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Managment of sulphur fertilizer in forage sorghum crop cultivated in eutrophic Cambisol with alkaline pH

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Abstract

The objective of this study was to analyze the effect of soil fertilization with sulfur-based fertilizers, sulfate and elemental sulfur forms on biomass production, nutrient characteristics of sorghum and soil chemical properties. The experiment was carried out in a 4 x 4 factorial scheme (four sulfur sources: single superphosphate, agricultural gypsum, elemental sulfur powder and elemental sulfur granulated with bentonite, and four sulfur doses: 0, 40, 80, 120 mgdm^{-3}) using four replications in a completely randomized design, being cultivated in pots under greenhouse conditions. The sorghum was cultivated for a period of 51 days after emergence of the seedlings. The shoot dry mass, shoot macronutrients content, root and soil and pH of the soil were evaluated. There were interactions between sources and sulfur doses in the variables such as shoot dry mass, sulfur in the root, sulfur and calcium in the soil. Elemental sulfur (granulate) showed lower concentrations of phosphorus, sulfur and N:S ratio in the shoot. The concentrations of potassium, calcium and magnesium did not show significant differences, both for the shoot and the root. The pH of the soil was reduced depending on the sources and doses of elemental sulfur. The sources and doses of sulfur did not influence the levels of phosphorus, potassium, and magnesium in the soil. The elemental sulfur in the form of powder is the best source of sulfur for forage sorghum cultivated in soil with alkaline pH.

Keywords: *Sorghum bicolor* (L.) Moench; agricultural gypsum; elemental sulfur; single superphosphate; sulphate; soil pH.
Abbreviations: AG_agricultural gypsum; CAPES_ Improvement of Higher Education Personnel; CEC_cation exchange capacity; CV_coefficient of variation; D1_dose 1; SDM_ shoot dry mass; m_aluminum saturation; MSD_minimum significant difference; O.M._organic matter; S1_source 1; SB_base sum; ESG_elemental sulfur granulate; ESP_elemental sulfur powder; SS_simple superphosphate;V_base saturation.

Introduction

Sorghum is a crop considered rustic, because it tolerates water deficits and can grow in soils with low fertility (Pinto, 2008). However, it can obtain dry mass and grain yield like maize crop, when cultivated with an adequate supply of water and nutrients (Resende et al., 2009). Forage sorghum (*Sorghum bicolor* (L.) Moench) can be supplied to ruminants, such as: green forage (grazing or stinging in the trough), silage and hay (Pinto, 2008). Therefore, it is an excellent cultivation option in the Northeast region of Brazil. However, despite the rusticity of the crop, the fertility of the soil should be seriously considered. This is due to the uptaking of nutrients by the harvest, especially when the entire plant is harvested.

In Brazil, for monitoring of soil fertility, the verification of sulfur (S) contents is usually neglected and is not part of the routine analysis of soil laboratories. This nutrient is classified in the legislation as a secondary macronutrient; however, several crops have a sulfur extraction higher than that of phosphorus (P), which is classified as a primary macronutrient (Vitti and Heirinchs, 2007).

Sulfur is a constituent of essential amino acids such as methionine and cystine (Malavolta et al., 1997). These amino acids, present in all proteins, are of great importance for animal and human nutrition in countries that mainly consume proteins with plant origin, such as sorghum and maize in Africa and rice in Asia (Vitti and Heirinchs, 2007).

Sulfur has a close relationship with nitrogen (N), in addition to the two constituents of the proteins. Sulfur participates in the activation of nitrate reductase enzyme, an enzyme responsible for the transformation of nitrate (NO_3^-) absorbed by plants into amino acids (Vitti and Heirinchs, 2007). The application of sulfur combined with nitrogen has presented better results than the isolated application of nitrogen in the production of dry mass of grasses (Bonfim-Silva et al., 2007).

Today, the occurrence of sulfur deficient soils has increase, being a limiting factor for large areas of production in Brazil (Horowitz and Meurer, 2005). There are several factors that contribute to the emergence of deficiencies, such as increased productivity and export by crops, reduction of fuels with high sulfur content leading to the reduction of sulfur in the atmosphere; less use of sulfur-containing pesticides; increase in the use of formulated fertilizers of high concentration or use of raw materials without sulfur or with a low sulfur concentration (Scherer, 2001; Horowitz and Meurer, 2005; Divito et al., 2015).
The main fertilizers with sulfur supply are: simple superphosphate, agricultural gypsum and ammonium sulfate, these sources which have sulfur in the form of sulphate (SO_4^{-2}) are readily available to the plants. Other fertilizers may be in the form of elemental sulfur (S°), requiring a process of oxidation by microorganisms for conversion to sulphate. This oxidation is faster in fertilizers with smaller particle size (Friesen, 1996; Horowitz and Meurer, 2005; Degryse et al., 2016).
The objective was to evaluate the effect of sulfur fertilizer application on sulfate and elemental forms of sulfur, and biomass yield, nutrient characteristics of forage sorghum and the chemical attributes of a Eutrophic Cambisol.

