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Fertilization with zinc improves the growth and photosynthetic performance of dwarf green coconut seedlings[1]

Fertilização com zinco melhora o crescimento e desempenho fotossintético de mudas de coqueiro anão verde

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HIGHLIGHTS:

Zinc concentration of 15 mg kg^{-1} in leaf tissue does not meet the needs of dwarf green coconut in the seedling phase.
Dwarf green coconut seedlings develop better with a zinc concentration of 82 mg kg^{-1} in leaf tissue.
Fertilization with up to 16 g of zinc per plant improves the metabolism of dwarf green coconut seedlings.

ABSTRACT: Zinc is an essential micronutrient for plant metabolism and has been studied in several crops of economic interest. However, there is no evidence of its use in coconut crops. The objective of this study was to evaluate the influence of foliar zinc fertilization with doses of zinc on dwarf green coconut seedlings based on their nutritional status, growth attributes, and gas exchange. The experimental design consisted of randomized blocks, and the treatments consisted of different zinc doses (0, 5, 10, 15, 20, and 25 g per plant) with five replicates. Seedlings were positively influenced by zinc dose, mainly in terms of growth variables and gas exchange. Zinc fertilization reduced iron and manganese content and increased zinc concentrations in the leaf tissue. Zinc fertilization promoted an increase in leaf area, height, shoot dry mass, and total dry mass. Furthermore, zinc fertilization improved photosynthesis, transpiration, stomatal conductance, internal CO_2 concentration, instantaneous water use efficiency, and intrinsic water use efficiency. The improvement in these growth indices and gas exchange, in most variables, was up to an estimated dose of approximately 16 g of zinc per plant and decreased with increasing doses.

Key words: *Cocos nucifera* L., micronutrient, fertilization management, best dose of zinc, seedlings

RESUMO: O zinco é um micronutriente de importância essencial para o metabolismo vegetal, é estudado para diversas culturas de interesse econômico, porém sem evidências de estudo para a cultura do coqueiro. Objetivou-se com este estudo avaliar a influência da fertilização com doses de zinco via foliar em mudas de coqueiro anão verde, por meio do estado nutricional, atributos de crescimento e trocas gasosas. O delineamento experimental foi em blocos ao acaso, e os tratamentos foram constituídos por doses de zinco (0, 5, 10, 15, 20 e 25 g por planta), com cinco repetições. As mudas foram influenciadas positivamente pelas doses de zinco principalmente nas variáveis de crescimento e nas trocas gasosas. No estado nutricional afetou de maneira decrescente o ferro e o manganês e aumentou o zinco no tecido foliar. O zinco proporcionou incrementos na área foliar, altura de plantas, massa seca da parte aérea e massa seca total. Além disso, melhorou a fotossíntese, transpiração, condutância estomática, concentração interna de CO_2, eficiência instantânea do uso da água e eficiência intrínseca do uso da água. A melhora nesses índices de crescimento e trocas gasosas, na maioria das variáveis, foi até a dose estimada de aproximadamente 16 g de zinco por planta e diminuiu com o aumento das doses.

Palavras-chave: *Cocos nucifera* L., micronutriente, manejo da fertilização, melhor dose de zinco, mudas

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Introduction

Coconut (*Cocos nucifera* L.) cultivation is an economically important agricultural activity in Brazil (Lins et al., 2021). The state of Ceará is the largest national producer, followed by Bahia, Pará, and Sergipe (IBGE, 2021). Pará, the state where this research was carried out, has 17.646 hectares harvested and a productivity of approximately 9.501 fruits per hectare (IBGE, 2021). Although there are places with high levels of technology, the increase in coconut production in Pará is mainly related to the increase in planted areas. The current challenges for coconut cultivation include production gain due to the increase in yield (Fróes Junior et al., 2019).

Mineral fertilization is used to promote growth and increase crop yield (Lins et al., 2021). For dwarf varieties, the need for fertilization is even greater because they extract more nutrients from the soil than traditionally cultivated genotypes (Teixeira et al., 2005). Studies in Brazil that evaluated the response of dwarf green coconuts to mineral fertilization have mainly focused on the macronutrients nitrogen, phosphorus, and potassium (Ribeiro et al., 2016), with no reports on zinc (Zn).

The importance of Zn fertilization has been reported for several crops of economic importance, such as maize (*Zea mays* L.) and 'paricá' (*Schizolobium amazonicum*) (Moreira et al., 2021; Callegari et al., 2022). Studies have confirmed that Zn fertilization positively affects the growth and photosynthetic performance of crops (Khan & Ahmed, 2022; Ahmed et al., 2022). Zn is essential for the growth and production of crops (Das et al., 2018), is a component of numerous enzymes, such as anhydrases, oxidases, and peroxidases, and plays an important role in cell division, photosynthesis, and auxin synthesis (Noulas et al., 2018).

In view of the above, the aim of this study was to evaluate the influence of foliar fertilization with different doses of Zn on dwarf green coconut seedlings in Brazil, through their nutritional status, growth attributes, and gas exchange.

Material and Methods

The experiment was performed in a greenhouse located at the Federal Rural University of the Amazon, Belém, PA, Brazil (1° 27' 07" S and 48° 26' 07" W, altitude of 52 m) between September 2021 and April 2022. During the experiment, the temperature and relative humidity of the air were measured using a thermo-hygrometer installed in the greenhouse, with 35.3 °C being the maximum average temperature, 28.1 °C the minimum and 77.1% the average relative air humidity. Two-month-old coconut seedlings of the Anão Verde do Brasil, with 2 months of age, produced by Sococo S.A., were used.

