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Nutrient accumulation in leaves, silicon dynamics in plants, and yield of different peanut genotypes cultivated in northwestern Paraná, Brazil

Acúmulo de nutrientes na folha, dinâmica do silício na planta e produtividade de diferentes genótipos de amendoim cultivados na região Noroeste do Paraná, Brasil

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Highlights

Macronutrient order in leaves: N > Ca > K > Mg > S > P.
Micronutrient order in leaves: Fe > Mn > Zn > B > Cu.
Silicon mainly accumulated in roots, then leaves, stems, pods, and grains.
BRS 427 OL and BRS 429 OL had the highest yields under rainfed conditions.

Abstract

Genetic factors, production environment, and crop management practices influence peanut crop performance. This study aimed to evaluate nutrient accumulation in leaves, silicon dynamics within the plant, and the productivity of different peanut genotypes grown in the northwestern region of Paraná, Brazil. The experiment followed a randomized block design with ten peanut genotypes and four replicates, comprising six cultivars (BRS 421 OL, BRS 423 OL, BRS 425 OL, BRS 427 OL, BRS 429 OL,

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and BRS 440 OL) and four breeding lines (2173 OL, 2717 OL, 3233 OL, and 3386 OL), cultivated under rainfed conditions. Analyses included leaf nutrient accumulation and silicon distribution among plant organs (roots, stems, leaves, pod husks, and grains), as well as yield components. Data were subjected to analysis of variance, and means were compared using the Scott–Knott test at a 5% significance level. Leaf macronutrient accumulation followed the order N > Ca > K > Mg > S > P, while micronutrient accumulation followed Fe > Mn > Zn > B > Cu. Silicon accumulated predominantly in the roots, followed by leaves, stems, pod husks, and grains. Among the genotypes, the cultivars BRS 427 OL (8,084.65 kg ha^{-1}) and BRS 429 OL (8,063.77 kg ha^{-1}) exhibited the highest yields.
Key words: *Arachis hypogaea.* Nutrient uptake. Production environment. Silicon in agriculture.

Resumo

O desempenho da cultura do amendoim está relacionado a fatores genéticos, ao ambiente de produção e ao manejo adotado na cultura. O estudo teve como objetivo analisar o acúmulo de nutrientes na folha, a dinâmica do silício na planta e a produtividade de diferentes genótipos e amendoim cultivados na região noroeste do estado do Paraná. O experimento foi conduzido em delineamento de blocos casualizados, com dez linhagens de amendoim e quatro repetições. O genótipo refere-se a seis cultivares (BRS 421 OL, BRS 423 OL, BRS 425 OL, BRS 427 OL, BRS 429 OL e BRS 440 OL) e quatro linhagens (2173 OL, 2717 OL, 3233 OL e 3386 OL). O cultivo foi realizado em condições de sequeiro. Foram analisados o acúmulo de nutrientes no tecido foliar, o acúmulo de silício nos componentes morfológicos da planta (raiz, caule, folha, casca e grão) e componentes produtivos da cultura do amendoim. Os dados foram obtidos por análise de variância e as médias comparadas pelo teste de Scott-Knott com significância de 5%. O acúmulo médio de macronutrientes nos tecidos foliares do amendoim segue a ordem N > Ca > K > Mg > S > P, enquanto os micronutrientes seguem a ordem Fe > Mn > Zn > B > Cu. O silício acumula-se predominantemente nas raízes, seguido pelas folhas, caules, cascas de vagens e, em menor proporção, nos grãos. Dentre as linhagens avaliadas, as cultivares BRS 427 OL (8.084,65 kg ha^{-1}) e BRS 429 OL (8.063,77 kg ha^{-1}) apresentaram maior produtividade.
Palavras-chave: *Arachis hypogaea.* Absorção de nutrientes. Ambiente de produção. Silício na agricultura.

Introduction

Peanut (*Arachis hypogaea*) is an oilseed crop of global significance, cultivated for oil production, fresh consumption, and other food industry products (Ferrari et al., 2012). The crop is adaptable to several agricultural regions in Brazil, with Paraná showing recent growth in cultivated area and high production potential (Saath et al., 2021, 2025).

Peanut yield potential is influenced by genetic, environmental, and management factors. To optimize production, research has focused on selecting high-yielding, disease-resistant genotypes (Heuert et al., 2020), identifying favorable production environments (Pereira et al., 2023; Saath et al., 2025), and improving cultivation practices to enhance plant performance (E. B. Silva et al., 2017; Cordeiro et al., 2023; Crusciol et al., 2023).

