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ORIGINAL ARTICLE

# Boron nutrition increase soybean seed yield and maintain the quality of germination in storage seeds

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**Abstract**
Boron (B) nutrition can contribute to the conservation of seed quality during storage. Thus, it is crucial to investigate which source and amount of B applied to the soil is most suitable to increase the yield and maintain the quality of germination and carbohydrate content in soybean seeds during 180 days of storage. The cultivar Bonus 8579 Ipro® was evaluated in a field experiment in a 5×2 factorial scheme, with five B doses: 0, 1, 2, 4 and 8 kg $ha^{-1}$, and two sources: boric acid and ulexite, arranged in randomized block design with three replicates. After harvest, the B content and accumulation of B in yield and seed quality were analyzed. Subsequently, the seeds were stored in a cold chamber at 17 °C and controlled relative humidity of 20% for 180 days. Soybean plants responded positively to the boric acid and ulexite with an increase in yield and seed quality up to the doses of 3.17 and 3.36 kg $ha^{-1}$ of B, respectively. Furthermore, both sources potentiated the carbohydrate content in the seeds over the storage time. Our findings reveal that the application from 3.2 to 4.0 kg $ha^{-1}$ of B using boric acid maintains high seed germination after 180 days of storage.

**Keywords** Boric acid · Plant nutrition · Ulexite · Seed physiology · Seed stored

## Introduction

Soybean (*Glycine max* L. Merril) has an essential role in agribusiness. When the crop is destined for seed production, it is necessary to adopt management techniques that make it possible to combine higher yield and seed quality (Coradi et al. 2020). Among these techniques, plant nutrition is among the needs for producing high-quality seeds since the crop demands fertilization with macro and micronutrients.

Soybean plants are sensitive to micronutrient deficiency, especially to boron (B) deficiency in the reproductive stage (Ross et al. 2006), and this deficiency causes losses in soybean yield (Hamurcu et al. 2019; Pawlowski et al. 2019, Mousavi et al. 2020). Mostly, B deficiency occurs in tropical soils due to the low content of organic matter, the source of the element, and the high leaching rate, because it is a nutrient with high mobility in soils (Tanaka and Fujiwara 2008). In this sense, borate fertilization is a common practice in modern agriculture (Rodrigues et al. 2019). However, the difference between the adequate amount and the excess of B is slight, and it is possible to verify the toxic effect of this element on the soybean crop when in high concentrations of the micronutrient (Bardhan et al. 2017).

In cerrado soils, fertilization with boric acid ($H_3BO_3$) as a B source is a widely used practice (Rodrigues et al. 2019). However, other boron sources such as ulexite, a mixed sodium-calcium borate rock (Helvaci and Palmer 2017), after increasing solubility, have been efficient in providing the micronutrient as observed in soybean, corn (*Zea mays* L.), switchgrass (*Panicum virgatum*), and wheat (*Triticum* spp.) (Bardhan et al. 2017).

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B also plays an important role in pollen grain germination, pollen tube growth, and lignin formation, thus affecting seed quality, susceptibility to cracking, stiffness, water permeability, and resistance to deterioration (Bellaloui et al. 2017). Furthermore, B helps the seeds acquire chemical reserve compounds, such as protein, carbohydrates and lipids, hence conferring greater storage resistance and increasing vigor and germination (Hussain et al. 2019).

Therefore, in soybean seed production fields, boron nutrition, depending on the source and dose for the mother plant crop, could increase yields and still produce high-quality seeds. This information will allow a new approach for the best use of borate fertilization for quality soybean seed production globally, as there are many regions with boron deficiency in tropical soils. In this scenario, it is crucial to investigate the hypothesis that borate fertilization, contingent upon both its source and dosage applied to the soil, enhances soybean crop yields significantly while also preserving the essential carbohydrate levels crucial for seed quality. Carbohydrates play a pivotal role in both structural integrity and energy provision within seeds, ensuring high germination rates. Furthermore, even when subjected to adverse storage conditions, such as inclement weather, seeds fortified with sufficient carbohydrate levels maintain their quality.

This work aimed to evaluate the effect of sources and doses of B applied to the soil on nutrition and grain yield, as well as the effects of these sources and doses on maintaining carbohydrate contents and their influence on soybean seed germination rates after 180 days of storage.

## Material and methods

### Characterizing the experimental area

A field experiment was carried out in the experimental area of Santo Antônio farm, municipality of Paraiso das Águas—MS (19°0′57″ S and 52°27′57″ O and altitude of 644 m). According to the Köppen classification (Alvares et al. 2013), the region climate is humid tropical (AW), with a rainy season in summer and a dry season in winter, with mean rainfall of 1627 mm and mean annual temperature of 22.5 °C. Maximum and minimum temperature and mean rainfall throughout the experimental period were recorded (Fig. 1). There was a wide variation in mean maximum temperature (44.5 °C ± 6.6 °C) and mean minimum temperature (29.7 °C ± 4.1 °C). Average rainfall was 96.1 mm, with the lowest intensity on 12/30 (7.9 mm) and the highest on 03/15 (210.4 mm). Possible periods of heat stress were observed during the experimental period since soybean plants develop adequately up to 35 °C, while the development is impaired at temperatures above 45 °C (Khan et al. 2020).

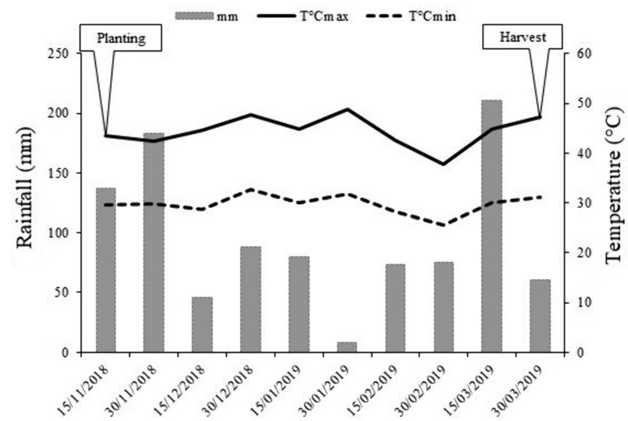


**Fig. 1** Rainfall (mm) and maximum and minimum air temperatures (ºC) in Paraiso das Águas—MS, Brazil, during the experimental period

Experimental research and field studies on plants (either cultivated or wild), including the collection of plant material, must comply with relevant institutional, national, and international guidelines and legislation. No proper permits and/or permits are required for the collection of plant or seed specimens.

