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CARLOS FELIPE DOS SANTOS CORDEIRO

CRESCIMENTO RADICULAR E PRODUTIVIDADE DE CULTIVARES DE AMENDOIM AFETADO PELO MANEJO DO FÓSFORO

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"To my parents José Carlos Cordeiro and Estela Cristina dos Santos Cordeiro, my brother Luis Fernando dos Santos Cordeiro, and my partner Maria Gabriela de Oliveira Andrade."

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ABSTRACT

Phosphorus (P) use efficiency has historically been low in agriculture, especially in highly weathered tropical soils, where much of the applied P becomes unavailable to plants. This challenge is even more pronounced in sandy soils, which are characterized by low water retention and poor organic matter content. Peanut (*Arachis hypogaea* L.) is a strategic crop due to its adaptation to low-fertility environments and its ability to access forms of P less available through a deep and efficient root system. However, there is limited information regarding the performance of modern cultivars, particularly those from the Virginia group, in the exploration of less labile soil P. This thesis aimed to identify cultivars efficient in acquiring less available P, elucidate the mechanisms involved in nutrient uptake across different soils, evaluate field performance under varying P and water availability, and determine the optimal P rate for distinct genotypes and edaphoclimatic conditions. Greenhouse and field experiments were conducted from 2021 to 2024 on soils contrasting in texture, P availability, and water regime. Although all cultivars initially utilized less labile forms of P—P-bound to iron and aluminum, the late-maturing cultivar IAC 503 exhibited greater biomass, root length and density, higher root hair density, and greater P uptake under P-deficient conditions, and was therefore selected, along with the early-maturing and less P-efficient cultivar IAC OL3, for subsequent studies. In soils located in temperate climate regions, the late-maturing cultivar maintained its superiority in root growth and P extraction, with up to 24% more P taken up. However, its efficiency in exploring less labile P was more influenced by the total P content than by soil texture. In field trials, although the early-maturing cultivar has shown greater initial growth, the late-maturing cultivar maintained higher light interception (leaf area index [LAI] up to 5.2), higher radiation use efficiency (RUE up to 2.18 g MJ^{-1}), more intense root growth in the surface layer, and up to 18% higher yield under reduced P rates in P-deficient soils and under water stress. The optimal P rate ranged from 17 to 52 kg ha^{-1}, depending on the cultivar, P availability, and water conditions. Multivariate analyses confirmed that deep rooting, LAI, and RUE were key traits underlying the superior performance of the late-maturing cultivar. Late-maturing cultivars are more efficient in exploring less available P, sustain high yields with moderate fertilizer rates, and exhibit greater resilience under water-limited conditions, making them strategic for tropical agricultural systems with low soil fertility and high climatic risk.

Keywords: *Arachis hypogaea* L.; residual phosphorus; rhizosphere; soil texture; water stress.

RESUMO

A eficiência de uso do fósforo (P) é historicamente baixa na agricultura, especialmente em solos tropicais altamente intemperizados, onde grande parte do P aplicado torna-se indisponível às plantas. O desafio é ainda mais acentuado em solos arenosos, com baixa retenção de água e pobres em matéria orgânica. O amendoim (*Arachis hypogaea* L.) é uma espécie estratégica por sua adaptação a ambientes de baixa fertilidade e pela capacidade de explorar formas menos disponíveis de P por meio de um sistema radicular profundo e eficiente. No entanto, há poucas informações sobre o desempenho de cultivares modernas, especialmente do grupo Virginia, quanto à exploração de P menos lábil dos solos. Esta tese teve como objetivo identificar cultivares eficientes na exploração de P menos disponível, elucidar os mecanismos envolvidos na absorção do nutriente em diferentes solos, avaliar o desempenho a campo sob variações de P e água, e determinar a dose ótima de P para distintos genótipos e condições edafoclimáticas. Foram conduzidos experimentos em casa de vegetação e em campo (2021–2024), em solos contrastantes quanto à textura, disponibilidade de P e regime hídrico. Apesar de todas cultivares avaliadas inicialmente utilizarem formas de P menos lábeis - ligadas e ferro e alumínio, a IAC 503 (maturação tardia) apresentou maior acúmulo de biomassa, comprimento e densidade radicular, maior densidade de pelos radiculares e maior absorção de P em condição de deficiência de P, sendo selecionada, juntamente com a cultivar precoce IAC OL3 (menos eficiente no uso do P), para os estudos subsequentes. Em solos de clima temperado, a cultivar tardia manteve superioridade no crescimento radicular e na extração de P, com até 24% mais P absorvido da rizosfera. No entanto, a eficiência dessa cultivar em explorar formas menos lábeis de P foi mais influenciada pelo teor total de P do que pela textura do solo. Nos ensaios de campo, embora a cultivar precoce apresentasse maior crescimento inicial, a de maturação tardia sustentou maior interceptação de luz (IAF até 5,2), maior eficiência no uso da radiação (EUR até 2,18 g MJ^{-1}), crescimento radicular mais intenso na camada superficial e produtividade até 18% superior sob doses reduzidas de P em solos deficientes e sob estresse hídrico. A dose ótima de P variou entre 17 e 52 kg ha^{-1}, dependendo da cultivar, disponibilidade de P e água. Análises multivariadas confirmaram que raízes profundas, IAF e EUR foram determinantes para o desempenho superior da cultivar de maturação tardia. Cultivares de maturação tardia são mais eficientes na exploração de P menos disponível, mantêm alta produtividade com doses moderadas de fertilizantes e mostram maior resiliência sob restrição hídrica, sendo estratégicas para sistemas agrícolas tropicais de baixa fertilidade e alto risco climático.

Palavras-chave: *Arachis hypogaea* L; Fósforo residual; Rizosfera; Textura do solo; Restrição hídrica.

