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# Influence of Boron Application on the Early Growth and Nutritional Management of Peanut (Arachis Hypogaea L.)

**Alisson Rodolfo Leite**
Professor PhD, IFSP, Brazil
alisson.rodolfo@ifsp.edu.br
0000-0003-0838-4566

**João Paulo Machado Mantovani**
Professor PhD, UNESP, Brazil
joao.mantovani@unesp.br
0000-0003-3083-8237

**Leandro Calixto Tenório de Albuquerque**
Professor MSc, IFSP, Brazil
leandroalbuquerque@ifsp.edu.br
0009-0005-4654-5166

**Camila Pires Cremasco Gabriel**
Professor PhD, UNESP, Brazil
camila.cremasco@unesp.br
0000-0003-2465-1361

**Luís Roberto Almeida Gabriel Filho**
Professor PhD, UNESP, Brazil
gabriel.filho@unesp.br
0000-0002-7269-2806

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# Influência da Aplicação de Boro no Crescimento Inicial e no Manejo Nutricional do Amendoim (Arachis Hypogaea L.)

**RESUMO**

**Objetivo** - O presente estudo teve como objetivo avaliar os efeitos da aplicação de diferentes doses de ácido bórico no tratamento de sementes de amendoim (Arachis Hypogaea L.), com ênfase nos impactos sobre a germinação, o crescimento radicular e o desenvolvimento da parte aérea das plântulas.

**Metodologia** - A pesquisa foi conduzida com abordagem quantitativa, de natureza aplicada, por meio de experimento realizado no Laboratório de Botânica da UNESP – Campus Tupã/SP. Utilizou-se delineamento em blocos casualizados com seis tratamentos e quatro repetições. Os dados obtidos foram submetidos à análise de variância (ANOVA) e ao teste de comparação de médias de Tukey, considerando-se um nível de significância de 5%.

**Originalidade/relevância** - O estudo preenche um gap relevante da literatura agronômica ao investigar experimentalmente os limites entre a deficiência e a toxidez do boro na cultura do amendoim – tema ainda pouco explorado para essa espécie. A originalidade reside na avaliação integrada da germinação e do desenvolvimento vegetativo em resposta a doses crescentes de boro.

**Resultados** - Os resultados demonstraram que doses superiores a 60 mg de boro por quilo de semente comprometem a germinação. No entanto, essas doses também favoreceram o crescimento das raízes e da parte aérea nas plantas que emergiram. A dose de 60 mg/kg destacou-se como a mais eficiente, por equilibrar germinação viável e vigor das plântulas.

**Contribuições teóricas/metodológicas** - O estudo reforça a importância do manejo nutricional de precisão no tratamento de sementes, contribuindo teoricamente para a compreensão da resposta fisiológica do amendoim ao boro e metodologicamente para o aperfeiçoamento de práticas experimentais em sementes.

**Contribuições sociais e ambientais** - Os achados oferecem subsídios para o uso mais eficiente de micronutrientes, promovendo práticas agrícolas sustentáveis e tecnicamente fundamentadas, especialmente em regiões produtoras de amendoim como Tupã/SP. A adoção dessas práticas pode reduzir o desperdício de insumos, melhorar a produtividade e contribuir para a agricultura responsável.

**PALAVRAS-CHAVE:** Boro. Amendoim. Manejo.

# Influence of Boron Application on the Early Growth and Nutritional Management of Peanut (Arachis Hypogaea L.)

**Objective** - This study aimed to evaluate the effects of different doses of boric acid applied to peanut seeds (Arachis Hypogaea L.), with emphasis on their impact on seed germination, root growth, and shoot development of seedlings.

**Methodology** - The research was conducted using a quantitative and applied approach, through an experiment carried out at the Botany Laboratory of UNESP – Campus Tupã/SP. A randomized block design was adopted, with six treatments and four replications. The data were subjected to analysis of variance (ANOVA) and Tukey's multiple comparison test, with a 5% significance level.

**Originality/Relevance** - This study addresses a relevant gap in agronomic literature by experimentally investigating the threshold between boron deficiency and toxicity in peanut crops—an area still underexplored for this species. Its originality lies in the integrated assessment of seed germination and vegetative development in response to increasing doses of boron.

**Results** - The results showed that doses exceeding 60 mg of boron per kilogram of seed negatively affected germination. However, these same doses promoted increased root and shoot growth in the seedlings that emerged. The 60 mg/kg dose stood out as the most effective, offering a balance between viable germination and seedling vigor.

**Theoretical/Methodological Contributions** - The study reinforces the importance of precision nutritional management in seed treatment, contributing theoretically to the understanding of the physiological responses of peanut plants to boron and methodologically to the refinement of experimental practices in seed analysis.

**Social and Environmental Contributions** - The findings provide technical support for more efficient use of micronutrients, promoting sustainable and evidence-based agricultural practices, especially in peanut-producing regions such as Tupã/SP. The implementation of such practices can reduce input waste, enhance productivity, and support responsible agriculture.

**KEYWORDS:** Boron. Peanut. Management.

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# Influencia de la Aplicación de Boro en el Crecimiento Inicial y en el Manejo Nutricional del Maní (Arachis Hypogaea L.)

**Objetivo** - El presente estudio tuvo como objetivo evaluar los efectos de diferentes dosis de ácido bórico aplicadas al tratamiento de semillas de maní (Arachis Hypogaea L.), con énfasis en su impacto sobre la germinación, el crecimiento radicular y el desarrollo de la parte aérea de las plántulas.

**Metodología** - La investigación se desarrolló con un enfoque cuantitativo, de carácter aplicado, mediante un experimento realizado en el Laboratorio de Botánica de la UNESP – Campus Tupã/SP. Se utilizó un diseño experimental en bloques al azar con seis tratamientos y cuatro repeticiones. Los datos obtenidos fueron sometidos a análisis de varianza (ANOVA) y a la prueba de comparación de medias de Tukey, con un nivel de significancia del 5%.