The experimental area consisted of a direct succession soybean/pasture management. The soil was classified as Neossolo Quartzarênico sandy texture (Souza and Lobato 2004). The soil was chemically evaluated in the 0–20 cm layer, according to the methodology described by Raji et al. (2001) presenting the following results: pH ($CaCl_2$): 5.00; P: 9.80 mg dm$^{-3}$; K, Ca, Mg, H + Al, CEC (Cation Exchange Capacity): 0.14; 1.50; 0.40; 2.30 and 4.34 cmolc dm$^{-3}$, respectively; S, B, Cu, Fe, Mn, Zn: 3.90; 0.14; 0.60; 40.00; 24.10; 2.50 mg dm$^{-3}$, respectively. The soil B content (Longkumer et al. 2017) was classified as low according to Souza and Lobato (Souza and Lobato 2004). A granulometric evaluation of the soil was also performed according to the methodology proposed by Donagema et al. (2011) with 45% sand, 5% silt, and 50% clay.

### Experimental design and experimental plot

The treatments were arranged in a 5 × 2 factorial scheme, with five B doses: 0 (Control); 1; 2; 4 and 8 kg ha$^{-1}$: and two sources: boric acid (175 g kg$^{-1}$ of B, density of 1.43 g cm$^{-3}$ and water solubility (20 °C) of 47.2 gL$^{-1}$) and ulexite (100 g kg$^{-1}$ of B, density of 1.96 g cm$^{-3}$ and water solubility (20 °C) of 10.9 gL$^{-1}$), arranged in randomized block design with three repetitions. The experimental plot was composed of seven 6-m-long rows spaced at 0.45 m apart, with the three 4-m-long central rows constituting the useful area, totaling 15.4 m$^2$.

## Sowing and application of treatments

The experiment involved sowing soybean seeds directly over *Brachiaria ruziziensis* plant remains within a non-till system. The seeds were pre-treated with 0.5 g of Fipronil + 0.05 g of Pyraclostrobin + 0.45 g of Thiophanate-methyl per kg of seed. Sowing was performed on November 24 with the cultivar BONUS 8579 IPRO®, maturity group 7.9 (medium), with a recommended density of 13 plants per linear meter. After sowing, all treatments were mixed with gypsum and 500 kg $ha^{-1}$ was applied manually, evenly distributed on the soil surface. Then, with the occurrence of rainfall, there was the incorporation into the soil of gypsum and boron. The sowing furrow was fertilized with 150 kg $ha^{-1}$ of monoammonium phosphate (N: 11%; P2O5: 52%) and 140 kg $ha^{-1}$ of potassium chloride ($K_2O$: 60%), divided into two applications: the first after sowing and the second 20 days after emergence, both plowed into the soil.

## Phytosanitary control

Weed control was performed in pre-sowing with application of 1.2 kg $ha^{-1}$ of glyphosate, 1.2 kg $ha^{-1}$ of 2,4-dichlorophenoxy and 20 g $ha^{-1}$ carfentrazone ethyl; and in V4 stage (fourth fully developed trefoil) with application of 1.6 kg $ha^{-1}$ of glyphosate. Disease control management was performed in a preventive manner with four applications: at 50 days after sowing (DAS) with 58.45 g $ha^{-1}$ fluxapyroxad, 116.55 g $ha^{-1}$ pyraclostrobin; at 65 DAS with 60 g $ha^{-1}$ picoxystrobin and 24 g $ha^{-1}$ cyproconazole); at 80 DAS with 60 g $L^{-1}$ trifloxystrobin and 70 g $ha^{-1}$ prothioconazole; and at 95 DAS with 75 g $ha^{-1}$ trifloxystrobin and 32 g $ha^{-1}$ cyproconazole.

For pest management at the V6 stage (sixth fully developed trefoil), methomyl (215 g $ha^{-1}$) was applied; at the R2 stage (full flowering), acetamiprid (50 g $ha^{-1}$) + chlorpyrifos (480 g $ha^{-1}$) + teflubenzuron (22.5 g $ha^{-1}$) were applied; and at the R5 stage (beginning of grain filling), flubendiamide (33.6 g $ha^{-1}$) was applied.

## Harvest and yield assessment

The harvest was done at the R9 stage (full maturity), with a seed moisture content of 16 ± 2%. Grain yield was evaluated after the harvest and the screening of the useful area of each plot. Afterward, the seeds were dried naturally sun-dried. After drying, the seed moisture was checked with a portable Agrologic Al-101® meter. With the moisture corrected to 13%, the thousand-grain mass was determined. Calculations were made to estimate the grain yield after trailing and discounting impurities, with the result expressed in kg $ha^{-1}$.

## B content in soybean seeds

Following harvesting, conducted 135 days after sowing, the B content of the seeds was assessed using the method described by Silva (2009). The dried seeds were ground in a Willey mill, and then 0.200 g of plant material was weighed and digested by drying in a muffle furnace at 600 °C for four hours, with one hour for the muffle to reach temperature and three hours for carbonization of the material. The determination of the B content was done by colorimetry through colorimetric reaction with azomethine-H, being determined in a spectrophotometer. B accumulation in the seeds was calculated as the product between the B content in the seeds and the yield, and expressed as exported B.