Under adverse conditions, such as water or heat stress common in rainfed cultivation plants exhibit variable biometric responses, including altered nutrient uptake, morphological development, and physiological processes that directly impact yield and quality (Arruda et al., 2015; Barbieri et al., 2017; Carrega et al., 2019). Evaluating the responses of different genotypes under these conditions is essential for selecting high-performing cultivars.

This study aimed to evaluate nutrient accumulation in grains, silicon dynamics in the plant, and the productivity of different peanut lines grown in the northwestern region of Paraná, Brazil.

Materials and Methods

Study location

The experiment was conducted during the 2023/2024 growing season at the Irrigation Technical Center (CTI) of the State University of Maringá (UEM), Maringá, Paraná State, Brazil (23°25' S, 51°57' W; 542 m altitude). The experimental design was a randomized block with ten peanut genotypes and four replicates. The genotypes included six cultivars (BRS 421 OL, BRS 423 OL, BRS 425 OL, BRS 427 OL, BRS 429 OL, and BRS 440 OL) and four breeding lines (2173 OL, 2717 OL, 3233 OL, and 3386 OL) from EMBRAPA's Peanut Breeding Program.

The soil in the experimental area is classified as a very clayey-textured Ultisol (72% clay, 16% silt, 7% fine sand, and 5% coarse sand). Each experimental unit measured 10.8 m² (3.6 × 3.0 m), consisting of four rows spaced 0.9 m apart, with a planting density of 18 plants per meter. Minimum and maximum temperatures and precipitation during the experiment are presented in Figure 1.

Experimental management

Seeds were treated with fipronil, pyraclostrobin, and thiophanate-methyl. Basal fertilization at sowing consisted of 120 kg ha^{-1} P_2O_5 (single superphosphate, 18%) and 60 kg ha^{-1} K_2O (potassium chloride, 60%), based on soil analysis (Table 1) and crop recommendations by Pauletti and Motta (2017). Cultivation was conducted under rainfed conditions without supplemental irrigation.