**Originalidad/Relevancia** - Este estudio aborda una laguna relevante en la literatura agronómica al investigar experimentalmente el umbral entre la deficiencia y la toxicidad del boro en el cultivo del maní, una temática aún poco explorada en esta especie. La originalidad radica en la evaluación integrada de la germinación y el desarrollo vegetativo en respuesta a dosis crecientes de boro.

**Resultados** - Los resultados indicaron que dosis superiores a 60 mg de boro por kilogramo de semilla perjudicaron la germinación. No obstante, estas mismas dosis favorecieron el crecimiento de raíces y la parte aérea en las plántulas emergidas. La dosis de 60 mg/kg se destacó como la más eficiente, proporcionando un equilibrio entre germinación viable y vigor de plántulas.

**Contribuciones teóricas/metodológicas** - El estudio refuerza la importancia del manejo nutricional de precisión en el tratamiento de semillas, aportando teóricamente a la comprensión de las respuestas fisiológicas del maní al boro y metodológicamente al perfeccionamiento de prácticas experimentales en análisis de semillas.

**Contribuciones sociales y ambientales** - Los hallazgos ofrecen fundamentos técnicos para un uso más eficiente de micronutrientes, promoviendo prácticas agrícolas sustentables y basadas en evidencia, especialmente en regiones productoras de maní como Tupã/SP. La adopción de tales prácticas puede reducir el desperdicio de insumos, mejorar la productividad y contribuir a una agricultura responsable.

**PALABRAS CLAVE:** Boro. Maní. Manejo

## 1 INTRODUCTION

Peanut (Arachis hypogaea L.) stands out as an important leguminous crop cultivated worldwide, covering approximately 26 million hectares and reaching an annual production of around 45 million tons (Patel *et al.*, 2022).

Economically, peanut cultivation is highly relevant in Brazil, particularly in the state of São Paulo. In recent years, Brazil has consolidated its position among the world's leading peanut producers and exporters, accounting for approximately 7% of global peanut trade in 2019 and ranking as the fifth largest international supplier. National production is strongly concentrated in the state of São Paulo, which is responsible for approximately 90–97% of total production and virtually all peanut exports from the country (Neves *et al.*, 2023).

In 2020, for example, the state of São Paulo accounted for 97% of Brazilian peanut exports, generating revenues of approximately US$ 427.8 million. Within São Paulo, traditional peanut-growing regions stand out, among which the Tupã region, located in the western part of the state, plays a prominent role. The Tupã microregion alone contributed approximately 20.7% of the total value of peanut exports in 2020, leading the state ranking, followed by municipalities such as Borborema (13.5%) and Jaboticabal (12.7%) (Neves *et al.*, 2023).

This dynamic reflects investments in technology and expansion of peanut cultivation in the region. Over the past 15 years, innovations in crop management and breeding have increased productivity and product quality, boosting both domestic consumption and exports (Neves et al., 2023). Beyond generating foreign exchange earnings, the peanut production chain also plays an important socioeconomic role at the local level, creating employment in agriculture and processing industries and integrating with other economic sectors (Neves *et al.*, 2023).

Peanut kernels exhibit high oil content (approximately 35–55%) and protein levels (20–30%), in addition to dietary fiber, vitamins, and minerals, which confer high nutritional value. In addition to being widely used for edible oil extraction, peanut kernels are consumed in various forms, including roasted, boiled, and processed products such as peanut butter and confectionery. They are considered functional foods due to the presence of bioactive compounds beneficial to human health, such as phytosterols, polyphenols (including resveratrol and flavonoids), and other antioxidants that contribute to the prevention of cardiovascular diseases, type II diabetes, and cancer (Çiftçi; Suna, 2022).

From an agronomic perspective, peanuts offer advantages as a legume capable of fixing atmospheric nitrogen through symbiosis with rhizobia, thereby contributing to soil fertility and reducing the need for nitrogen fertilizers (Paudel *et al.*, 2023)

Consequently, their inclusion in crop rotation systems, such as during sugarcane field renovation, helps restore soil nutrients and promotes more sustainable production systems (Neves *et al.*, 2023). Regional studies highlight the expansion of peanut cultivation for industrial purposes and its territorial implications, indicating that rationalization of production systems requires practices capable of preserving soil quality and sustaining competitiveness (De Oliveira Cruz; Marques de Magalhães, 2013; Oliveira; Lourenzani, 2011). This dual aptitude, both nutritional and agronomic, makes peanut a crop of great interest for human consumption and agricultural systems alike. Thus, peanuts are consolidated not only as a market-oriented crop but also as a relevant component of diversification and rotation strategies, often associated with agronomic and operational benefits.

Morphologically, peanut (Arachis hypogaea L.) is an annual herbaceous plant with low stature and predominantly prostrate or semi-prostrate growth habit, characterized by compound tetrafoliolate leaves and small yellow flowers with a predominance of self-pollination. A unique morphophysiological characteristic of the species is geocarpy, a phenomenon in which, after pollination, the fertilized ovary gives rise to a specialized structure known as the gynophore (“peg”). This organ elongates toward the soil, guided by gravitropic and hormonal stimuli, penetrating the substrate so that fruit (pod) development occurs underground. This particular reproductive mechanism provides physical protection to the seeds but also makes peanut highly dependent on soil physicochemical conditions and adequate nutrient availability during both initial and reproductive stages, directly influencing yield and final product quality (Cui *et al.*, 2024).

The initial phases of the crop cycle, including seed germination and seedling emergence, are considered critical for crop establishment, as they determine stand uniformity and the initial capacity of the root system to explore the soil. This stage is followed by vegetative growth, characterized by leaf expansion and intensification of photosynthetic activity, culminating approximately 30 to 40 days after emergence in the onset of the reproductive phase, marked by continuous flowering. Fruiting occurs as gynophores develop and penetrate the soil, where pods grow and mature underground over a period of approximately 3 to 5 months, depending on the cultivar, environmental conditions, and, decisively, the availability of essential micronutrients for plant metabolism.