The soil used in the experiment was an Entisol (United States, 2014) that corresponds to the Neossolo in the Brazilian Soil Classification System, collected at the Reunidas Sococo farm in the municipality of Santa Isabel, Pará state, Brazil. The soil was collected from the arable layer (0-20 cm), and its chemical and particle size characteristics before the experiment are listed in Table 1. Prior to planting the coconut seedlings, the soil samples were air-dried, sieved through a 4-mm mesh and placed in pots with a capacity of 17 kg. Irrigation was performed daily, and soil moisture concentration was maintained throughout the experiment through manual irrigation using a 1 L beaker. The amount of water was in accordance with the needs of each pot.

A randomized block design was used, with treatments consisting of Zn doses (0, 5, 10, 15, 20, and 25 g per plant) with five replicates, totaling 30 experimental units. At 60 days before transplanting, each pot received 13.6 g of dolomitic limestone to increase base saturation from 29 to 60%. The seedlings were fertilized in the first, third and fifth months of age with 1.35, 2.7, and 4.05 g per plant of nitrogen; 7.2, 14.4 and 21.6 g per plant of phosphorus; 6, 12, and 18 g per plant of potassium; 1.5, 3, and 4.5 g per plant of magnesium, respectively, and 0.3 g per plant of boron in the fifth month. Zn doses were foliar-applied according to the defined treatments, and ZnO was used as the oxide.

Treatment effects were evaluated 240 days after transplantation by analyzing nutritional status, growth, and gas exchange. The nutritional status of the plants was evaluated based on the macro and micronutrient concentration in the leaf tissue. The macronutrients evaluated were nitrogen (N), phosphorus (P), potassium (K), sulfur (S), calcium (Ca), and magnesium (Mg), and the micronutrients were boron (B), copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn). To evaluate the concentrations of nutrients in the leaf, leaf tissue samples were collected and dried in an air circulation oven at 60 °C until reaching constant weight. The dried material was crushed using a Wiley mill (MA 340, Marconi, BR). The analyses were performed according to EMBRAPA (2000).

Plant growth was evaluated by measuring the height (H), leaf area (LA), shoot dry mass (SDM), root dry mass (RDM), and total dry mass (TDM). H (cm) was measured using a tape measure, considering the vertical distance between the plant collar and the tip of the largest stretched leaf. LA (cm^2 per plant) was measured immediately after plant collection using an area integrator (LI-3100; Li-Cor, Inc. Lincoln, NE, USA) and the leaves were removed from the plant and individually analyzed using the device. To obtain RDM, SDM, and TDM, the plants were harvested and, after separation of shoots and roots, they were dried in an air circulation oven, at 70 °C, until

Table 1. Chemical and particle-size characteristics of Entisol, in the 0-20 cm layer

pH H_2O	pH $CaCl_2$	H + Al	Ca^{+2}	Mg^{+2}	Al^{+3}	K^+	CEC pH7	P	S	V	m
		($cmol_c\ dm^{-3}$)						($mg\ dm^{-3}$)		(%)	
4.2	3.4	2.8	0.8	0.3	0.3	0.02	3.92	1.5	3	29	20.3

B	Cu	Fe	Mn	Zn	Sand	Silt	Clay
($mg\ dm^{-3}$)					($g\ kg^{-1}$)		
0.25	0.5	330	4.7	1	861.7	47.6	90.7

*Phosphorus (P), manganese (Mn), iron (Fe), copper (Cu), zinc (Zn) – Mehlich 1 extractant; calcium (Ca), magnesium (Mg), potassium (K) – resin extractant; and boron (B) – hot water method. Hydrogen potential in water (pH H2O), hydrogen potential in calcium chloride (pH $CaCl_2$), potential acidity (H+Al), aluminum (Al), cation exchange capacity (CTC), sulfur (S), base saturation (V%), and aluminum saturation (m%)

reaching constant weight. The dry biomass (g) of each sample was quantified using an analytical balance.

