (WthWS).

Mineral	WoWS	WthWS	WoWS	WthWS	WoWS	WthWS
	Protein		Fiber		Carbohydrates	
P	0.48**	0.65**	0.39*	0.07	0.27*	0.53**
K	0.09	0.12*	0.17*	0.02	0.04	0.15
Ca	0.19*	0.28**	0.08	0.17	0.20*	0.12
Mg	0,50**	0.63**	0.27*	0.06	0.27*	0.44**
S	0.73**	0.77**	0.29*	0.12	0.37**	0.53**
Cu	0.54**	0.57**	0.35*	0.16	0.31*	0.50**
Fe	0.56**	0.40**	0.42**	0.27*	0.37*	0.55**
Mn	0.47**	0.54**	0.24*	0.09	0.24*	0.37*
Zn	0.47**	0.60**	0.24*	0.15	0.34**	0.37*

* $p \leqslant 0.05$ (*t*-test).
** $p \leqslant 0.01$ (*t*-test).

Table 4
Estimates of Pearson correlations between sorghum minerals grown in environments without water stress (WoWS) and with water stress (WthWS).

Environment	Mineral	P	K	Ca	Mg	S	Cu	Fe	Mn	Zn
WoWS	P	1.00								
	K	0.37**	1.00							
	Ca	0.04	0.46**	1.00						
	Mg	0.89**	0.33**	0.14	1.00					
	S	0.57**	0.30*	0.33**	0.63**	1.00				
	Cu	0.33**	0.13	0.28*	0.36**	0.42**	1.00			
	Fe	0.50**	0.25*	0.28**	0.58**	0.67**	0.59**	1.00		
	Mn	0.42**	0.35**	0.47**	0.53**	0.57**	0.43**	0.52**	1.00	
	Zn	0.46**	0.20**	0.34**	0.48**	0.61**	0.61**	0.64**	0.49**	1.00
WthWS	P	1.00								
	K	0.17	1.00							
	Ca	0.18	0.04	1.00						
	Mg	0.86**	0.24*	0.16	1.00					
	S	0.62**	0.10	0.29*	0.56**	1.00				
	Cu	0.57**	0.12	0.33**	0.42**	0.56**	1.00			
	Fe	0.38**	0.06	0.22*	0.34**	0.32**	0.48**	1.00		
	Mn	0.51**	0.12	0.44**	0.56**	0.46**	0.48**	0.34**	1.00	
	Zn	0.64**	0.14	0.19	0.54**	0.59**	0.59**	0.45**	0.45**	1.00

* $p \leqslant 0.05$ (*t*-test).
** $p \leqslant 0.01$ (*t*-test).