Among these micronutrients, boron (B) plays a central role in plant development, including in legumes such as peanut. From a physiological standpoint, boron is essential for the formation and stability of the cell wall, acting mainly in the cross-linking of pectic polysaccharides such as rhamnogalacturonan II, thereby conferring mechanical strength and structural integrity to plant cells. In addition, boron is involved in maintaining membrane integrity, carbohydrate, protein, and nucleic acid metabolism, as well as regulating sugar transport and growth-related hormonal signaling (Vera-Maldonado, Cristóbal *et al.*, 2024; Vera-Maldonado, Peter *et al.*, 2024).

Due to these structural and metabolic functions, boron deficiency preferentially manifests in tissues with rapid growth and high meristematic activity, such as root apices, young shoots, reproductive organs, and vascular systems. Limitation of this micronutrient compromises cell division and elongation, reduces the efficiency of photoassimilate transport, and negatively affects the differentiation of conductive tissues, potentially resulting in uneven growth and reduced plant vigor. In peanut specifically, boron deficiency is associated with deformities in cotyledon and pod development, leading to the formation of empty or malformed kernels, which significantly reduces seed physiological quality and crop productivity. This effect largely results from poor vascular system formation under boron deficiency, which limits the flow of assimilates from leaves to developing storage organs and increases plant sensitivity to water stress (Cordeiro *et al.*, 2024).

Conversely, excess boron also causes adverse effects, as this micronutrient has a narrow physiological range between sufficiency and toxicity. High doses may induce physiological disturbances such as reduced photosynthetic activity, membrane damage, accumulation of reactive compounds, and visible symptoms of phytotoxicity, including leaf burn. In seeds, excessive boron concentrations may impair germination and vigor by affecting essential early processes, such as membrane reorganization during imbibition and the mobilization of energy reserves. Thus, both boron deficiency and excess result in losses in peanut growth and productivity, reinforcing the need for careful management of this micronutrient.

Therefore, appropriate boron management is essential, since maintaining optimal levels of this micronutrient throughout the peanut crop cycle contributes to vigorous root development, proper formation of reproductive tissues (pods and seeds), and increased tolerance to stress, resulting in more productive plants and seeds with high physiological value (Camacho-Cristóbal; Rexach; González-Fontes, 2008; Cordeiro *et al.*, 2024)

In summary, although required in small amounts, boron is a determining factor for the success of peanut cultivation and must be carefully monitored and balanced to ensure full agronomic and qualitative performance of this legume. In this study, we evaluate the effects of different boron doses on peanut germination and early growth, aiming to establish parameters for the management of this micronutrient during the initial developmental stages.

## 2 MATERIALS AND METHODS

To conduct this study, a quantitative applied approach was adopted, characterizing the research as a field experiment based on the proposed objectives and procedures employed. The experiment was carried out at the Botany Laboratory of the School of Engineering and Biosystems Sciences, UNESP, Tupã campus, São Paulo State, Brazil, between February and April 2023, a period considered suitable due to favorable regional climatic conditions.

To evaluate the effects of boron on seed germination and early development of peanut plants, 24 trays filled with previously washed and sterilized sand were used to ensure uniformity and prevent biological contamination. Each tray received 80 seeds of the IAC 505 cultivar, which is widely cultivated in the Alta Paulista region due to its high productivity and adaptability to local climatic conditions. The seeds were distributed in the trays and divided into four replications of 20 seeds each, ensuring adequate statistical precision. Thus, the experiment consisted of six treatments with four replications per treatment, totaling 480 seeds.

The treatments comprised five different boron doses applied directly to the seeds, using boric acid as the boron source, containing 17% boron in its composition. The treatments were defined as follows: T1, control (no boron application); T2, 20 mg B/kg of seeds; T3, 40 mg B/kg of seeds; T4, 60 mg B/kg of seeds; T5, 80 mg B/kg of seeds; and T6, 100 mg B/kg of seeds.

A randomized block design was adopted, as it allows effective control of environmental variability and provides greater accuracy in comparative analyses. Prior to boric acid treatment, the seeds received preventive protection against fungi and insects using the fungicides Sementhiran and Maxim XL and the insecticide Cruiser, applied as a mixture at a rate of 600 mL per 100 kg of seeds, according to technical recommendations for peanut cultivation.

Accurate weighing of seeds and chemical products was performed using a Bel analytical digital balance (model M214AI), with a maximum capacity of 220 g and a resolution of 0.0001 g, ensuring precision and reproducibility of measurements. Seed treatment with boric acid was carried out proportionally using a digital micropipette (Olen, model K1-100C + K31-201Y), with a minimum volumetric capacity of 0.1 mL, ensuring rigor and uniformity in the applied doses.

After boric acid treatment, the seeds were carefully sown in the sand-filled trays and exposed to outdoor conditions under controlled management, receiving standardized irrigation every two days, with a fixed volume of 2 L of water per tray. This irrigation regime was designed to maintain adequate moisture for early plant development while avoiding water stress that could interfere with the experimental results.

Fifteen days after sowing, detailed evaluations were performed, including germination percentage, shoot height and fresh weight, as well as root length and fresh weight of the emerged plants. To ensure measurement accuracy, instruments such as a millimeter-graduated ruler, pruning shears for proper separation of plant parts, and a precision digital balance for mass determination were used.

The collected data were organized and subjected to statistical analysis using R software version 4.4.3 in conjunction with RStudio version 2024.12.1+563 (R Core Team, 2025; RStudio Team, 2020). Initially, an analysis of variance (ANOVA) was performed to assess the existence of significant differences among treatments. Subsequently, Tukey's multiple comparison test was applied at a 5% significance level ($\alpha$ = 0.05) to validate the tested hypotheses, ensuring robustness and reliability of the obtained results.

## 3 RESULTS AND DISCUSSION

This study adopted a quantitative approach, being characterized as descriptive in terms of its objectives and, with respect to procedures, combining bibliographic research with field experimentation. Statistical analysis of the collected data was performed using R and RStudio software, and a significance level ($\alpha$) of 5% was adopted for all tests conducted (R Core Team, 2025; RStudio Team, 2020).

