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ResearchArticle

Soybean agronomic performance in response to foliar spraying of elemental sulfur

Desempenho agronômico da soja em resposta à aplicação foliar de enxofre elementar

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ABSTRACT

Among the sulfur sources employed in soybean fertilization, it is highlighted the elemental sulfur (ES) due to its high concentration. Its foliar uptake is reported in literature, however few are the studies carried out so far. The study had as goal to assess the biometric and grain yield performance of soybean in response to foliar spraying of ES in R1 and R5.2 growth stages. It was carried out a study in randomized block design with four repetitions, comprised of ten treatments resultant of a factorial scheme 2 x 5 (with or without ES spraying in R1 and 5 increasing doses of ES spraying in R5.2). It were assessed: chlorophyll index; final plant stand; stem diameter; first pod insertion height; plant height; contents of oil, protein and sulfur in the grain; number of pods by plant; number of grains by plant; mass of 100 grain; and grain yield. It was not observed effect of ES sprayed isolated in R1 and in R5.2 with increasing doses, neither of the associated application in both growth stages, over soybean biometric and grain yield performance, even the soil presenting low sulfur content in the 0-20 cm layer. Sampling the soil also in the 20-40 cm layer to assess the sulfur content is advised in future studies.

KEYWORDS: Foliar fertilizer. Oil. Protein. Grain yield.

RESUMO

Dentre as fontes de enxofre empregadas na adubação da soja, destaca-se o enxofre elementar (EE) devido possuir alta concentração. Sua absorção foliar é relatada na literatura, porém poucos são os trabalhos realizados até o momento. O trabalho teve como objetivo avaliar o desempenho fitométrico e produtivo da soja em resposta à aplicação via foliar de EE nos estádios fenológicos R1 e R5.2. Foi conduzido experimento em delineamento de blocos casualizados com quatro repetições, composto de dez tratamentos resultantes de um esquema fatorial 2 x 5 (com ou sem aplicação de EE em R1 e 5 doses crescentes de aplicação de EE em R5.2). Foram avaliados: índice de clorofila; estande final de plantas; diâmetro do caule; altura de inserção da primeira vagem; altura de planta; teores de óleo, proteína e de enxofre no grão; número de vagens por planta; número de grãos por planta; massa de 100 grãos; e produtividade. Não foi observado efeito da aplicação de EE aplicado isoladamente em R1 e em R5.2 com o aumento das doses, nem da aplicação associada em ambos os estádios fenológicos, sobre o desempenho fitométrico e produtivo da soja, mesmo o solo apresentando baixo teor de enxofre na camada de 0-20 cm. Amostrar o solo também na camada de 20-40 cm para avaliar o teor de enxofre é aconselhado em estudos futuros.

PALAVRAS-CHAVE: Fertilizante foliar. Óleo. Proteína. Produtividade.

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INTRODUCTION

The average gain in soybean grain yield in Brazil based on data of the last ten years gets close to 68 kg ha^{-1} $year^{-1}$ (CONAB 2025), which invariably entails greater removal of nutrients from the soil, to be quoted sulfur. For each ton of grain produced, soybean uptakes from the soil 4.2 kg of sulfur, being 2.8 kg directed to the grain and 1.4 to crop remains, therefore, it is exported 66% (OLIVEIRA JUNIOR et al. 2020). Based on that, if its supply in subsequent crops is not adequate, it might happen deficiency.

Sulfur in the soil is present as organic (linked to organic matter) and inorganic (S^0 and SO_4^{2-}) forms (FUENTES-LARA et al. 2019). Its organic form represents more than 95% of sulfur in the soil, and it only becomes available to plants through its mineralization, a process carried out by microorganisms and that, therefore, depends on environmental conditions. Its inorganic form is derived from atmospheric deposition and mainly, in agriculture, from fertilizers which comprise sulfur, as potassium sulfate (18% of S), calcium sulfate, also known as gypsum (19% of S); potassium magnesium sulfate (23% of S); ammonium sulfate (24% of S); ammonium tiosulfate (26% of S); and elemental sulfur (ES) (>90% of S) (NARAYAN et al. 2023).

The amount of sulfur available has decreased in soils, and among the factors responsible for its decreasing, it may be highlighted the reduction of sulfur in atmosphere due to reduction of industrial pollution, selection of more productive varieties, reduction in the use of fungicides and insecticides comprising sulfur, and also utilization of sulfur free fertilizer formulations. Aiming to compensate its absence in formulations, the ES proves to be as an alternative source to provide this nutrient (SHARMA et al. 2024).