## Total soluble carbohydrates and germination of soybean seeds after storage

After drying, the seeds were stored in a cold chamber at a temperature of 17 °C and humidity of 60% for 180 days, and biochemical and physiological evaluations were performed at 0 and 180 days of storage. The determination of the total soluble carbohydrate content in soybeans was performed by the method described by DuBois et al. (1956). For this, 50 mg of dry seed mass were weighed, previously ground, placed in 15 mL test tubes, homogenized with 5 mL of distilled water, and placed in a water bath for 30 min at 100 °C. After the water bath, the test tubes were centrifuged in a bench top centrifuge (1000 rpm) for 10 min. Subsequently, a 100 µL aliquot of the supernatant was removed (performing the dilution test) and transferred, along with 400 µL of distilled water, to other test tubes under vigorous agitation for homogenization by the vortex. Finally, 0.5 mL of 5% phenol and 2.5 mL of $H_2SO_4$ were added to the test tubes under constant stirring. After shaking, the tubes were left to stand for 20 min followed by spectrophotometric reading at a wavelength of 490 nm. A glucose standard curve was used to calculate the total soluble carbohydrate content and the results were expressed as g MS.

For the germination test, four repetitions of 50 seeds were used and distributed on two germitest® paper sheets moistened with water equivalent to 2.5 times the mass of the non-hydrated substrate and kept in a germinator at 25 °C. The evaluation of germination was performed eight days after the test installation and the results were expressed in percentage of normal seedlings. The first germination count was performed together with the germination test by computing the average percentage of normal seedlings obtained five days after the test (MAPA 2009).

### Statistical analyses

Data were submitted to analysis of variance using the F test. For the qualitative factor (B sources), the Tukey test was applied to compare means. For the quantitative factor (B doses), regression analysis was performed. In both cases, 5% probability was adopted. Afterward, a principal component analysis (PCA) was performed to verify the similarity between treatments, and a heatmap was constructed. All analyses were processed by the statistical program Sisvar (Ferreira 2014) and R (Team 2018).

## Results and discussion

For the first time, it was demonstrated that borate fertilization utilizing both boric acid and ulexite sources effectively supplied micronutrient to soybean plants, resulting in their content to up to 5.66 and 5.67 kg ha$^{-1}$ of B, respectively (Fig. 2a). The accumulation of B in the seeds (Fig. 2b) also exhibited an increase, displaying a quadratic response with a maximum point observed with the application of 4.68–4.74 kg ha$^{-1}$ of B from boric acid and ulexite, respectively. This phenomenon occurred because at these optimal B dose, which were very similar between the sources, there was a favorable enhancement in B availability in the soil during the crop's reproductive stage, coupled with sufficient water availability during this period (Fig. 1). This facilitated B uptake by the roots and subsequent translocation to the seeds, driven by the transpiration rate of the organ.

Recent research on the application of B in soil to enhance soybean plant productivity has predominantly focused on increasing grain yield, with limited attention to its effects on seed quality (Freitas et al. 2024, Libório et al. 2014). This raises concerns, particularly in regions dedicated to seed production, where the quality of the agricultural product is paramount. To advance research in this area, it is imperative to first ascertain whether the source or dosage of the micronutrient could influence B content in the seeds.

The uptake of B in plants depends on its availability in the soil, and B contact with the root occurs through mass flow, after which it is transported from the root to all organs, including the seeds. Therefore, an increase in B content in the seed depends solely on the micronutrient coming from the root via the xylem, with no redistribution from leaves to seed because B is immobile in the phloem (Prado 2021). Thus, enriching seeds with B depends on the transpiration rate of this organ and the nutrient availability in the soil, which varies with the dose of the micronutrient applied to the soil and the source used.

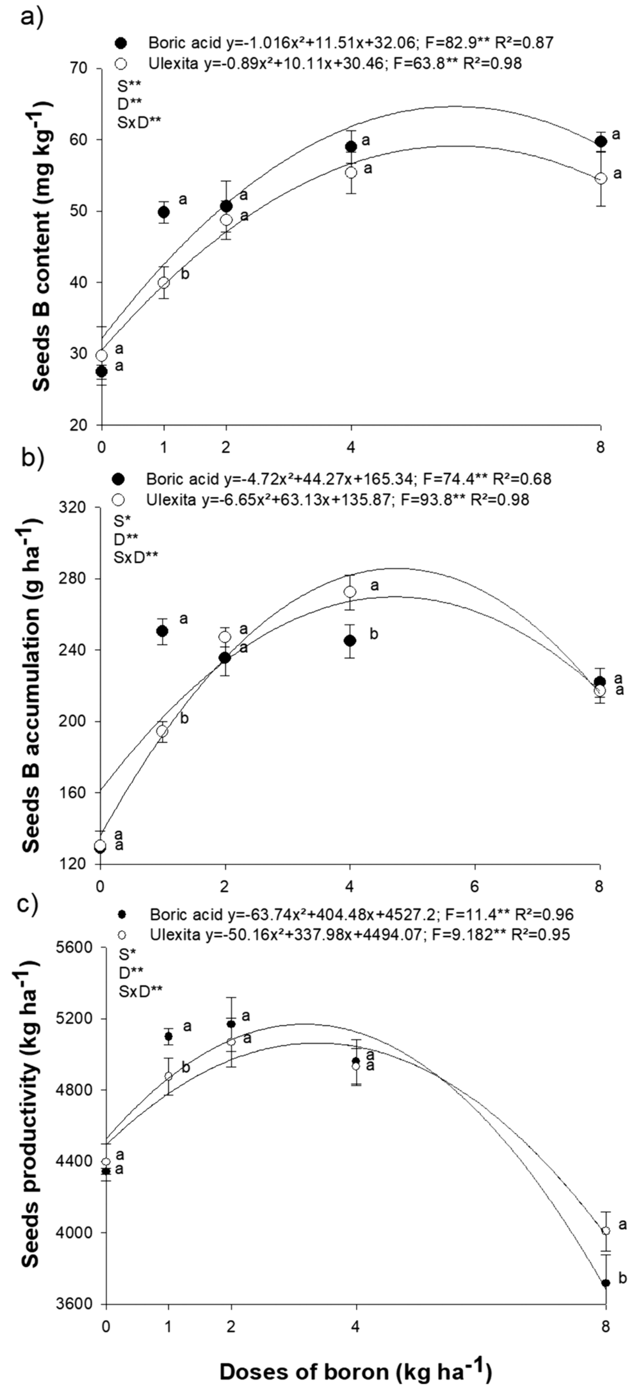


**Fig. 2** B content **a** and B accumulation **b** in soybean seeds grown under different sources and doses of B.**—significant at 1% probability by Tukey's test. Letters compare the two sources at the same dose

