Physiological responses and initial growth of eggplant under nutrient exclusion from nutrient solution

Respuestas fisiológicas y de crecimiento inicial de la berenjena bajo la exclusión de nutrientes en la solución nutritiva

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ABSTRACT

In order to grow eggplant, a certain amount of mineral nutrients is needed to meet plant requirements at the initial phase of growth; with the absence of some nutrients, its physiological responses become compromised. This research aimed to study the physiological responses and initial growth of eggplant under nutrient omission in nutrient solution. The experiment was carried out in 2023 at the Fundação Educacional de Andradina located in the municipality of Andradina, state of São Paulo (Brazil). The experimental design was completely randomized, with nutrient exclusion of magnesium (Mg), boron (B), zinc (Zn), manganese (Mn), or copper (Cu) plus a control group with the supply of all mineral nutrients, with four replicates totaling 20 plots. Magnesium exclusion caused greater damage to the initial growth of eggplant in nutrient solution, with a 33.76% reduction in the concentrations of chlorophylls *a* and *b*; the contents of chlorophylls correlated with the concentration of organic nitrogen in the leaves. Boron exclusion caused deformations of leaf blades.

Key words: *Solanum melongena* L., magnesium, boron, zinc, manganese.

RESUMEN

Para cultivar berenjena, se necesita una cantidad de nutrientes minerales para cubrir sus necesidades en la fase inicial de crecimiento y con la exclusión de algunos nutrientes, sus respuestas fisiológicas se ven comprometidas. Este trabajo tuvo como objetivo estudiar las respuestas fisiológicas y el crecimiento inicial de berenjenas cultivadas bajo exclusión de nutrientes de la solución nutritiva. El experimento se realizó en 2023, en la Fundación Educacional de Andradina, ubicada en el municipio de Andradina, estado de São Paulo (Brasil). El diseño experimental fue completamente al azar, con omisión de los siguientes nutrientes: magnesio (Mg), boro (B), zinc (Zn), manganeso (Mn) o cobre (Cu) más un grupo control con el aporte de todos los nutrientes, con cuatro repeticiones y en total 20 parcelas. La eliminación de magnesio causó mayor daño al crecimiento inicial de la berenjena en la solución nutritiva, lo que provocó una reducción del 33,76% en las concentraciones de clorofilas *a* y *b*, y los contenidos de clorofilas se correlacionaron con la concentración de nitrógeno orgánico en las hojas. La exclusión de boro provocó deformaciones de las láminas foliares.

Palabras clave: *Solanum melongena* L., magnesio, boro, zinc, manganeso.

Introduction

Eggplant (*Solanum melongena* L.) stands out among vegetables as it is grown all over the world due to its nutritional characteristics; it contains dietary fiber, vitamins, and several essential elements such as zinc and iron. Furthermore, it is rich in flavonoids, phenolics and thiamine, which play an important role in human health, with anti-cancer, anti-asthmatic, antioxidant and anti-diabetic effects (Abubakar *et al*., 2023).

The eggplant requires certain quantities of mineral nutrients for its growth and development. This means the plant demands an exact amount of each essential mineral element to complete its cycle (Ghani *et al*., 2023; Rengel *et al*., 2023).

Magnesium (Mg) is a macronutrient that can be found in the soil solution in the form of Mg^{2+}. When its availability is restricted, plants present interveinal chlorosis in older leaves, and, in fruits, magnesium deficiency results in a reduction in size, altering fruit acidity and vitamin C content. Magnesium has several functions in plant metabolism, such as in the activation of enzymes and as part of pigments, where it is positioned at the center of chlorophyll and coordinated by four nitrogen atoms. In addition, Mg acts in ribosome function in the formation of the RNA polymerase

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enzyme, which is fundamental for the synthesis of proteins (Lisboa *et al*., 2024; Shaul, 2002; Taiz & Zeiger, 2013).