According to the results obtained from the analysis of variance (ANOVA), treatments with increasing boron doses caused significant changes in peanut seed germination rates, as detailed in

Table 1. Subsequent analysis using Tukey's multiple comparison test revealed specific groupings among the treatments. As shown in Table 1, the control treatment (0 mg B/kg of seeds) and the treatment with 20 mg B/kg of seeds did not differ significantly from each other, forming the group with the highest mean germination values. An intermediate grouping included the treatments with 40 mg and 60 mg B/kg of seeds, whereas the treatments with 80 mg and 100 mg B/kg of seeds differed significantly, forming isolated groups and exhibiting the lowest mean germination values.

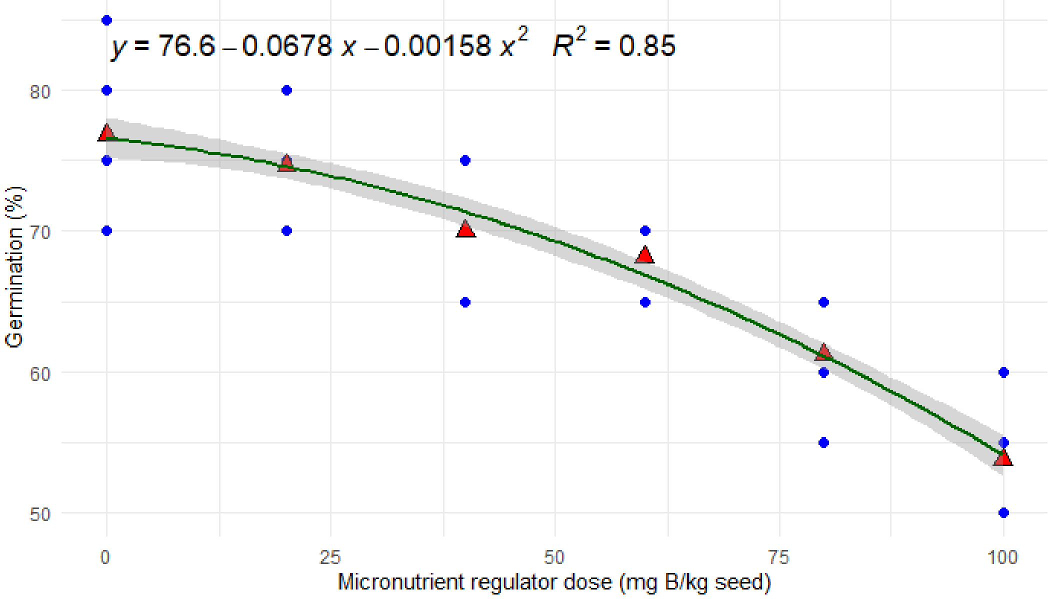
Table 1: Summary of peanut seed germination data

| Name | Treatments (mg/kg) | N | Mean (#) | Standard Deviation | Grouping |
|---|---|---|---|---|---|
| T1(control) | 0 | 16 | 15,375 | 0,885 | A |
| T2 | 20 | 16 | 14,938 | 0,574 | A |
| T3 | 40 | 16 | 14,000 | 0,632 | B |
| T4 | 60 | 16 | 13,625 | 0,500 | B |
| T5 | 80 | 16 | 12,250 | 0,577 | C |
| T6 | 100 | 16 | 10,750 | 0,683 | D |

Source: Prepared by the authors using R and RStudio (R Core Team, 2025; RStudio Team, 2020).

The presented results suggest a clear inversely proportional relationship between boric acid dosage and seed germination capacity. This trend may be explained by the progressive acidification of the growth medium caused by increasing boric acid doses, since acidic pH conditions are widely recognized as unfavorable to early seed development. As illustrated in Figure 1, increasing boric acid concentrations led to a significant reduction in germination, reflecting the constraints imposed by substrate acidification.

Figure 1 - Effects of different micronutrient regulator doses on peanut germination




Source: Prepared by the authors using R and RStudio RStudio (R Core Team, 2025; RStudio Team, 2020)

The technical literature related to agricultural production emphasizes that the optimal pH for healthy development of peanut seeds and seedlings is close to neutrality (approximately pH 7). Under practical field conditions, corrective measures such as liming are frequently recommended to neutralize excessive soil acidity, thereby ensuring optimal conditions for germination and early crop development. Therefore, the appropriate and controlled application of boron should consider not only the specific nutritional requirements of the plant but also the impact of the product on the physicochemical properties of the substrate, reinforcing the importance of accurate assessments and continuous pH monitoring during seed nutritional management.

In this context, considering that boron has been extensively studied due to its multiple essential roles in plant metabolism, particularly for its positive influence on seed productivity and quality, the results obtained in this study are consistent with the findings reported by Silva Berti et al.(2019). These authors observed that the application of increasing boron doses during soybean seed germination led to progressive soil acidification, which consequently hindered seed germination (Silva Berti *et al.*, 2019)

When analyzing the results related to root fresh weight after the 15-day experimental period, using standardized procedures across all treatments and varying only the boron doses, the analysis of variance (ANOVA) revealed significant differences attributable to the applied dosages. As shown in Table 2, the mean values and their respective standard deviations indicate that, following Tukey's multiple comparison test, distinct groupings were formed among treatments. The control treatment (0 mg) and the 20 mg treatment formed the same group, while the 40 mg and 60 mg treatments constituted an intermediate grouping, with the 60 mg treatment showing a transitional behavior toward the subsequent group represented by the 80 mg dose. The 100 mg treatment was clearly distinct from all others, presenting the highest mean value.