Plants primarily uptake B in the form of boric acid ($H_3BO_3$) through passive diffusion facilitated by transport channels or active transport via specific carriers present in the roots. Consequently, at lower concentrations (1 kg ha$^{-1}$), boric acid serves as a preferred source for enhancing B content and accumulation in plants (Fig. 2a, b) due to its immediate available. Refined boron sources with higher solubility have shown greater efficacy in increasing B content in various crops, including corn, panicum grass, soybean, and wheat, as observed by Bardhan et al. (2017). However, treatment with sulfuric acid enhances the solubility of ulexite, promoting the formation of boric acid (Küçük and Kocakerim 2005), thereby demonstrating comparable efficiency to boric acid in supplying micronutrient to soybean, particularly at concentrations exceeding 2 kg ha$^{-1}$ (Fig. 2a, b).

Boron plays crucial roles in various physiological and metabolic processes within plants, including nitrogen (N) and phosphorus (P) metabolism, sugar translocation, carbohydrate metabolism, and absorption of anions and cations (Al-Amery et al. 2011). Additionally, B is essential for pollen tube development (da Silva Berti et al. 2019) and pollen grain growth (Asad et al. 2001), maintenance of cell wall stability, meristem growth, and cell membrane permeability. Consequently, B deficiency significantly impairs plant growth (Lima et al. 2013).

The application of high B doses may lead to toxicity symptoms, resulting in reduced accumulation of the element in the shoot, as observed in soybean plants by Bardhan et al. (2017). Toxicity can also induce a decrease in B content and accumulation in soybean seeds (Fig. 2a, b), likely attributed to inhibited transport of the element to the seeds, leading to higher accumulation of the nutrient in the roots and leaves. This phenomenon represents a primary defense mechanism of plants against B toxicity (Küçük and Kocakerim 2005; Shah et al. 2017).

The increase in applied B concentration led to a quadratic increase in seed yield, with the maximum point observed at doses of 3.17 and 3.36 kg ha$^{-1}$ of B for boric acid and ulexite, respectively (Fig. 3). However, a decrease in seed yield was observed beyond the maximum point due to the toxic effect of B on soybean plants, indicating the crop's sensitivity to high B doses, as previously reported in the literature (Bardhan et al. 2017; Pawlowski et al. 2019). The higher efficiency of boric acid in supplying B to soybean plants (Fig. 2a, b) contributed to its better efficiency in increasing seed yield at low doses of the element (1 kg ha$^{-1}$). Additionally, the combination of 0.44 mg kg$^{-1}$ of B with sulfur (S) resulted positively in a yield of 7.3 g pot$^{-1}$ of soybean seeds (Kumar and Sidhu 2013; Oliveira et al. 2020). Conversely, at high concentrations, boric acid resulted in higher seed yield reduction than ulexite (Fig. 3), possibly due to the higher solubility of boric acid.

The plants treated with B in the form of boric acid achieved a maximum seed yield of 5168.885 kg ha$^{-1}$ with B content in the seeds of 58.33 g kg$^{-1}$. Soybean plants treated with B in the form of ulexite also reached maximum

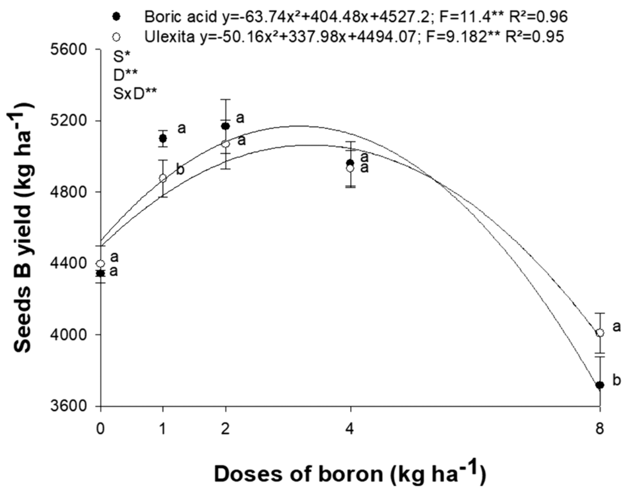


Fig. 3 Yield of soybean seeds grown under doses (D) and sources (S) of B. **—significant at 1% probability by Tukey test. Letters compare the two sources at the same dose

yield (5063.396 kg ha$^{-1}$) with B content in the seeds of 54.38 g kg$^{-1}$. These results, unprecedented for the soybean seed cultivar Bonus 8579 ipro® indicate the optimal concentration of the micronutrient in the seeds for both boric acid and ulexite. These values are closely align with the optimum leaf B content (54.82 g kg$^{-1}$ of B) in soybean plants reported by Gomes et al. (2017), obtained at the dose of 3.51 kg ha$^{-1}$ of B. Additionally, they surpass the B content reported by Rigo et al. (2018) in soybean seeds of various cultivar and in seeds of species such as *Camelina sativa* (2.0 kg ha$^{-1}$), as found in a study by Khan et al. (2016). Thus, it can be inferred that the cultivar Bonus 8579 Ipro® exhibits improved seed quality after adequate fertilization with B in the form of boric acid or ulexite, resulting in seeds with higher B content.

Boron has been extensively studied in various crops due to its ability to enhance two key components of grain crop productivity: increasing grain number and dry mass (Dell, Huang 1997; Prado 2021). However, its residual effects on soybean seeds after storage remain poorly understood.

Both sources maintain carbohydrate content (Fig. 4b) and increase soybean seed germination (Fig. 4d) after 180 days of storage with quadratic adjustment. The maximum point is observed at dose of 5.6 and 4.04 kg ha$^{-1}$ for boric acid, and at 3.64 and 3.30 kg ha$^{-1}$, for ulexite. Boron plays a crucial role in carbohydrate metabolism, stimulating specific metabolic pathways and enhancing carbohydrate transport, consequently increasing accumulation in storage organs such as seeds (Nejad and Etesami 2020).