Results and discussion

Based on the results of the analysis of variance, it was possible to verify that there was no significant effect of the treatments for the variables nitrogen, potassium, calcium and magnesium on shoots and roots of plants (P> 0.05) and also for phosphorus, potassium and magnesium in the soil (P> 0.05).

Shoot dry mass

The dry mass of the shoot was significantly affected by interaction between sources and doses of sulfur (P ≤0.01). The highest dry mass averages were occurred using S-elementar in the form of powder at a sulfur dose of 80 mg dm^{-3} and single superphosphate at a sulfur dose of 40 mg dm^{-3} (Table 1).
The sulfur dose of elemental sulfur (granulate) and elemental sulfur (powder) showed significant effect on shoot dry mass parameters. The effects were fit on linear regression model. The increments of 16.4, 4.7, and 3.3%, were observed in dry mass of the shoot using AG: Agricultural gypsum, ESG: elemental sulfur granulate, ESP: elemental sulfur powder, respectively, when compared to control (Fig 1). However, for simple superphosphate, there was adjustment to the quadratic model, with the highest dry mass production (35.26) for sulfur dose of 68.4 mg dm^{-3} (Fig 1).
This result corroborates with several authors who found an increase in the dry mass of the shoot of different crops, such as Marandu grass (Batista and Monteiro, 2006; Lavres Júnior et al., 2008), Brachiaria grass (Bonfim- Silva et al., 2007), garlic (Resende et al., 2011) due to the application of sulfur. Osorio Filho (2006) cultivated sorghum in four soil types and four accumulated levels of sulfate and they did not observe any significant difference in dry mass production, despite recording a linear increase in the absorption of sulfur. This was explained by the "luxury consumption" in the plant.

Phosphorus concentrations in shoot

Phosphorus concentrations in shoot (P ≤0.01) and sorghum (P ≤0.05) were significant only for sources. The elemental sulfur (powder) source showed higher concentration of phosphorus, both for the shoot and root (Table 2).
The elemental sulfur in the oxidation process releases H^+ which reduces the pH of the soil and helps to provide native phosphorus in alkaline soils and in the fertilizers, thus increasing the concentration of phosphorus in the plants. This corroborates with Frandoloso et al. (2010) who studied sources of phosphorus and elemental sulfur and found an increase in the efficiency of phosphate fertilizers associated with elemental sulfur.

Sulfur content in the shoot

According to the analysis of variance, significance was identified for the isolated effect of sulfur sources and doses (P ≤0.01) on the sulfur content in the shoot of sorghum. Sources of sulfur such as simple superphosphate, agricultural gypsum and elementar S (powder) provided a higher concentration of sulfur in the shoot of the plants but did not differ from each other; while elemental sulfur (granulate) had the lowest concentration (Table 3).
In relation to the isolated effect of the doses, it was significant to the linear regression model. In comparison with the higher sulfur dose with the absence of application, the increase was 15.3% of sulfur in the shoot of sorghum (Fig 2).

Sulfur concentration in the roots

The sulfur concentration in the roots of the plants was significant for the interaction between sources and doses of sulfur (P ≤0.01). The highest sulfur concentration averages were recorded in agricultural gypsum and elemental sulfur (powder) sources at a sulfur dose of 120 mg dm^{-3}, and with the elemental sulfur (powder) in the sources with sulfur doses of 40 and 80 mg dm^{-3} (Table 4).
When analyzing the effect of the doses on each source, it can be observed that all the sources fit the linear regression model (Fig 3). There was an increase in the sulfur concentration in the root when compared to the higher sulfur dose. In the absence of the application, the values were 34.5, 44.6, 19.6, and 38.2% for single superphosphate, agricultural gypsum, elemental sulfur (granulate) and elemental sulfur (powder), respectively (Fig3).
Plant nutrient concentrations were increased with greater availability of nutrients in the soil due to native soil contents or addition of fertilizers. Lavres Júnior et al. (2008) found an increase in the concentration of sulfur in grasses when the applied sulfur doses were increased. The reason for obtaining a lower concentration for elemental sulfur (granulate) can be explained by the physical and chemical form of the fertilizer. Elemental sulfur (granulate) must be oxidized to sulphate. However, to do so, it is necessary to disintegrate the fertilizer granules. This requires a longer time for the formation of sulphate in the soil. This corroborates the results of Friesen (1996), Horowitz and Meurer (2005), and Degryse et al. (2016) who stated that the sulfur particle size is very important for the oxidation

process, where the oxidation is inversely proportional to the particle size of elemental sulfur.