Table 2 - Summary of root fresh weight data

| Name | Treatments (mg/kg) | N | Mean (#) | Standard Deviation |
|---|---|---|---|---|
| T1(control) | 0 | 1,885 | 0,4760 | A |
| T2 | 20 | 3,6306 | 0,3716 | A |
| T3 | 40 | 3,7200 | 0,1413 | B |
| T4 | 60 | 3,9985 | 0,3427 | BC |
| T5 | 80 | 4,4245 | 0,2303 | C |
| T6 | 100 | 4,6450 | 0,2458 | D |

Source: Prepared by the authors using R and RStudio(R Core Team, 2025; RStudio Team, 2020)

Additionally, Figure 2 illustrates the relationship between root weight and the applied boron doses, with a second-degree polynomial curve fitted to the data, which presented a coefficient of determination ($R^2$) of 81%, indicating a good fit to the observed values. It is clearly observed that doses between 80 mg and 100 mg provided the best results in terms of root development, suggesting a possible saturation effect and indicating that higher doses might not only stagnate but eventually reduce this growth. Since boron is a micronutrient absorbed directly by plant roots, incremental doses resulted in a significant increase in root weight, thus confirming its direct importance in the early development of peanut plants.

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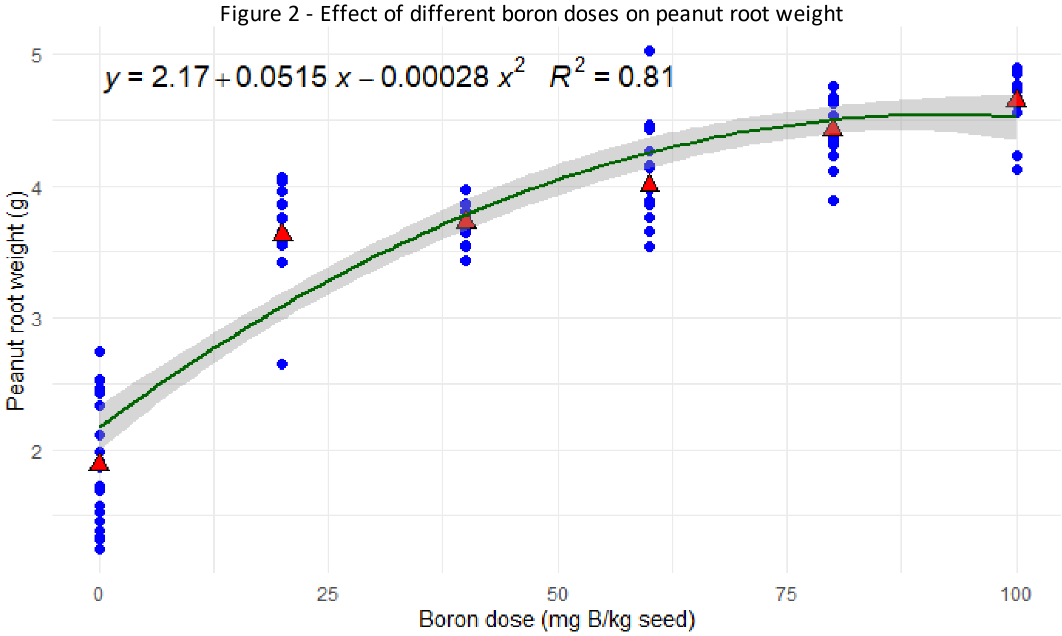
Figure 2 - Effect of different boron doses on peanut root weight




Source: Prepared by the authors using R and RStudio(R Core Team, 2025; RStudio Team, 2020)

The importance of boron in root development is supported by specialized literature, which highlights its crucial role in plant metabolism, including cell wall formation and stability, efficient carbohydrate transport, hormonal regulation, and protein synthesis (Prado, 2020). Silva (2017) also emphasizes that boron deficiency can significantly impair root growth, resulting in short, thin roots with reduced efficiency in nutrient and water uptake. Conversely, adequate boron application improves root health and vigor, enhancing their exploratory capacity and efficient absorption of essential soil nutrients.

The analysis of results related to root length further confirmed the significant influence of the applied boron doses (Table 3). The statistical tests revealed clear groupings among treatments, with the control and 20 mg treatments being statistically similar, while the intermediate doses of 60 mg and 80 mg formed a distinct grouping. The 40 mg and 100 mg doses exhibited isolated behaviors, indicating a differential response in root development.

Table 3 - Summary of peanut root length data

| Name | Treatments (mg/kg) | N | Mean (#) | Standard Deviation | Grouping |
|---|---|---|---|---|---|
| T1(control) | 0 | 20 | 8,40 | 0,416 | A |
| T2 | 20 | 20 | 8,45 | 0,320 | A |
| T3 | 40 | 20 | 9,25 | 0,574 | B |
| T4 | 60 | 20 | 12,42 | 1,092 | C |
| T5 | 80 | 20 | 12,35 | 0,890 | C |
| T6 | 100 | 20 | 10,12 | 0,916 | D |

Source: Prepared by the authors using R and RStudio(R Core Team, 2025; RStudio Team, 2020)

Figure 3 presents the results regarding the relationship between root length and the applied treatment doses, including a trend line fitted by a second-degree polynomial equation. A clear peak in root growth is observed near the dose of 60 mg B/kg of seeds, followed by a gradual decline at higher dosages. This behavior can be explained by the acidic nature of boron,