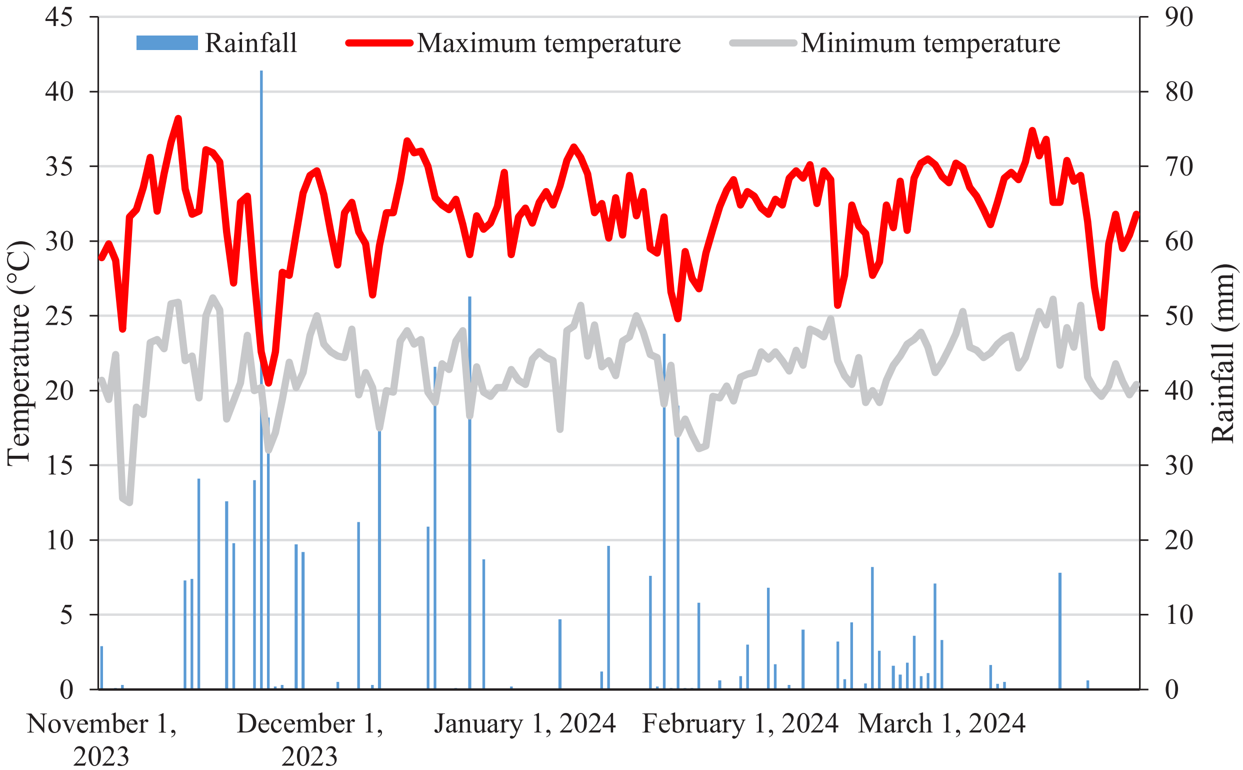

Figure 1. Temperature and rainfall throughout the study period. Maringá-PR, Brazil. 2023/2024.

Table 1
Chemical analysis of the experimental area soil from 0.00-0.20 and 0.20-0.40 m depth layers before peanut crop establishment

Depth layer	K	Ca	Mg	H+Al	Al	CEC	m	V
---- m ----	---------------------------cmol$_c$ dm^{-3}---------------------------						----%----	
0.00-0.20	0.36	4.03	1.83	3.52	0.04	9.74	0.64	63.86
0.20-0.40	0.15	2.93	1.40	3.37	0.14	7.85	3.03	57.07
Depth	P	S	Cu	Fe	Mn	Zn	Si	OM	pH
---- m ----	-----------------------------cmol$_c$ dm^{-3}---------------------------							g dm^{-3}	$CaCl_2$
0.00-0.20	4.24	6.55	16.56	62.28	111.96	1.68	10.89	1.71	5.00
0.20-0.40	1.73	16.62	15.96	58.14	43.38	0.18	11.05	0.89	4.80

*CEC - cation exchange capacity; m – aluminum saturation; V- base saturation; OM - organic matter.

All cultural and phytosanitary practices were performed according to technical recommendations. Pest and disease control was carried out as needed, based on infestation levels, and weeds were controlled manually within the plots.

Sample collections and evaluations

Only the central rows of each plot (useful area of 3.6 m²) were considered for evaluations. Leaf samples were collected to determine concentrations of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), boron (B), copper (Cu), iron (Fe), manganese (Mn), zinc (Zn), and silicon (Si), following the method of F. C. Silva (2009).

Plants were harvested between 110 and 140 days after emergence (DAE), when 70% of pods were mature (R8 stage, brown endosperm), as recommended by Okada et al. (2021). During harvest, samples of plant components (roots, stems, leaves, pods, and grains) were collected for silicon quantification, following F. C. Silva (2009).

Productivity was determined by measuring pod weight, grain weight, number of grains per plant, and plant population per unit area, with moisture content standardized to 8% (wet basis).

Data analysis

Data were subjected to analysis of variance (ANOVA) using the F-test, and means were compared using the Scott–Knott test at a 5% significance level, performed with SISVAR software (Ferreira, 2019).

Results and Discussion

The results of the macronutrient analysis are presented in Table 2, showing the average accumulation in the order N > Ca > K > Mg > S > P. Sulfur did not exhibit significant variation among the lines (Table 2), while the other macronutrients varied depending on the genotype. BRS 423 OL showed significantly higher nitrogen accumulation, whereas BRS 421 OL had higher phosphorus and potassium accumulations. Line 2717 OL stood out, exhibiting higher accumulations of phosphorus, potassium, calcium, and magnesium compared to the other breeding materials.

Table 2
Macronutrient content in peanut leaves from different genotypes grown under rainfed conditions in northwestern Paraná State, Brazil, during the 2023/2024 season

Genotype	N	Ca	K	Mg	S	P
	-----------------------	(g kg^{-1})	---------------------			
BRS 421 OL	31.67 d	18.57 c	13.60 a	7.26 c	1.41ns	1.48 a
BRS 423 OL	37.03 a	14.98 c	15.81 a	6.62 c	1.48	1.57 a
BRS 425 OL	34.97 b	15.37 c	10.31 b	5.88 c	1.45	1.40 b
BRS 427 OL	32.87 c	26.25 a	12.66 b	10.42 a	1.49	1.16 c
BRS 429 OL	35.16 b	25.57 a	10.79 b	10.36 a	1.51	1.41 b
BRS 440 OL	35.08 b	21.31 b	11.69 b	8.58 b	1.42	1.25 c
2173 OL	33.52 c	26.64 a	13.43 a	9.74 b	1.46	1.39 b
2717 OL	33.70 c	25.77 a	14.50 a	10.59 a	1.48	1.52 a
3233 OL	33.67 c	15.87 c	10.71 b	6.19 c	1.49	0.85 d
3386 OL	33.49 c	25.56 a	12.67 b	10.22 a	1.60	1.49 a
Mean	34.11	21.59	12.62	8.58	1.47	1.35
Coefficient of variation (%)	4.35	22.93	14.12	22.38	22.83	15.92

*Means followed by distinct letters within columns belong to different clusters according to the Scott-Knott test at 5% probability.