Nitrogen:sulfur ratio in the shoot

According to the result of analysis of variance, the nitrogen concentration was not significant (P>0.05), the relationship between the (N:S) effect was significant for the isolated effect of sources and doses of sulfur (P≤0.01). Elemental sulfur (granulate) was the fertilizer that recorded the highest average N:S ratio (Table 3), although the highest value of the ratio remained below of the ratio considered ideal for plants (15 to 17) (Malavolta et al., 1997).

The increase in sulfur doses caused a reduction of the N:S ratio values, by adjusting to the quadratic regression model (Fig4). The lowest value of the N:S ratio (12.4) was obtained with the sulfur dose of 112.2 mg dm^{-3}.

The N:S ratio was reduced because the nitrogen concentration (denominator) did not present statistical difference and the sulfur (numerator) increased with increasing doses. In studies with sulfur doses in bean cover, Crusciol et al. (2006) observed a reduction of the N:S ratio with increasing sulfur doses.

Soil pH

The soil pH was significantly affected with the isolated effect of the doses and sulfur sources (P ≤0.05). The mean values of pH were lower for elemental sulfur sources. The physical form of powder showed a greater reduction of the pH value compared to the granular elemental form (Table 5).

The pH of the soil was reduced linearly with increasing sulfur doses (Fig 5). The decrease in soil pH was 1.1% when compared to the absence of sulfur application with the highest dose.

When we compared the sulfur fractions alone, the soil pH reduction effect was promoted using elemental sulfur fertilizers, since agricultural gypsum and simple superphosphate had no effect on soil pH. In the elemental sulfur oxidation process, H^+ was released to the soil solution (Horowitz and Meurer, 2006; Heydarnezhad et al., 2012). Horowitz and Meurer (2005) observed a reduction of soil pH with the application of elemental sulfur. It is a good source for the correction of alkaline soils (Sierra et al., 2007). The reduction of soil pH or substrates with increasing doses of elemental sulfur was also observed by Kämpf et al. (2009) and Barbaro et al. (2010). However, Frandoloso et al. (2010) did not find a significant difference in the soil pH value applying 30 kg ha^{-1} of elemental sulfur. However, this result was obtained because the applied sulfur dose was low.

Soil sulfur content

The soil sulfur content was statistically significant for interaction between the factors (P≤0.01). The highest value of interactions were occurred with agricultural gypsum when a sulfur dose of 120 mg dm^{-3} was applied, although it did not differ statistically from simple superphosphate (Table 6).

A significant effect was observed for effect of doses in each source: simple superphosphate, agricultural gypsum and elemental sulfur (powder), in relation to the soil sulfur content, after adjusting to the linear regression model. The increase in soil sulfur content with simple superphosphate, agricultural gypsum and elemental sulfur (powder) was 58.7, 50.7, 49.4%, respectively, when compared to the higher sulfur dose in the absence of application (Fig 6)

The higher supply of sulfur to the soil via agricultural gypsum was due to the fact that it was in the powder form, thus producing a faster release of sulfur. It also released sulfur in the form of sulfate and did not need to undergo oxidation processes. Rheinheimer et al. (2005) considered gypsum as the cheapest and most efficient source for increasing the soil sulfate content. Zambrosi et al. (2007), Soratto and Crusciol (2008), Caires et al. (2011) and Souza et al. (2012) observed increases in soil sulfate content with the application of agricultural gypsum. Degryse et al. (2018) considered elemental sulfur as a good source of sulfur, but pointed out that nutrient availability to the plant is not immediately compared to the sources containing sulfate.The same author pointed out that although elemental sulfur is not readily available to plants, this source has advantages because it has a slow release to the soil solution. So that losses occur due to leaching and the absorption of sulfur by plants is increased.

