ISSN 1807-1929
Revista Brasileira de Engenharia Agrícola e Ambiental
Brazilian Journal of Agricultural and Environmental Engineering
v.28, n.10, e277817, 2024
Campina Grande, PB – http://www.agriambi.com.br – http://www.scielo.br/rbeaa

DOI: http://dx.doi.org/10.1590/1807-1929/agriambi.v28n10e277817

Original Article

Grafting increases tolerance to aluminum in dwarf cashew seedlings[1]

Enxertia aumenta tolerância ao alumínio em mudas de cajueiro-anão

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HIGHLIGHTS:
Grafting is a tool for tolerance of abiotic stress.
Aluminum reduces the accumulation of nutrients in dwarf cashew.
More tolerant clones and grafted seedlings are adaptive measures for planting dwarf cashew in soils with acidic reaction.

ABSTRACT: Using grafted and aluminum (Al) tolerant seedlings can be a strategy to enable the cultivation of dwarf cashew (*Anacardium occidentale* L.) in regions with predominance of soils with acidic reaction and high concentrations of exchangeable Al. In this context, the objective was to evaluate the influence of grafting on dwarf cashew genotypes cultivated in the presence of Al. For this, the experimental design was completely randomized in a 3 × 2 × 2 factorial scheme, with seedlings of three dwarf cashew genotypes (‘CCP 06’, ‘CCP 09’, and ‘CCP 76’) and two types of seedlings (ungrafted and self-grafted), cultivated in the absence and presence of Al (30 mg L^{-1}), with six replicates. One hundred and ten days after the beginning of Al application, the seedlings were evaluated for growth, dry matter and accumulation of nutrients and Al (in shoots and roots). Al caused reductions in the height (25.8%), stem diameter (6.7%), number of leaves (43.3%), leaf area (46.3%), stem dry matter (29.8%), and shoot dry matter (37.0%) of dwarf cashew. Application of 30 mg L^{-1} of Al increased the accumulation of Al in the roots and, as a consequence, reduced the accumulation of N, P, K, Ca, Mg, S, Cu, Fe and Zn in the shoots and roots. Dwarf cashew accumulates greater amount of Mn in the leaves and smaller amount in the roots, contrary to what occurs with Al. Al limits growth and nutrient accumulation in the clones ‘CCP 06’, ‘CCP 09’, and ‘CCP 76’; however, the use of grafted seedlings increases the tolerance of the plants to this element.

Key words: *Anacardium occidentale*, soil acidity, nutrient accumulation, aluminum stress

RESUMO: A utilização de mudas enxertadas e tolerantes ao alumínio pode ser uma estratégia para viabilizar o cultivo do cajueiro-anão (*Anacardium occidentale* L.) em regiões com predomínio de solos com reação ácida e altas concentrações de alumínio trocável. Nesse sentido, objetivou-se avaliar a influência da enxertia em genótipos de cajueiro-anão cultivados na presença de alumínio. Para isso, o delineamento experimental foi inteiramente casualizado em esquema fatorial 3 × 2 × 2, com mudas de cajueiro-anão de três genótipos (‘CCP 06’, ‘CCP 09’, e ‘CCP 76’) e dois tipos de muda (pé-franco e auto-enxertada), cultivadas na ausência e presença de alumínio (30 mg L^{-1}), com seis repetições. Cento e dez dias após o início da aplicação do alumínio as plantas foram avaliadas quanto ao crescimento, matéria seca e acúmulo de nutrientes e alumínio (na parte aérea e nas raízes). O alumínio causou reduções na altura (25,8%), diâmetro do caule (6,7%), número de folhas (43,3%), área foliar (46,3%), massa seca do caule (29,8%) e massa seca da parte aérea (37,0%) do cajueiro-anão. A aplicação de 30 mg L^{-1} de alumínio incrementou o acúmulo do Al nas raízes e, como consequência, reduziu o de N, P, K, Ca, Mg, S, Cu, Fe e Zn na parte aérea e nas raízes. O cajueiro-anão acumula maior quantidade de Mn nas folhas e menor nas raízes, de maneira inversa ao que acontece com o Al. O alumínio limita o crescimento e o acúmulo de nutrientes nos clones ‘CCP 06’, ‘CCP 09’, e ‘CCP 76’, entretanto, a utilização de mudas enxertadas aumenta a tolerância da planta ao elemento.

Palavras-chave: *Anacardium occidentale*, acidez do solo, acúmulo de nutrientes, estresse por alumínio

• Ref. 277817 – Received 22 Aug, 2023
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• Accepted 30 May, 2024 • Published 19 Jun, 2024
Editors: Toshik Iarley da Silva & Walter Esfrain Pereira

Introduction

Cashew (*Anacardium occidentale* L.) is a fruit tree originating in Brazil, found throughout the national territory, especially in the Northeast region, responsible for producing about 120,000 tons of cashew nuts per year, with Ceará being the largest producer (CONAB, 2021). In addition to the cashew nut, its peduncle is an important product for the processing industry as it is rich in vitamins, polyphenols, sugars, minerals, amino acids, and dietary fiber (Das & Arora, 2017).

Aiming at improving the yield of cashew crop and facilitating its management, due to the unevenness in size and yield caused by the use of seminal seedlings (ungrafted), clones of dwarf cashew have been developed and grafting techniques have been introduced in the production of seedlings (Martins et al., 2019). The grafting technique allows the production of seedlings that are healthy, more vigorous and tolerant to biotic and abiotic stresses, especially due to the vigor characteristics of the rootstock, contributing to a greater efficiency of nutrient absorption (Singh et al., 2020). In addition, grafting triggers the production of numerous enzymes related to defense against biotic and abiotic stresses (Nawaz et al., 2018).

It is important to highlight that plant development and yield are limited by factors linked to soil acidity, especially low pH and high aluminum saturation (Zhang et al., 2019a). Under these conditions, planting grafted seedlings proves to be feasible, since the grafting process increases the formation of antioxidant enzymes that can neutralize the production of reactive oxygen species (Gomes et al., 2016). Among these enzymes produced, superoxide dismutase (SOD) and guaiacol peroxidase (GPOX) play an important role in stresses caused by metals (Usman et al., 2020) and may inhibit the phytotoxicity of Al.