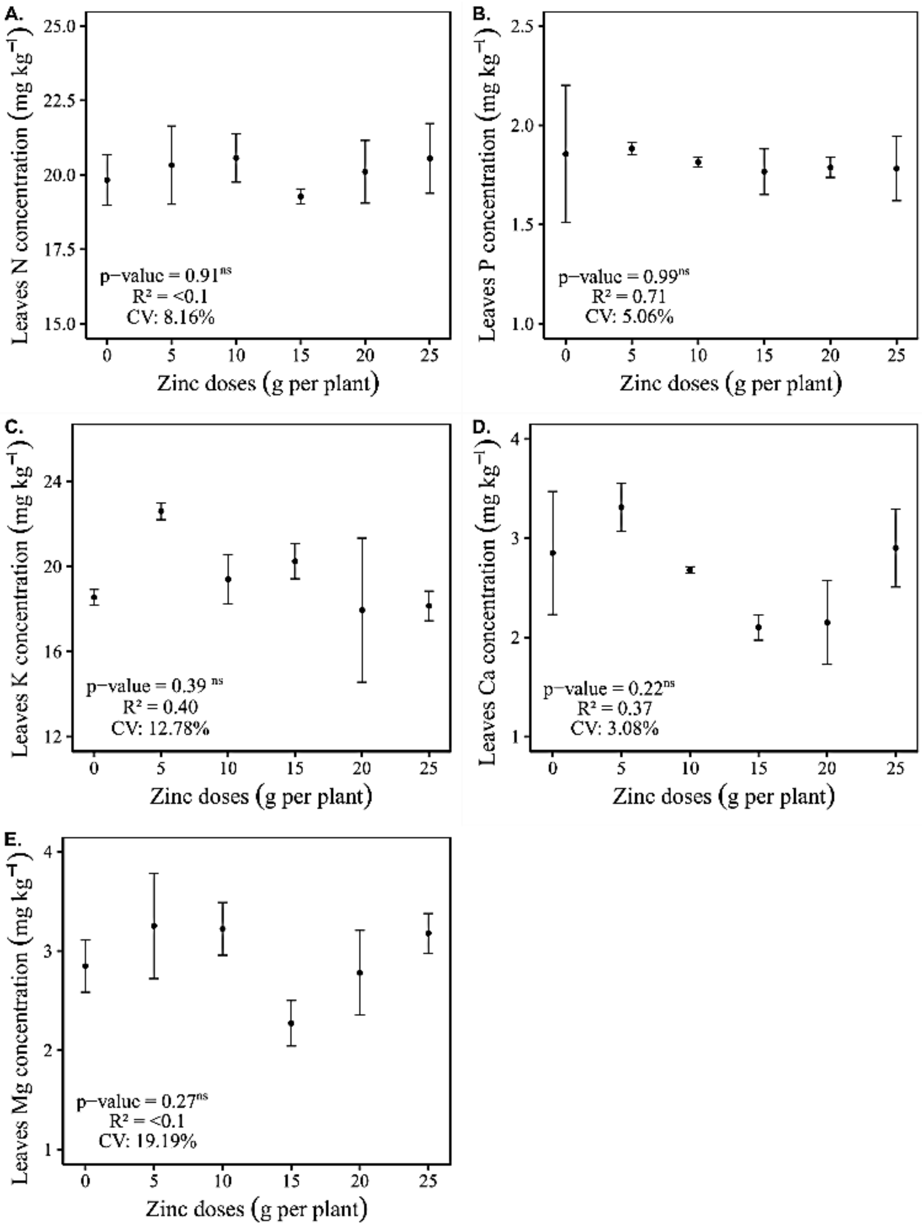
Gas exchange was determined based on photosynthesis (A - μmol CO_2 m^{-2} s^{-1}), transpiration (E - mmol H_2O m^{-2} s^{-1}), stomatal conductance (gs - mol H_2O m^{-2} s^{-1}), internal CO_2 concentration (Ci - μmol CO_2 mol air^{-1}), instantaneous water use efficiency (WUE – A/E), and intrinsic water use efficiency (iWUE – A/Ci). These variables were evaluated in the third leaflet of the fourth fully expanded leaf of each plant using a portable infrared gas analyzer (IRGA, LI–6400XT model, LICOR®). The artificial light intensity used in the gas exchange evaluations was 1,000 μmol m^{-2} s^{-1}, and the environmental conditions of air temperature and CO_2 concentration were maintained. The evaluations were performed in the morning, between 9:00 and 11:00 hours, at temperature of 34.51 °C and relative air humidity of 59.12% inside the greenhouse.

Statistical analyses were performed using the statistical program R version 4.2.0. For the nutrition, growth, and gas exchange results, regression analyses (linear and quadratic) were performed, and the equations were chosen based on the significance of the coefficients. Principal component analysis (PCA) (Factoextra package) and Pearson correlation analysis (ggcorrplot2 package) were performed using multivariate analysis of growth and gas exchange variables. For variables with quadratic behavior, the maximum point was determined, that is, the calculated maximum technical efficiency, by deriving the equation.

Results and Discussion

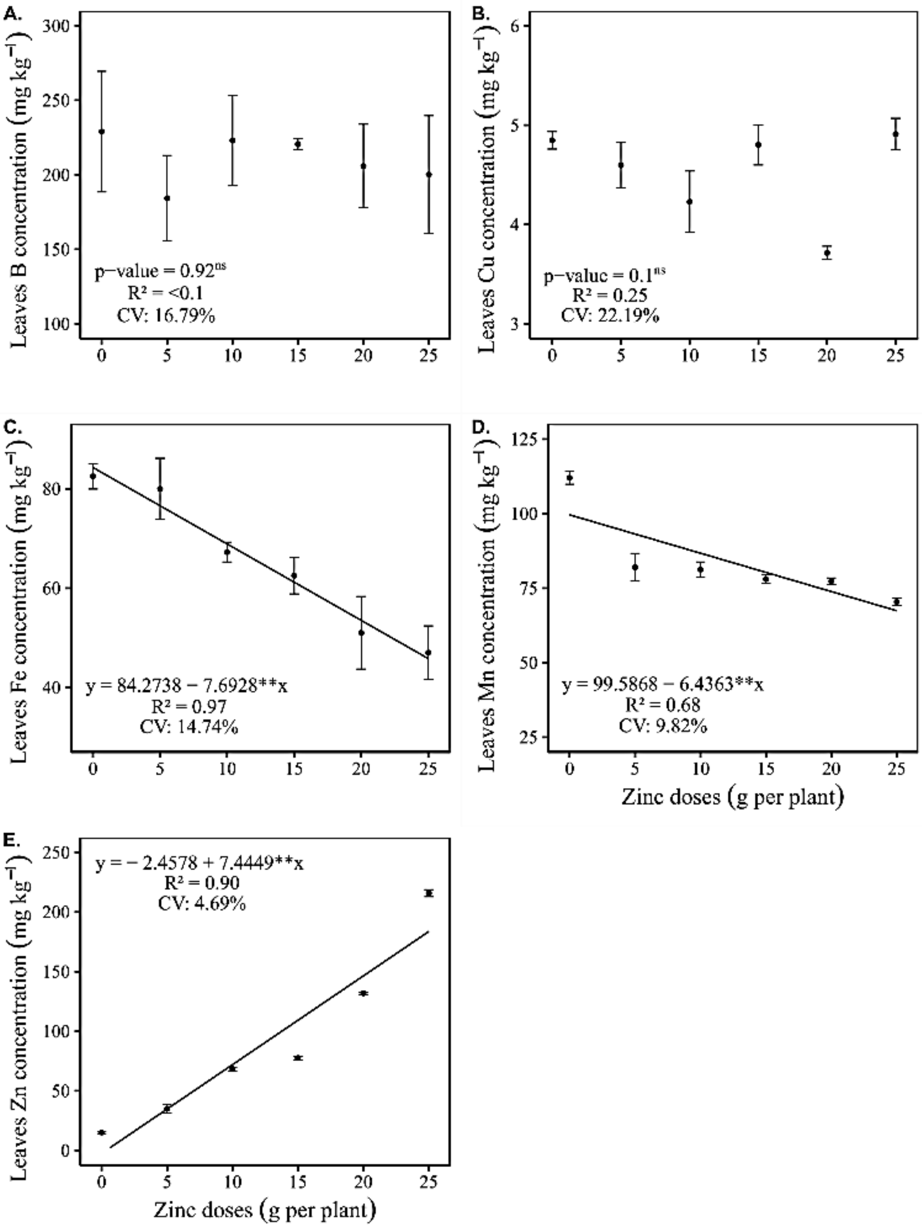
According to the results of the present study, the dose of Zn did not influence the levels of macronutrients in the leaf tissue of coconut seedlings (Figure 1).