It was observed that fertilizers in the forms of granules did not have enough time for complete disintegration, leaving some granules behind, leading to a lower release of nutrients to the soil solution. This contributes to the lower efficiency of granulated sources in relation to the powdered forms. In sulfur fertilizers, sulfate and agricultural gypsum (powder) provided more sulfur than simple superphosphate (granulate) (Fig 6). The fertilizers with elemental sulfur, (powder) were more efficient than elemental sulfur (granulate) in the supply of sulfur to the soil (Fig 6).

Soil calcium contents

Soil calcium contents were significant for interaction between the factors (P ≤0.01). In the interaction, when the effects of the doses within each source were observed, higher mean values were observed with the simple superphosphate sources and agricultural gypsum when a sulfur dose of 120 mg dm^{-3} was applied, thereby increasing the soil calcium contents (Table 6).

Analysis of doses of simple superphosphate and agricultural gypsum showed a trend of the linear regression model. There was increase in the soil calcium levels with increasing doses (Fig 7). When comparing the higher sulfur dose with the absence of fertilizer application, the increase in calcium concentration with the applied simple superphosphate and agricultural gypsum were 25.9 and 19.5%, respectively.

This increase was due to the facts that these two fertilizers have calcium as constituent (simple superphosphate ($Ca(H_2PO_4)_2$ + $2CaSO_4.2H_2O$) and gypsum ($CaSO_4.2H_2O$)). Several researches have observed increases in the levels of calcium available in the soil after the application of agricultural gypsum (Zambrosi et al., 2007; Soratto and Crusciol, 2008; Carires et al., 2011; Ferreira et al., 2013).

Table 1. Development of the interaction between sources and sulfur doses, comparing the dose effects of each source on dry weight of forage sorghum, at 51 days after emergence.

Source	Sulfur (mg dm^{-3})			
	0	40	80	120
	----------------Shoot dry mass (g vase^{-1})----------------			
Simple Superphosphate	33.33 a	35.14 a	35.14 ab	34.50 a
Agricultural gypsum	22.64 a	32.78 b	34.80 b	35.88 a
Elemental S (granulate)	33.33 a	33.54 b	34.29 b	34.92 a
Elemental S (powder)	34.87 a	33.78 ab	36.46 a	35.30 a
MSD	1.57117			
CV (%)	2.4			

Means followed by the same letter, lowercase in the column, do not differ statistically by the Tukey test at the 5% probability level. MSD: minimum significant difference and CV: coefficient of variation.

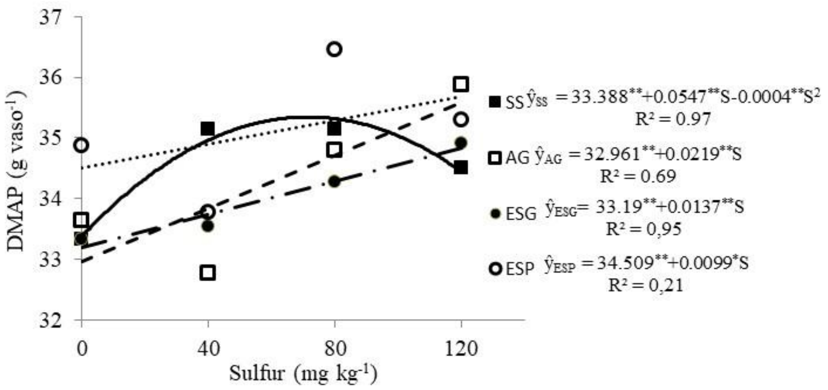

Fig 1. Effect of sulfur sources and doses on in the shoot dry mass (SDM) of forage sorghum, 51 days after emergence. ** and * significant at 1% and 5% probability, respectively with t-test. SS: simple superphosphate, AG: Agricultural gypsum, ESG: elemental sulfur granulate, ESP: elemental sulfur powder.

Table 2. Comparison of the means of sulfur sources for nitrogen, phosphorus and potassium in the shoot, as well as phosphorus and potassium in fodder sorghum root, 51 days after emergence

	Shoot			Root	
Source	N^{ns}	P	K^{ns}	P	K^{ns}
	------------------------------------g kg^{-1}------------------------------------				
Simple Superphosphate	15.35	1.15 ab	19.06	0.87 ab	4.68
Agricultural gypsum	15.52	1.07 bc	19.47	0.84 b	4.78
Elemental S (granulate)	15.52	1.02 c	19.74	0.85 ab	4.76
Elemental S (powder)	15.54	1.18 a	19.83	0.93 a	4.49
MSD	0.45	0.09	1.42	0.08	0.43
CV (%)	3.11	9.03	7.74	10.21	9.78

Means followed by the same letter in the column do not differ statistically by the Tukey test at the 5% probability level. ^{ns} Not significant, MSD: minimum significant difference, CV: coefficient of variation. No nitrogen analysis was performed at root.