The presence of aluminum in the soil is a reality in the Northeast region, which limits the development of the crop. With regard to cashew cultivation in acidic soils, there are two possibilities: the neutralization of exchangeable aluminum by means of liming, but which is restricted to the layer of limestone incorporation into the soil; or the use of Al-tolerant plants. In this context, the objective was to evaluate the influence of grafting on dwarf cashew genotypes cultivated in the presence of Al.

Material and Methods

The experiment was conducted in a greenhouse belonging to Embrapa Agroindústria Tropical, located in Fortaleza, Ceará, Brazil (3º 75’ 26.4” S and 38º 57’ 57.0” W) The experimental design was completely randomized in a 3 × 2 × 2 factorial scheme, with three cashew genotypes as rootstocks (‘CCP 06’, ‘CCP 76’, and ‘CCP 09’) and two types of seedlings (ungrafted and self-grafted), cultivated in the absence and presence of aluminum (Al - 30 mg L^{-1}), with six replicates. Each experimental unit was formed by a 5 L pot containing two seedlings.

The seedlings were produced in the Pacajus Experimental Field, belonging to Embrapa Agroindústria Tropical, located in the municipality of Pacajus, Ceará, Brazil (4º 11’ 26.62” S and 38º 29’ 50.78” W). After successful grafting, the seedlings were transported to the greenhouse of Embrapa Agroindústria Tropical, in Fortaleza, Ceará, where the experiment was installed. Washed sand was used as substrate in the production of cashew seedlings. For washing, the sand was placed in a 10% HCl solution (v:v) and kept for about 24 hours, followed by rinsing with tap water until obtaining the pH of the water + sand mixture close to neutrality. Then, the sand was dried and used to fill tubes with capacity of 288 mL. Sowing was carried out by planting one seed-nut of ‘CCP 06’, ‘CCP 76’ or ‘CCP 09’ per tube. In this phase, the tubes were irrigated daily by sprinkling, and fertilization was not performed.

The seedlings were grafted by means of side grafting with the genotypes (‘CCP 06’, ‘CCP 76’ and ‘CCP 09’) at 70 days after sowing (DAS). At 60 days after grafting (DAG), the seedlings were transferred to 5 L plastic pots containing washed sand, and the nutrient solution of Hoagland & Arnon (1950), with 100% concentration, began to be applied once a week. After grafting, the seedlings were transferred to the greenhouse, where the experiment was conducted.

After the acclimatization period of the plants (three weeks), the nutrient solution of Hoagland & Arnon (1950) at 20% concentration of macronutrients and 100% concentration of micronutrients was used. Diluted nutrient solution was used because it better represents the conditions of the soil solution.

In the treatments with Al in the nutrient solution, 30 mg L^{-1} of Al in the form of $AlCl_3.6H_2O$ was applied. According to Visual MINTEQ 3.1 software (Gustafsson, 2012), the interactions of Al with the other chemical elements in the nutrient solution resulted in 71.5, 9.4, 5.6, 5.4 and 8.1% in the forms of Al^{3+}, $AlSO_4^{+}$, $Al_2PO_4^{3+}$, $AlHPO_4^{+}$ and other forms, respectively.

The pH in water of the nutrient solution, both in the absence and in the presence of Al, was maintained around 4.0 by adding 1 M HCl, to avoid precipitation of Al. The nutrient solution was applied daily in the early morning on all cashew seedlings, and drainage was performed once a week.

After 110 days of application of Al, the cashew plants were evaluated for the following variables: seedling height (from the collar to the apical bud), with a measuring tape graduated in cm; stem diameter at 5 cm from the collar (grafting point), measured with a digital caliper in mm; number of leaves, by counting; and leaf area, determined using the leaf area integrator (LI-3100C, LI-COR®).

Leaves and stems were separated, washed with water, 3% hydrochloric acid (v:v) and deionized water, placed in a paper bags and dried in a forced air circulation oven at 65 ºC until reaching constant mass. After drying, leaf dry matter and stem dry matter were determined. Roots were washed in water, 0.02 mol L^{-1} EDTA solution, 3% hydrochloric acid (v:v) and deionized water, and then placed in paper bags and dried in a forced air circulation oven until reaching constant mass to obtain the dry matter.

The dried samples were ground and subjected to chemical analysis according to procedures described in Miyazawa et al. (2009). The accumulation of nutrients and Al in the parts of dwarf cashew plants was obtained by multiplying the dry matter production by the content of the respective element.

The data were subjected to analysis of variance, and the means were compared by Tukey test ($p \leq 0.05$), using the statistical program Sisvar (Ferreira, 2010).

