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Boron nutrition improves peanuts yield and seed quality in a low B sandy soil

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ABSTRACT: Peanuts are mainly grown in sandy soils with low boron content, which may limit the crop yield, especially runner-type cultivars that have high-yields. Boron deficiency causes hollow heart in peanut seeds, reducing yield and seed quality, but the best strategy to supply boron to peanut is still not known. This study aimed to evaluate peanuts nutrition, yield, and seed quality as a function of boron rate, source, and application form. The study was conducted for two years in sandy soils with low boron in southeastern Brazil. Treatments included application of boron via soil: control (boron unfertilized), boric acid at 1.5 kg ha^{-1} of B, Ulexite (1.5 and 3.0 kg ha^{-1} of B), and sodium tetraborate (1.5 and 3.0 kg ha^{-1} of B) combined with foliar fertilization (sub-plots): 0, 400, 800 and 1200 g ha^{-1} of B (boric acid) with four replicates. Boron fertilization via soil and foliar increased peanuts yield by 20 % (1100 kg ha^{-1}) and 14 % (700 kg ha^{-1}) - the average of the two crops, respectively. Combined use of soil and foliar fertilizer was justified only in years with water deficit and when the rate applied via soil was low (<3.0 kg ha^{-1}). Boron application via soil or application of 400 g ha^{-1} of B via foliar fertilization increased seed germination rate by 10 to 13 %. Boron fertilization increased the percentage of normal seedlings, seedling weight, and length and reduced the germination time. Foliar and soil boron applications efficiently improved peanut seed nutrition, yield, and quality. However, soil application performed better, showing a higher percentage of yield increase.

Keywords: soil fertilization, foliar fertilization, boron sources, sufficiency range.

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INTRODUCTION

Peanut (*Arachis hypogaea* L.) is cultivated on 26 M ha worldwide with a total production of 45 M ton (Rachaputi et al., 2021). About 80 % of the world's peanut production occurs in rainfed areas in semi-arid tropical regions with low fertility soils, water deficits, and high temperatures (Rachaputi et al., 2021). In Brazil, it is cultivated on about 250,000 ha, usually in crop renewal of sugarcane crops and in degraded pasture areas in sandy soils, usually with low investment in fertilizer (Bassanezi et al., 2021). Predominantly, runner cultivars are used with high oleic seed standards and high yield potential (between 5000 and 9000 kg ha^{-1}), which have a higher nutrient demand compared with older cultivars of Valencia and Spanish groups (erect growth) (Crusciol et al., 2021). However, the literature about the response of runner cultivars to boron fertilization remains scarce.

Boron (B) deficiency in peanuts causes deformities in the formation of the cotyledons, which leads to the occurrence of hollow heart in the seeds, reducing their quality and yield (Harris and Brolmann, 1966; Rerkasem et al., 1993). This occurs because B deficiency leads to the poor formation of the conducting vessels (phloem and xylem), reducing carbohydrate transport from leaves to fruits (Li et al., 2017). Besides, an inadequate supply of B also negatively affects root growth, making the plant more sensitive to drought (Kohli et al., 2023). It was recently reported that the critical level of boron in soil for peanuts grown in sandy soil is 1.25 mg kg^{-1} (Kumar et al., 2023), but in Brazil peanuts are grown in poor B soils, between 0.1 and 0.5 mg kg^{-1}, and plants are exposed to deficiency with high frequency.

Adequate B nutrition improves the uptake of nitrogen and calcium by peanuts and increases the number of pods per plant and yield (Mantovani et al., 2013), reflecting the increased photosynthetic rate and synthesis and carbohydrates (Mousavi et al., 2022). It is worth mentioning that the range of boron sufficiency in the leaf of crops is narrow and that higher rates cause toxicity to plants, which reduces yield and seed quality (Kohli et al., 2023).

In sandy soils, B deficiency is mainly associated with low organic matter content (Schmidt et al., 2021) and a higher leaching rate (Dhassi et al., 2019). Use of high solubility sources such as boric acid results in high mobility of boron in the soil, causing toxicity, as reported in cotton plants, when applied at rates higher than 2 kg ha^{-1} and not nourishing the plant adequately until the end of the cycle, mainly when it is used in systems without cover crops (Cordeiro et al., 2022). Peanut is grown in conventional soil tillage methods, thus, a similar response is expected. One of the strategies to reduce boron leaching and improve boron uptake by crops grown on sandy soils is to use gradual-release boron sources (Silva et al., 2018), such as sodium tetraborate and ulexite. Additionally, boron application via soil can improve soil fertility, benefiting production systems (Kumar et al., 2023).

Peanut has been reported to efficiently remobilize boron in the phloem, so foliar fertilization may be a good option for the crop (Konsaeng et al., 2010). Yield increments have also been reported with foliar application between 1.0 and 1.5 kg ha^{-1} of boron to peanuts in soils with low boron content (Mantovani et al., 2013; Foloni et al., 2016). On the other hand, fertilization with 2 kg ha^{-1} of boron via soil is sufficient to improve crop nutrition (Singh et al., 2017). In soils with adequate fertility management, there is no positive response to foliar fertilization (Pierre et al., 2019).

However, it is not yet known whether, in tropical environments and sandy soils subject to leaching and drought, with low boron soil content, what is the best recommendation for boron supply for modern runner varieties of peanuts. Yield and seed quality may increase, but the risk of phytotoxicity has to be considered, as well as the use of less soluble sources. It is also necessary to understand whether the adequate rate of boron for peanut depends on the boron source and the initial boron content in the soil and whether there are benefits from associating soil fertilization with foliar fertilization.

Finally, it is necessary to establish the critical foliar boron level for modern runner-type peanut cultivars.

We hypothesized that soil fertilization with less soluble boron sources is the best option for the adequate nutrition of modern peanut cultivars. The aim of the study was to evaluate nutrition, yield, and quality of peanut seeds as a function of rate, source, and form of application in soils with distinct B contents.

MATERIALS AND METHODS

Site characterization

The field experiment was carried out in Regente Feijó, São Paulo, Brazil, at 22° 13’ 9” S, 51° 18’ 25” W, 483 m elevation with sandy Arenic Hapludults (*Argissolo Vermelho-Amarelo Distrófico*) soil of low fertility and iron and aluminum oxides during the 2020/2021 and 2021/2022 seasons. Peanuts were cultivated in different areas during the seasons, with no residual effect of boron in the soil.

Soil was cultivated alternating peanuts (Oct-Feb) and forage grass (*Urochloa brizantha*) (Mar-Sep). The chemical properties and soil texture before peanut sowing are shown in table 1. Precipitation, maximum and minimum temperature during the studies is shown in figure 1.