Sulfur is uptaken predominantly via soil, and when in its elemental form (S^0) in specific, it needs to be oxidized by soil microorganisms so that it can be converted to sulfate (SO_4^{2-}), form uptaken by plants (SINGH et al. 2018). However, VITTI et al. (2007) working with soybean in green house conditions reported that its elemental form, when foliar sprayed, is assimilated regardless of the dose and nature of the source employed, and presents superior efficiency in relation to via soil. Positive result with ES foliar sprayed is also reported by NETO et al. (2018).

Positive results as the ones previously quoted adopting foliar spraying highlight the importance of continuing with studies in this line of research, since it is a practice that, besides confer benefits to the producer, it is featured for causing less impact to environment in relation to soil fertilization, once the nutrients may be sprayed directly in the target and in critical growth stages to plant development (FERNÁNDEZ et al. 2013). In soybean crop, it is observed increase in sulfur uptaking close to R1 growth stage, and increase in its grain concentration from R5 growth stage (BENDER et al. 2015).

Considering the fact that the addition of sulfur in the areas of grain production has decreased over the last years, as mentioned previously, it was raised the hypothesis that, in soil with low sulfur content in the 0-20 cm layer, its foliar application in the elemental form, which is the most concentrated, could positively influence the soybean crop. Besides it, considering the nutrient uptaking march and its dynamic in the soil and in the plant, it was also tested the hypothesis that the

association of two ES sprayings, one in R1 and the other in R5.2, could favor soybean performance, aiming yet to establish the best dose to be utilized in the second application. Based on that, it was aimed to assess the biometric and grain yield performance of soybean in response to foliar spraying of ES in R1 and R5.2 growth stages.

MATERIALS AND METHODS

Description of study site

The study was carried out in 2022/2023 growing season, in the municipality of Londrina-PR, under geographical coordinates 23°20'29"S e 51°12'40"W, and 560 m height. The soil is classified as Latossolo Vermelho, in the Brazilian classification (SANTOS et al. 2018) and Rhodic Eutrodox, in the USA classification (SOIL SURVEY STAFF 2022). The regional climate according to Köppen classification is of the Cfa type, described as humid subtropical, with warm summer, presenting not frequent freezing and tendency of rain concentration in the summer months, however without defined dry season (NITSCHE et al. 2019).

Data of temperature referring to periods of study conduction were obtained from the meteorological station of Rural Development Institute of Parana at Londrina (IDR), and precipitation data were collected in the study site. The values of accumulated precipitation, maximum, medium and minimum temperatures were: 1,074 mm, 29.3 °C, 22.9 °C and 18.2 °C, respectively (Figure 1).

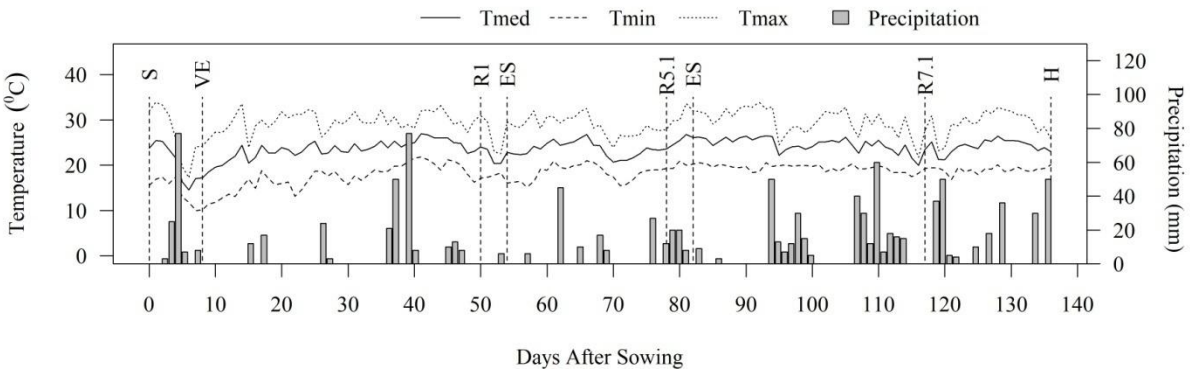


Figure 1. Daily data of precipitation, maximum, medium and minimum temperatures referring to the period of study conduction. S: sowing; VE: emergency; R1: 50% of plants with one open flower; ES: elemental sulfur; R5.1: grains tactible to 10% filled; ES elemental sulfur; R7.1: beginning to 50% yellowing of leaves and pods; H: harvesting.