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SUMMARY

GENERAL INTRODUCTION

Increasing reliance on tropical agricultural systems to meet the global demand for food, fiber, and bioenergy highlights the urgent need to improve the efficiency of natural resource use, particularly essential nutrients such as phosphorus (P) (Roy *et al*., 2016; Withers *et al*., 2018). In highly weathered tropical soils, P is one of the main limiting factors for yield due to its low availability, resulting from strong adsorption to iron and aluminum oxides and accumulation in less labile forms (Alovisi *et al*., 2020). Less than 50% of the P applied as fertilizer is absorbed by plants (Solangi *et al*., 2023; Silva *et al*., 2024; Gotz *et al*., 2025), compromising the economic and environmental sustainability of agriculture in these environments. This scenario is further exacerbated by the increasing scarcity of mineral phosphate sources and the accumulation of large stocks of residual soil P—the so-called “legacy P”—which remains largely unavailable to plants (Pavinato *et al*., 2020).

Cultivars with higher efficiency in P acquisition represent a promising strategy to reduce dependence on phosphate fertilizers and close the yield gap in low-fertility soils (McDowell *et al*., 2024). This efficiency is associated with morphophysiological adaptations such as greater fine root density, organic acid exudation, increased phosphatase activity, and enhanced root and root hair growth in depth—traits that promote access to less available forms of P (Gao *et al*., 2023; Wen *et al*., 2022). In tropical environments frequently exposed to water stress, these traits become even more critical, as water limitation restricts P mobility in the soil (Rosolem *et al*., 2023).

Among tropical crops, peanut (*Arachis hypogaea* L.) stands out for its high adaptation to sandy and low-fertility soils, with a recognized ability to explore deeper soil layers and access less labile forms of P (Ketring & Reid, 1993; Otani & Ae, 1996; Kraimat & Bissati, 2017). Globally, peanut cultivation has been expanding, dominated by Virginia-type cultivars (A. *hypogaea* subsp. hypogaea), characterized by prostrate growth, indeterminate habit, a cycle of 120 to 170 days, and high grain quality (Kunta *et al*., 2022). These cultivars differ from older Valencia and Spanish types, which had shorter cycles, lower yield, and limited response to P (Marubayashi *et al*., 1994). In Brazil, Virginia-type cultivars currently account for more than 90% of the cultivated area, especially in the main producing regions of São Paulo state, where sandy soils and tropical climate predominate.

Peanut cropping systems in Brazil are highly diverse and include areas under rotation with sugarcane and previously fertilized pastures—where greater accumulation of residual P is found—as well as areas undergoing the renovation of degraded pastures, where available P levels are very low. In both cases, soil texture and mineralogy strongly influence P adsorption and dynamics (Fink *et al*., 2016). In sandy soils, characterized by low cation exchange capacity, poor water retention, and low organic matter content, P availability tends to be even more limited, especially in organic forms (Saentho *et al*., 2022). Therefore, the presence of active roots, combined with the release of organic compounds and microbial activity, becomes essential for accessing P retained in less labile forms and in deeper soil layers.

Although late-maturing cultivars exhibit greater canopy growth and P accumulation compared to early-maturing ones (Cordeiro *et al*., 2025), information on their efficiency in exploring less labile forms of P remains limited, particularly through mechanisms such as deeper root growth, root hair formation, and organic acid exudation in the rhizosphere. This knowledge gap is particularly relevant given the need to develop strategies that optimize the use of legacy P, minimizing the environmental impact of fertilization and increasing the resilience of production systems. Moreover, it remains unclear whether the efficiency of modern cultivars in acquiring less labile P persists under different edaphoclimatic conditions—highlighting the importance of studies conducted in both tropical and temperate soils.

Thus, it was hypothesized that modern peanut cultivars can maintain the ability to exploit less labile forms of P, but late-maturing cultivars exhibit greater efficiency compared to early-maturing ones. This capacity would be reflected in a better exploration of legacy P, greater adaptation to soils with low P availability, and lower fertilizer requirements to achieve optimal growth and yield. To test this hypothesis, greenhouse and field experiments were conducted in tropical and temperate climate soils contrasting in texture, P availability, and water regime. The specific objectives of this study were: (i) to select cultivars with greater efficiency in exploring less labile soil P forms; (ii) to elucidate the main mechanisms underlying this efficiency across different soil types and P availabilities; (iii) to evaluate, under field conditions, the growth and yield performance of these cultivars under varying P and water availability; and (iv) to determine the optimal P rate for different genotypes and edaphoclimatic conditions.

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GENERAL CONCLUSION

Modern peanut cultivars retain the ability to utilize less labile forms of phosphorus and to exploit residual soil P. However, late-maturing peanut cultivars exhibit greater efficiency in P acquisition in both tropical and temperate soils, mainly due to their capacity to access less labile forms of the nutrient. Adaptation to soils with low labile P availability was more dependent on the total soil P content than on soil texture. Deep root growth, high root hair density, increased rhizosphere acid phosphatase activity, and the maintenance of P uptake even under low availability highlighted this cultivar as physiologically more efficient. Moreover, this efficiency was consistent across different soils and climatic conditions, particularly under water-limited environments, where the late-maturing cultivar sustained higher light interception, greater radiation use efficiency, and higher yield with moderate P rates. The results demonstrated that the agronomic performance of peanut cultivars is directly associated with their ability to uptake “P legacy” soil P and their response to P fertilization. The optimal P rate was lower for the late-maturing cultivar, reflecting greater agronomic efficiency and reduced dependence on high fertilizer inputs. Thus, late-maturing cultivars with greater root growth represent a promising strategy to enhance agronomic P use efficiency in tropical and temperate agricultural systems, with direct impacts on productive sustainability in low-fertility and high-climate-risk areas.

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