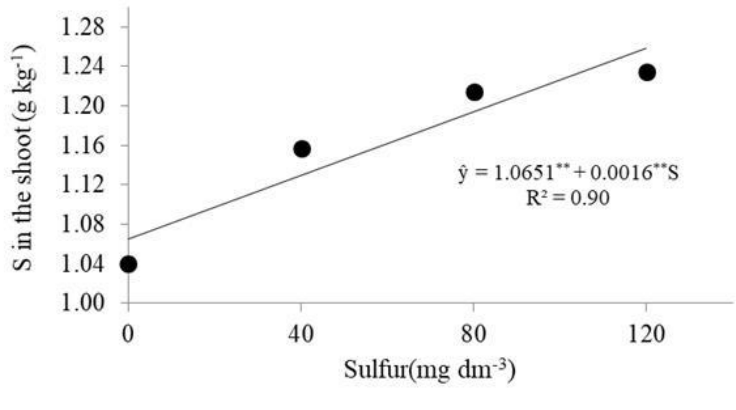

Fig 2. Effect of sulfur doses on the sulfur concentration in the shoot of forage sorghum, 51 days after emergence. ** indicates significance at 1% probability, by t test.

Table 3. Comparison of means of sulfur sources for calcium, magnesium, sulfur and nitrogen:sulfur ratio in the shoot, as well as calcium and magnesium of forage sorghum at 51 days after emergence

Source	Shoot				Root	
	Ca^{ns}	Mg^{ns}	S	N:S	Ca^{ns}	Mg^{ns}
	------------------------------------g kg^{-1}------------------------------------					
Simple superphosphate	14.33	2.92	1.20 a	13.01 b	3.15	1.51
Agricultural gypsum	14.40	2.86	1.20 a	13.12 b	3.19	1.42
Elemental S (granulate)	13.44	2.68	1.08 b	14.40 a	3.19	1.55
Elemental S (powder)	14.30	2.91	1.17 a	13.35 b	3.18	1.45
MSD	1.21	0.26	0.08	0.94	0.26	0.13
CV (%)	9.14	9.63	7.54	7.46	8.85	9.71

Means followed by the same letter in the column do not differ statistically by the Tukey test at the 5% probability level. ns Not significant, MSD: minimum significant difference, CV: coefficient of variation. The N:S evaluation was not performed in the root, because there was no nitrogen data in the root.

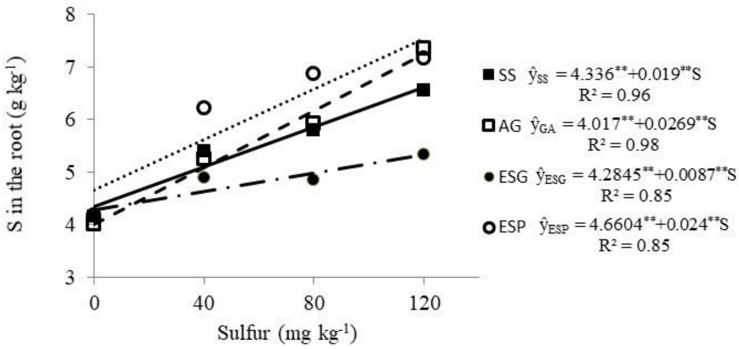

Fig 3. Effect of sulfur sources on sulfur concentration in forage sorghum root, 51 days after emergence. **significant at 1% probability, by t-test. SS: simple superphosphate, AG: agricultural gypsum, ESG: elemental sulfur granulate, ESP: elemental sulfur powder.

Table 4. Deviation of the interaction between sulfur sources and doses, comparing the dose effects in each source for sulfur concentration in the root of fodder sorghum at 51 days after emergence.

Source	Sulfur (mg dm^{-3})			
	0	40	80	120
	-----------------Sulfur in the root (g kg^{-1})-----------------			
Simple superphosphate	4.16 a	5.39 b	5.80 b	6.56 b
Agricultural Gypsum	4.00 a	5.24 b	5.92 b	7.36 a
Elemental S (granulate)	4.15 a	4.89 b	4.84 c	5.33 c
Elemental S (powder)	4.17 a	6.22 a	6.86 a	7.16 a
MSD	0.57390			
CV (%)	5.54			

Means followed by the same letter, lowercase in the column, do not differ statistically by the Tukey test at the 5% probability level. MSD: minimum significant difference and CV: coefficient of variation.