Experimental design

The experimental design was a complete randomized block with a split-plot scheme with four replications. Treatments included the application of boron via soil (plots): control (unfertilized with boron), boric acid at 1.5 kg ha^{-1} of B, Ulexite (1.5 and 3.0 kg ha^{-1} of B), and sodium tetraborate (1.5 and 3.0 kg ha^{-1} of B) combined with foliar fertilization (sub-plots): 0, 400, 800 and 1200 g ha^{-1} of B (boric acid). The plots were 3.6 m wide and 6.0 m long.

Peanut management

In August 2020 and 2021, liming was performed at 1600 and 1000 kg ha^{-1}, respectively, and dolomitic limestone (31 % CaO and 21 % MgO) was applied to the soil. In September,

Table 1. Chemical and particle size analyses of the soil of the experimental area in the layers of of 0.00-0.20 m and 0.20-0.40 m

Layer	pH($CaCl_2$)	O.M	P	S	Al^{3+}	H+Al	K	Ca^{2+}	Mg^{2+}	CEC	BS
m		g kg^{-1}	mg kg^{-1}		mmol$_c$ kg^{-1}						%
					2020/2021						
0.00-0.20	4.9	17.3	4.4	2.3	0.3	18.6	1.1	10.4	6.4	36.5	49.1
0.20-0.40	4.0	14.9	2.9	2.4	3.7	26.9	0.8	3.2	2.0	32.9	18.4
					2021/2022						
0.00-0.20	4.5	14.9	12.5	2.1	1.2	16.7	0.8	9.0	6.2	32.7	48.9
0.20-0.40	4.8	13.5	9.5	3.8	3.0	19.2	0.8	5.1	4.8	29.9	35.9
	B	**Cu**	**Fe**	**Mn**	**Zn**		**Sand**	**Silt**	**Clay**		
	mg dm^{-3}						g kg^{-1}				
					2020/2021						
0.00-0.20	0.07	0.80	17.3	7.8	0.70		833	26	141		
0.20-0.40	0.06	0.90	19.8	5.8	0.50		814	38	148		
					2021/2022						
0.00-0.20	0.20	0.70	14.9	4.8	0.60		833	26	141		
0.20-0.40	0.08	0.60	14.8	3.0	0.50		814	38	148		

OM: organic matter; CEC: cation exchange capacity; BS: base saturation.

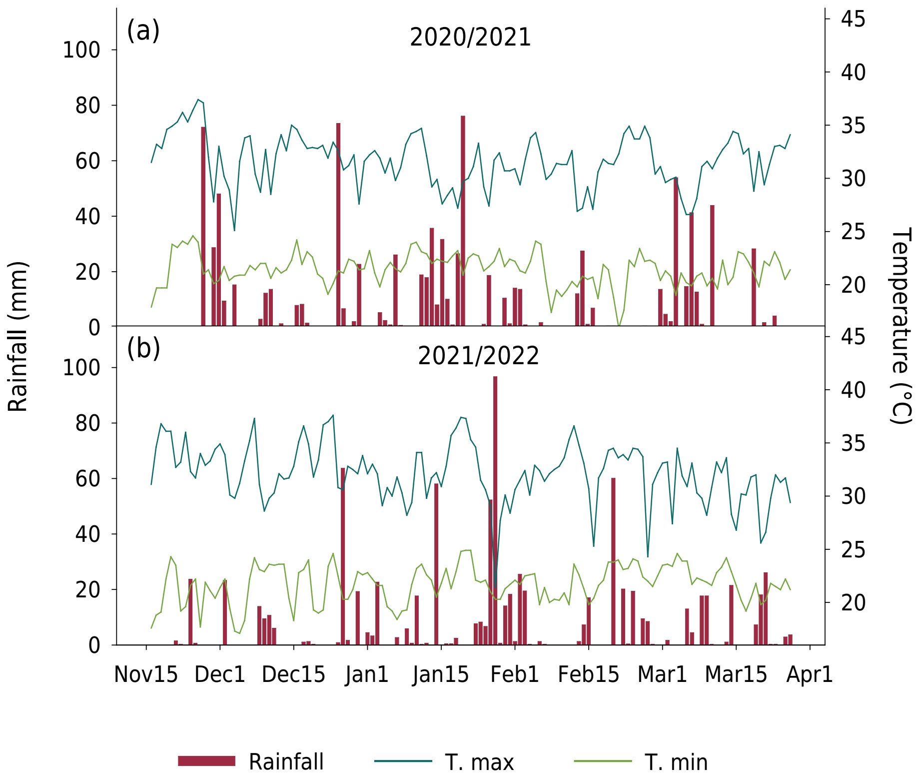

Figure 1. Precipitation, maximum and minimum temperatures recorded during the studies. Regente Feijó-São Paulo, Brazil, seasons 2020/2021 e 2021/2022.

conventional soil tillage was performed. Peanut was sowed on November 21st, 2020, and November 22nd, 2021, using the runner-type cultivar Granoleico. A twin-row pattern was used with 25 seeds m^{-1} and 90 cm spacing outer to outer row and 17 cm between adjacent rows. At the time of sowing the peanut was applied 20, 43, and 25 kg ha^{-1} of N, P, and K, respectively, using urea (45 % N), triple superphosphate (41 % P_2O_5), and potassium chloride (60 % K_2O), respectively.

Boron application via soil was manually carried out on the day of sowing. This application was carried out right after sowing, not being mixed with NPK fertilizers. Boron foliar was applied in four equal applications (21, 28, 35, and 42 days after emergence) with a pressurized CO_2 sprayer at 200 L ha^{-1}. At 48 days after emergence (R3- beginning of pod formation – according to Boote (1982), 20 leaves were collected from each plot, washed in running water, dried at 65 °C for 72 h, grinded, and then the boron content in the leaves was determined (Chapman and Pratt, 1962).

At pod maturity (70 % of mature pods - R8 and R9), all rows were mechanically dug and inverted using a digger/inverter and two linear meters were harvested manually from each plot to evaluate the plant stand (final density of 20 plants per linear meter), yield components (number of pods, number of seeds per pod and weight of 100 seeds), pod yield and kernel percentage (dry matter of kernel in relation to the dry matter of the shell). Seed moisture was corrected at 7 % (peanut marketing standard). A sub-sample of 200 g seeds was separated to evaluate seed quality.

Management of pests, diseases, and weeds was carried out according to the commercial area's standards. Weekly evaluations of weed, pest and disease indices were carried out and then the applications of herbicides, insecticides and fungicides registered for the peanut crop were programmed.

Seed quality

Sixty days after peanut harvest (expected time to reduce seed domency), the seeds germination test was installed on paper rolls with 25 seeds per replication. The substrate, consisting of three sheets of paper, two as a base and one for seed cover, was moistured with distilled water in the proportion of 2.5 times the weight of dry paper. The rollers were kept in a constant Mangelsdorf type germinator at 25 °C. The evaluations were daily, considering the seed with root protrusion above 0.5 cm. Germination stabilized six days after sowing, and daily evaluations were inserted in germinator software (GERMINATOR) (Joosen et al., 2009) to obtain the maximum germination values and mean germination time. At six days after sowing, normal seedlings with roots greater than 3 cm were counted and separated. The hypocotyl + roots were measured to obtain the average length and dry mass after drying the seedlings in an oven at 65 °C for 48 h.