Results and Discussion

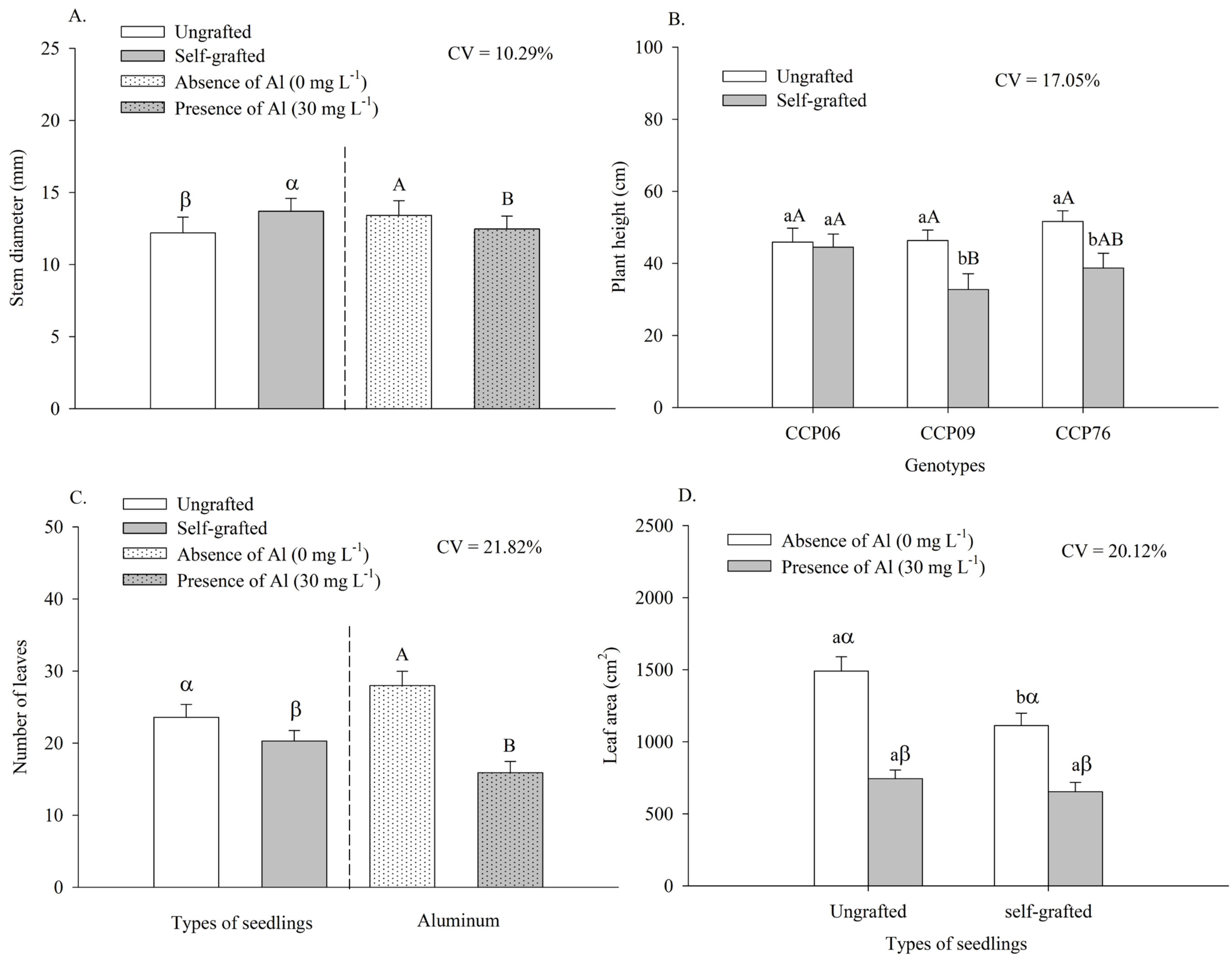
The plant height, stem diameter and number of leaves of cashew plants were influenced both by the type of seedling (ungrafted or grafted) and by the presence of aluminum (Al), while the clones led to differences only in plant height. Grafted seedlings had a greater average stem diameter, with 13.7 mm, compared to ungrafted seedlings, with 12.2 mm (Figure 1A). Stem diameter may be a characteristic that influences seedling survival in the field.

The interaction between clones and types of seedlings was significant for plant height (Figure 1B). The 'CCP 09' and 'CCP 76' clones of ungrafted seedlings showed greater height when compared to the self-grafted ones. The grafting process may have influenced these results, since grafted seedlings go through a period of adaptation until the transport of nutrients to all parts of the plant is established (Serrano & Cavalcanti Junior, 2016).

Self-grafted plants showed a smaller number of leaves compared to ungrafted plants (Figure 1C). In the side grafting process, the aerial part of the rootstocks is cut for the graft incision, and new leaves grow back after 20 and 30 days, while ungrafted seedlings do not go through this phase of growth of new leaves (Serrano & Cavalcanti Junior, 2016).

The presence of Al caused reductions of 6.7% in stem diameter and 43.2% in the number of leaves of dwarf cashew plants (Figure 1A and C).

According to Riaz et al. (2018), the presence of Al is a severe restriction on the agricultural performance of crops, mainly affecting nutrient absorption and plant physiology, causing oxidative stress and membrane damage, aspects that in turn reduce plant growth and development. Similarly, Sami et al. (2020) found that the presence of Al caused a decrease in the height of *Brassica napus* L. In addition, Sousa et al. (2018) found that multiple stress caused by high levels of Al and Mn resulted in reductions in stem diameter and number of leaves of sugarcane genotypes, similar to what occurred with cashew plants in the present study.



Means followed by capital letter for clones, lower case for type of seedlings and Greek letter for presence of aluminum do not differ by Tukey's test ($p \leq 0.05$)

Figure 1. Growth of dwarf cashew plants as a function of clone, types of seedlings and presence of aluminum