Fertilization with Zn influenced the levels of Fe, Mn, and Zn in the leaf tissue (Figure 2). Fe and Mn concentrations were linearly and decreasingly affected by the Zn dose (Figures



ns - Not significant by the F test; R^2 - Coefficient of determination; CV - Coefficient of variation. Vertical bars indicate standard error of the mean (n = 5)

Figure 1. Influence of zinc doses on Nitrogen - N (A), phosporus - P, (B) potassium - K (C), calcium - Ca (D) and magnesium - Mg (E) concentration in the leaf tissue of dwarf green coconut seedlings



ns – Not significant; ** - Significant at $p \leq 0.01$ by the F test; R^2 – Coefficient of determination; CV – Coefficient of variation; Vertical bars indicate standard error of the means (n = 5)

Figure 2. Influence of zinc doses on boron - B (A), cupper - Cu (B), iron - Fe (C), manganese - Mn (D) and zinc - Zn (E) concentration in the leaf tissue of dwarf green coconut seedlings

2C and D), and the Zn concentration was linearly influenced (Figure 2E).

Plants fertilized with Zn had lower Fe and Mn concentrations than non-fertilized plants. The highest reduction occurred at a Zn dose of 25 g per plant, at which the Fe concentration decreased by 45% (Figure 2C) and the Mn concentration decreased by 38% (Figure 2D). Similar results have been reported by Callegari et al. (2022) for 'paricá' (*Schizolobium parahyba* var. *amazonicum*) and Kume et al. (2021) for maize (Zea mays L.), with reductions in the leaf concentrations of Fe and Mn as a function of Zn fertilization. This can be attributed to the antagonistic effect between Zn and Fe and between Zn and Mn in the processes of absorption, transport, and chemical reactions within plant cells (Rai et al., 2021; Almendros et al., 2022).

The reduction in Fe concentration as a function of Zn application allowed the concentration of this micronutrient to be closer to 40 mg kg^{-1}, which is considered adequate for coconut crops (Brasil et al., 2020). The Fe concentration in the leaf tissue of the control plants was 82.50 mg kg^{-1}, 100% above the recommended level for the crop, but no visual symptoms of toxicity were identified in the plant. Excess Fe in leaf tissue can cause nutritional imbalances in plants, inducing a deficiency of nutrients such as P, Ca, K, and Mg. It can also induce the formation of reactive oxygen species and cause severe reductions in plant growth and yield (Jucoski et al., 2016).

Regarding Mn concentration, plants fertilized with Zn showed values between 82 and 70.40 mg kg^{-1}, which are below those reported by Brasil et al. (2020), 100 mg kg^{-1}. However, none of the plants exhibited visual symptoms of Mn deficiency, which is characterized by chlorosis on the surface of young leaves (Prado, 2020).

For every 1 g of Zn applied, there was an increase of 7.44 mg of Zn in the leaf tissue of green dwart coconut seedlings. At the highest dose (25 g per plant), there was an increase of up to 1333%, reaching a concentração of 215 mg kg^{-1} of dry mass (Figure 2E).