Data analysis

After testing for homogeneity and normality, data were subjected to analysis of variance (ANOVA). As crop seasons had significant effects, they were analyzed separately. The experiment was arranged in a randomized complete block design, with two fixed factors (soil fertilization and foliar fertilization) and four replications. Statistical analysis was performed from variance analysis and treatment averages compared by the t-Test (LSD) at 5 % probability ($p<0.05$). The model used was a split-plot. The analyses were performed using the Sisvar® statistical software, and plots were generated using Sigmaplot®.

RESULTS

Yield and yield components

Average peanut pod yield was 6300 kg ha^{-1} in 2020/2021 , and 4980 kg ha^{-1} in 2021/2022 (Figure 2). In the 2020/2021 crop, even with high yield, when boron was applied via soil, regardless of the source or rate, there was no need to apply boron via foliar, and the yield increment was 1000 kg ha^{-1} or 18 % (average of soil treatments - compared with control). In the absence of soil fertilization, it was necessary to apply 800 g ha^{-1} of B to obtain a maximum increment of 600 kg ha^{-1} (10 %) relative to the control (Figure 2a).

In the 2021/2022 crop, even with the application of 1.5 kg ha^{-1} of B via boric acid, sodium tetraborate, or ulexite, it was necessary to apply a supplementary rate of foliar boron (400 g ha^{-1}) to obtain the maximum yield (Figure 2b). However, with 3 kg ha^{-1} via sodium tetraborate or ulexite, there was no need for foliar boron application. In the absence of soil fertilization, foliar application (400 g ha^{-1}) increased peanut yield by 19 % (800 kg ha^{-1} of pod yield) (Figure 2b). In both crops, the association of soil boron with high foliar boron rate reduced peanut yields (Figure 2).

We report no significant interaction between the forms of boron application (soil or foliar) on the yield components of peanut production and kernel percentage (Table 2). Boron application via soil (independent of the rate or source) and foliar application (with a rate between 400 and 800 g ha^{-1}) improved the yield components of peanuts. However, in the 2020/2021 crop, the foliar application did not affect the number and kernel percentage; in the 2021/2022 crop, there was no effect of foliar and soil application on the number of kernel per pod (Table 2).

Leaf boron content

Soil application of boron increased the leaf boron content of peanuts in the absence of foliar fertilization compared to the control. The highest leaf contents were with 3 kg ha^{-1} of B in sodium tetraborate source in 2020/2021 and 3 kg ha^{-1} of sodium tetraborate and ulexite in 2021/2022. Application of 1.5 kg ha^{-1} of boron in sodium tetraborate source

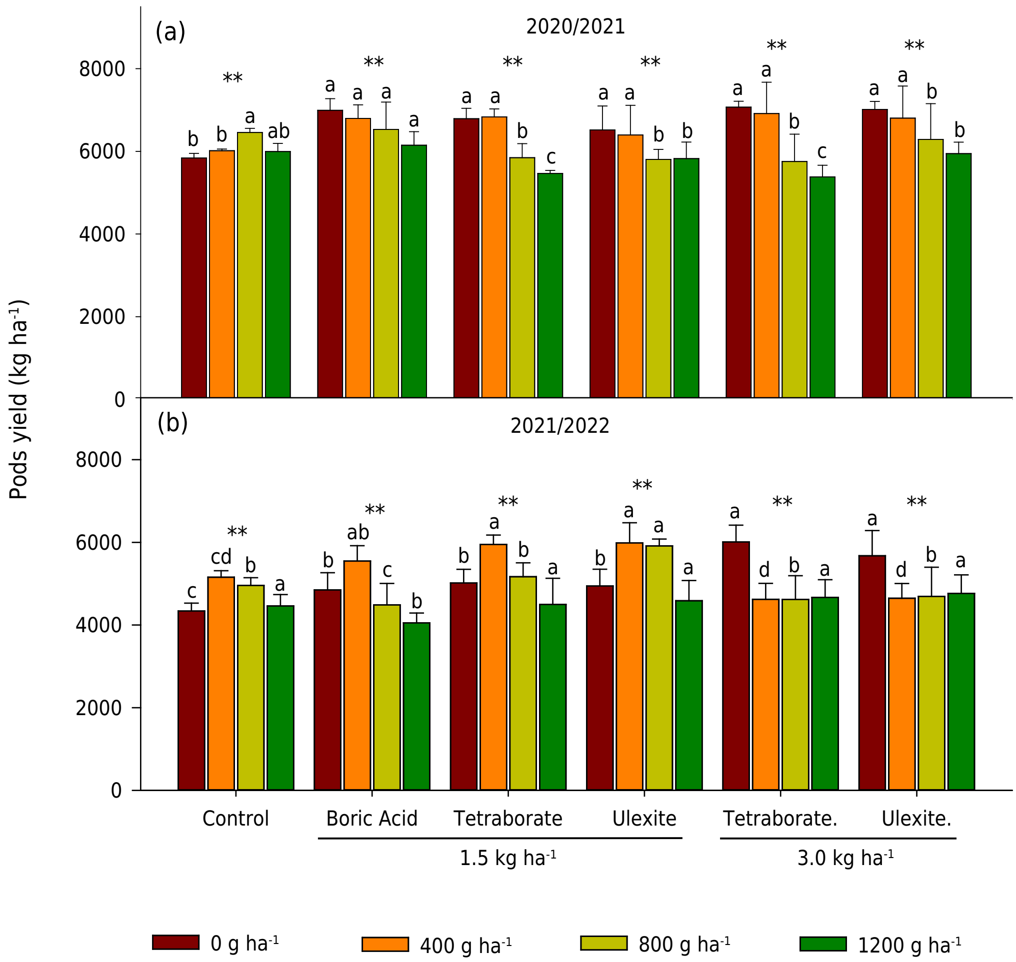

Figure 2. Peanut pods' yield as a function of boron fertilizer management via soil and foliar during crop seasons2020/2021 and 2021/2022. Letters compare treatments with soil boron application. Asterisks show the effect of foliar application within each soil treatment. Vertical bars represent the standard error.

resulted in the highest foliar B content (2021/2022 - no foliar boron). In the absence of foliar fertilization, leaf boron contents were 114 % (40.4 mg kg^{-1}) and 89 % (36.1 mg kg^{-1}) higher with 3 kg ha^{-1} of sodium tetraborate compared to the control, in 2020/2021 and 2021/2022, respectively (Figure 3). In the absence of soil fertilization, foliar application of 1200 g ha^{-1} of boron increased leaf boron content by 53 % (to 54.3 mg kg^{-1}) and 36 % (to 75.5 mg kg^{-1}) on 2020/2021 and 2021/2022 seasons, respectively. (Figure 3). Leaf B content was not affected by foliar fertilization only when 3 kg ha^{-1} of sodium tetraborate was applied via soil in crop 2021/2022, in the other treatments, even with soil application, foliar fertilization increased the leaf boron content of peanut (Figure 3b).