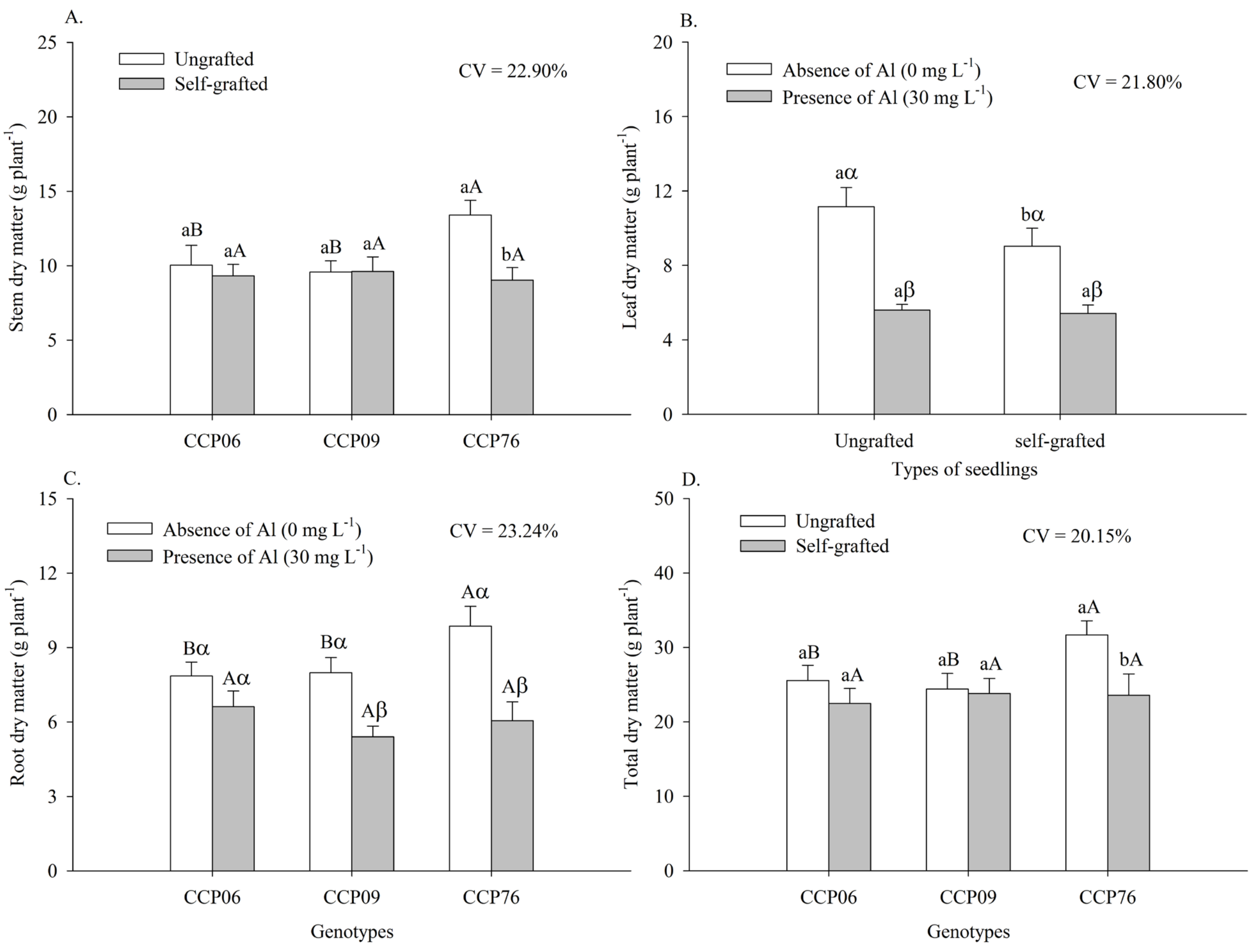
In the absence of Al, grafted plants showed a smaller leaf area compared to ungrafted plants, which was expected, since their shoots were cut at the time of grafting (Figure 1D). On the other hand, ungrafted plants were negatively affected by the presence of Al than grafted ones, with decreases of 50 and 41.2% in leaf area, respectively.

The decrease in leaf area observed in Figure 1D is related to the interference of Al in the uptake, transport and utilization of nutrients such as phosphorus, potassium, calcium, magnesium and iron, essential in the growth and formation of new plant organs (Borges et al., 2020). In addition, the presence of Al in the leaves induces the formation of reactive oxygen species (ROS), causing lipid membrane peroxidation, protein denaturation, oxidative damage to lipids, impairment of enzyme activity, carbohydrate oxidation and breakdown of pigments, resulting in programmed cell death (apoptosis) and consequent decrease in leaf area (Singh et al., 2017). The less pronounced effect of Al on grafted plants is related to the production of antioxidant enzymes, which are produced by stress induction and are able to inhibit the formation of ROS and their consequences (Usman et al., 2020), in addition to acting on the homeostasis of plant metabolism. The decrease in leaf area caused by Al affects the interception of light and consequently the photosynthesis of plants, negatively affecting other aspects of growth. Similarly, Melo et al. (2019) evaluated the effect of liming on the development of *Campomanesia adamantium* and found that the increase in limestone doses in a substrate based on Latossolo Vermelho distroférrico (Oxisol) promoted linear increments in leaf area, associating these results with pH correction, decrease of toxic Al, and increase in soil Ca and Mg concentrations. Stem dry matter, leaf dry matter, root dry matter and total dry matter were influenced by the clones, type of seedling and presence of Al in the nutrient solution (Figure 2A, B, C, and D).

In the presence of Al, stem dry matter (StDM) and total dry matter (TDM) were 29.8 and 34.9% lower than in dwarf cashew plants grown in the absence of the element, respectively (Figure 2A and D).

Ungrafted plants showed greater stem dry matter production when compared to the self-grafted ones (Figure 2A). The stem dry matter in the clone 'CCP 76' was 13.41 g per plant, when the seedlings were ungrafted, and 9.03 g per plant for grafted seedlings. The clone 'CCP 76' showed significant differences in the total dry matter production between ungrafted plants (31.68 g per plant) and the grafted ones (23.57 g per plant) (Figure 2D).

These results show the negative effect of Al on the dry matter accumulation of dwarf cashew and may be associated with the smaller leaf area in the presence of Al, which consequently caused decreases in photosynthesis and accumulation of photoassimilates especially from the biochemical step or Calvin-Benson cycle, whose main products are sugars necessary to plant development and dry matter accumulation (Taiz et al., 2017).



Means followed by capital letter for clones, lower case for type of seedlings and Greek letter for presence of aluminum do not differ by Tukey's test ($p \leq 0.05$)

Figure 2. Dry matter production of dwarf cashew plants as a function of clone, types of seedlings and presence of aluminum