No difference was observed between the sources and doses in the carbohydrate content of soybean seeds at 0 days of storage (Fig. 4a). However, the application of B in the form of ulexite showed a greater increase in carbohydrate

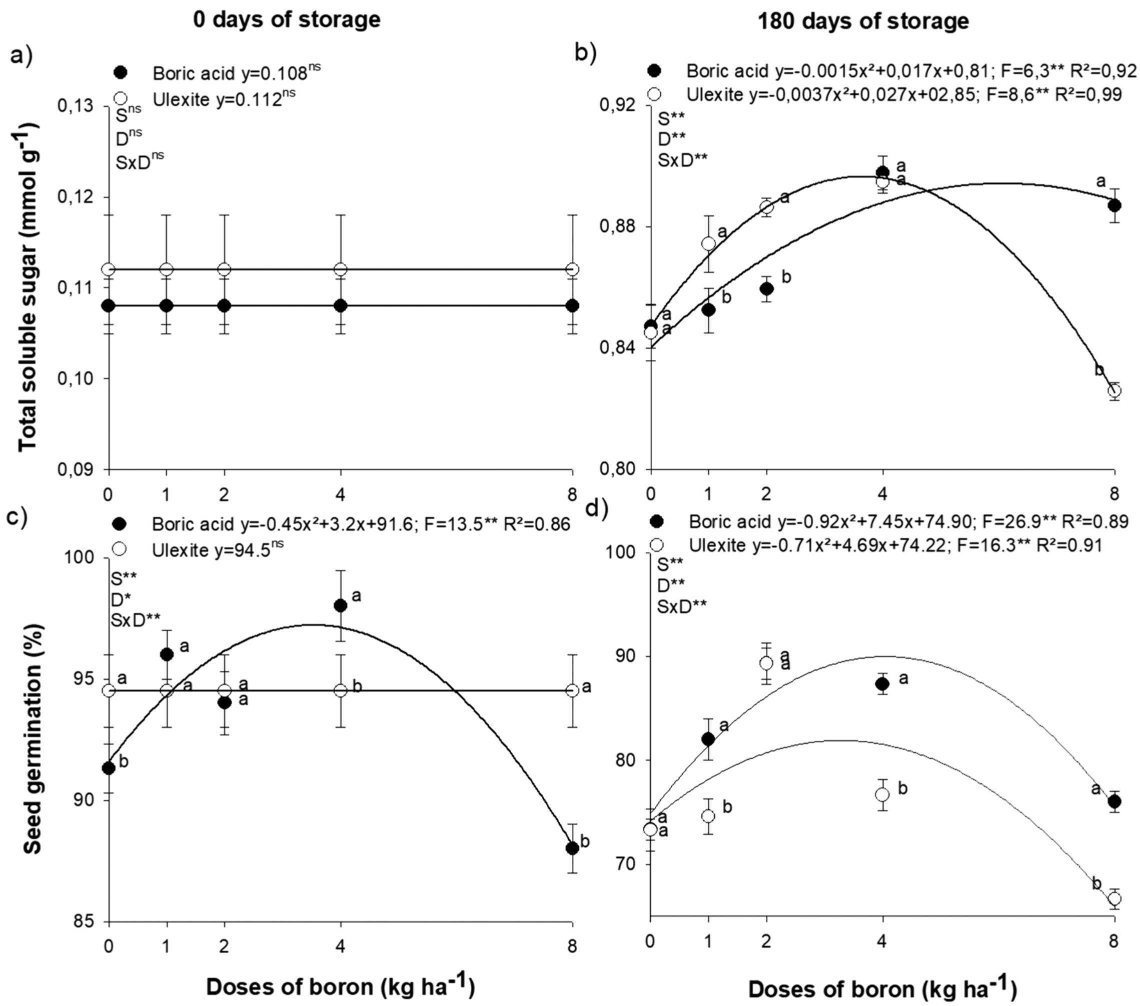


**Fig. 4** Total soluble sugar **a**, **b** and germination **c**, **d** in soybean seeds grown under different doses (D) and two sources (S) of B after 0 and 180 days of storage. **—significant at 1% probability by Tukey test. Letters compare the two sources at the same dose

content in seeds after 180 days of storage (Fig. 4b), compared to boric acid, particularly at concentrations of 1 and 2 kg ha$^{-1}$. There was no difference between sources for this variable at the concentration of 4 kg ha$^{-1}$. At the highest concentration studied (8 kg ha$^{-1}$), boric acid exhibited the highest soluble carbohydrate content in the seeds. Carbohydrates serve a signaling function, regulating the expression of various genes involved in the metabolic processes of plant growth, development, and defense (Zhao et al. 2015; Aguirre et al. 2018; Yang et al. 2019). Consequently, the stress condition induced by high B concentration during cultivation and seed production stages (Fig. 3) has been observed to maintain carbohydrate production and sustained soluble carbohydrate content in soybeans even after 180 days of storage (Fig. 4b).

At the onset of the storage period (0 days of storage), immediately following seed harvesting, no significant difference was observed in the germination of soybean seeds among the various dosage of B applied in the form of ulexite. This indicates that ulexite, even at higher concentration, does not impair soybean seed germination. Conversely, B applied in the form of boric acid increased germination up to the concentration of 3.5 kg ha$^{-1}$ (Fig. 4c). After 180 days of storage, an increase in the B application rate up to 4.0 and 3.3 kg ha$^{-1}$, in the form of boric acid and ulexite, respectively, resulted in enhanced seed germination.

While many studies on B in plants. Focus on its deficiencies to demonstrate its benefits in seed production, there is a notable lack of understanding regarding its effects under conditions of toxicity in the mother plant and its repercussions on newly harvested or long-term stored seeds. In vascular plants, boron toxicity has been shown to induce various physiological changes, including alterations in chlorophyll levels and photosynthetic rates in leaves, reduction in root cell division, metabolic disturbances, and decreased lignin and suberin levels (Reid 2007).