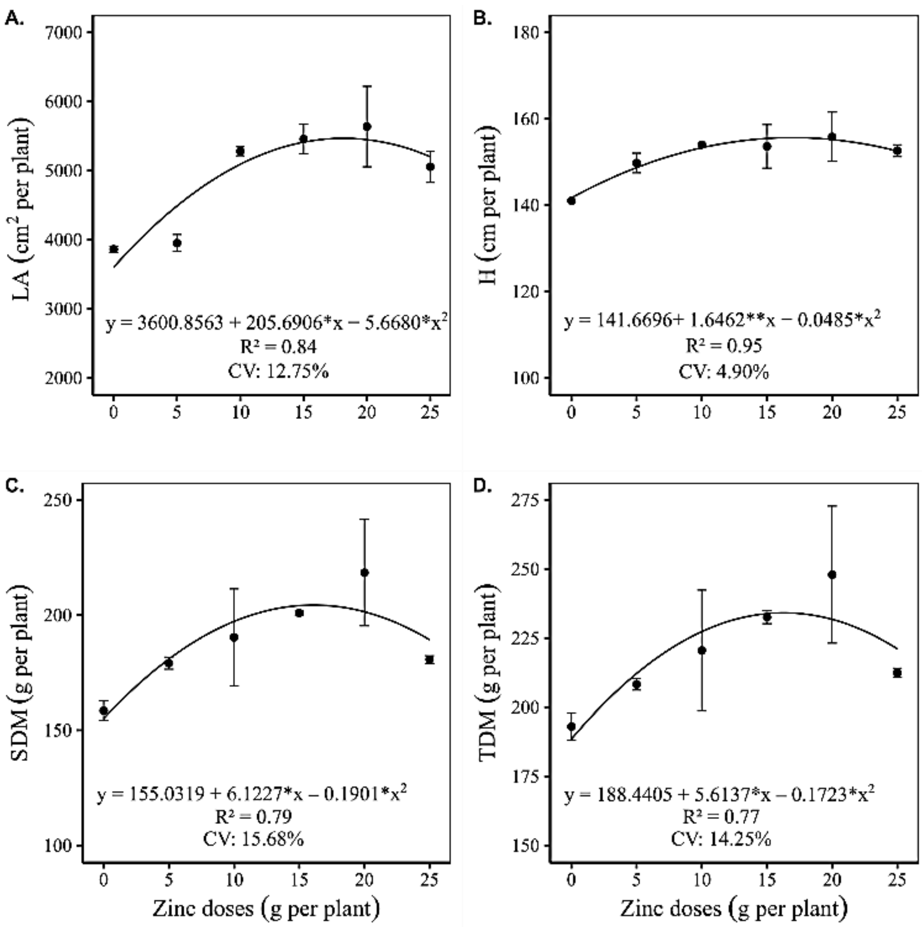
Studies have shown that sensitivity to Zn varies depending on the dose applied and plant species (Gelsleichter et al., 2021). The results presented below show that the increase in the zinc dose, even when increasing the foliar zinc concentration at all doses used (Figure 2E), allowed most growth variables and gas exchange to increase only up to an estimated dose of approximately 16 g per plant, whose Zn concentration in the leaf was approximately 82 mg kg^{-1} of dry mass, gradually decreasing with increasing Zn dose and increased concentration of zinc in the leaf, which was also observed for the garden pea crop by Borah & Saikia (2022).

This demonstrates the importance of managing Zn fertilization in green dwarf coconut seedlings. According to Brasil et al. (2020), the nutritional requirement of young dwarf coconut palms is 15 mg kg^{-1}; therefore, the concentrations of Zn present in the plants that showed the greatest increments in the analyzed variables were above the value required by the culture, with values between 68 and 82 mg kg^{-1}.

LA, H, SDM, and TDM were affected quadratically by Zn foliar fertilization, except for RDM, which was not affected in any way (Figure 3). For LA, the Zn dose estimated at the maximum point was 18.14 g of Zn per plant, with a gain of 205.6 cm^2 per plant for each gram of Zn applied and allowed an increment of 40% when compared to the control treatment, decreasing after this dose (Figure 3A). For H, the dose of maximum technical efficiency was around 16.87 g of Zn per plant, with an increase of 1.66 cm per plant for each gram applied, allowing a gain of 7% when compared to non-fertilized plants, with a decrease from this value (Figure 3B). The SDM head its maximum increase at the estimated dose of 16.10 g of Zn, increasing 6.12 g per plant for each gram added and showed an increase of 29% and a decrease with a dose above 16.10 g of Zn (Figure 3C). And TDM was improved up to the estimated dose of 16.29 g of Zn per plant, with a gain of 5.61 g for each gram of zinc applied, with an increase of 22% when compared to the control treatment (Figure 3D).

The results obtained in this research are similar to those reported in studies conducted with green bean (*Phaseolus vulgaris* L.) by Almeida et al. (2020), eggplant (*Solanum melongena* L.) by Semida et al. (2021), and 'paricá' (*Schizolobium amazonicum*) by Callegari et al. (2022). Thus, zinc fertilization at adequate doses in different cultures is important.

The increase in the growth of coconut seedlings is believed to be because Zn is a regulator of genes involved in the synthesis of amino acids, proteins, carbohydrates, and tryptophan (Liu et al., 2022), which is a precursor of indole acetic acid (IAA), a plant growth hormone that stimulates the development and elongation of young plants (Taiz et al., 2017; Castillo-González et al., 2018). Additionally, the growth of coconut seedlings can be attributed to the enzymatic activation of Zn. The same was suggested by Ahmed et al. (2018) and Khan & Ahmed (2022) who found that Zn improved the growth of mango plants (*Mangifera indica* L.) by activating enzymatic reactions. Zn is a cofactor for more than 300 enzymes, including alcohol



*, ** - Significant at $p \leq 0.05$ and $p \leq 0.01$ by the F test, respectively; R^2 - Coefficient of determination; CV - Coefficient of variation; Vertical bars indicate standard error of the means (n = 5)