Physiological quality of the seeds

Control treatment had a germination rate of 67 and 82 % in the seasons 2020/2021 and 2021/2022, respectively, that is, in general, the quality of the seeds 2021/2022 was superior (Figure 4). Boron application via soil associated with foliar application reduced the seed germination rate, especially when the foliar rate was greater than 400 g ha^{-1}. In the absence of soil fertilization, the application of 400 g ha^{-1} of B increased the germination rate by 10 and 13 percentage points, in 2020/2021 and 2021/2022, respectively, compared to the control. Regarding soil fertilization maximum germination was with 1.5 kg ha^{-1} via boric acid (78 %) and 3.0 kg ha^{-1} via sodium tetraborate (81 %) (2020/2021) and with 1.5 kg ha^{-1} of boron via sodium tetraborate (97.5 %) and ulexite (98.5 %) and 3.0 kg ha^{-1} of boron via sodium tetraborate (96.7 %) and ulexite (95.5 %) (2021/2021) (Figure 4).

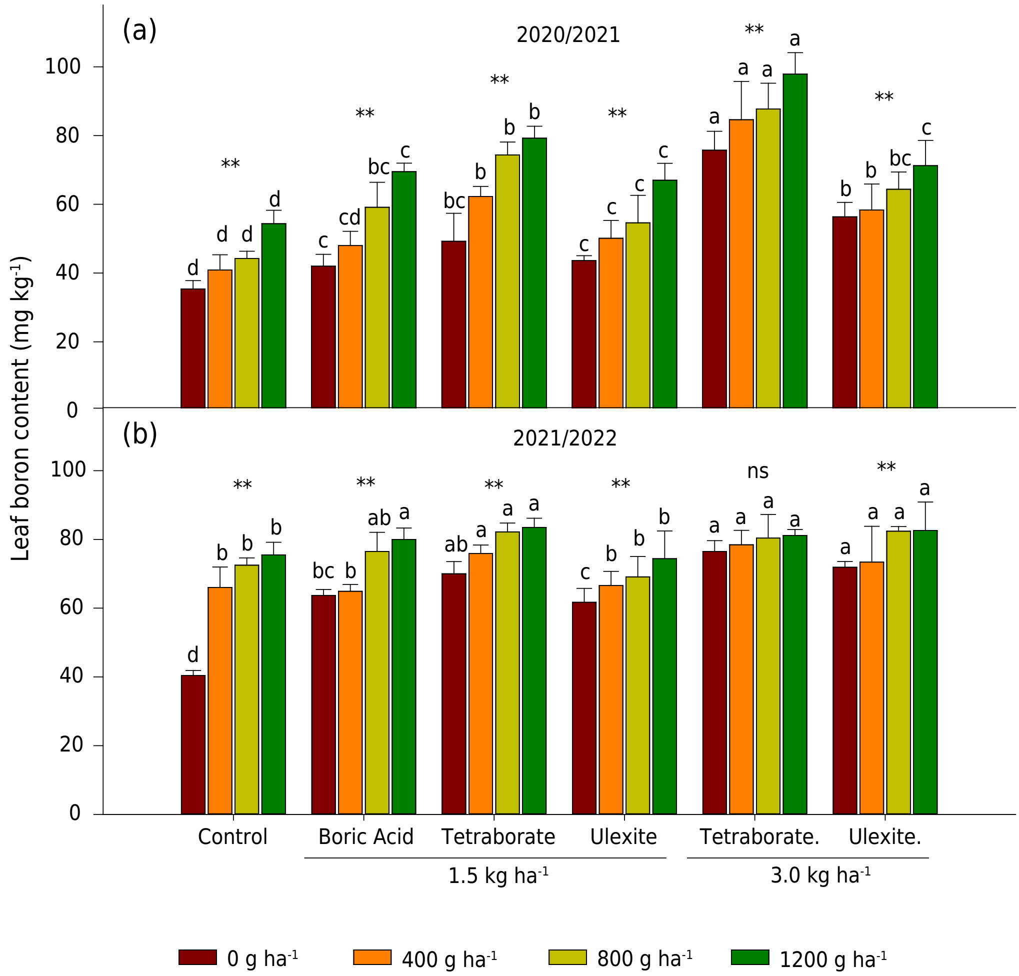

Figure 3. Leaf boron content as a function of boron fertilizer management via soil and foliar during 2020/2021 and 2021/2022 seasons. Letters compare the treatments with boron application via soil. Asterisks show the effect of foliar application within each soil treatment. Vertical bars represent the standard error.

Boron fertilization effect on mean germination time occurred mainly in the second season (2021/2022). Foliar fertilization with 400 g ha^{-1} of boron reduced germination time by 12 % (2021/2022). Also, in the 2021/2022 season, the application of sodium tetraborate and ulexite reduced the average germination time of peanut seeds, independent of the boron rate used. In the absence of foliar fertilization, the application of 1.5 kg ha^{-1} via boric acid (soil) increased the percentage of normal seeds by 111 % (2020/2021), while in the second crop (2021/2022), the best treatments were with sodium tetraborate and ulexite, with an average increase of 15 % over the control. Foliar fertilization also increased the percentage of normal seedlings with a rate between 800 g ha^{-1} (2020/2021) and 400 g ha^{-1} (2021/2022) (Table 3).

There was no effect of the association between soil and foliar fertilization on the dry weight of peanut seedlings. However, the foliar application of 400 g ha^{-1} of boron increased dry matter mass by 29 and 7% in 2020/2021/2021/2022, respectively, compared to the control. Applying 1.5 kg ha^{-1} of boron via soil (ulexite) also increased dry matter mass by 30 and 18 % in crops 2020/2021 and 2021/2022, respectively, compared to the control. Interestingly, the greatest seedling length was also greater with 400 g ha^{-1} of boron via foliar (both crops) or with 1.5 kg ha^{-1} of boron via soil (ulexite) (2020/2021) and with sodium tetraborate or ulexite (regardless of rate) (2021/2022) (Table 3).

Table 2. Yield components of peanut as a function of soil or foliar boron fertilization in seasons 2020/2021 and 2021/2022.