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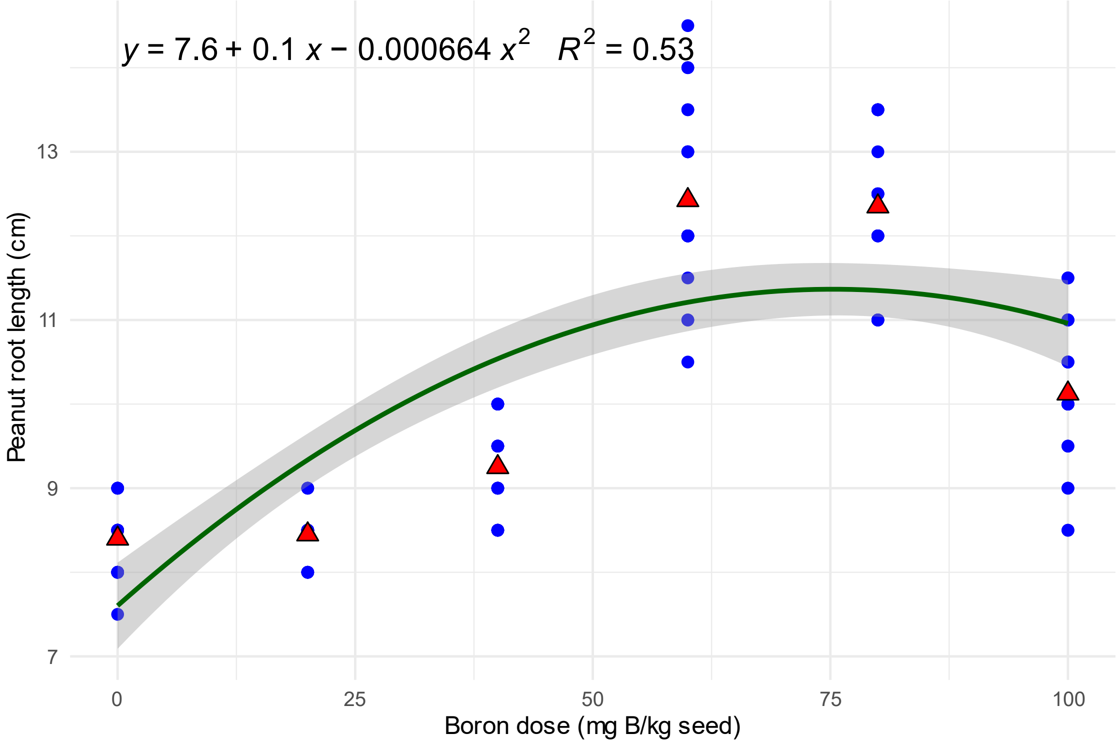
which, despite being essential to plant metabolism, requires precise application to avoid phytotoxic effects at elevated concentrations. Based on the results of this study, a dose of approximately 60 mg B/kg of seeds appears to be optimal, promoting maximum root development without compromising plant health due to toxicity associated with excessive boron.

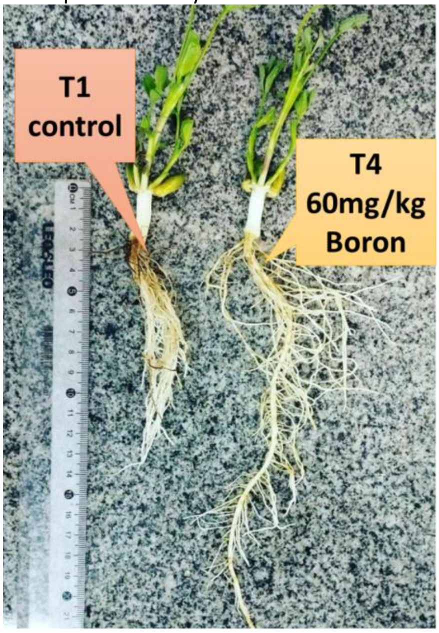
Figure 3 - Effect of different micronutrient regulator doses on peanut root length




Source: Prepared by the authors using R and RStudio(R Core Team, 2025; RStudio Team, 2020)

In this regard, Bissoto (2022) emphasizes that proper adjustment of boric acid doses through careful nutritional management is essential for adequate root development. The author also notes that several studies in the literature have investigated boron application, particularly in soybean cultivation, reporting divergent results. This variability highlights the importance of conducting further studies to deepen the understanding of the appropriate use of this micronutrient across different crops. Figure 4 visually illustrates root size for treatments T1 (control) and T4 (60 mg), highlighting the positive impact that an appropriate boron dose has on root growth.

Figure 4 - Comparative analysis between treatments T1 and T4




Source: By authors

It is also necessary to evaluate the shoot of the plants, as this structure plays a fundamental role in light interception and, consequently, in the photosynthetic process. When shoot parameters were measured and the analysis of variance (ANOVA) was applied, the treatments were found to significantly influence both shoot fresh weight and shoot length of the studied species.

Table 4 presents the mean values, standard deviations, and statistical groupings of the treatments based on Tukey's test for shoot weight data. It is observed that only treatments T1 (control) and T4 (60 mg) showed significant differences from each other and from the remaining treatments. The other treatments exhibited statistical similarity: T2 grouped with T5 and T6, while T3 also shared a grouping with T5 and T6. These results suggest that the effects of boron on shoot development exhibit a more stable behavior at intermediate and higher doses, with T5 (80 mg) and T6 (100 mg) being statistically equivalent.