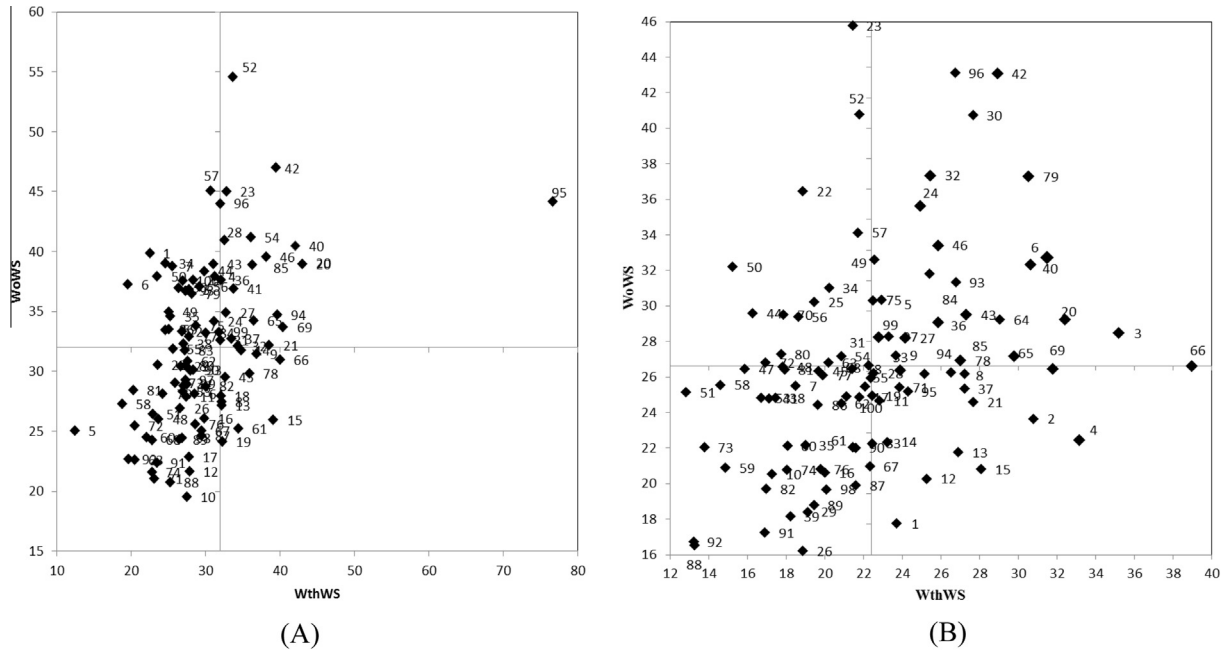

Fig. 1. Dispersion of the iron (A) and zinc (B) contents (mg/kg) of 100 sorghum genotypes grown in environments without (WoWS) and with water stress (WthWS).

superoxide dismutase enzymes, that scavenge free radicals, is common during water stress. These enzymes often use metals such as iron, zinc, copper, or manganese as electron acceptors. This may explains the higher correlation between protein and minerals in the WthWS environment in comparison with the correlation between mineral and protein in the WoWS environment.

3.4. Dispersion of genotypes in two contrasting environments to Fe and Zn

Among the minerals evaluated in this study, Fe and Zn were highlighted in relation to the influence of drought stress, because, they are the most frequent the minerals lacking in the human diet (White & Broadley, 2005), especially in the semiarid regions such as the Northeast Brazil. According to Table 2, Fe and Zn are influenced by both genotype and water stress. Thus, to facilitate the visualization of Fe and Zn content variability in 100 grain sorghum accessions in both environments, the averages were plotted in scatterplots, considering the WoWS and the WthWS environments (Fig. 1). The joint data analysis in these two environments showed that the genotypes positioned in the upper right quadrants of the graphs were those with the highest levels of each mineral. In contrast, the lowest concentrations appear in the lower left quadrant. The best two genotypes to Fe content were SC21 and SC655 and the best to Zn content were SC320 and SHAN QUI RED, which showed great potential for use in biofortification projects.

Similar to the present study, Kayodé et al. (2006) evaluated 76 farmers' varieties of sorghum from Benin for their Fe, Zn, and phytate concentrations to assess the impact of genetic and environmental effects on the composition of the grains and to identify farmers' varieties with high potential Fe and Zn availability. They concluded that the grain-Fe and grain-Zn did not show consistent linkage to genetic variation, but varied significantly across field locations, suggesting a predominant environmental impact. Different from our study, no varieties provide adequate Zn to meet nutritional requirements of sorghum consumers. In their study the most promising varieties for Fe supply were tokogbessenou, mahi swan, biodahu, saï maï, mare dobi, sakarabokuru, and chabicouma.

4. Conclusions

There was a large amount of genetic variability for mineral content of the 100 genotypes evaluated. Usually, sorghum cultivation under water stress decreases the S, P, Mg and Mn levels. The genotypes SC21, SC655, SC320 and SHAN-QUI-RED were highlighted as potential sources of Fe and Zn for use in sorghum improvement programs for nutritional quality and biofortification programs.

As genetic, soil and climate variations may influence concentration of minerals; the next step of this study will be to evaluate the effect of environment on the mineral contents in these superior materials, grown in regions with different soils and climate conditions.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foodchem.2016.07.067.

References

Afify, A. M. R., El-Beltagi, H. S., Abd El-Salam, S. M., & Omran, A. A. (2012). Effect of soaking, cooking, germination and fermentation processing on proximate analysis and mineral content of three white sorghum varieties (*Sorghum bicolor* L. Moench). *Notulae Botanicae Horti Agrobotanici Cluj-Napoca, 40*, 92–98.

Awika, J. M., Yang, L., Browning, J. D., & Faraj, A. (2009). Comparative antioxidant, antiproliferative and phase II enzyme inducing potential of sorghum (*Sorghum bicolor*) varieties. *LWT – Food Science and Technology, 42*, 1041–1046.

Bänziger, M., & Long, J. (2000). The potential for increasing the iron and zinc density of maize through plant-breeding. *Food and Nutrition Bulletin, 21*(4), 397–400.

Borges, C. V. D., Veiga, A. P. B., Barroso, G. S., Jesus, E. F. O., Serpa, R. F. B., Moreira, S., et al. (2007). Association among serum concentration of minerals,

anthropometric indices and diarrhea in low-income children in the metropolitan region of Rio de Janeiro, Brazil. *Revista de Nutrição, 20*(2), 159–169.