Treatment	Pods plant^{-1}	Seeds pod^{-1}	Kernel 100 weight (g)	Kernel percentage
			g	%
		2020/2021		
Soil Fertilization (S)				
Control	17.3 b	1.68 ab	60.9 c	66.1 b
Boric acid 1.5 kg ha^{-1} of B	19.7 a	1.67 ab	63.3 b	66.8 b
Tetraborate 1.5 kg ha^{-1} of B	18.4 a	1.76 a	63.4 b	70.1 a
Ulexite 1.5 kg ha^{-1} of B	19.5 a	1.70 ab	65.9 a	70.9 a
Tetraborate 3.0 kg ha^{-1} of B	19.4 a	1.67 ab	63.8 b	70.2 a
Ulexite 3.0 kg ha^{-1} of B	20.0 a	1.60 b	62.9 b	65.1 b
Foliar fertilization (F)				
0 g ha^{-1} of B	19.0 b	1.71 a	63.5 ab	69.1 a
400 g ha^{-1} of B	20.1 a	1.69 a	66.8 a	68.6 a
800 g ha^{-1} of B	19.5 ab	1.69 a	62.6 b	67.2 a
1200 g ha^{-1} of B	18.9 b	1.68 a	61.4 b	67.9 a
p value				
S	0.0054	0.0183	0.0381	0.0000
F	0.1792	0.3876	0.0193	0.2577
S*F	0.9623	0.3392	0.9338	0.1630
CV%	8.7	7.2	9.3	9.8
		2021/2022		
Soil Fertilization (S)				
Control	15.0 c	1.56 a	62.0 b	68.9 c
Boric acid 1.5 kg ha^{-1} of B	16.3 b	1.57 a	62.2 b	71.2 b
Tetraborate 1.5 kg ha^{-1} of B	17.4 b	1.48 a	64.2 a	70.0 b
Ulexite 1.5 kg ha^{-1} of B	19.7 a	1.47 a	64.4 a	75.1 a
Tetraborate 3.0 kg ha^{-1} of B	17.2 b	1.52 a	62.9 b	73.9 a
Ulexite 3.0 kg ha^{-1} of B	16.5 b	1.53 a	62.7 b	72.0 b
Foliar fertilization (F)				
0 g ha^{-1} of B	16.4 b	1.50 a	63.0 b	72.7 b
400 g ha^{-1} of B	18.2 a	1.51 a	65.0 a	75.9 a
800 g ha^{-1} of B	16.2 b	1.52 a	62.2 b	71.2 c
1200 g ha^{-1} of B	15.6 b	1.56 a	61.0 c	71.0 c
p value				
S	0.0000	0.2860	0.0001	0.0280
F	0.0000	0.5831	0.0000	0.0159
S*F	0.1620	0.2580	0.0000	0.1898
CV%	10.7	9.0	12.1	9.9

DISCUSSION

The higher yield in the 2020/2021 season is likely a result of the higher accumulated rainfall (918 mm) compared to 2021/2022 (730 mm) (Figure 1). Nevertheless, in both crops, boron fertilization improved the yield, nutrition, and seed quality of peanuts, but the extent of the improvement depended on the rate, source, and form of application of boron. The greater number of pods and heavier kernels may explain the higher yield of peanuts (Tables 2 and 4), reflecting the increased fruit set (pollen germination and pollen tube elongation) by improved boron nutrition (Wang et al., 2003). In addition, B increases the photosynthetic rate of the plant, carbohydrate production (Mousavi et al.,

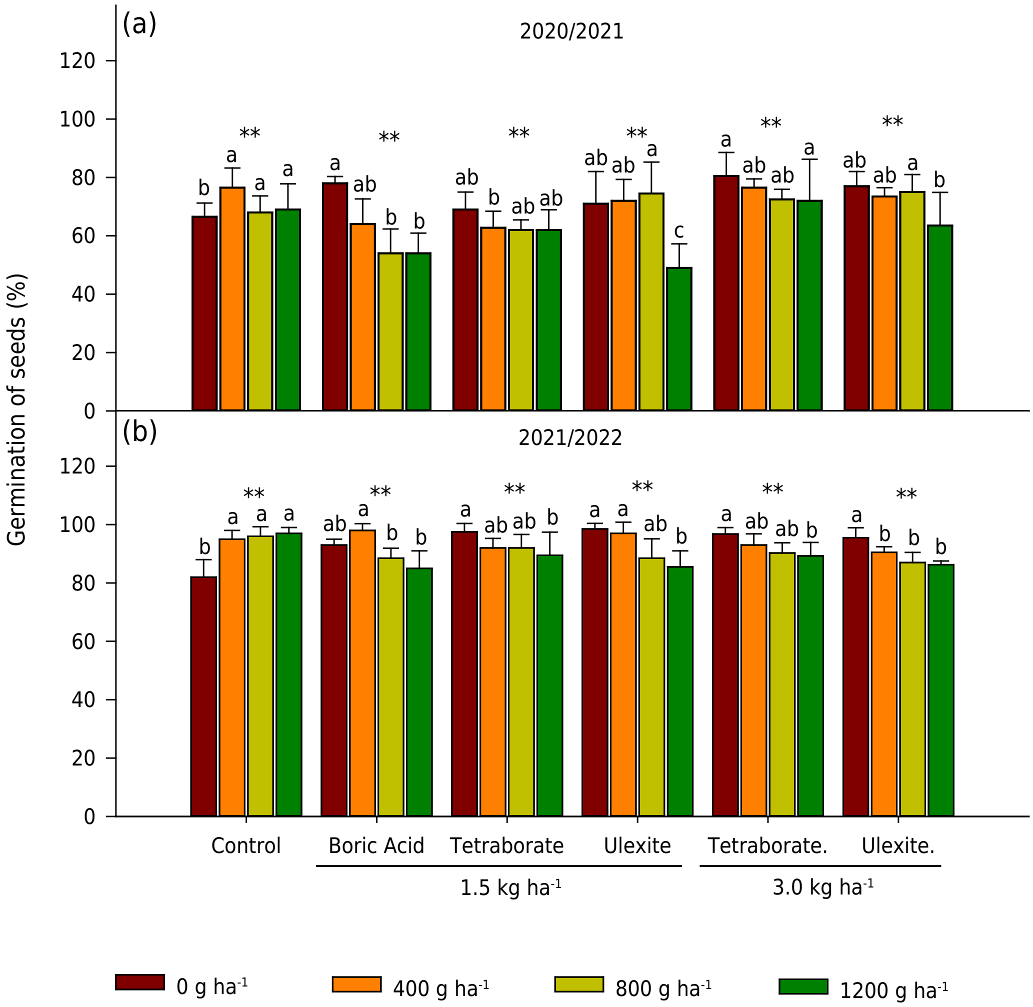

Figure 4. Peanut seed germination as a function of boron fertilizer management via soil and foliar during 2020/2021 and 2021/2022 seasons. Letters compare the treatments with boron application via soil. Asterisks show the effect of foliar application within each soil treatment.

2022), and also improves carbohydrate transport from leaves to reproductive structures (Bogiani et al., 2013; Wimmer and Eichert, 2013; Li et al., 2017), increasing seed weight.