The micronutrient boron (B) can be found in the soil as boric acid (H_3BO_3) or borate anion $[B(OH)_4]^-$. This element participates in the biosynthesis of the cell wall along with other physiological processes, including translocation of organic metabolites and biosynthesis of some proteins (Sharma *et al*., 2022). Symptoms of boron deficiency vary between plant species. The most common are a reduction in growth and deformations of organs in the growth zones, especially in the stem apices, with brittle leaves that may be more intensely green (Kohli *et al*., 2023).

Zinc (Zn) can be found in the soil solution in the form of the Zn^{2+} cation, which moves in the soil by diffusion. The loss of Zn from soil through leaching and basic soil pH create the conditions for Zn deficiency in plants. A pH lower than 7.0 is favorable for the uptake of this element by plants (Fernandes, 2006). Zn deficiency manifests in the youngest plant parts as the shortening of the nodes, chlorosis of leaves, reduction in size and deformations in leaf shape (Lisboa *et al*., 2024). It is estimated that 8% to 10% of all eukaryotic proteins contain at least one Zn atom, particularly in oxidoreductases, transferases, hydrolases, lyases, isomerases or ligases, which implies that this element is an activator in the vast majority of enzymes. Zn is now recognized as the most widely used trace element in nature, along with iron (Fe) (Clemens, 2021).

Manganese (Mn) could be highly available in soils, second to iron (Fe) under suitable pH conditions (6.5). It plays an important role in photosynthesis, respiration, and activation of enzymes involved in oxidative stress, particularly in the elimination of reactive oxygen species (ROS). Manganese deficiency compromises growth, development and productivity of plants due to metabolic disorders (Silva & Berti, 2022).

In addition, to the importance of iron and molybdenum in plant growth at the initial stages, copper (Cu) also acts in the formation of the cell wall and regulates the transport of transcription proteins. Under copper limitation, biological processes such as photosynthesis, respiration, antioxidant protection against stress, and metabolic functions of plants are interrupted, affecting the productivity of crops (Yruela, 2005). This study aimed to understand the physiological responses and initial development of eggplant grown under nutrient exclusion from nutrient solution.

Materials and methods

Conditions of the experiment and experimental design

The experiment was carried out in 2023 in the Plant Morphology and Physiology laboratory, with an average temperature of 26°C and relative humidity of 75%, under artificial light provided by light-emitting diode (LED) at a constant intensity of 1000 μmol m^{-2} s^{-1} of photosynthetically active radiation (PAR). The laboratory is located at the Andradina Educational Foundation in the municipality of Andradina, state of São Paulo (Brazil). The experimental design was completely randomized, with exclusion of nutrients, namely magnesium (Mg), boron (B), zinc (Zn), manganese (Mn), and copper (Cu), with a control group with all nutrients. There were four replicates totaling 20 plots, where each plot consisted of one seedling. The seedlings of the Napoli® Sakata variety were obtained from a commercial nursery located in the same municipality, with an average size of 11.95 cm and 3±1 leaflets per seedling.

The seedlings were grown in a nutrient solution with the following concentrations of each nutrient (Furlani, 1998): 0.75 g L^{-1} $Ca(NO_3)_2$; 0.53 g L^{-1} KCl; 0.15 g L^{-1} P_2O_5; 0.4 g L^{-1} $MgSO_4$; $1.5x10^{-2}$ g L^{-1} $CuSO_4$; $2.0x10^{-2}$ g L^{-1} $ZnSO_4$; $1.5x10^{-1}$ g L^{-1} $MnSO_4$; $1.5x10^{-1}$ H_3BO_3; $1.5x10^{-2}$ g L^{-1} Na_2MoO_4; 3.0 g L^{-1} Fe-EDTA (6%). The electrical conductivity was adjusted daily to 2,000±100 μS cm^{-1}, with a pH of 6.4±0.2. Black plastic pots with a capacity of 10 L were used for plant growth, and the nutrient solutions were changed weekly.