These macronutrient results differ from those reported by E. B. Silva et al. (2017), in which potassium accumulation exceeded calcium, with the decreasing order N > K > P > Ca > Mg > S. The lower potassium content in leaf tissue observed in this study may be due to limited soil availability (Table 1). Additionally, as noted by Cordeiro et al. (2023), high plant population density under rainfed cultivation may also reduce potassium uptake.

When compared to the reference sufficiency ranges for peanut crops proposed by Pauletti and Motta (2017), nitrogen and calcium levels in this study were adequate, while phosphorus, potassium, and sulfur were below the recommended levels (1.8–3 g kg^{-1} for P, 15–20 g kg^{-1} for K, and 2–4 g kg^{-1} for S). In contrast, magnesium levels (adequate range: 3–6 g kg^{-1}) were higher than recommended in all samples.

For micronutrients, accumulation followed the order Fe > Mn > Zn > B > Cu (Table 3), consistent with findings by E. B. Silva et al. (2017) in Brazilian conditions. The high iron accumulation (543.34–1480.81 mg kg^{-1} is noteworthy and is likely associated with the high soil iron content, as also observed by Crusciol et al. (2023). When compared to the reference levels provided by Pauletti and Motta (2017), all micronutrients were within or above the adequate range. Genotypes 2717 OL and 2173 OL showed the highest micronutrient accumulation, consistent with observations by Crusciol et al. (2023) that modern peanut cultivars tend to have greater micronutrient requirements.

Table 3
Micronutrient content in peanut leaves from different genotypes grown under rainfed conditions in northwest Paraná State, Brazil, during the 2023/2024 season

Genotype	Fe	Mn	Zn	B	Cu
		---------------------- ($mg\ kg^{-1}$) ----------------------			
BRS 421 OL	630.08 c	190.81 c	67.58 c	64.44 a	17.89 c
BRS 423 OL	1067.43 b	166.04 c	75.12 b	54.73 b	7.91 d
BRS 425 OL	958.97 b	172.07 c	65.74 c	63.80 a	13.53 c
BRS 427 OL	1133.54 b	237.34 a	96.84 a	58.41 b	32.28 a
BRS 429 OL	729.15 c	220.23 b	92.43 a	61.72 a	20.54 b
BRS 440 OL	853.36 c	226.43 b	88.87 b	67.13 a	23.13 b
2173 OL	967.18 b	285.30 a	119.57 a	66.89 a	30.78 a
2717 OL	1480.81 a	243.87 a	104.35 a	64.49 a	29.31 a
3233 OL	543.34 c	157.74 c	77.12 b	63.52 a	15.19 c
3386 OL	951.88 b	234.16 a	105.64 a	57.68 b	28.32 a
Mean	931.57	213.40	89.32	62.27	21.89
Coefficient of variation (%)	28.89	19.05	19.93	6.59	37.70

*Means followed by distinct letters within columns belong to different clusters according to the Scott-Knott test at 5% probability.

Regarding silicon accumulation, significant differences were observed among lines and plant components (Table 4). Silicon accumulated primarily in roots (28.12–36.51 $mg\ dm^{-3}$), followed by leaves (10.73–16.70 $mg\ dm^{-3}$), stems (8.72–15.79 $mg\ dm^{-3}$), pod husks (6.65–12.89 $mg\ dm^{-3}$), and grains (6.65–9.00 $mg\ dm^{-3}$). Although silicon is classified as a nonessential but beneficial element, its management in peanut cultivation is important due to its positive physiological and yield effects, particularly under stress conditions such as drought (Souza et al., 2021; Patel et al., 2021). Evaluating silicon accumulation among genotypes is relevant for identifying materials with higher demand for the element, especially in low-silicon soils, as observed in this study. Silicon enhances nutrient absorption and translocation, increases phosphorus availability, and reduces aluminum and heavy metal solubility (Singh et al., 2011).