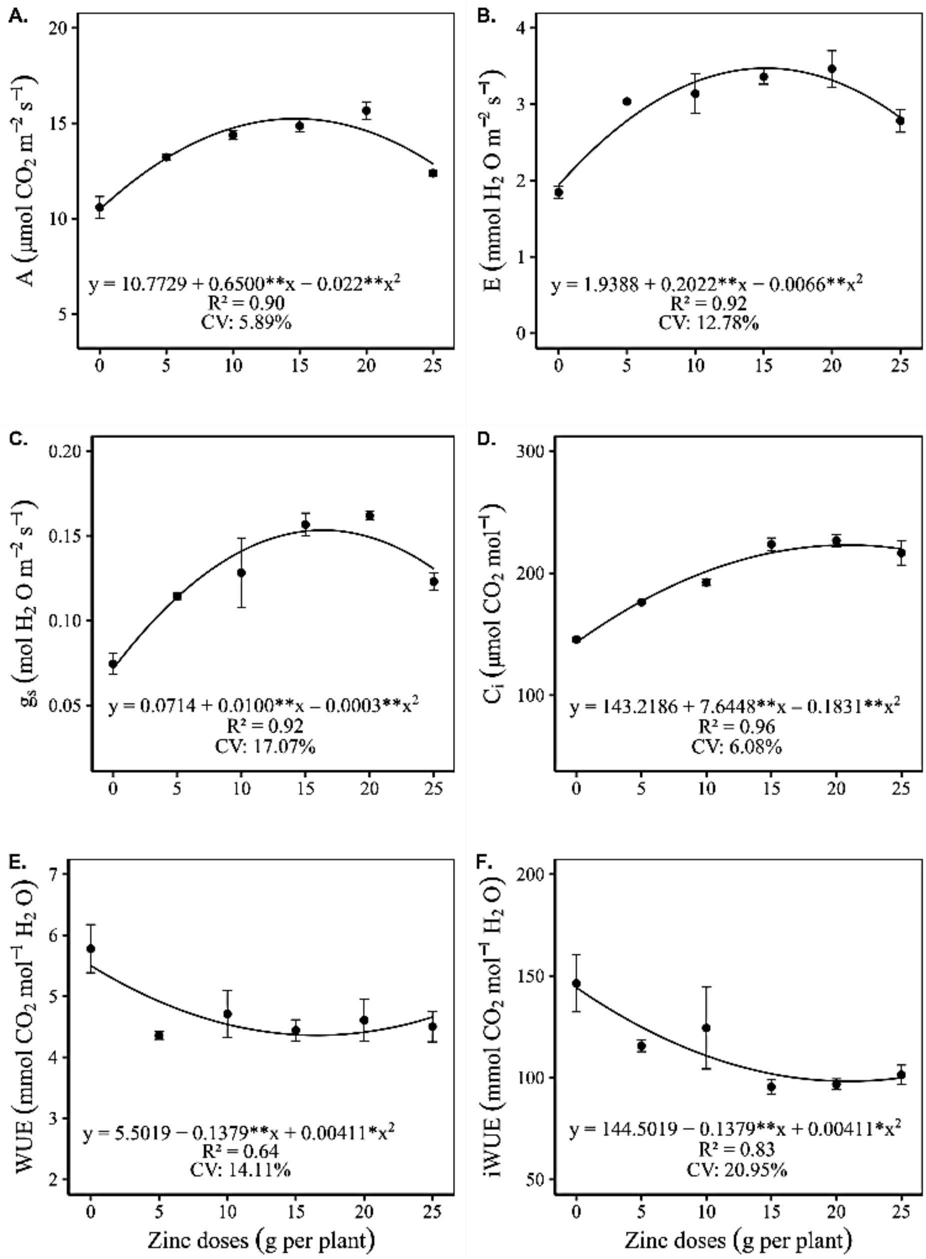
Figure 3. Influence of zinc doses on leaf area - LA (A), height - H (B), shoot dry mass - SDM (C) and total dry mass - TDM (D) of dwarf green coconut seedlings

dehydrogenase, carbonic anhydrase, and RNA polymerase (Castillo-González et al., 2018). RNA polymerase synthesizes RNA; therefore, plants with a low Zn supply show a decrease in protein synthesis due to the lack of messenger and transfer RNAs, which directly compromises the growth of plants (Prado, 2020).

Adequate Zn nutrition is crucial for augmenting plant growth (Ullah et al., 2019). Just as the absence of Zn fertilization compromises plant growth, excess Zn can also cause a reduction in growth rates owing to physiological disturbances, as reported in other plants (Khan et al., 2022). This finding explains the results of the present study. The growth rates of coconut tree seedlings improved with an increase in Zn provided by foliar fertilization; however, as previously mentioned, most growth variables benefited from Zn fertilization up to a dose of 16 g per plant, and reduced in plants that received a dose above that. Thus, both the absence and excess application of Zn can compromise the growth of coconut seedlings. Therefore, it is necessary to adjust the management of this micronutrient to cultivate green dwarf coconut trees.

Zn doses had a positive effect on A, E, gs, Ci, WUE, and iWUE in dwarf green coconut seedlings. The variations in the main variables of gas exchange were similar to those observed for the production of plant biomass; control plants exhibited the lowest values of A, E, gs, and Ci, which increased quadratically with increasing Zn doses (Figure 4).