Krudnak et al. (2013) reported that boron levels exceeding 11.3 kg $ha^{-1}$ negatively impacted boron absorption, pollen viability, and sunflower seed formation. In soybeans, it is important to note that B toxicity was observed at the highest concentration studied (8 kg $ha^{-1}$), resulting in decreased grain yield (Fig. 3), carbohydrate content (Fig. 4a), and seed germination (Fig. 4b) after 180 days of storage. Boron toxicity leads to various losses in plant growth, primarily attributed to oxidative stress, as observed in pea (*Pisum sativum*) and oilseed rape (*Brassica napus*), and changes in B transport, stimulating the biosynthesis of chelating compounds such as polyols and phenols (Landi et al. 2019). Additionally, the storage period of seeds also contributes to increase the embryo deterioration due to elevate oxidative stress, as seen in cotton seeds (Foel et al. 2003). In this context, carbohydrates play a crucial role in attracting and neutralizing reactive oxygen species by balancing them with the HO-C-H group and stabilizing cell osmotic potential (Pommerrenig et al. 2018). Thus, adequate borate nutrition enhances carbohydrate production and maintenance, resulting in increased seed germination rates after 180 days of storage at appropriate concentrations (Fig. 4b). Conversely, the application of high amounts of B (8 kg $ha^{-1}$) impaired germination by reducing carbohydrate content and consequently diminishing the seed resistance to stress during the storage period.

To comprehend the interrelation and impact of the variable evaluated for different sources and doses of B, multivariate analysis was conducted (Fig. 5). PCA reveals the existence of two groups of treatments with similarities. Group 1 comprises the control (absence of boron application) and the treatments of boric acid at 8 kg $ha^{-1}$ and ulexite at 1 and 8 kg $ha^{-1}$. This group exhibited the lowest means for the evaluated variables (see the bottom of Fig. 5B). On the other hand, group 2 includes the treatments boric acid at doses of 1, 2 and 4 kg $ha^{-1}$ and ulexite at doses of 2 and 4 kg $ha^{-1}$. This group stood out by obtaining the highest averages for the variables evaluated.

These findings support the hypotheses that the boric acid and ulexite sources, particularly those contained in cluster 2 (Fig. 5), are effective in increasing the content and accumulation of B in soybean seeds. This promotes the maintenance of carbohydrates in the seeds and enhances the germination rate after 180 days of storage.

Future perspectives suggest that new research should explore the effects of boron management in the mother plant on the quality of stored seeds in other grain crops. This endeavor aims to enhance understanding of seed nutrition and quality, with global implications given the prevalence of seed-producing fields across various countries. The practical significance of this research is substantial, as high-quality seeds with elevated vigor are less prone to mortality and reduction in plant popular during cultivation, thereby mitigating loses in crop productivity.

## Conclusion

In conclusion, the study demonstrates the effectiveness of borate fertilization, using both boric acid and ulexite sources, in supplying micronutrients to soybean plants, resulting in significant B accumulation in seeds. This accumulation exhibits a quadratic response, suggesting an optimal dosage

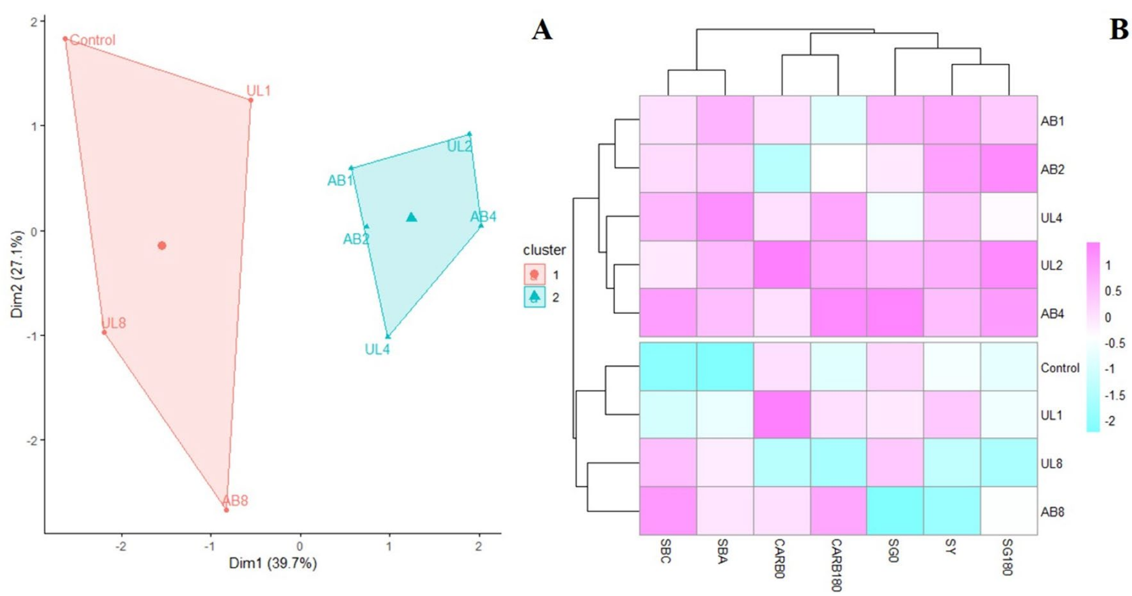


**Fig. 5** Principal component analysis (**A**) and heatmap (**B**) to verify the similarity between the boron sources (*AB* boric acid and *UL* ulexite) at the different doses applied

of 3.2 and 4.0 kg ha$^{-1}$, for boric acid and ulexite, respectively, for enhancing both seed yield and quality parameter. Future research should delve into the influence of boron management on seed quality in other grain crops, contributing to a deeper understanding of seed nutrition and quality, ultimately enhancing crop productivity and resilience to environmental stressors during cultivation. Additionally, exploring the residual effects of boron on stored seeds could further elucidate its role in maintaining seed quality over time, with potential global implications for agriculture.