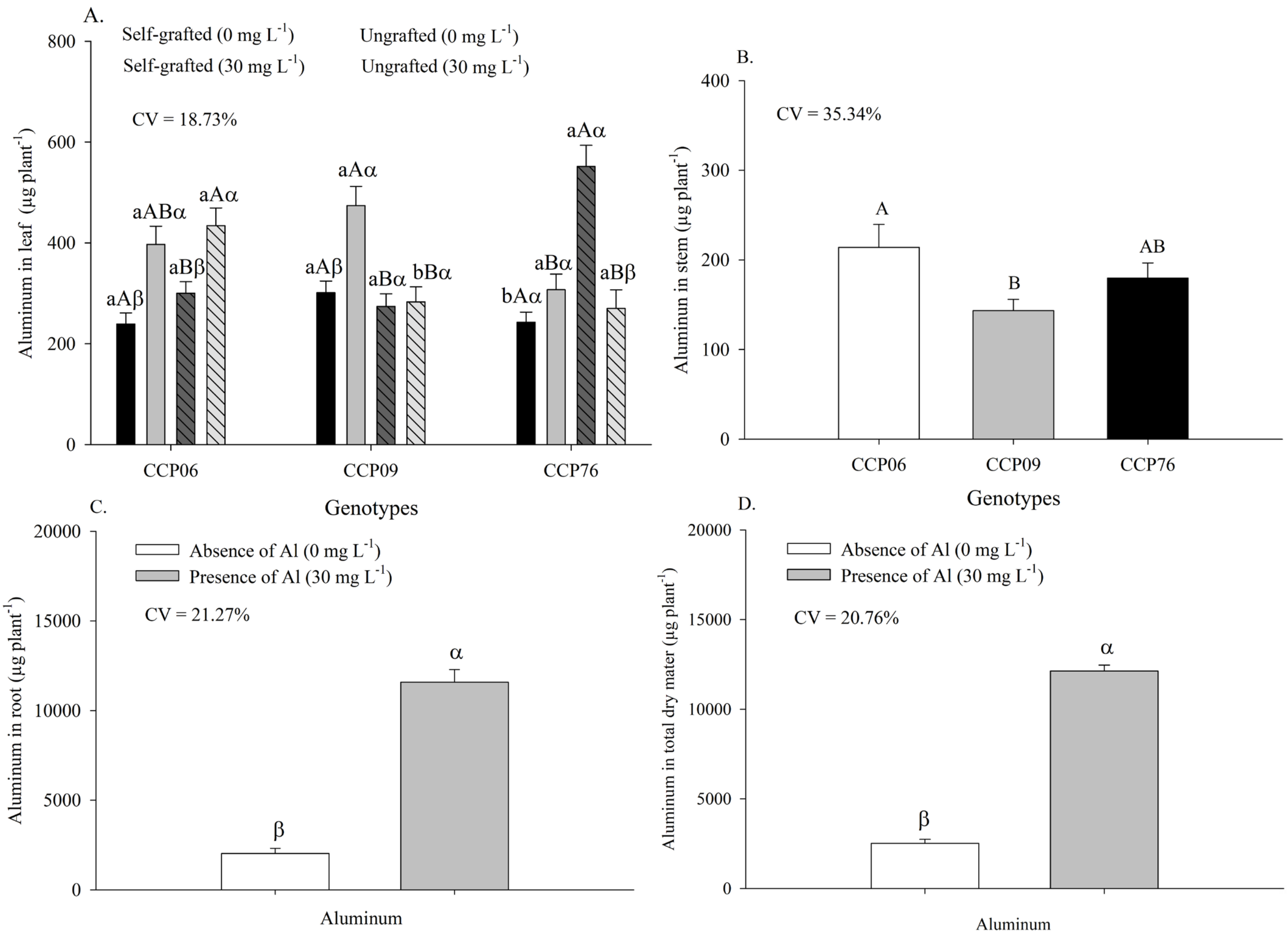
Leaf dry matter production was influenced by the interaction between the type of seedling and the presence of Al, similarly to what occurred with leaf area, for which in the absence of Al, grafted plants showed lower leaf dry matter compared to ungrafted plants (Figure 2B). This occurred due to the toxic effect of aluminum on the development of the cashew tree, directly interfering with the accumulation of leaf dry mass. In the presence of Al, no differences were found between the types of dwarf cashew seedlings; however, ungrafted plants were negatively influenced by the element than grafted ones, with decreases of 51.4 and 38.0% in leaf dry matter production, respectively.

The decrease in leaf dry matter due to the presence of Al, which was less accentuated in grafted plants, can be explained by stress-relieving mechanisms associated with the absorption and supply of nutrients and water, since the stress can be compensated by the connection between scion and rootstock, positively assisting in the physiological and biochemical processes of plants, contributing to dry matter accumulation (Wimmler et al., 2022).

In the absence of Al, plants of the clone 'CCP 76' showed higher root dry matter production than those of clones 'CCP 06' and 'CCP 09'; however, in the presence of the element, the clones did not differ. The presence of Al in the growing medium caused decreases of 32.4 and 38.7% in root dry matter production in the clones 'CCP 09' and 'CCP 76', respectively (Figure 2C). For 'CCP 06', the presence of Al did not cause reduction in root dry matter, indicating greater tolerance of this clone to the element. This result has practical importance, since the 'CCP 06' clone is the most used as rootstock because it has a high germination rate and compatibility with other cashew scions.

More tolerant soybean genotypes show greater root dry matter accumulation compared to more sensitive ones, resulting in a higher index of Al stress tolerance (Cabral et al., 2022). This can be explained by the fact that tolerant genotypes develop mechanisms against the deleterious effects of Al, which include the production of antioxidant enzymes and the allocation of Al in the roots (Guo et al., 2018) aiming to balance the accumulation of essential elements in all organs of the plant. According to Rahman et al. (2018), Al toxicity rapidly inhibits root growth and subsequently affects the absorption of water and nutrients in plants, limiting their development.

The application of 30 mg L-1 of Al influenced the accumulation of Al in the roots, increasing by 5.7 times the amount of the element compared to dwarf cashew plants cultivated in its absence (Figure 3C); however, there was no significant effect on their leaves and stem (Figure 3A and B). The preferential accumulation of Al in the roots may be a stress tolerance strategy, which explains the absence of



Means followed by capital letter for clones, lower case for type of seedlings and Greek letter for presence of aluminum do not differ by Tukey's test (p≤0.05)

Figure 3. Accumulation of Al of dwarf cashew plants as a function of clone, types of seedlings and presence of aluminum

visible symptoms of Al toxicity in the leaves of dwarf cashew, both in the present study and in the one reported by Araújo et al. (2020). The total accumulation of aluminum in dwarf cashew plants was higher in the presence of aluminum (Figure 3D).