In variable A, zinc fertilization positively influenced up to the estimated dose of 14.77 g of Zn per plant, with an increase of 0.65 µmol de CO_2 m^{-2} s^{-1} for each 1 g of Zn applied, this is equivalent to an increase of 38% in the photosynthetic rate compared with to the control treatment (Figure 4A). After a dose of 14.77 g of Zn per plant, the photosynthetic rate dropped



*, ** - Significant at p ≤ 0.05 p ≤ 0.01 by the F test, respectively; R^2 - Coefficient of determination; CV - Coefficient of variation; Vertical bars indicate standard error of the means (n = 5)

Figure 4. Influence of zinc doses on photosynthesis - A (A), stomatal conductance - gs (B), internal CO_2 concentration - Ci (C), transpiration - E (D), instantaneous water use efficiency - WUE (E), intrinsic water use efficiency iWUE (F) of dwarf green coconut seedlings

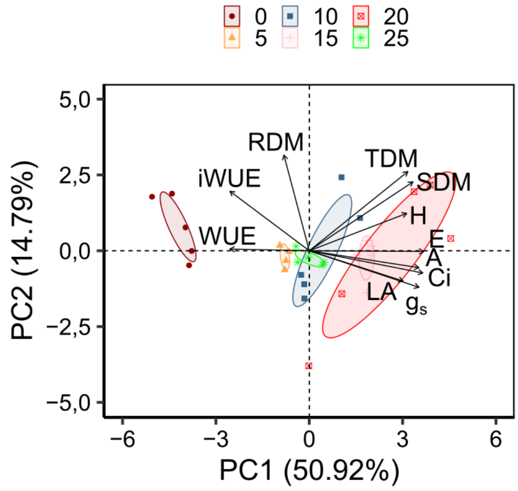
by 0.002 μmol CO_2 m^{-2} s^{-1} for each 1 g of Zn applied (Figure 4A). Therefore, Zn fertilization in coconut palm cultures should be carried out moderately so that the plants are not harmed by excess Zn.

Studies have shown that fertilization with adequate doses of Zn significantly improves the photosynthetic processes of plants (Callegari et al., 2022; Moreira et al., 2021; Ahmed et al., 2022). The results obtained in the present study corroborate those observed in dwarf coconut seedlings. It is suggested that the increase in the A of coconut plants that received Zn is related to the following factors:1) Zn is a cofactor of the plant metalloenzyme called carbonic anhydrase (Taiz et al., 2017); 2) Zn improves chlorophyll concentration in plants (Ahmed et al., 2022; Rehman et al., 2018); 3) Zn is an activator of aldolase, a key enzyme in glycolysis (Castillo-González et al., 2018); and 4) Zn acts in the activation of ribulose 1,5-diphosphate carboxylase, an enzyme of fundamental importance in the photosynthetic process of plants (Prado, 2020).

Carbonic anhydrase catalyzes the dissolution of carbon dioxide, which in turn participates in the neutralization of cellular pH and facilitates the transfer of CO_2/HCO_3 for photosynthetic fixation of carbon dioxide (Taiz et al., 2017). In addition, carbonic anhydrase plays a fundamental role in chlorophyll formation (Ahmed et al., 2022), which improves chlorophyll content and positively affects plant photosynthesis (Ahmed et al., 2022; Das et al., 2018). Aldolase helps to increase the photosynthetic capacity, growth rate, and efficiency of biomass and requires the plant to be well nourished with Zn to function (Castillo-González et al., 2018). Finally, Zn activates ribulose 1,5-diphosphate carboxylase, an enzyme present in chloroplasts, and its presence in adequate amounts in the leaf tissue of crops significantly affects their photosynthetic rate (Prado, 2020). Thus, it was inferred that Zn fertilization at doses of up to 14.77 g per plant was sufficient to improve the processes carried out by carbonic anhydrase, aldalose, ribulose, and chlorophyll, which allowed dwarf coconut seedlings to improve their photosynthetic rates.

In E, Zn fertilization also shows positive influence up to a dose of 15.32 g of Zn per plant, with an increase of 0.20 mmol H_2O m^{-2} s^{-1} in the transpiration rate for each 1 g of Zn applied, with an increase of around of 67% when compared with the plants that did not receive Zn. At a dose of 15.32 g there was a reduction of approximately 0.0066 mmol H_2O m^{-2} s^{-1} for each 1 g of Zn applied (Figure 4B). With regard to gs, Zn fertilization promoted an increase of 0.0010 mol H_2O m^{-2} s^{-1} for each gram of Zn applied up to an estimated dose of 16.73 g of Zn per plant, providing an increase of 83% per plant, compared with the control treatment, and from this dose onwards, Zn caused a decrease of 0.0003 mol H_2O m^{-2} s^{-1} for each gram of Zn applied (Figure 4C). For Ci, the highest value obtained by Zn fertilization was estimated at a dose of 20.88 g of Zn per plant and this dose allowed the increment of Zn to increase Ci by 7.64 μmol CO_2 mol^{-1} per gram applied, thereby, it is clear that Ci decreased by 0.18 μmol CO_2 mol^{-1} per gram of Zn applied with a dose above 20.88 g of Zn per plant (Figure 4D).

It was observed that the increases in E, gs, and Ci due to Zn fertilization showed a strong and positive correlation (Figure 5). In addition, it is important to emphasize that a dose of 16 g of Zn per plant was sufficient to obtain maximum gains for most of the studied variables, both in the analysis of growth and gas exchange. Therefore, 16 g of Zn per plant is the dose for green dwarf coconut trees in the seedling phase.