Brinch-Pedersen, H., Borg, S., Tauris, B., & Holm, P. B. (2007). Molecular genetic approaches to increasing mineral availability and vitamin content of cereals. *Journal of Cereal Science, 46*, 308–326.

Carr, T. P., Weller, C. L., Schlegel, V. L., Cuppett, S. L., Guderian, D. M., & Johnson, K. R. (2005). Grain sorghum lipid extract reduces cholesterol absorption and plasma non-HDL cholesterol concentration in hamsters. *Journal of Nutrition, 135*(9), 2236–2240.

Casa, A. M., Pressoir, G., Brown, P. J., Mitchell, S. E., Rooney, W. L., Tuinstra, M. R., et al. (2008). Community resources and strategies for association mapping in sorghum. *Crop Science, 48*, 30–40.

Cramer, G. R., Urano, K., Delrot, S., Pezzotti, M., & Shinozaki, K. (2011). Effects of abiotic stress on plants: A systems biology perspective. *BMC Plant Biology, 11*, 163–177.

Cruz, C. D. (2006). *Programa genes: Biometria* (1st ed.). Viçosa: Editora UFV.

Davidsson, L., & Nestel, P. (2004). *Efficacy and effectiveness of interventions to control iron deficiency and iron deficiency anemia*. Washington: International Nutritional Anemia Consultative Group. 2004, URL <http://www.unscn.org/files/Working_Groups/Micronutrients/Other_material/INACG_efficacy_and_effectiveness.pdf>. Accessed 27.06.16.

Dicko, M. H., Gruppen, H., Traore, A. S., van Berkel, W. J. H., & Voragen, A. G. J. (2006). Review: Sorghum grain as human food in Africa: Relevance of content of starch and amylase activities. *African Journal of Biotechnology, 5*(5), 384–395.

Ferreira, V. M., Magalhaes, P. C., Durães, F. O. M., Vasconcellos, C. A., & Araújo Neto, J. C. (2008). Acúmulo e distribuição de macronutrientes em dois híbridos duplos de milho, em função da disponibilidade de água no solo. *Revista Brasileira de Milho Sorgo, 7*(1), 1–17.

Guimarães, P. E. O., Machado, J. R. A., & Guimarães, L. J. M. (2009). Plotagem em quadrantes para estudos de adaptabilidade e estabilidade em pares de grupos de ambientes. In *Anais do 5. Congresso Brasileiro de Melhoramento de Plantas*. Vitória: Incaper.

Hussain, A., Larsson, H., Kuktaite, R., & Johansson, E. (2010). Mineral composition of organically grown wheat genotypes: Contribution to daily minerals intake. *International Journal of Environmental Research and Public Health, 7*, 3442–3456.

Institute of Medicine (U.S.). (2003). *Committee on use of dietary reference intakes in nutrition labeling. Dietary reference intakes: Guiding principles for nutrition labeling and fortification*. URL <http://www.nap.edu/catalog/10872.html/> Accessed 17.02.16.

Jogaiah, S., Govind, S. R., & Tran, L. S. P. (2013). Systems biology-based approaches toward understanding drought tolerance in food crops. *Critical Reviews in Biotechnology, 33*(1), 23–39.

Kayodé, A. P. P., Linnemann, A. R., Hounhouigan, J. D., Nout, M. J. R., & van Boekel, M. A. J. S. (2006). Genetic and environmental impact on iron, zinc, and phytate in food sorghum grown in Benin. *Journal of Agricultural and Food Chemistry, 54*, 256–262.

Long, J. K., Bänziger, M., & Smith, M. E. (2004). Diallel analysis of grain iron and zinc density in southern African-adapted maize inbreds. *Crop Science, 44*, 2019–2026.

Martino, H. S. D., Tomaz, P. A., Moraes, E. A., da Conceição, L. S., Oliveira, D. S., Queiroz, V. A. V., et al. (2012). Chemical characterization and size distribution of sorghum genotypes for human consumption. *Revista do Instituto Adolfo Lutz, 71*(2), 337–344.

Moraes, E. A., Natal, D. I. G., Queiroz, V. A. V., Shaffert, R. E., Cecon, P. R., Paula, S. O., et al. (2012). Sorghum genotype may reduce low-grade inflammatory response and oxidative stress and maintains jejunum morphology of rats fed a hyperlipidic diet. *Food Research International, 49*, 553–559.

Morris, G. P., Ramu, P., Deshpande, S. P., Hash, C. T., Shah, T., Upadhyaya, H. D., et al. (2013). Population genomic and genome-wide association studies of agroclimatic traits in sorghum. *Proceedings of the National Academy of Sciences of the United States of America, 110*, 453–458.