The greater accumulation of Al in the roots is due to the fact that this organ is the primary site of action of Al (Kong et al., 2018) and may also be a strategy of plants against stress, because despite affecting the development of roots and, consequently, the absorption of nutrients, it prevents the main photosynthesizing organ (leaves) from being directly affected by the toxicity, which would significantly reduce gas exchange and sugar production.

Regarding the accumulation of Al in the leaves, differences were observed between the type of seedling and the application of Al (Figure 3A). In the absence of Al, ungrafted plants showed greater accumulation of this element in the leaves, compared to grafted plants (Figure 3A). On the other hand, in the presence of Al there was a 19.5% increase in the amount of the element in the leaves of grafted plants, compared to ungrafted ones.

Although grafted dwarf cashew plants accumulated more Al in the leaves than ungrafted plants, the amount of the element was not sufficient for the manifestation of toxicity symptoms in the leaves. The grafting process promotes the activation of stress-relieving mechanisms, such as the production of antioxidant enzymes (Zhang et al., 2019b) and the provision of resources obtained by the rootstock, such as water and nutrients (Wimmler et al., 2022). In addition, the increase in organic acid production and the formation of chelates in the cytosol contribute to the capacity to inactivate and store Al in non-toxic forms in leaves (Yaashikaa et al., 2022).

The effect of Al on nutrient accumulation is variable and depends on the concentration of the metal, time of exposure, genotype and type of plant (Bojórquez-Quintal et al., 2017). In the case of primary macronutrients, the application of 30 mg L^{-1} of Al reduced the accumulation of N (47.5% in shoots), P (62.5% in shoots) and K (45.3% in shoots) in the dwarf cashew plants (Figure 4A, B, and C). Similarly, Borges et al. (2020) found that the presence of Al caused a decrease in nutrient accumulation for sugarcane.

However, there were no observed effect of the clone × aluminum and type of seedling × aluminum interactions on the accumulation of these macronutrients. For theses macronutrients, ungrafted plants showed greater accumulation of N, P and K in the shoots, compared to grafted plants. Plants of the clone ‘CCP 76’ showed greater accumulation of P in the shoots than those of clones ‘CCP 06’ and ‘CCP 09’; however, the accumulation of K in the clone ‘CCP 09’ for ungrafted plants was lower compared to the other clones (Figure 4A, B and C). The absorption and accumulation of these nutrients, especially N, can directly affect the initial development of the plants formed. N is required in large quantities by cashew trees and is a structural

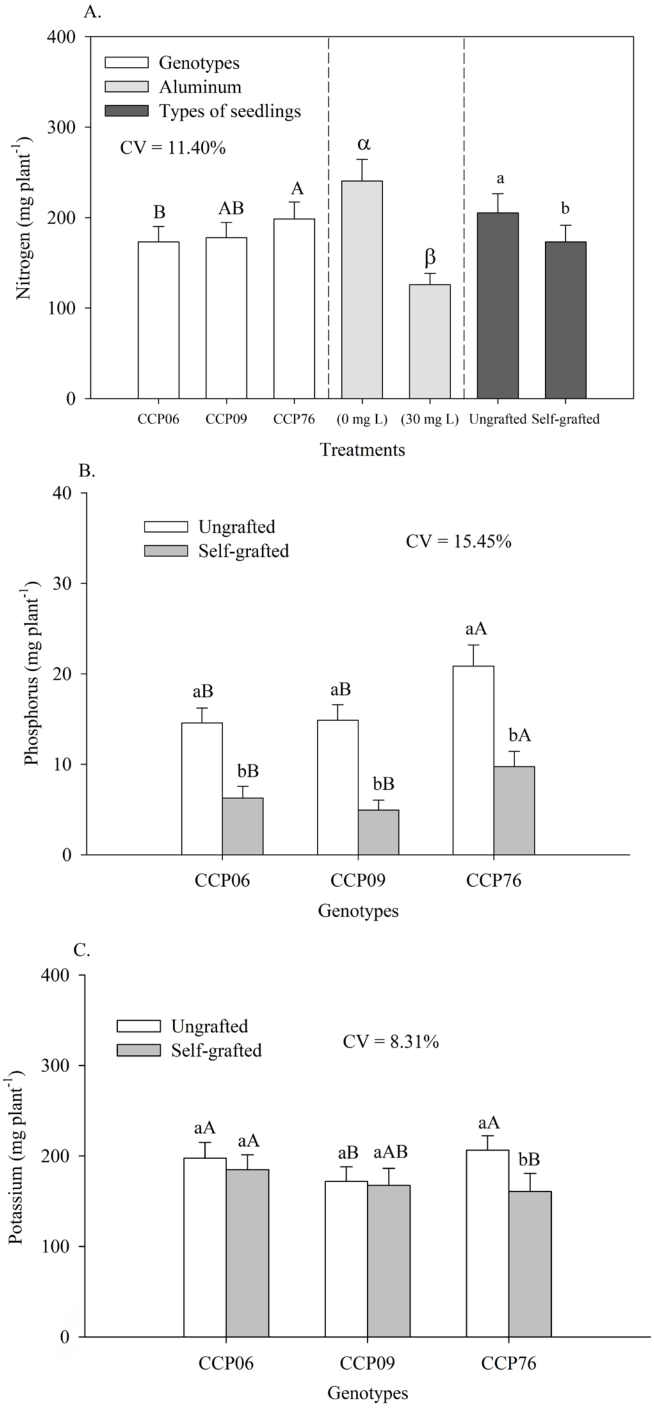


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Figure 4. Accumulation of nitrogen, phosphorus and potassium in the shoots of dwarf cashew as a function of clone, types of seedlings and presence of aluminum

nutrient, being fundamental as a structural component of amino acids, proteins and nucleic acids. P is important in energy storage and K in the establishment of cell turgor and maintenance of cellular electroneutrality (Taiz et al., 2017).