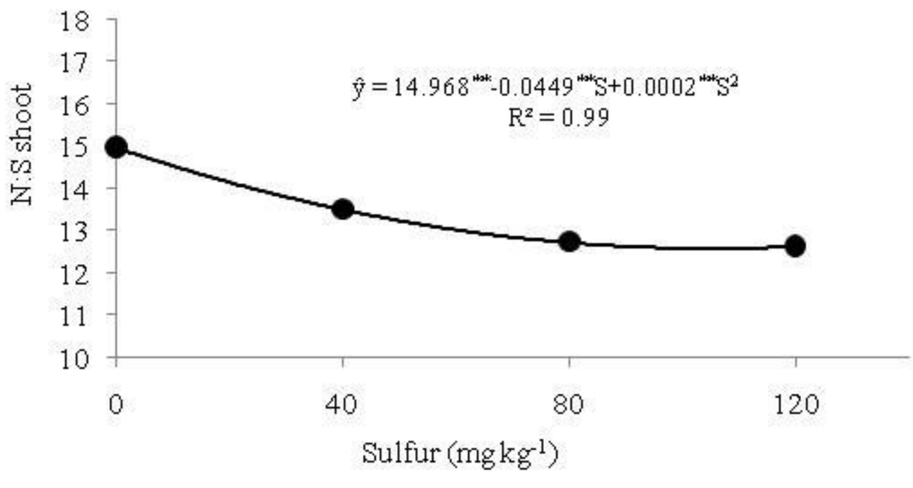

Fig 4. Effect of sulfur doses on the nitrogen/sulfur ratio on the shoot of forage sorghum at 51 days after emergence. ** Indicates significance at 1% probabilityafter t-test.

Table 5. Comparison of sulfur sources means for the variables: phosphorus, potassium, magnesium and soil pH, 51 days after the emergence of forage sorghum.

Source	P^{ns}	Soil		
		K^{ns}	Mg^{ns}	pH
	---mg dm^{-3}---	-----------$cmol_c$ dm^{-3}-----------		
Simple superphosphate	15.63	0.61	7.84	7.36 a
Agricultural gypsum	15.65	0.60	8.60	7.34 a
Elemental S (granulate)	15.23	0.59	8.14	7.33 ab
Elemental S (powder)	16.23	0.62	8.02	7.27 b
MSD	1.98	0.03	0.99	0.06177
CV (%)	13.43	5.22	12.87	0.90

Means followed by the same letter in the column do not differ statistically by the Tukey test at the 5% probability level. [ns] Not significant, MSD: minimum significant difference, CV: coefficient of variation.

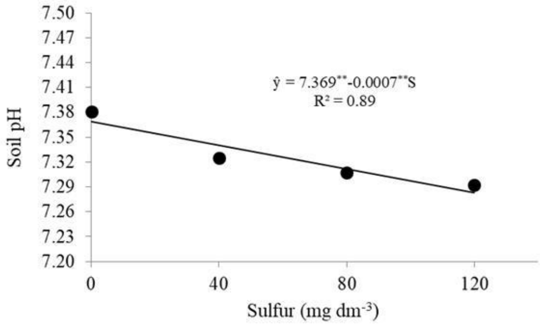

Fig 5. Effect of sulfur doses on pH of soil cultivated with forage sorghum 51 days after emergence. **Significant at 1% probability, by t-test.

Table 6. Breakdown of the interaction between sulfur sources and doses, comparing the dose effects in each source, for the variables: soil sulfur and calcium, at 51 days after emergence of forage sorghum.

Sources	Sulfur (mg dm^{-3})			
	0	40	80	120
	--------------------Soil sulfur (mg dm^{-3})-------------------			
Simple superphosphate	11.29 a	16.62 ab	18.09 b	27.85 ab
Agricultural gypsum	15.83 a	20.79 a	25.78 a	31.96 a
Elemental S (granulate)	14.56 a	13.56 b	13.82 b	15.14 c
Elemental S (powder)	11.59 a	14.61 b	16.71 b	22.89 b
	-----------------Soil calcium ($cmol_c$ dm^{-3})-----------------			
Simple superphosphate	8.40 a	9.07 a	9.10 a	11.53 a
Agricultural gypsum	8.37 a	9.47 a	9.45 a	10.65 a
Elemental S (granulate)	8.85 a	9.00 a	8.57 a	8.67 b
Elemental S (powder)	8.40 a	8.73 a	9.00 a	8.40 b
	Soil S	Soil Ca		
MSD	6.1013	1.25770		
CV (%)	16.54	7.23		

Means followed by the same letter, lowercase in the column, do not differ statistically by the Tukey test at the 5% probability level. MSD: minimum significant difference and CV: coefficient of variation.