Before study installation it was collected subsamples of soil in the 0-20 cm layer, which after being homogenized resulted in a unique compound sample that was utilized for characterization of chemical attributes. Interpretation of contents of sulfate (SO_4^{2-}) and organic matter (OM) were made according to OLIVEIRA JUNIOR et al. (2020) (Table 1).

Table 1. Soil chemical attributes in the 0-20 cm layer.

[1]pH $CaCl_2$	H+Al	Al^{+3}	Ca^{+2}	Mg^{+2}	K^{+}	P	SO_4^{2-}	OM	CEC effective	CEC pH 7.0
-------	----------$cmol_c\ dm^{-3}$----------					--mg dm^{-3}--		%	---$cmol_c\ dm^{-3}$---	
4.92	4.64	0.00	5.02	1.92	0.92	21.78	4.48	3.35	7.86	12.50

[1]SO_4^{2-}: low content, determined by calcium phosphate/spectrophotometry; OM: medium content, determined by sodium dichromate/spectrophotometry.

Study design and treatments employed

The study design was of randomized block, with four repetitions. Each study unit, or plot, comprised six rows of 5 m length, spaced at 0.45 m, totaling 13.5 m^2. The useful area was represented by the four central rows of each plot, discounting 1.0 m from the ends, totaling 5.4 m^2. Treatments resulted of a factorial scheme 2 x 5 (with or without ES spraying in R1 and five increasing doses of ES spraying in R5.2), totaling ten treatments.

Implementation and conduction

Sowing was carried out on 10/27/2022, in a mechanized way, with a planter comprising six rows spaced at 0.45 m, utilizing the cultivar NA5909 RG of indeterminate growth type and maturation group 6.2, aiming to establish 320,000 plants ha^{-1}. At the sowing time, seeds were inoculated with peat inoculant (*Bradyrhizobium elkani* + *Bradyrhizobium diazoefficiens*), at the dose of 60 g ha^{-1}.

Base and cover fertilization were adjusted according to chemical analysis of soil characterization and following technical recommendation (OLIVEIRA JUNIOR et al. 2020). Base fertilization consisted of 70 kg ha^{-1} of P_2O_5 utilizing the fertilizer 11-52-00 (MAP); it was not carried out cover fertilization with potassium chloride as a function of absence of need, according to the soil analysis.

At R1 growth stage, it was sprayed the liquid formulation of ES with density of 1,380 g L^{-1} (being 50% ES), at dose of 690 g ha^{-1} of ES. At R5.2 growth stage, it was sprayed the same formulation, at doses of 0; 690; 1,380; 2,070 e 2,760 g ha^{-1} of ES. It was added adjuvant at dose of 1 mL L^{-1}. At the R1 growth stage, it was applied a lower dose as a function of a lower demand, while in R5.2, the doses were increased as a function of a higher demand (BENDER et al. 2015). The spraying was carried out with a backpack sprayer with a spraying bar comprising four nozzles spaced at 0.32 m, adjusted to 175 L ha^{-1} of spraying volume. During the growing season, besides spraying of treatments, it was carried out monitoring of pests and diseases, making management when it was needed.

Harvesting was carried out after plants have reached physiological maturity, cutting plants close to the ground. First, it was counted the final plant stand in the useful area of each plot, and then, it was collected 10 plants in a row in one of the two central rows and tied in a bundle for biometric and yield components assessments. The remaining plants of the useful area were harvested and tied in another bundle, and then threshed in a stationary thresher. During the processing of samples, 600 g of grain were classified in 6.0 mm discs, separated and stored in cool chamber, at 10 °C, until the moment of carrying out analysis for determination of contents of oil, protein and of sulfur in the grains.

Assessments carried out

Twenty one days after spraying of treatments at R5.2 growth stage, at R5.5 growth stage, the chlorophyll index was assessed in ten plants by plot (5 random plants within the useful area of each central row). It was considered for assessment the third open trefoil from top down, carrying out assessment in the central leaflet, always excluding the main nerve (YOKOYAMA et al. 2018). For assessment, it was utilized a Falker's brand Electronic Chlorophyll Measure Taker (clorofiLOG – CFL1030).