Al influenced the accumulation of nutrients in the shoots of the three clones of dwarf cashew (Figure 5 and 6). Differences were observed in the accumulation of Ca, Mg, S, Cu, Mn and Zn in shoots. In the absence of Al, the clones showed differences in the accumulation of nutrients in the shoots, especially ‘CCP 76’, which accumulated more

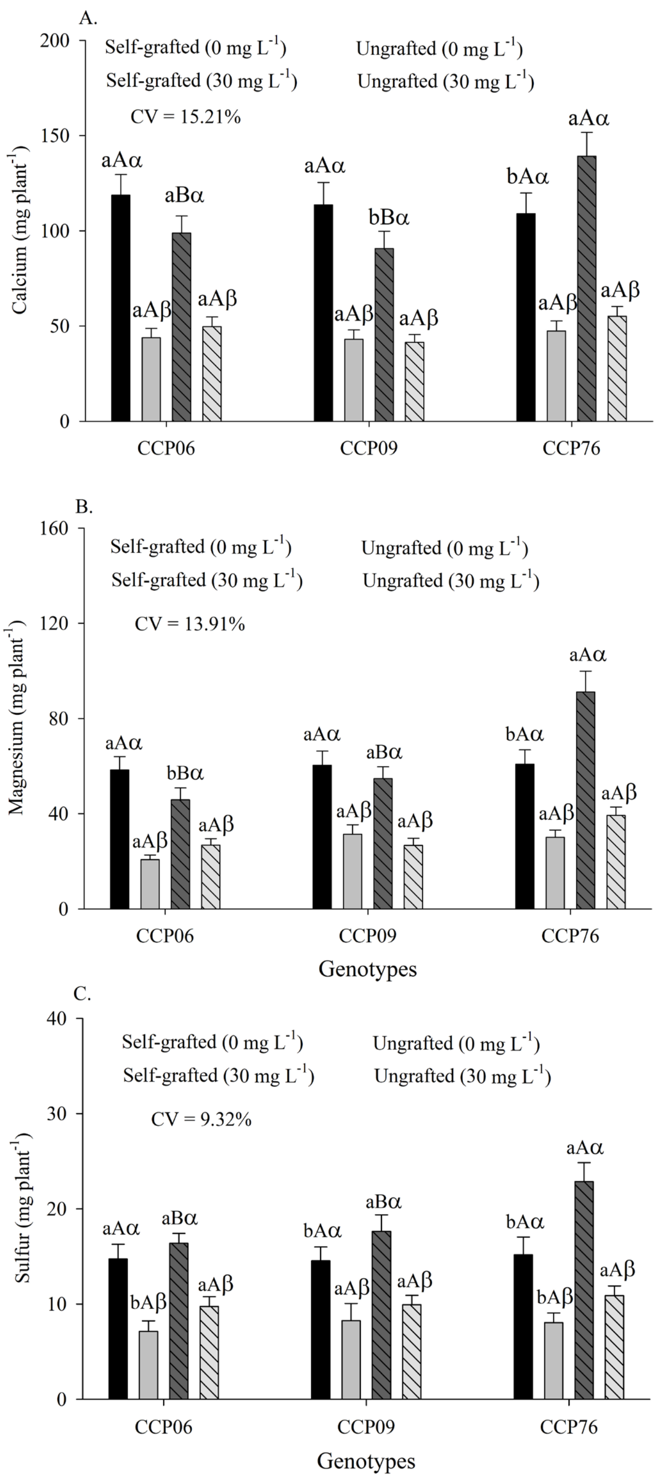

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Figure 5. Accumulation of calcium, magnesium and sulfur in the shoots of dwarf cashew as a function of clone, types of seedlings and presence of aluminum

Mg, S, Cu and Zn than 'CCP 06'; however, in the presence of the element, no differences were found between the clones, except for Mg (Figure 5).

The presence of Al reduced the accumulation of Ca, Mg, S, Cu and Zn in the shoots of the three clones of dwarf cashew, with values ranging from 33.7 to 53.9%, except for Cu and Zn in clones 'CCP 06' and 'CCP 76', respectively. Al can induce nutrient deficiency in the shoots of crops, due to its interference in the absorption and utilization of nutrients by plants, inhibiting the development of species (Rahman et al., 2018), which can be confirmed by the results presented here.

In the absence of Al, ungrafted plants of 'CCP 76' showed greater accumulation of Ca, Mg and S in the shoots (Figure 5A, B and C). In short, grafting and aluminum affect some processes, such as nutrient absorption and transport, with implications in the functioning of plant organs above soil. Ca acts as a structural constituent of the cell wall and membrane, Mg is a constituent of the chlorophyll molecule, and S is part of carbon compounds (Taiz et al., 2017), thus indicating the importance of these elements for plant development.

Contrary to the results presented for most nutrients, Al stress increased the accumulation of Mn in the shoots of the dwarf cashew clones (Figure 6D). This occurs because these nutrients compete for the same absorption site, favoring the accumulation of one, to the detriment of the other. Thus, the decrease in leaf dry matter production observed in Figure 2B can be attributed to the excess of Mn and not to Al, since there was no increase in Al in this part of the dwarf cashew plants (Figure 3A), besides a decrease in the accumulation of the other nutrients (Figures 4, 5 and 6). In the presence of Al (Figure 6D), the clones 'CCP 06', 'CCP 09' and 'CCP 76' showed increments of 23.0, 122.2 and 28.1% in the accumulation of Mn in the shoots, respectively.

A greater amount of Mn in the shoots can inhibit growth and root development, besides negatively influencing physiological processes, since Mn participates directly in photosynthesis (acting in enzymatic activation, photolysis and formation of chlorophylls), Krebs cycle and enzymatic defense systems of plants, as an enzymatic co-factor (Taiz et al., 2017; Liu et al., 2020). In this context, the greater accumulation of Mn in the shoots may have caused phytotoxicity in the dwarf cashew plants, which caused reduction in the accumulation of the other nutrients evaluated.

Differences were observed in the accumulation of Fe in the shoots of grafted and ungrafted plants; grafted plants accumulated less Fe than ungrafted plants (Figure 6B). The decrease in Fe accumulation with the grafting process explains the deficiency of this micronutrient in the leaves in development. Fe is a key element in the flow of electrons during the CO_2 fixation process in photosynthesis (Taiz et al., 2017).