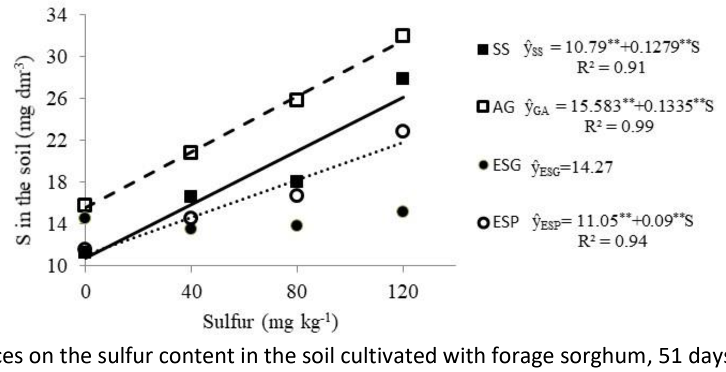

Fig 6. Effect of sulfur sources on the sulfur content in the soil cultivated with forage sorghum, 51 days after emergence. ** Indicates significance at 1% probability, by t test. SS: simple superphosphate, AG: agricultural gypsum, ESG: elemental sulfur granulate, ESP: elemental sulfur powder.

Table 7. Treatments formed by the combination of doses and sources of sulfur.

	Sulfur Dose (mg dm^{-3})	0	40	80	120
Source		D-0	D1	D2	D3
Simple Superphosphate	S1	F1-D0*	F1-D1	F1-D2	F1-D3
Agricultural gypsum	S2	F2-D0	F2-D1	F2-D2	F2-D3
Elemental S (granule)	S3	F3-D0	F3-D1	F3-D2	F3-D3
Elemental S (powder)	S4	F4-D0	F4-D1	F4-D2	F4-D3

* Read: Treatment formed by the simple superphosphate source and dose of 0 mg dm^{-3} of S. The means of S of the treatments were calculated according to the concentration of S of the fertilizers used in the experiment.

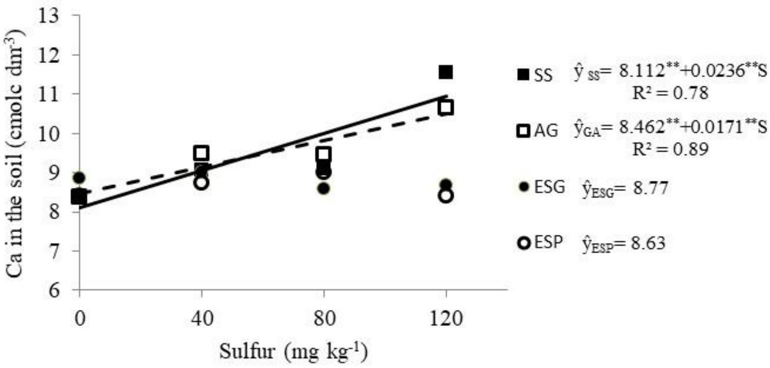

Fig 7. Effect of the doses in the sulfur sources on the calcium content in the soil cultivated with forage sorghum 51 days after emergence. **Indicates significance at 1% probability, by t-test. SS: simple superphosphate, AG: agricultural gypsum, ESG: elemental sulfur granulate, ESP: elemental sulfur powder.

Materials and methods

Plant materials

Forage sorghum (*Sorghum bicolor* (L.) Moench) cultivar BRS Ponta Negra was cultivated due to its wide adaption to the Brazilian semiarid conditions, drought tolerant and having high biomass production with low production costs (Embrapa, 2018).

Study site

The experiment was carried out in a greenhouse at the Federal University of Ceará in Fortaleza, Brazil, from August to October 2014. The climate was classified as Aw, according to the Köppen classification. A decision was made to carry out this study under controlled conditions, due to the possibility of studying a series of combinations between sources and doses of sulfur and to avoid the interference of external factors.