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**Author contribution** Dágila Melo Rodrigues: formal analysis, investigation, field experiment conduction, statistical analysis, writing-original draft preparation, writing-review and editing. Cid Naudi Silva Campos: conceptualization, formal analysis, investigation, writing-original draft preparation, writing-review and editing. Jonas Pereira de Souza Junior, Charline Zaratin Alves, Paulo Carteri Coradi e Paulo Eduardo Teodoro: conceptualization, methodology, field experiment conduction, writing-original draft preparation, writing-review and editing. Larissa Pereira Ribeiro Teodoro: statistical analysis, writing-review and editing. Ana Carina da Silva Cândido, Jonas Pereira de Souza Junior, Carlos Henrique Oliveira de David e Renato de Mello Prado: methodology, investigation, field experiment conduction, statistical analysis, writing-review and editing.

**Data availability** All data relevant to the study are included in the article.

## Declarations

**Conflict of interests** The authors declare that they have no competing interests.

## References

Aguirre M, Kiegle E, Leo G, Ezquer I (2018) Carbohydrate reserves and seed development: an overview. Plant Reprod 31:263–290. https://doi.org/10.1007/s00497-018-0336-3

Al-Amery MM, Hamza JH, Fuller MP (2011) Effect of boron foliar application on reproductive growth of sunflower (Helianthus annuus L.). Int J Agron 2011(1):230712

Alvares CA, Stape JL, Sentelhas PC, Gonçalves JLM, Sparovek G (2013) Köppen's climate classification map for Brazil. Meteorol Zeitschrift 22:711–728. https://doi.org/10.1127/0941-2948/2013/0507

Asad A, Bell RW, Dell B (2001) A critical comparison of the external and internal boron requirements for contrasting species in boron-buffered solution culture. Plant Soil 233:31–45

Bardhan S, Chattopadhyay AK, Jose S, Chandrasoma J (2017) Impact of boron additions in marginal soils for grouth of corn, wheat, soybean, and switchgrass. Intern J Agric Sci Res 7:155–159. https://www.osti.gov/biblio/1769638-impact-boron-additions-marginal-soils-growth-corn-wheat-soybean-switchgrass

Bellaloui N, Smith JR, Mengistu A (2017) Seed nutrition and quality, seed coat boron and lignin are influenced by delayed harvest in exotically-derived soybean breeding lines under high heat. Front Plant Sci 8:1563. https://doi.org/10.3389/fpls.2017.01563

Coradi PC, Oliveira MB, Carneiro LO, Souza GAC, Elias MC, Brackmann A, Teodoro PE (2020) Technological and sustainable strategies for reducing losses and maintaining the quality of soybean grains in real production scale storage units. J Stored Prod Res. https://doi.org/10.1016/j.jspr.2020.101624

da Silva Berti MP, de Sá ME, Benett CGS, Rocha EC, Berti CLF (2019) Doses e épocas de aplicação de boro na qualidade de sementes de soja. Revista Cultura Agronômica 28(2):123

Dell B, Huang L (1997) Physiological response of plants to low boron. Plant Soil 193:103–120. https://doi.org/10.1023/A:1004264009230

Donagema GK, Campos DBVB, Calderano SB, Teixeira WG, Viana JH (2011) Manual of soil analysis methods, 2. Rio de Janeiro

DuBois M, Gilles KA, Hamilton JK, Rebers PA, Smith F (1956) Colorimetric method for determination of sugars and related substances. Anal Chem 28:350–356. https://doi.org/10.1021/ac60111a017

Ferreira DF (2014) Sisvar: a guide for its bootstrap procedures in multiple comparisons. Cien Agrotecnol 38:109–112. https://doi.org/10.1590/S1413-70542014000200001

Foel A, Goel AK, Sheoran IS (2003) Changes in oxidative stress enzymes during artigicial ageing in cotton (*Gossypium hirsutum* L.) seeds. J Plant Physiol 160(9):1093–1100. https://doi.org/10.1078/0176-1617-00881

Freitas IL, Teixeira GCM, Campos CNS, Teodoro LPR, Rodrigues DM, Alvarez RCF, Prado RM, Teodoro PE (2024) Impact of boron fertilisation on soybean grain yield as affected by associated physiological factors. NZ J Crop Hortic Sci. https://doi.org/10.1080/01140671.2024.2307872

Gomes IS, Benett CGS, Junior RLS, Xavier RC, Benett KSS, Silva AR, Coneglian A (2017) Boron fertilisation at different phenological stages of soybean. Australian J Crop Sci 11:1026–1032. https://doi.org/10.21475/ajcs.17.11.08.pne558

Hamurcu M, Arslan D, Hakki EE, Ozcan MM, Pandey A, Khan MK, Gezgin S (2019) Boron application affecting the yield and fatty acid composition of soybean genotypes. Plant Soil Environ 65(5):238–243. https://doi.org/10.17221/679/2018-PSE

Helvaci C, Palmer MR (2017) Origin and distribution of evaporite borates: the primary economic sources of Boron. Elem 13:249–254. https://doi.org/10.2138/gselements.13.4.249

Hussain S, Iqbal N, Rahman T (2019) Shade effect on carbohydrates dynamics and stem strength of soybean genotypes. Environ Exp Bot 162:374–382. https://doi.org/10.1016/j.envexpbot.2019.03.011

Khan S, Rehman H, Wahid MA, Saleem MF, Cheema MA, Basra SMA, Nadeem M (2016) Boron fetilization improves seed yield and harvest index of *Camelina sativa* L. by affecting source-sink. J Plant Nutr 39:1681–1687. https://doi.org/10.1080/01904167.2016.1161787

Khan MA, Asaf S, Khan AL, Jan R, Kang SM, Kim KM, Lee IJ (2020) Thermotolerance effect of plant growth-promoting Bacillus cereus SA1 on soybean during heat stress. BMC Microbiol 20:175. https://doi.org/10.1186/s12866-020-01822-7

Krudnak A, Wonprasaid S, Machikowa T (2013) Boron affects pollen viability and seed set in sunflowers. African J Agric Res 8(2):162–166. https://doi.org/10.5897/AJAR12.1471