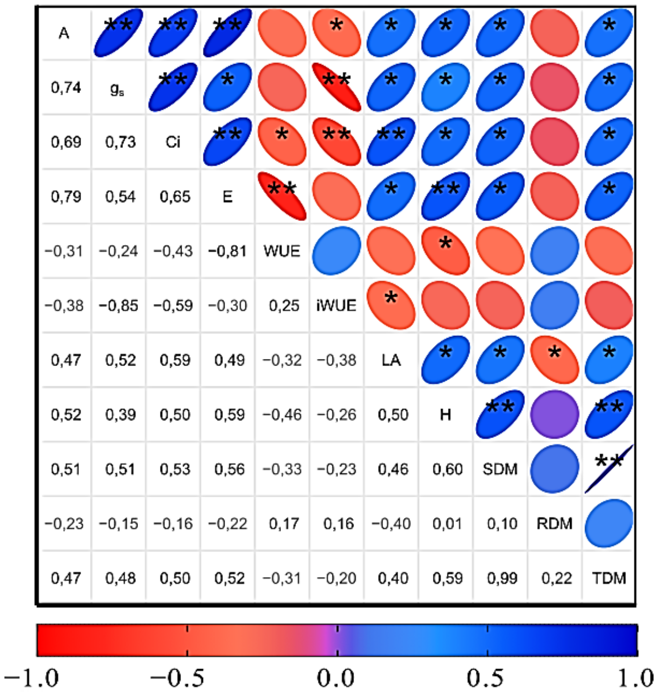
Leaf area (LA), height (H), shoot dry mass (SDM), root dry mass (RDM), total dry mass (TDM), photosynthesis (A), transpiration (E), stomatal conductance (gs), internal CO_2 concentration (Ci) instantaneous water use efficiency (WUE) and intrinsic water use efficiency (iWUE)

Figure 5. Principal component analysis (PCA) of the studied variables of dwarf green coconut seedlings as a function of zinc doses: 0 (without zinc), 5 (5 g of zinc per plant), 10 (10 g of zinc per plant), 15 (15 g of zinc per plant), 20 (20 g of zinc per plant), 25 (25 g of zinc per plant)

The gains observed in E, gs, and Ci were related to the involvement of Zn in the regulation of guard cells (Taiz et al., 2017). Moreira et al. (2021) found a 31% increase in the gs of maize plants as a function of Zn fertilization and attributed this result to the fact that Zn is involved in the functioning of the carbonic anhydrase enzyme, which maintains adequate levels of carbonic acid in the guard cells, controls the uptake of potassium ions (K^+), and maintains the proper functioning of the stomata. The degree of stomatal opening determines the rate of gas exchange through the epidermis (Taiz et al., 2017).

WUE and iWUE decreased in plants treated with Zn, with the best fit for the quadratic model (Figures 4E and F, respectively). A similar result was reported by Moreira et al. (2020), suggesting that Zn increments may increase water-use efficiency, but excess Zn may result in plants with a lower tolerance to water deficit. In this study, the reductions observed for WUE and iWUE can be explained by the increments in E and gs in plants that received Zn and are also due to the supply of water in adequate quantities, allowing the dwarf green coconut seedlings to maintain a high degree of stomatal opening and a high transpiration rate, which was confirmed by the strong negative correlation between WUE and iWUE with E, Ci, and gs (Figure 6).

A two-dimensional representation, known as a biplot, shows the gradient of influence on the growth and gas exchange variables and correlation groups for each Zn dose used in this study (Figure 5). The model, including the principal components, accounted for 65.71% of the total variance explained by the five Zn doses applied and the control (50.92% for PC1 and 14.79% for PC2). The first principal component (PC1) explained 50.92% of the variance and was



*, ** - Significant at $p \leq 0.05$ at $p \leq 0.01$, by Pearson's. The slope of the circles and the degree of coloring are proportional to Pearson's correlation, according to the legend at the bottom of the figure

Figure 6. Correlation matrix showing leaf area (LA), height (H), shoot dry mass (SDM), root dry mass (RDM), total dry mass (TDM), photosynthesis (A), stomatal conductance (gs), internal CO_2 concentration (Ci), transpiration (E), instantaneous water use efficiency (WUE), intrinsic water use efficiency (iWUE) of dwarf green coconut seedlings

positively correlated with TDM, SDM, H, E, A, Ci, LA, and gs and negatively correlated with RDM, WUE, and iWUE. The second principal component (PC2) was positively correlated with TDM, SDM, iWUE, and RDM and negatively correlated with gs and LA, representing 14.79% of the total variance of the data (Figure 5).

Principal component analysis (PCA) showed that the growth and gas exchange variables were positively correlated and influenced by the 20 g dose of Zn per plant. LA and the gas exchange variables A, Ci, and gs were separated in the third quadrant, whereas the other growth variables remained together in the first quadrant. This behavior can be explained by the fact that during the development cycle, the plant depends on the leaves as photosynthesizing organs, and the growth rate depends on both leaf area expansion and the photosynthetic rate per leaf area unit (Guerra et al., 2020). Thus, the evaluation of growth and gas exchange attributes is a key strategy for understanding the importance of Zn fertilization in dwarf green coconut seedlings.

A clear similarity between the SDM and TDM curves was observed in the regression curves (Figures 3C and E), these variables were strongly positively correlated (Figure 6). This suggests that an increase in SDM is a determinant of the results obtained in TDM. These two variables were positively correlated with LA and H (Figure 6).

The productivity of plants is largely determined by their ability to maintain normal growth and the function of their active photosynthetic system (Kaznina et al., 2022). These results demonstrate the importance of fertilization with adequate doses of Zn for the growth and gas exchange of dwarf green coconut seedlings and the need to adapt the nutrition management of the coconut to include Zn as part of the standard fertilization program for the crop in the seedling phase. This will probably result in more vigorous, and consequently, more productive plants.

Conclusions

1. Zn fertilization reduced leaf Fe and Mn concentrations in dwarf green coconut seedlings at all doses used.
2. Zn fertilization up to a dose of 16 g per plant improved the growth rate and photosynthetic performance of green dwarf coconut seedlings.
3. The recommended Zn dose for the maximum technical efficiency of dwarf green coconut seedlings was 16 g per plant.

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