The accumulation of S in the shoots of dwarf cashew plants was influenced by the type of seedling and by Al (Figure 5C). Grafted plants accumulated less S than ungrafted plants, and the presence of Al reduced the accumulation of S in the shoots of dwarf cashew. Sulfur is able to relieve the toxicity caused by Al, as it produces compounds (amino acids) capable of inactivating it (Rahman et al., 2018) and, at the same time, the grafting process increases the action of antioxidant enzymes to neutralize stress caused by Al (Gomes et al., 2016). However, in dwarf cashew, the accumulation of S in the shoots decreased in a similar way, by 47.4 and 46.7%, in ungrafted and grafted plants, respectively, contradicting the observation made by Gomes et al. (2016).

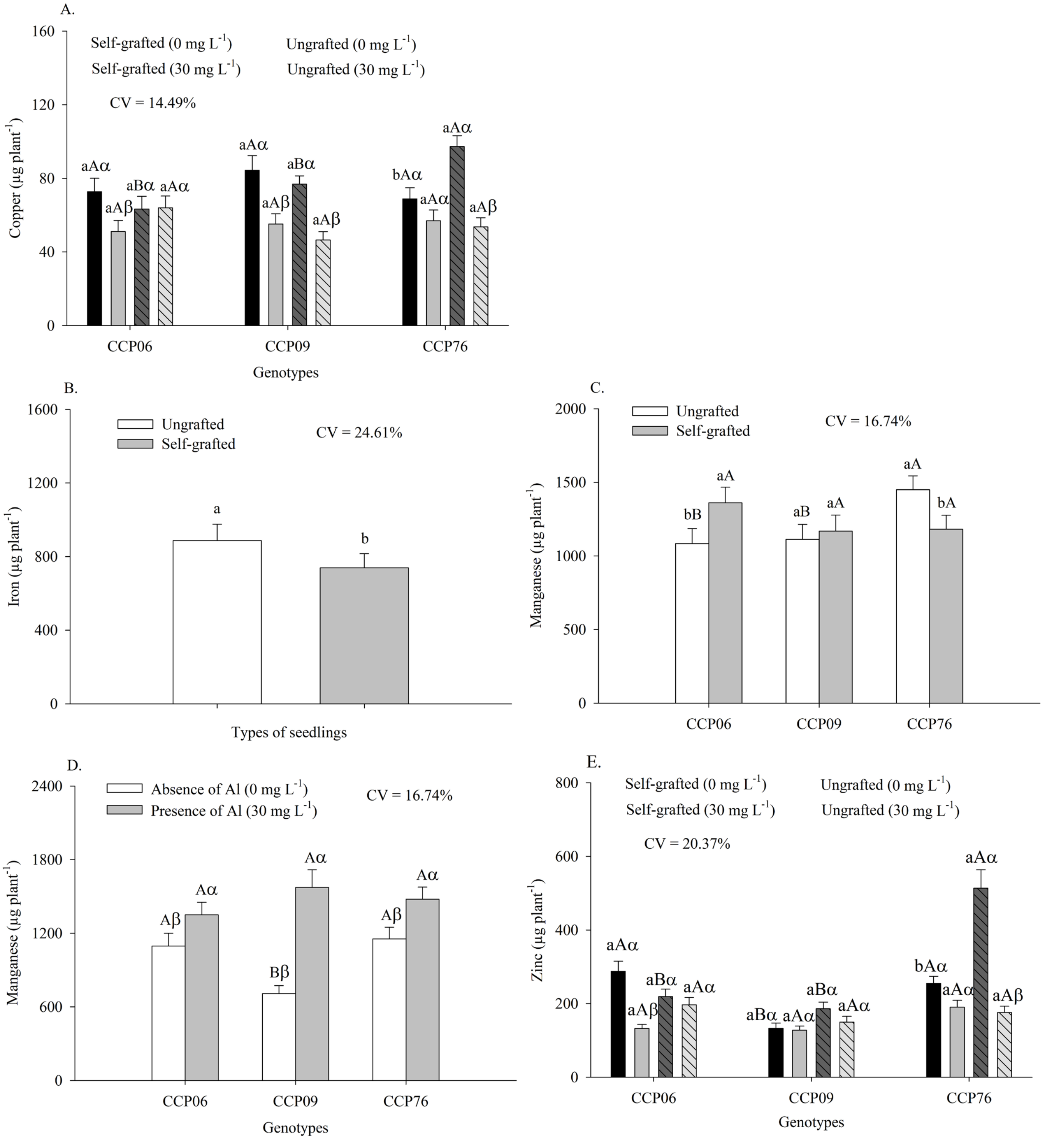

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Figure 6. Accumulation of copper, iron, manganese and zinc in the shoots of dwarf cashew as a function of clone, types of seedlings and presence of aluminum.

Conclusions

1. Aluminum stress reduces leaf area and leaf dry matter production of dwarf cashew, in a less pronounced manner in grafted seedlings.

2. The presence of aluminum reduces the accumulation of nutrients in the dwarf cashew clones 'CCP 06', 'CCP 09' and 'CCP 76'.

3. Using grafted seedlings of dwarf cashew is an alternative to expand its cultivation in regions with acidic soils.

Contribution of authors: Adriana G. Artur: supervision and writing; Esraelda A. de Araújo: investigation and writing; Rafael S. da Costa: formal analysis and writing; Luiz A. L. Serrano: conceptualization; Carlos A. K. Taniguchi: conceptualization and writing; William Natale: writing; Rosilene O. Mesquita: writing. All the authors read, discussed, and approved the final version of this manuscript.

Supplementary documents: There are no supplementary sources.

Conflict of interest: The authors declare no conflict of interest.

Financing statement: There are not financing statements to declare.

Acknowledgments: To the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for granting the scholarship during the entire period of the third author's master's degree. To Embrapa Agroindústria Tropical for all field and laboratory assistance for conducting the study.

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