Although the highest yield gains were with soil boron application, the foliar application also considerably improved peanut yield in sandy soils with low boron content. The higher efficiency of foliar fertilization in peanuts relative to other crops is related to the greater redistribution of boron in the phloem (Konsaeng et al., 2010). Moreover, our study applied foliar fertilization four times between the V5 and R2 stages with weekly applications. It is important to mention that between the V5 and R2 stages, the peanut had not yet closed the canopy, i.e., part of the boron applied to the leaf fell into the soil and was probably uptake via the root system.

Previous studies also reported that foliar application between 1.0 and 1.5 kg ha^{-1} applied between V1 and R5 in sandy soils with low initial boron content improves peanut yield, and rates higher than this may cause yield reduction due to toxicity (Mantovani et al., 2013; Foloni et al., 2016). However, for peanuts, the positive response to foliar fertilization seems to occur only in soils with low boron content because, in soils with adequate levels, there was no effect of foliar fertilization with B (Pierre et al., 2019). Our results indicate that the application of rates higher than 800 g ha^{-1} via foliar reduces yield due to high leaf boron contents (Figure 3), even in soils with low boron content (between 0.07 and 0.20 mg dm^{-3}), that is, it is not recommended to apply more than 200 g ha^{-1} of boron per

Table 3. Mean germination time, percentage of normal seedlings (>3cm), dry matter mass, and length of peanut seedlings as a function of soil and foliar borate fertilizer management crops 2020/2021 and 2021/2022

Soil fertilization	Average time of germination (h)				Seedlings >3 cm (%)			
	Foliar fertilization (g ha^{-1})							
	0	400	800	1200	0	400	800	1200
2020/2021								
Control	48.5 Aa	48.8 Ac	47.4 Aab	47.4 Abc	26.2 Ce	33.0 Bb	42.0 Aa	35.0 Aba
Boric acid 1.5 kg ha^{-1} of B	48.8 Aa	47.8 Ac	46.2 Ab	44.2 Bc	55.5 Aa	28.0 Bb	26.5 Bb	19.5 Cc
Tetraborate 1.5 kg ha^{-1} of B	51.0 Ba	63.0 Aa	51.6 Ba	55.2 Ba	38.5 Ac	26.5 Bb	27.0 Bb	29.5 Bb
Ulexite 1.5 kg ha^{-1} of B	47.0 Ba	50.7 Abc	49.5 Aab	51.4 Aab	35.0 Ad	29.5 Bb	26.0 Bb	19.0 Cc
Tetraborate 3.0 kg ha^{-1} of B	46.9 Aa	49.4 Ac	48.3 Aab	47.7 Abc	49.5 Aab	29.0 Bb	29.0 Bb	23.0 Bbc
Ulexite 3.0 kg ha^{-1} of B	49.8 Ba	54.0 Ab	51.4 Aa	53.5 Aa	45.0 Abc	47.0 Aa	29.0 Ab	21.5 Bv
CV%	6.3				17.96			
	Seedling dry weight (mg $seedling^{-1}$)				Seedling length (cm)			
Control	43.8 Bb	56.3 Aa	55.2 Aa	52.5 Aa	4.8 Bc	5.8 Aab	5.3 ABb	4.6 Bb
Boric acid 1.5 kg ha^{-1} of B	50.2 Aab	47.4 Abc	48.5 Abc	47.9 Aab	5.5 Ab	5.5 Aab	5.4 Ab	4.9 Bb
Tetraborate 1.5 kg ha^{-1} of B	46.1 Ab	37.8 Bd	38.2 ABd	39.7 ABc	5.4 Abc	5.2 Ab	5.0 Ab	5.0 Ab
Ulexite 1.5 kg ha^{-1} of B	56.9 Aa	43.9 Bcd	42.6 Bcd	26.0 Cd	6.3 Aa	5.4 Bab	5.3 Bb	4.9 Bb
Tetraborate 3.0 kg ha^{-1} of B	50.3 Aab	43.2 Acd	43.5 Abc	42.6 Abc	6.1 Aab	5.4 Bab	5.5 Bb	4.9 Bb
Ulexite 3.0 kg ha^{-1} of B	50.1 Aab	52.6 Aab	51.5 Aab	44.4 Bbc	5.9 Aab	5.9 Aa	6.5 Aa	6.1 Aa
CV%	12.1				9.4			
2021/2022								
	Average time of germination (h)				Seedlings >3cm (%)			
Control	61.9 Aa	55.4 Ba	55.5 Ba	54.6 Bab	78.0 Bb	88.0 Aa	89.0 Aa	90.0 Aa
Boric acid 1.5 kg ha^{-1} of B	60.3 Ab	55.9 Aba	54.8 Aba	52.9 Bb	84.5 Ab	82.0 Aa	83.0 Aab	79.5 Ab
Tetraborate 1.5 kg ha^{-1} of B	55.6 Ac	55.1 Aa	53.3 Aa	56.9 Aab	90.0 Aa	84.0 Ba	83.5 Bab	83.0 Bab
Ulexite 1.5 kg ha^{-1} of B	53.6 Bc	56.0 Aa	58.6 Aa	56.8 Aab	85.0 Aab	81.0 Aa	75.0 Cb	80.0 Bb
Tetraborate 3.0 kg ha^{-1} of B	52.1 Bc	57.7 Aa	56.4 Aa	57.7 Aab	92.0 Aa	87.0 Aa	83.0 Aab	88.0 Aab
Ulexite 3.0 kg ha^{-1} of B	54.0 Bc	60.4 Aa	57.4 Aba	59.6 Aba	88.0 Aa	88.0 Aa	84.0 Aab	83.0 Aab
CV%	7.1				8.2			
	Seedling dry weight (mg $seedling^{-1}$)				Seedling length (cm)			
Control	76.7 Bb	82.3 Aab	82.3 Aab	80.0 Aab	6.2 Bb	7.9 Aa	7.3 Aab	7.7 Aa
Boric acid 1.5 kg ha^{-1} of B	72.7 Bc	85.7 Aab	77.8 ABb	73.6 Bb	6.0 Bb	7.1 Aab	6.9 Aab	6.8 Aab
Tetraborate 1.5 kg ha^{-1} of B	82.9 Bbc	90.9 Aa	85.7 Aab	82.6 Bab	7.9 Aa	7.4 Aab	7.1 Aab	7.0 Aab
Ulexite 1.5 kg ha^{-1} of B	90.8 Aa	89.8 Aab	91.7 Aa	87.8 Aba	8.2 Aa	7.6 ABab	7.7 Aa	6.9 Bab
Tetraborate 3.0 kg ha^{-1} of B	87.7 Aab	83.8 Aab	84.4 Aab	77.8 Bab	7.3 Aa	7.9 Aa	7.6 Aa	7.1 Aab
Ulexite 3.0 kg ha^{-1} of B	82.9 Abc	76.4 Ab	75.4 Ab	75.6 Aab	7.6 Aa	6.7 ABb	6.5 Bb	6.3 Bb
CV%	9.7				10.4			

Equal letters, lowercase in the column and uppercase in the rows, indicate equal means by the t-Test (LSD) at 5 % of probability (p<0.05).

application, via boric acid. However, new studies should be performed with foliar boron sources with greater efficiency, such as sorbitol and manitol, since the boron complex with sorbitol resulted in a slight increase in boron transport in cotton (Rosolem et al., 2020), but this is not yet known for peanuts.