Ndukwe, O. K., Edeoga, H. O., & Omosun, G. (2015). Varietal differences in some nutritional composition of ten maize (*Zea mays* l.) varieties grown in Nigeria. *International Journal of Academic Research and Reflection, 3*(5), 1–11.

Ng'uni, D., Geleta, M., Johansson, E., Fatih, M., & Bryngelsson, T. (2011). Characterization of the Southern African sorghum varieties for mineral contents: Prospects for breeding for grain mineral dense lines. *African Journal of Food Science, 5*(7), 436–445.

Osendarp, S. J. M., West, C. E., & Black, R. E. (2003). The need for maternal zinc supplementation in developing countries: An unresolved issue. *The Journal of Nutrition, 133*(3), 817S–827S.

Pontieri, P., Mamone, G., de Caro, S., Tuinstra, M. S., Roemer, E., Okot, J., et al. (2013). Sorghum, a healthy and gluten-free food for celiac patients as demonstrated by genome, biochemical, and immunochemical analyses. *Journal of Agricultural and Food Chemistry, 61*, 2565–2571.

Pontieri, P., Troisi, J., Di Fiore, R., Di Maro, A., Bean, S. R., Tuinstra, M. R., et al. (2014). Mineral contents in grains of seven food-grade sorghum hybrids grown in a Mediterranean environment. *Australian Journal of Crops Science, 8*(11), 1550–1559.

Proietti, I., Mantovani, A., Mouquet-Rivier, C., & Guyot, J. P. (2013). Modulation of chelating factors, trace minerals and their estimated bioavailability in Italian and African sorghum (*Sorghum bicolor* (L.) Moench) porridges. *International Journal of Food Science and Technology, 48*, 1526–1532.

Queiroz, V. A. V., Guimarães, P. V. O., Queiroz, L. R., Guedes, E. O., Vasconcelos, V. D. B., Guimarães, L. J., et al. (2011). Iron and zinc availability in maize lines. *Ciência e Tecnologia de Alimentos, 31*(3), 577–583.

Queiroz, V. A. V., Silva, C. S., Menezes, C. B., Schaffert, R. E., Guimarães, F. F. M., Guimarães, L. J. M., et al. (2015). Nutritional composition of [*Sorghum bicolor* (L.) Moench] genotypes cultivated without and with water stress. *Journal of Cereal Science, 65*, 103–111.

Ray, C. L., Shipe, E. R., & Bridges, W. C. (2008). Planting date influence on soybean agronomic traits and seed composition in modified fatty acid breeding lines. *Crop Science, 48*, 181–188.

Silva, F. C. (1999). *Manual de análises químicas de solos, plantas e fertilizantes* Embrapa Informação Tecnológica. Rio de Janeiro: Embrapa Solos.

Singh, S., Gupta, A. K., & Kaur, N. (2012). Influence of drought and Sowing Time on protein composition, antinutrients and mineral contents of wheat. *The Scientific World Journal, 12*, 1–9.

Sukumaran, S., Xiang, W., Bean, S. R., Pedersen, J. F., Kresovich, S., Tuinstra, M. R., et al. (2012). Association mapping for grain quality in a diverse sorghum collection. *The Plant Genome Journal, 5*, 126–135.

Taylor, J., Taylor, J. R. N., & Kini, F. (2012). Cereal biofortification: Strategies, challenges and benefits. *Cereal Foods World, 57*(4), 165–169.

Teixeira, F. F., Costa, F. M., de O. Sabato, E., Leite, C. E. P., Meirelles, W. F., Guimarães, C. T., et al. (2013). Pré-melhoramento de milho quanto à resistência a enfezamentos. *Pesquisa Agropecuária Brasileira, 48*(1), 51–58.

USDA. United States Department of Agriculture. (2013). *Germplasm resources information network*. Washington. URL: <http://www.ars-grin.gov/> Accessed 12.06.15.

White, P. J., & Broadley, M. R. (2005). Biofortifying crops with essential mineral elements. *Trends in Plant Science, 10*(12), 586–593.

Zhang, Y., Song, Q., Yan, J., Tang, J., Zhao, R., Zhang, Y., et al. (2010). Mineral element concentrations in grains of Chinese wheat cultivars. *Euphytica, 174*, 303–313.

Zhao, F. J., Su, Y. H., Dunham, S. J., Rakszegi, M., Bedo, Z., McGrath, S. P., et al. (2009). Variation in mineral micronutrient concentrations in grain of wheat lines of diverse origin. *Journal of Cereal Science, 9*, 290–295.