For biometric assessments, it was measured the following variables: stem diameter, first pod insertion height and plant height. For yield components, the following variables: number of pods by plant, number of grains by plant, mass of 100 grains and grain yield, considering that the last three had its mass corrected to 130 g of water by kilo of grain. The grain yield was determined summing the mass of the 10 plants harvested to the remaining of the useful area of plots, considering that the last ones were threshed in a stationary thresher.

Protein and oil contents in grains were determined by the near infrared reflectance technique (FT-NIR, model Antaris II, ThermoFisher Scientific) using 30 g samples of grain according do HEIL (2010) and using an integrating sphere with readings ranging from 1100 to 2500 nm. Mathematical models developed by Embrapa Soybean in 2011-2012 were used to predict the protein content (180 standards, correlation coefficient (r) = 0.97, and root mean square error of calibration (RMSEC) = 0.64) and the oil content (170 standards, (r) = 0.98, and (RMSEC) = 0.45).

The content of sulfur was determined in 200 g of grain classified in 6.0 mm discs, resultant of grouping 50 g of each repetition of treatments, which formed a compound sample by treatment. These samples were analyzed according to the methodology proposed by the Brazilian Company of Agriculture Research (SILVA 2009).

Data analysis

Data of chlorophyll index, final plant stand, biometric, yield components, grain yield and contents of oil and protein were tested for normality of errors (Shapiro-Wilk test), homogeneity of variances (Bartlett test) and independence of errors (Durbin-Watson test); then, it were submitted to analysis of variance for randomized block design; for the factor ES in R1, it was applied the F conclusive test; and for the factor ES in R5.2, polynomial regression analysis until second degree. For the content of sulfur in the grain, as a function of grouping the repetitions, the data were exposed just for observation. In all analysis it was adopted the probability level of 5%, considering that all were run through R software, utilizing the AgroR package (SHIMIZU et al. 2024).

RESULTS AND DISCUSSION

Minimum, medium and maximum temperatures were close to the historical averages, proving not to be limiting to soybean growth. It is highlighted, however, that in the first 10-day period there was a fall in average temperatures, which caused slight delay in initial development. Regarding accumulated precipitation, of 1,074 mm,

this matched the crop need, from 765 to 875 mm according to estimates of TAGLIAPIETRA et al. (2021). Added to that, precipitation was well distributed with the course of the crop development, with accumulated volumes in all 10-day periods (Figure 1).

It was not observed isolated effect nor of interaction between the factors assessed over chlorophyll index. Sulfur is a component of the chlorophyll molecule (NARAYAN et al. 2023), then the absence of significance shows that, if it was uptaken, probably it was not integrated to that. It was not observed isolated effect nor of interaction between the factors assessed over final plant stand, which is important to highlight before interpreting the other results, so that any alteration in biometric and grain yield performance is not attributed to this variable. It was also not observed isolated effect nor of interaction between the factors assessed over biometric performance of soybean (Table 2). The increase in sulfur uptake is intensified close to R1 growth stage (BENDER et al. 2015), then, it was expected that its foliar spraying could come to supply eventual deficiency in plants, once the content of sulfur in the 0-20 cm layer was low (Table 1), influencing biometric performance, however it was not observed significant effect.

Table 2. Summary of analysis of variance comprising the averages and significances (*p* value) for chlorophyll index (CHLOR), final plant stand (FPS), stem diameter (SD), first pod insertion height (FPIH) and plant height (PH), as a function of the treatments employed.

SV(1)	TREAT	CHLOR	FPS	SD	FPIH	PH
	g ha^{-1}	-----	plants ha^{-1}	mm	cm	cm
BLOCK	*p* value	0.00	0.00	0.00	0.08	0.16
ESR1	0	48.57	302,870	5.99	24.22	90.71
	690	48.99	299,074	6.05	23.33	92.36
	p value	0.45	0.50	0.71	0.23	0.50
ESR5.2	0	49.87	300,231	5.92	23.73	90.75
	690	47.93	300,231	5.96	24.04	89.09
	1,380	49.13	301,388	5.86	23.34	90.93
	2,070	48.97	299,537	6.29	22.83	91.94
	2,760	47.99	303,472	6.08	24.96	94.95
	p value	0.17	0.99	0.55	0.44	0.64
ESR1 x ESR5.2	*p* value	0.41	0.19	0.37	0.54	0.90
CV(%)	----------	3.65	5.97	9.13	9.69	8.46
AVERAGE	---------	48.78	300,972	6.03	23.78	91.54

SV(1): source of variation; ESR1: ES at R1; ESR5.2: ES at R5.2; CV: coefficient of variation; TREAT: treatments; significant at 5% ($p<0.05$); significant at 1% ($p<0.01$); significant at 0.1% ($p<0.001$).