Soil samples were collected in the 0.0 to 0.2 m depth layer in an area of native forest (Caatinga), without agricultural use, in eutrophic Cambisol Tb latossolic in Chapada do Apodí, in the municipality of Limoeiro do Norte, in the State of Ceará. These soil samples were placed in plastic pots, with 4 kg soil. The chemical and physical characteristics of the soil sample is as follows: pH (H_2O) = 7.39; O.M. = 26.7 g kg^{-1}; P-Mehlich 1 = 7 mg dm^{-3}; S = 10 mg dm^{-3}; K = 0.73cmol$_c$ dm^{-3}; Ca = 6.8 cmol$_c$dm^{-3}; Mg = 1.90 cmol$_c$dm^{-3}; H+ Al = 1.32 cmol$_c$ dm^{-3}; SB = 9.50 cmol$_c$dm^{-3} e CEC = 10.80 cmol$_c$dm^{-3}; V = 88% and m = 2%; clay = 234g kg^{-1}; silt = 221g kg^{-1}; sand = 545 g kg^{-1}.

Experimental field design

The experimental design was a completely randomized design, in the 4 x 4 factorial scheme, corresponding to four sulfur sources (simple superphosphate, agricultural gypsum, elemental sulfur (powder) and elemental sulfur (granulate)) and four doses (0, 40, 80 and 120 mg dm^{-3}), with four replications, totaling 64 experimental units. The combinations are represented in Table 7. Each experimental unit was composed of one pot, with 4 kg of soil and 3 plants of forage sorghum, of the variety BRS Ponta Negra.

Soil moisture was corrected daily to 80% of the field capacity, by weighing the pots, to replace the water lost by evapotranspiration. A fertilization with all nutrients, except for sulfur, was carried out to meet the nutritional need of the sorghum. At the time of sowing, a dose of 240 mg dm^{-3} of P_2O_5 was applied at 7 days after plant emergence 125 and 75 mg dm^{-3}of N and K_2O were applied, at 10 days after emergence 3; 6.25; 1.25; 4; 2; 0.25 mg dm^{-3}, respectively of Fe, Mn, Cu, Zn, B and Mo and at 25 days after emergence of the plants 125 and 125 mg kg^{-1} of N and K_2O were applied. Fertilizer treatments with (Simple Superphosphate, Agricultural Gypsum, elemental sulfur (granulate), elemental sulfur (powder)) were applied to maintain their physical characteristics, so that some treatments were not favored. Triple superphosphate was added in treatments with agricultural gypsum, elemental sulfur (powder) elemental sulfur (granulate), to match the phosphorus content provided by treatment with single superphosphate.

Description of evaluations

The plants were collected at 51 days after emergence of the plants, where they were cut close to the soil, each repetition was packed in a paper bag and taken to the forced air circulation oven at a temperature of 65ºC until reaching constant mass and later, weighed for determination of dry mass. The concentrations of macronutrients in the shoots and roots of the plants were analyzed. The extracts for analysis of phosphorus, potassium, calcium, magnesium and sulfur contents were subjected to nitroperchloric digestion. In addition, the phosphorus was determined by colorimetry, potassium by flame photometry, calcium and magnesium by atomic absorption spectrometer and sulfur by turbidimetry (Tedesco et al., 1995; Malavolta et al., 1997). The extract for the total nitrogen determination was subjected to sulfur digestion and the concentration was determined by titration using the Kjeldahl method (Malavolta et al., 1997). The relationship between sulfur nitrogen (N:S) was also analyzed. In the soil, the available phosphorus was extracted with Mehlich-1 and the content determined by colorimetry, and the extractions of calcium and magnesium were prepared by 1 mol L^{-1} KCl and quantified using an atomic absorption spectrophotometer, the potassium was extracted with Mehlich 1, quantified by photometry of the sulfate and was extracted with 0.01 mol L^{-1}monocalcium phosphate and the turbidimetry content was determined according to the methodology described by Tedesco et al. (1995). The pH was analyzed in water according to the methodology described by Tedesco et al. (1995).

Statistical analyses

In cases where the interaction sources and doses of sulfur were significant, a regression analysis was performed on the dose distribution in each sulfur source and Tukey's test was conducted for sulfur sources at each dose. The statistical program used was SISVAR 5.3 (Ferreira, 2011).

Conclusion

Fertilizers in the form of elemental sulfur have similar efficiencies to the sulfate forms on biomass production as well as the nutritional characteristics of forage sorghum, when added to the soil in the physical form of powder. The application of elemental sulfur, either in the physical form of powder or granules, reduces the pH of the soil. The decrease in pH is proportional to the increase in the applied doses of elemental sulfur. The sulfur dose of 120 mg dm^{-3} is the one that favors a better development of forage sorghum and improves the sulfur content in the soil.

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