Table 4
Silicon content in morphological components of peanuts from different genotypes grown under rainfed conditions in northwestern Paraná, Brazil, during the 2023/2024 season

Genotype	Root	Stem	Leaf	Bark	Grain
	------------------------------		($mg\ kg^{-1}$)	------------------------------	
BRS 421 OL	36.51 a	12.65 b	13.68 b	7.17 c	8.53 a
BRS 423 OL	32.06 b	12.98 b	16.40 a	10.78 b	9.00 a
BRS 425 OL	31.59 b	11.72 b	13.54 b	9.84 b	7.03 b
BRS 427 OL	31.82 b	12.18 b	13.07 b	12.23 a	7.31 b
BRS 429 OL	28.12 c	13.41 a	12.84 b	10.03 b	8.10 a
BRS 440 OL	31.54 b	8.72 c	12.46 b	7.26 c	8.53 a
2173 OL	35.53 a	12.23 b	10.73 c	8.53 c	8.90 a
2717 OL	28.38 c	15.79 a	12.04 b	9.37 b	6.65 c
3233 OL	34.35 a	10.97 b	11.25 c	12.89 a	7.96 b
3386 OL	35.06 a	13.45 a	12.65 b	6.65 c	8.39 a
Mean	32.50	12.41	12.87	9.47	8.04
Coefficient of variation (%)	8.57	14.41	11.88	21.80	10.05

*Means followed by distinct letters in the column belong to different clusters by the Scott-Knott test, at 5% probability.

In general, higher silicon accumulation was observed in vegetative organs roots, stems, and leaves while the fruit (husk and seed) contained relatively low amounts. This suggests that the proportion of silicon removed at harvest is small compared to total plant uptake, indicating that much of the silicon remains in the system through crop residues.

Regarding productivity, cultivars BRS 427 OL (8,084.65 kg ha^{-1}) and BRS 429 OL (8,063.77 kg ha^{-1}) outperformed the other materials (Table 5). The productivity ranking was as follows: BRS 421 OL > BRS 423 OL > BRS 425 OL > BRS 440 OL > 3386 OL > 3233 OL > 2173 OL > 2717 OL.

Table 5
Yield components from different peanut genotypes grown under rainfed conditions in northwest Paraná, Brazil, during the 2023/2024 season

Genotype	100-pod weight (g)	100-pod husk weight (g)	Grain number	1000-grain weight (g)	Grain yield (kg ha^{-1})
BRS 421 OL	173.50 a	37.47 a	186.25 b	722.45 a	7420.90 b
BRS 423 OL	164.62 a	30.63 b	202.25 a	659.94 b	6690.40 b
BRS 425 OL	132.71 b	27.79 b	177.00 c	591.15 c	7116.34 b
BRS 427 OL	158.05 a	29.06 b	191.25 a	675.92 b	8084.65 a
BRS 429 OL	148.34 b	27.04 b	199.00 a	609.66 c	8063.77 a
BRS 440 OL	148.14 b	28.14 b	183.25 b	655.33 b	6924.40 b
2173 OL	142.98 b	33.59 a	172.75 c	633.39 b	5547.56 d
2717 OL	151.00 b	32.69 a	196.75 a	601.14 c	4124.20 d
3233 OL	147.28 b	28.55 b	190.50 a	628.03 c	6370.43 c
3386 OL	162.02 a	32.30 a	198.00 a	658.80 b	7517.58 b
Mean	152.86	30.73	189.70	643.58	6786.02
Coefficient of variation (%)	7.73	10.65	5.18	6.12	17.83

*Means followed by distinct letters within columns belong to different clusters according to the Scott-Knott test at 5% probability.

In similar conditions, Pereira et al. (2023) reported lower yields but higher grain weight for cultivars BRS 421 OL, BRS 423 OL, and BRS 425 OL in the 2021/2022 growing season. Saath et al. (2025) observed higher yields with genotypes 2173 OL and 2091 OL, as well as cultivars BRS 425 OL and BRS 427 OL, in northwestern Paraná (Brazil). In other regions, such as Goiás, yields reported by Heuert et al. (2020) in the 2019/2020 season were higher, likely reflecting the interaction between genetic potential and production environment. Further research is needed to identify high-yielding, well-adapted genotypes and to refine management practices across different growing environments.

Conclusion

The average accumulation of macronutrients in leaf tissue followed the order N > Ca > K > Mg > S > P, while micronutrient accumulation followed the order Fe > Mn > Zn > B > Cu. Silicon accumulated predominantly in the roots, followed by the leaves, stems, pod husks, and, to a lesser extent, the grains. Among the genotypes evaluated, cultivars BRS 427 OL (8,084.65 kg ha^{-1}) and BRS 429 OL (8,063.77 kg ha^{-1}) exhibited the highest yield indices.

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