It was not observed isolated effect nor of interaction between the factors assessed over contents of oil and protein, yield components and grain yield (Table 3). Sulfur is a nutrient important to formation of protein in the grain as well as nitrogen, since the concentration of sulfur in the grain is associated to the concentration of protein in a constant N:S relation (BORJA REIS et al. 2021). The absence of response for chlorophyll index (Table 2), summed to the absence of response for contents of protein and sulfur in the grain (Table 3), indicate that sulfur did not have effect in the plants. ASSEFA et al. (2019) highlight that the increase in

grain yield is related in a slightly negative way with content of protein in grain, in 66% of studies assessed.

On the other hand, they highlight a positive relation with content of oil, in 63% of studies assessed. In the present study, it was not observed effect of treatments over contents of oil and protein, as well as over yield components and grain yield (Table 3). Positive result in soybean production in pot as a function of ES is reported by VITTI et al. (2007), carrying out spraying in V4 and R1; and in soybean grain yield in field conditions by NETO et al. (2018), carrying out spraying in R1 and R5.1 growth stages. Studies as the ones by REZENDE et al. (2009), carrying out spraying in R3, and by OHSE et al. (2025), carrying out spraying between V3 and V4 associated to glyphosate, also report increase in soybean grain yield as a function of the sulfur sources they employed.

Table 3. Summary of analysis of variance comprising the averages and significances (*p* value) for contents of oil (OIL), protein (PROT), and sulfur in the grain (S), number of pods by plant (NPPL), number of grains by plant (GRPL), mass of 100 grains (100), and grain yield (GY), as a function of the treatments employed.

SV(1)	TREAT	OIL	PROT	S	NPPL	GRPL	M100	GY
	g ha^{-1}	%	%	g kg^{-1}	n°	n°	g	kg ha^{-1}
BLOCK	*p* value	0.05	0.96	w/s	0.04	0.15	0.05	0.11
ESR1	0	21.54	38.70	2.53	38.31	79.52	16.53	3,887
	690	21.25	39.33	2.43	39.38	80.54	16.84	3,848
	p value	0.25	0.12	w/s	0.58	0.79	0.23	0.66
ESR5.2	0	21.12	39.30	2.55	38.51	77.25	17.04	3,866
	690	21.23	39.29	2.49	36.62	75.58	16.47	3,768
	1,380	21.31	38.83	2.51	36.69	76.38	16.83	3,875
	2,070	21.63	39.19	2.48	42.18	85.92	16.57	3,873
	2,760	21.67	38.46	2.38	40.22	85.04	16.51	3,955
	p value	0.55	0.62	w/s	0.33	0.30	0.59	0.77
ESR1 x ESR5.2	*p* value	0.56	0.91	w/s	0.37	0.25	0.34	0.89
CV(%)	---------	3.71	3.25	w/s	15.82	15.73	4.86	7.25
AVERAGE	---------	21.40	39.01	2.48	38.85	80.04	16.69	3,867

SV(1): source of variation; ESR1: ES at R1; ESR5.2: ES at R5.2; CV: coefficient of variation; TREAT: treatments; w/s: without statistical analysis as a function of grouping the repetitions, making a compound sample by treatment; significant at 5% (p<0.05); significant at 1% (p<0.01); significant at 0.1% (p<0.001).

Aiming to understand the absence of response as a function of the spraying, the understanding of foliar uptaking of nutrients is needed. The uptaking might occur via cuticle, wounds and imperfections of cuticle, stomata and tricomes. The success of the process is linked to the formulation of the product to be applied, to atomization of the solution to be sprayed, to deposition of droplets on the leaf surface, to wetting, to spreading and retention of the solution on the leaf surface, to formation of spraying residue on the leaf surface, and to penetration and distribution of the nutrient to the target site (FERNÁNDEZ et al. 2013).