Table 4 - Summary of plant shoot weight data

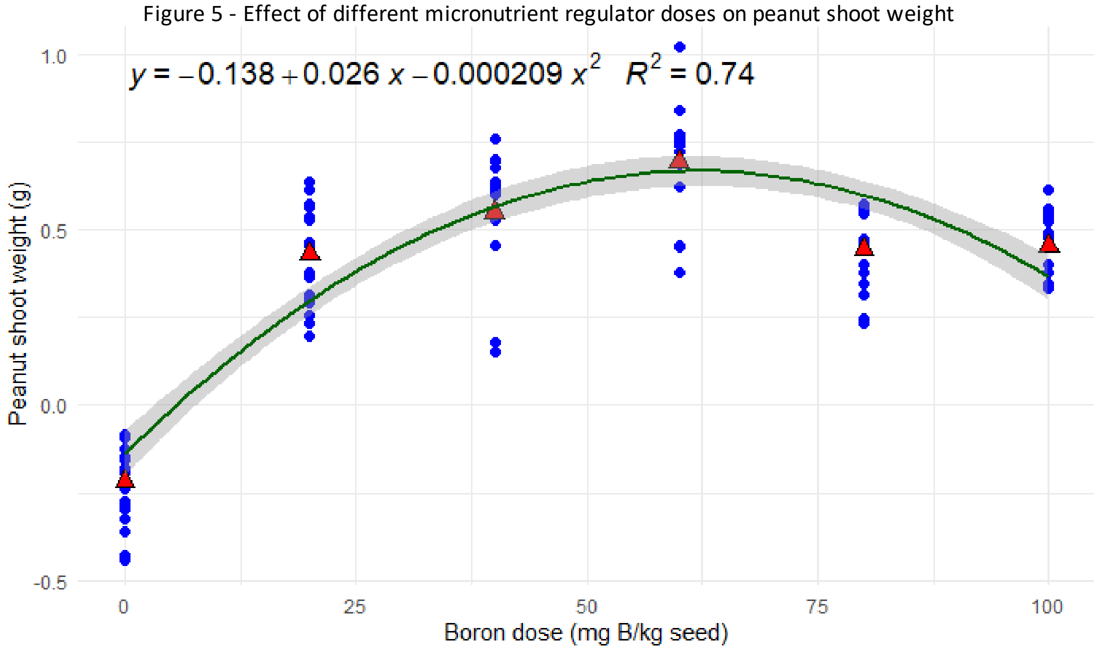
| Name | Treatments (mg/kg) | N | Mean (#) | Standard Deviation | Grouping |
|---|---|---|---|---|---|
| T1(control) | 0 | 20 | 0,8020 | 0,0939 | D |
| T2 | 20 | 20 | 1,5042 | 0,1789 | C |
| T3 | 40 | 20 | 1,6720 | 0,2425 | B |
| T4 | 60 | 19 | 1,8789 | 0,2196 | A |
| T5 | 80 | 20 | 1,5185 | 0,1355 | BC |
| T6 | 100 | 20 | 1,5270 | 0,1080 | BC |

Source: Prepared by the authors using R and RStudio(R Core Team, 2025; RStudio Team, 2020)

With regard to shoot development, the relationship between shoot weight and the different boron doses followed a second-degree polynomial curve pattern, as evidenced in Figure 6. The maximum point of the curve occurred near the 60 mg dose (T4), reinforcing the trend already observed for root development. This behavior indicates that a dose of 60 mg of boron per kilogram of seed not only favors root growth but also promotes greater biomass accumulation in the shoot.

Figure 6 illustrates the measured values and the fitted curve expressing the trend of shoot weight data, confirming that moderate boron application can be beneficial for overall peanut plant growth, provided that it is controlled within appropriate limits to avoid toxic effects or physiological inhibition.

Figure 5 - Effect of different micronutrient regulator doses on peanut shoot weight




Source: Prepared by the authors using R and RStudio(R Core Team, 2025; RStudio Team, 2020)

Considering that boron application can directly influence shoot development due to its essential role in cell formation and elongation, nutrient translocation, sugar transport, and protein synthesis, Souza and Roman (2018) report that beyond certain boric acid concentrations, a reduction in shoot growth and shoot weight occurs in soybean plants.

Adequate boron application, however, is fundamental to promote healthy shoot growth, since this micronutrient participates in several essential physiological processes related to plant tissue formation and biomass accumulation. When boron levels are balanced, plants tend to exhibit improved nutrient uptake, greater photosynthetic efficiency, and enhanced energy production, resulting in increased growth and shoot biomass (FUJIYAMA, 2019).

Similarly to roots, boron exerts a direct influence on shoot development. Ferrari e Boiago (2022) emphasize that high boric acid doses may cause toxicity in soybean crops, negatively affecting the growth of the upper plant parts.

Table 5 presents the mean shoot length values of peanut plants, along with their respective standard deviations and groupings formed by Tukey's test. It is observed that treatments T1 (control) and T2 (20 mg) were statistically grouped, as were treatments T5 (80 mg) and T6 (100 mg). In contrast, treatments T3 (40 mg) and T4 (60 mg) differed from the others, suggesting that these doses exhibited distinct performance in stimulating shoot height growth.

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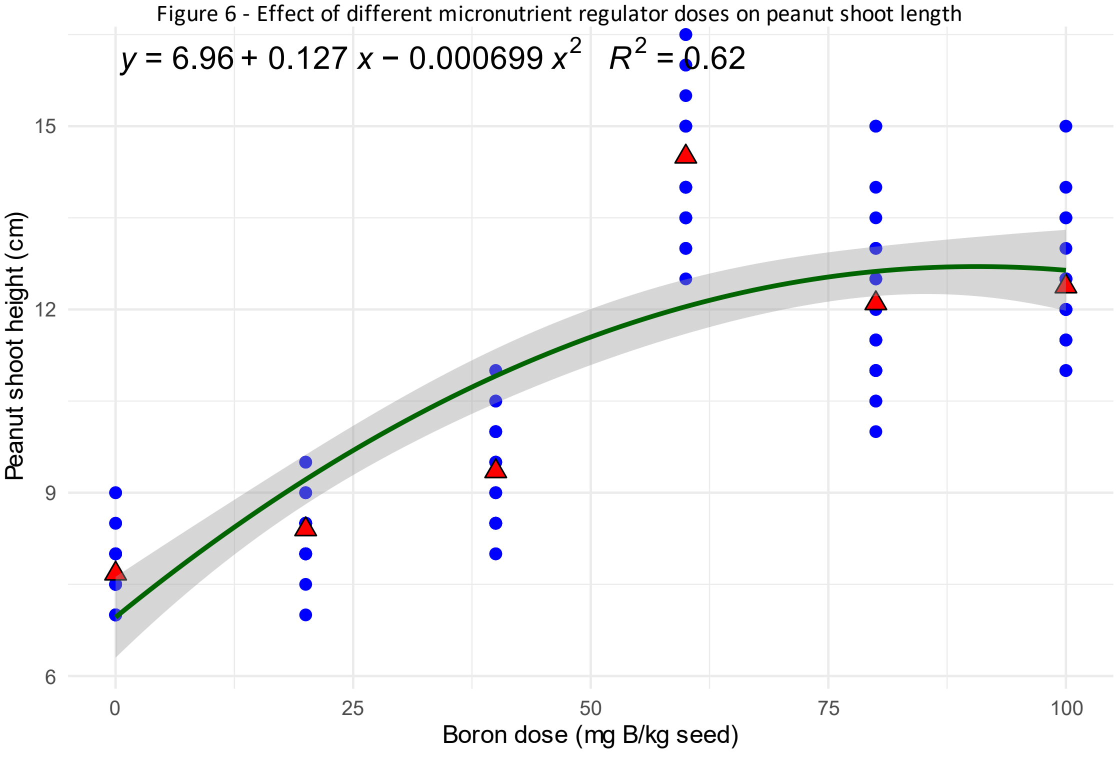
Table 5 - Summary of shoot length data