Küçük Ö, Kocakerim MM (2005) Optimization of dissolution of ulexite in water saturated with sulphur dioxide. Chem Eng Proc Proc Intens 44:1005–1011. https://doi.org/10.1016/j.cep.2004.11.006

Kumar D, Sidhu SS (2013) Response of soybean to soil applied sulfur and boron in a calcareous soil. J Plant Nutr 36(11):1795–1807

Landi M, Margaritopoulou T, Papadakis IE, Araniti F (2019) Boron toxicity in higher plants: Na update. Planta 24:1–22. https://doi.org/10.1007/s00425-019-03220-4

Libório IF, Campos CNS, Santana DC, Oliveira IC, Oliveira JLG, Teodoro LPR, Baio FHR, Theodoro GF, Teodoro PE (2014) Boron Fertilization Improves the Agronomic Performance of Soybean Genotypes in the Brazilian Cerrado. Agriculture 14:27. https://doi.org/10.3390/agriculture14010027

Lima ML, Cardoso FR, Galante AHA, Teixeira GCDS, Teixeira IR, Alves SMDF (2013) Fontes e doses de boro na qualidade de sementes de feijão-comum e mamona sob consórcio. Revista Caatinga 26(4):31–38

Longkumer LT, Singh AK, Jamir Z, Kumar M (2017) Effect of sulfur and boron nutrition on yield and quality of soybean (*Glycine max* L.) grown in na acid soil. Commun Soil Sci Plant Anal 45(4):405–411

MAPA (2009) Ministério da Agricultura. Rules for seed analysis. (MAPA/ACS, Ed.), Brasília.

Mousavi SM, Motesharezadeh B (2020) Boron deficiency in fruit crops. In Fruit Crops, pp. 191–209. https://doi.org/10.1016/B978-0-12-818732-6.00015-0

Nejad SAG, Etesami H (2020) The importance of boron in plant nutrition. In: Metalloids in plants, Eds. Deshmukh R, Tripathi DK, Guerriero G, pp. 433–449. https://www.cropnutrition.com/resource-library/importance-of-boron-in-plant-growth

Oliveira KR, Souza Junior JP, Bennett SJ, Checchio MV, Alves RC, Felisberto G, Prado RM, Gratão PL (2020) Exogenous silicon and salicylic acid applications improve tolerance to boron toxicity in field pea cultivars by intensifying antioxidant defence systems. Ecotoxicol Environ Saf. https://doi.org/10.1016/j.ecoenv.2020.110778

Pawlowski ML, Helfenstein J, Frossard E, Hartman GL (2019) Boron and zinc deficiencies and toxicities and their interactions with other nutrients in soybean roots, leaves, and seeds. J Plant Nutr 42:634–649. https://doi.org/10.1080/01904167.2019.1567782

Pommerrenig B, Ludewig F, Cvetkovic J, Trentmann O, Klemens PAW, Neuhaus HE (2018) In concert: orchestrated changes in carbohydrate homeostasis are critical for plant abiotic stress tolerance. Plant DNA Cell Physiol 59:1290–1299. https://doi.org/10.1093/pcp/pcy037

Prado RM (2021) Mineral nutrition of tropical plants. Switzerland: Springer Nature Switzerland AG

R Core Team (2018). A language and environment for statistical computing (R Foundation for Statistical Computing)

Raij BV, Andrade JC, Cantarella H, Quaggio JA (2001) Chemical analysis to assess the fertility of tropical soils. Agronomic Institute of Campinas

Reid R (2007) Update on boron toxicity and tolerance in plants. Adv Plant Animal Boron Nutr 1:83–90

Rigo GA, Schuch LOB, Vargas RL, Barros WS, Szareski VJ, Carvalho IR, Pedo T (2018) Micronutrient content and physiological quality of soybean seeds. J Agric Sci 10:223–230. https://doi.org/10.5539/jas.v10n4p223

Rodrigues LU, Nascimento VL, Peluzio JM, Santos ACM, Silva RR (2019) Morphophysiological and grain yield responses to foliar and soil application of boric acid on soybean. Commun Soil Sci Plant Analyt 50:1640–1651. https://doi.org/10.1080/00103624.2019.1631331

Ross JR, Slaton NA, Brye KR, DeLong RE (2006) Boron fertilization influences on soybean yield and leaf and seed boron concentrations. Agron J 98:198–205. https://doi.org/10.2134/agronj2005-0131

Shah A, Wu X, Ullah A, Fahad S, Muhammad R, Yan L, Jiang C (2017) Deficiency and toxicity of boron: Alterations in growth, oxidative damage and uptake by citrange orange plants. Ecotoxicol Environ Saf 145:575–582. https://doi.org/10.1016/j.ecoenv.2017.08.003

Silva FC (2009) Manual of chemical analyzes of soils, plants and fertilizers. Manual of chemical analyzes of soils, plants and fertilizers, 2 th. Embrapa Informação Tecnológica: Brasília, DF

Souza DMG, Lobato E (2004) Cerrado: correção do solo e adubação, 2 th. Embrapa Informações Tecnológicas: Brasília, DF, 416p. https://www.embrapa.br/busca-de-publicacoes/-/publicacao/555355/cerrado-correcao-do-solo-e-adubacao

Tanaka M, Fujiwara T (2008) Physiological roles and transport mechanisms of boron: perspectives from plants. Eur J Physiol 456:671–677. https://doi.org/10.1007/s00424-007-0370-8

Yang J, Zhang C, Wang Z, Sun S, Zhan R, Zhao Y, Ma B, Ma F, Li M (2019) Melatonin-mediated sugar accumulation and growth inhibition in apple plants involves down-regulation of fructokinase 2 expression and activity. Front Plant Sci. https://doi.org/10.3389/fpls.2019.00150

Zhao H, Su T, Huo L, Wei H, Jiang Y, Xu L, Ma F (2015) Unveiling the mechanism of melatonin impacts on maize seedling growth: sugar metabolism as a case. J Pineal Res 59:255–266. https://doi.org/10.1111/jpi.12258