Sulfur is a low mobility nutrient within the plant (LI et al. 2020), therefore, it will have greater effect on the tissues that directly receive the foliar spraying (FERNÁNDEZ et al. 2013). This way, it is raised the hypothesis that this might have been one of the factors that favored the obtention of positive results in previous

studies. In the study by VITTI et al. (2007), it were sprayed all the leaves of the plants present in the pots, with a spraying volume equivalent to 2,000 L ha^{-1}. In the study by NETO et al. (2018), in field conditions, it was utilized 200 L ha^{-1}. These values of spraying volume were superior to the present study, which employed 175 L $ha^{-1.}$

Another factor to be considered is that in conditions of low sulfur availability, there is increase in SO_4^{2-} transporters in membrane cells, which increases its uptaking and assimilation (FUENTES-LARA et al. 2019). In the present study, the content of SO_4^{2-} in the soil in the 0-20 cm layer was low (Table 1), however, even like that, there was no yield response with the foliar spraying. It is important to highlight, that the soil was not sampled in the 20-40 cm layer, and the sulfur content is greater at this layer (BALBINOT JUNIOR et al. 2024), so this layer might have served as a source of sulfur to plants, contributing to the absence of positive response.

Added to that, in the present study, the content of organic matter in the soil, of 3.35% (Table 1), was superior to the studies by VITTI et al. (2007) and by NETO et al. (2018), which had 0.77% and 2.84%, respectively. The greatest content of organic matter might also be an explanation to the absence of response in the present study, given that, as highlighted by NARAYAN et al. (2023), more than 95% of sulfur in the soil is linked to organic matter, and it becomes available to plants by the mineralization process. The absence of response with foliar application of sulfur was also highlighted by MAHATO (2023), in soil with organic matter content greater than 3% in the 0-15 cm layer.

Regarding the meteorological conditions, the application in R1 was carried out between 06 h 30 and 08 h 00 a.m., day in which the minimum, medium and maximum temperatures were 16.1, 22.7 and 29.6 °C, respectively, and in which did not occur precipitation, only in the previous day, totaling 6 mm. The application in R5.2 was carried out between 08 h 00 and 10 h 00 a.m., day in which the minimum, medium and maximum temperatures were 20.2, 25.1 and 32.0 °C, respectively, also not having occurred precipitation after application, only in the day before, totaling 8 mm, and in the following day, totaling 9 mm.

It was chosen to carry out application early in the morning, which favors the aperture of stomata as a function of the lower temperatures (OGUNKANMI et al. 2022), via in which may occur foliar uptaking (FERNÁNDEZ et al. 2013). It is highlighted also, that the lower temperatures also favor the reduction of losses due to solution evaporation after it reaches the foliar surface (ADEGAS & GAZZIERO 2020). Like that, it is considered that the applications were carried out in conditions of temperature close to the ideal soybean development, which is between 20-30 °C (NEUMAIER et al. 2020), and also in conditions with lower chances of losses by evaporation.

In search for positive response, future studies should consider be carried out in soils with inferior sulfur content in the 0-20 cm layer in relation to the present study and of the previously already carried out, and also consider the assessment of sulfur content in the 20-40 cm layer for more assertive conclusions. Also, it is important that they be carried out in soils with content of organic matter inferior to the present study and of the previously already carried out. Added to that, limiting conditions of sulfur associated to the adoption of a greater spraying volume aiming a greater droplet

deposition over the canopy of the crop (WEBER et al. 2017), or even other possible variations to be carried out regarding spraying technology, might contribute to a better understanding of ES foliar spraying.

CONCLUSION

It was not observed effect of ES sprayed isolated in R1 and in R5.2 with increasing doses, neither the associated application in both growth stages, over soybean biometric and grain yield performance, even the soil presenting low sulfur content in the 0-20 cm layer. Sampling the soil also in the 20-40 cm layer to assess the sulfur content is advised in future studies.

NOTES

AUTHOR CONTRIBUTIONS

Conceptualization, methodology, and formal analysis, Cazarim PH, Ferreira AS, Zucareli C, and Fonseca ICB; software and validation, Cazarim PH, Ferreira AS and Fonseca ICB; investigation, Cazarim PH, Lima AD, Favoretto MR, Shibayama LK; resources and data curation, Cazarim PH and Ferreira AS; writing-original draft preparation, Cazarim PH; writing-review and editing, Cazarim PH and Ferreira AS; visualization, Cazarim PH and Ferreira AS; supervision, Zucareli C, and Fonseca ICB; project administration, Cazarim PH; funding acquisition, Zucareli C, and Fonseca ICB. All authors have read and agreed to the published version of the manuscript.

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INSTITUTIONAL REVIEW BOARD STATEMENT

Not applicable for studies not involving humans or animals.

INFORMED CONSENT STATEMENT

Not applicable because this study did not involve humans.

DATA AVAILABILITY STATEMENT

The data can be made available under request.

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CONFLICTS OF INTEREST

There are no conflicts of interest.

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