| Name | Treatments (mg/kg) | N | Mean (#) | Standard Deviation | Grouping |
|---|---|---|---|---|---|
| T1(control) | 0 | 20 | 7,675 | 0,674 | D |
| T2 | 20 | 20 | 8,400 | 0,620 | D |
| T3 | 40 | 20 | 9,350 | 0,947 | C |
| T4 | 60 | 20 | 14,500 | 1,181 | A |
| T5 | 80 | 20 | 12,100 | 1,447 | B |
| T6 | 100 | 20 | 12,375 | 1,011 | B |

Source: Prepared by the authors using R and RStudio(R Core Team, 2025; RStudio Team, 2020)

Shoot height exhibited a trend like that observed for root length in response to the treatments, with the optimal dose identified at 60 mg. The experiment demonstrated that beyond this dosage, a decline in plant development occurs, likely associated with toxicity caused by excess boron. Nevertheless, the plants that were able to develop under these conditions exhibited greater overall size compared to those originating from untreated seeds, both in terms of shoot and root growth, as shown in Figure 6.

Figure 6 - Effect of different micronutrient regulator doses on peanut shoot length




Source: Prepared by the authors using R and RStudio(R Core Team, 2025; RStudio Team, 2020)

Shoot height exhibited a trend similar to that observed for root length in response to the treatments, with the optimal dose identified at 60 mg. The experiment demonstrated that beyond this dosage, a decline in plant development occurs, likely associated with toxicity caused by excess boron. Nevertheless, the plants that were able to develop under these conditions exhibited greater overall size compared to those originating from seeds not treated with boron, both in terms of shoot and root growth.

In general, boron application directly affects plant growth and height, with effects depending on the cultivated species, environmental conditions, and the presence of micronutrient deficiency or excess. According to Ascoli(2020), under conditions of boron deficiency, proper application promotes a considerable increase in plant growth and tissue elongation, as boron plays a fundamental role in cell division and expansion.

However, when application exceeds the optimal range, the effects may be reversed. Ecco; Backes; Reuter (2022) demonstrated that high boric acid doses cause a significant reduction in root and shoot development in soybean, compromising the structural and functional formation of the plant. These findings are consistent with the results obtained in the present study on peanut, demonstrating that, although essential, boron requires balanced and technically grounded management.

Thus, the data presented herein reinforce the importance of defining appropriate boron doses in seed treatment, as application at moderate levels, particularly around 60 mg/kg, significantly contributed to enhanced root and shoot development in peanut with out inducing toxicity symptoms. Higher values, although associated with increased growth in certain parameters, showed a tendency toward saturation or reduced development, suggesting a typical micronutrient response curve.

These results provide relevant technical support for peanut nutritional management and highlight the need for complementary studies to evaluate boron interactions with other nutrients, as well as their implications throughout the entire crop cycle.

## 4 CONCLUSION

It can therefore be concluded that the application of boric acid in peanut seed treatment directly influences the early stages of plant development. Higher doses impaired germination, possibly due to substrate acidification; however, paradoxically, they promoted greater development in the plants that were able to emerge. The treatment with 60 mg of boron per kilogram of seed (T4) stood out as the most efficient, providing significantly superior results in both root and shoot growth.

These findings indicate that boron is a micronutrient with high physiological impact, whose use must be carefully planned and adjusted according to the specific requirements of the crop and soil characteristics. Furthermore, the importance of further research is emphasized to broaden the understanding of boron behavior at different phenological stages of peanut, considering its critical role not only during early development but also in reproductive growth and final crop productivity. Thus, the present study contributes to the advancement of technical and scientific knowledge, serving as a basis for more sustainable and effective agricultural practices.

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## STATEMENTS

### EACH AUTHOR'S CONTRIBUTION

When describing each author's contribution to the manuscript, the following criteria were used:

**Study Conception and Design:** João Paulo Machado Mantovani, Alisson Rodolfo Leite.
**Data Curation:** Alisson Rodolfo Leite, Leandro Calixto Tenório de Albuquerque, Camila Pires Cremasco Gabriel.
**Formal Analysis:** Alisson Rodolfo Leite.
**Funding Acquisition:** João Paulo Machado Mantovani.
**Investigation:** João Paulo Machado Mantovani, Alisson Rodolfo Leite.
**Methodology:** All authors.
**Writing – Original Draft:** João Paulo Machado Mantovani.
**Writing – Review and Critical Editing:** All authors.
**Review and Final Editing:** Alisson Rodolfo Leite, Luís Roberto Almeida Gabriel Filho.
**Supervision:** Luís Roberto Almeida Gabriel Filho.

### CONFLICT OF INTEREST DECLARATION

We, Alisson Rodolfo Leite, João Paulo Machado Mantovani, Camila Pires Cremasco Gabriel, Leandro Calixto Tenório de Albuquerque, and Luís Roberto Almeida Gabriel Filho, declare that the manuscript entitled "Influence of Boron Application on the Early Growth and Nutritional Management of Peanut (Arachis Hypogaea L.)":

1. **Financial Interests:** The authors declare that they do not have any financial relationships that could influence the results or interpretation of this work. No funding institution or entity was involved in the development of this study.
2. **Professional Relationships:** The authors declare that they do not have any professional relationships that could affect the analysis, interpretation, or presentation of the results.
3. **Personal Conflicts:** The authors declare that they do not have any personal conflicts of interest related to the content of the manuscript.