Foliar fertilization should be adjusted according to the crops' initial soil boron content and yield potential because the greater the yield potential, the greater the demand for boron, as occurred in the first crop (2020/2021). An important fact was that in a dry year (2021/2022), peanuts were responsive to higher boron rates via soil and supplemental foliar fertilization (soil+foliar). This is because, with low water availability, the mineralization of organic matter is lower, thus, the availability and uptake of boron via the root system are lower since boron is taken up via mass flow (Kohli et al., 2023). Thus, when there is a risk of water deficit, supplemental foliar fertilization is a good strategy to improve the yield of peanuts when lower rates of B are used in the soil.

A possible explanation for the better response of soil-applied boron to peanuts is related to root growth. This is because improved boron nutrition improves root growth (Kohli et al., 2023) and reduces aluminum (Al) toxicity (Riaz et al., 2018). Reducing Al toxicity is particularly important for peanut in Brazil, which is usually grown on acidic soils, degraded pasture reform, or sugarcane reform, and the interval between lime application and peanut sowing is usually short due to lease contracts. Vigorous root growth allows the plant to tolerate drought, and this may explain the higher peanut yield with soil boron application, with rates between 1.5 and 3.0 kg ha^{-1} of boron. In this scenario, our study offers two options to peanut growers for soil boron application: (i) to perform boron application along with pre-emergent herbicide (plant-applied) via boric acid (1.5 kg ha^{-1} of B); or (ii) to apply boron broadcasting before peanut sowing via ulexite or sodium tetraborate (3.0 kg ha^{-1} of B). The effect of foliar fertilization on root growth is small because, normally, the first foliar application occurs late in the vegetative stage of the peanut, and the maximum root growth rate occurs by the onset of pod formation (Rachaputi et al., 2021).

Singh et al. (2017) also reported a greater increase in yield by applying 2 kg ha^{-1} of B via soil, regardless of the source used. This option was better compared to foliar fertilization. Thus, soil fertilization seems to be the best option for peanut crop. With respect to the source, the yield and germination rate of the seeds were not affected by the sources of boron, but the use of sodium tetraborate was more efficient in increasing the boron content of peanut leaves. This is because this source is 100 % water soluble but with a gradual release of B, which reduces boron losses by leaching and improves the uptake of B by crops throughout the cycle, as reported previously by Silva et al. (2018).

One of the main challenges of micronutrient nutrition, including B, is to adjust the sufficiency range of the crops because there is a small variation between B deficiency and toxicity, so care is needed in the formulation of fertilizers and optimum influx of B to avoid toxicity (Kohli et al., 2023). There are still few studies for runner-peanut to define the adequate range of B in the leaf. In the past, it was determined in Brazil that for peanut cultivars of the Valencia and Spanish group (upright bearing), the leaf boron sufficiency range was between 20 and 50 mg kg^{-1} (Nakagawa and Rosolem, 2011), with higher levels causing toxicity. However, our data show that in the treatments with higher pod yields, the leaf boron content was between 40 and 75 mg kg^{-1}, and the control treatment (low pod yield) showed a boron content of 35 - 40 mg kg^{-1} (Figure 3). Mantovani et al. (2013) also reported a higher yield of *runner*-type peanut with leaf boron content between 40 and 45 mg kg^{-1}, but yielded only 4800 kg ha^{-1} of pods. This suggests that the sufficiency range should be between 40 and 75 mg kg^{-1} for modern cultivars of runner-type peanuts with high yield potential.

Improved boron nutrition is an important strategy to improve the physiological quality of peanut seeds. This is important since it is challenging to have a high germination rate of peanut seeds due to uneven maturation (Okada et al., 2021). However, it can be improved through plant mineral nutrition. Boron deficiency affects the cotyledons' interior and causes the plumules' tips to become small and pointed (Harris and Brolmann, 1966). This leads to the occurrence of hollow hearts in peanut seeds (Rerkasem et al., 1993), resulting in a low germination rate, a high percentage of abnormal seeds (<3 cm), and shorter primary root length (Figure 4 and Table 3).

A relevant point observed was that there was a positive correlation between seed weight and seed germination rate in both crops. Thus, better nutrition with boron improved the transport of carbohydrates to seeds (Wimmer and Eichert, 2013; Li et al., 2017), resulting in higher seed weight due to higher reserves and, consequently, higher germination.

Another important point that improved boron nutrition increased peanut primary root length, which is an important strategy for drought tolerance in the early stages of the crop. To our knowledge, this is the first study to report the main positive effects of improved boron nutrition on the physiological quality of peanut seeds, and it can help peanut seed producers.

CONCLUSION

Borate fertilization improved peanut seed nutrition, yield, and seed quality. The highest gains in yield and quality occurred with soil boron fertilization (1.5 and 3 kg ha^{-1}), being dependent on the source of boron used. The response to boron rate was not dependent only on the initial soil boron content but was related to each season water availability. Combining soil and foliar fertilization is justified only in dry years and if low boron rates are applied via soil. Slow-release sources applied via soil were more efficient in increasing the leaf boron content of peanuts. The results suggest a new critical level of boron on leaves for modern *runner-type* cultivars (40 and 75 mg kg^{-1}).

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DATA AVAILABILITY

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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REFERENCES

Bassanezi ILA, Rodrigues DR, Cordeiro CFS, Echer FR. Produtividade de cultivares de amendoim no Oeste Paulista – safra 2020/2021. South Am Sci. 2021;2(edesp1):e21120. https://doi.org/10.52755/sas.v.2i(edesp1)120

Bogiani JC, Amaro ACE, Rosolem CA. Carbohydrate production and transport in cotton cultivars grown under boron deficiency. Sci Agric. 2013;70:442-8. https://doi.org/10.1590/S0103-90162013000600010

Boote KJ. Growth stages of peanut (Arachis hypogaea L.). Peanut Sci. 1982;9:35-40. https://doi.org/10.3146/i0095-3679-9-1-11

Chapman HD, Pratt PF. Methods of analysis for soils, plants and waters. Soil Sci Soc Am J. 1962;93:68. https://doi.org/10.2136/sssaj1963.03615995002700010004x

Cordeiro LFS, Cordeiro CFS, Ferrari S. Cotton yield and boron dynamics affected by cover crops and boron fertilization in a tropical sandy soil. Field Crops Res. 2022;284:108575. https://doi.org/10.1016/j.fcr.2022.108575

Crusciol CAC, Portugal JR, Bossolani JW, Moretti LG, Fernandez AM, Garcia JLN, Garcia GLB, Pilon C, Cantarella H. Dynamics of macronutrient uptake and removal by modern peanut cultivars. Plants. 2021;10:2167. https://doi.org/10.3390/plants10102167

Dhassi K, Drissi S, Makroum K, Er-Rezza H, Amlal F, Housa AA. Soil boron migration as influenced by leaching rate and soil characteristics: A column study. Commun Soil Sci Plant Anal. 2019;50:1663-70. https://doi.org/10.1080/00103624.2019.1631333

Foloni JSS, Barbosa ADM, Catuchi TA, Calonego JC, Tiritan CS, Dominato JC, Creste JE. Efeitos da gessagem e da adubação boratada sobre os componentes de produção da cultura do amendoim. Sci Agrar Parana. 2016;15:202-8. https://doi.org/10.18188/1983-1471/sap.v15n2p202-208

Harris HC, Brolmann JB. Comparison of calcium and boron deficiencies of the peanut II. Seed quality in relation to histology and viability. Agron J. 1966;58:578-82. https://doi.org/10.2134/agronj1966.00021962005800060008x

Joosen RV, Kodde J, Willems LA, Ligterink W, van der Plas LHW, Hilhorst HWM. GERMINATOR: A software package for high-throughput scoring and curve fitting of Arabidopsis seed germination. Plant J. 2010;62:148-59. https://doi.org/10.1111/j.1365-313X.2009.04116.x

Kohli SK, Kaur H, Khanna K, Handa N, Bhardwaj R, Rinklebe J, Ahmad P. Boron in plants: Uptake, deficiency and biological potential. Plant Growth Regul. 2023;100:267-82. https://doi.org/10.1007/s10725-022-00844-7

Konsaeng S, Dell B, Rerkasem B. Boron mobility in peanut (Arachis hypogaea L.). Plant Soil. 2010;330:281-9. https://doi.org/10.1007/s11104-009-0199-3

Kumar D, Patel KC, Shukla AK, Behera SK, Ramani VP, Suthar B, Patel RA. Long-term impact of boron addition at various dosages to a groundnut-cabbage system on crop yield and boron dynamics in typic haplustepts. Agriculture. 2023;13:248. https://doi.org/10.3390/agriculture13020248

Li M, Zhao Z, Zhang Z. Effect of boron deficiency on anatomical structure and chemical composition of petioles and photosynthesis of leaves in cotton (Gossypium hirsutum L.). Sci. Rep. 2017;7:4420. https://doi.org/10.1038/s41598-017-04655-z

Mantovani JPM, Calonego JC, Foloni JSS. Adubação foliar de boro em diferentes estádios fenológicos da cultura do amendoim. Rev Ceres. 2013;60:270-8. https://doi.org/10.1590/S0034-737X2013000200017

Mousavi SM, Nejad SAG, Nourgholipour F, Zoshkey SA. Agronomic aspects of boron: Fertilizers, agronomical strategy, and interaction with other nutrients. In: Aftab T, Papadakis IE, Brown PH, Landi M, Araniti F, editors. Boron in plants and agriculture. Cambridge: Academic Press; 2022. p. 249-70. https://doi.org/10.1016/B978-0-323-90857-3.00011-4

Nakagawa J, Rosolem CA. O amendoim: Tecnologia de produção. Botucatu: Fepaf; 2011.

Okada MH, Oliveira GRFD, Sartori MMP, Crusciol CAC, Nakagawa J, Silva EAA. Acquisition of the physiological quality of peanut (Arachis hypogaea L.) seeds during maturation under the influence of the maternal environment. PLoS ONE. 2021;16:e0250293. https://doi.org/10.1371/journal.pone.0250293

Pierre AK, Mulvaney MJ, Rowland DL, Tillman B, Grey TL, Iboyi JE, Leon RG, Perondi D, Wood CW. Foliar fertilization as a strategy to increase the proportion of mature pods in peanut (Arachis hypogaea L.). Peanut Sci. 2019;46:140-7. https://doi.org/10.3146/PS17-20.1

Rachaputi R, Chauhan YS, Wright GC. Peanut. In: Sadras VO, Calderini DF. Crop physiology: Case histories for major crops. Cambridge: Academic Press; 2021. p. 360-82. https://doi.org/10.1016/B978-0-12-819194-1.00011-6

Rerkasem B, Bell RW, Lodkaew S, Loneragan JF (1993). Boron deficiency in soybean [Glycine max (L.) Merr.] peanut (Arachis hypogaea L.) and black gram [Vigna mungo (L.) Hepper]: Symptoms in seeds and differences among soybean cultivars in susceptibility to boron deficiency. Plant Soil. 1993;150:289-94. https://doi.org/10.1007/BF00013026

Riaz M, Yan L, Wu X, Hussain S, Aziz O, Jiang C. Mechanisms of organic acids and boron induced tolerance of aluminum toxicity: A review. Ecotoxicol Environ Saf. 2018;165:25-35. https://doi.org/10.1016/j.ecoenv.2018.08.087

Rosolem CA, Almeida DS, Cruz CV. Polyol-ester impact on boron foliar absorption and remobilization in cotton and coffee trees. Rev Bras Cienc Solo. 2020;44:e0200023. https://doi.org/10.36783/18069657rbcs20200023

Schmidt MP, Siciliano SD, Peak D. The role of monodentate tetrahedral borate complexes in boric acid binding to a soil organic matter analogue. Chemosphere. 2021;276:130150. https://doi.org/10.1016/j.chemosphere.2021.130150

Silva RC, Baird R, Degryse F, McLaughlin MJ. Slow and fast-release boron sources in potash fertilizers: Spatial variability, nutrient dissolution and plant uptake. Soil Sci Soc Am J. 2018;82:1437-48. https://doi.org/10.2136/sssaj2018.02.0065

Singh AL, Jat RS, Zala A, Bariya H, Kumar S, Ramakrishna YA, Rangaraju F, Masih M, Bhanusali TB, Vijaykumar S, Somasundaram E, Singh M. Scaling-up of boron sources for yield and quality of large-seeded peanut cultivars under varied agro-ecological conditions in India. J Plant Nutr. 2017;40:2756-67. https://doi.org/10.1080/01904167.2017.1382522

Wimmer MA, Eichert T. Mechanisms for boron deficiency-mediated changes in plant water relations. Plant Sci. 2013;203:5-32. https://doi.org/10.1016/j.plantsci.2012.12.012

Wang Q, Lu L, Wu X, Li Y, Lin J. Boron influences pollen germination and pollen tube growth in Picea meyeri. Tree Physiol. 2003;23:345-51. https://doi.org/10.1093/treephys/23.5.345