Growth variables

After 30 d from the beginning of the experiment, the following variables were measured: plant height (PH), obtained as the difference between the final length minus the initial length expressed in cm using a ruler graduated in mm; number of fully expanded leaves (NL), obtained by the difference between the final and initial number of leaves; leaf area (LA), measured using the Easy Leaf Area application (Easlon & Bloom, 2014); and total dry mass (TDM), weighing together the aerial part and roots, obtained through drying the plants in a circulation and air renewal oven at a constant temperature of 65°C until reaching a constant weight.

Contents of chlorophylls *a* and *b* and organic nitrogen

The first fully expanded leaf was selected from the apex of the plants, where the levels of chlorophyll *a* and *b* (Chlo *a* and Chlo *b*, μmol m^{-2}) were determined through direct reading using a Falker® clorofiLOG device, with values recorded in SPAD units (Parry *et al*., 2014) and subsequently converted into absolute concentrations of pigments as described by Chang and Troughton (1972). The content of organic nitrogen (N-org) in the leaves, expressed in g kg^{-1} of dry mass, was estimated according to Ferreira (2006).

Statistical analysis

For statistical analysis, the variables were subjected to normality tests using the Shapiro-Wilk test; analysis of variance was performed using the F test ($P<0.05$) and the means were compared using the Scott & Knott test at 5% probability (Banzatto & Kronka, 2013). A Pearson correlation analysis was performed using the statistical program R (R Core Team, 2015).

Results and discussion

A statistical difference between the treatments was observed in plant height (PH), where the exclusion of magnesium and then boron and manganese presented the lowest averages, reflecting a reduction of approximately 14.81% in relation to plants that received all nutrients (Tab. 1).

The photosynthetic rate may have been reduced due to magnesium restriction, as this element is a key component of the chlorophyll molecule (Taiz & Zeiger, 2013). Its restriction may compromise photosynthetic electron transport, impairing water photolysis and decreasing the availability of H^+ ions necessary for the formation of $NADPH^+$. As a consequence, CO_2 fixation would be compromised, potentially affecting the development of the eggplant aerial parts (Lisboa *et al*., 2024). A strong positive correlation was observed between LA and NL, as shown in Figure 1.

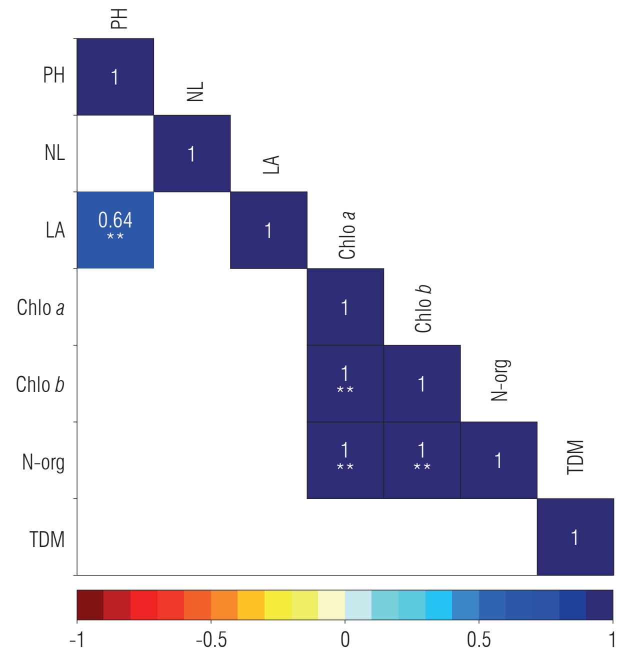

FIGURE 1. Significant Pearson correlation matrix between the variables of plant height (PH), number of leaves (NL), leaf area (LA), chlorophylls *a* and *b* (Chlo *a* and Chlo *b*), organic nitrogen content (N-org) and total dry mass (TDM) of eggplant grown under nutrient exclusion from the nutrient solution.

Therefore, a reduction in the LA of plants may reduce the photosynthetic rate, negatively influencing PH, as shown in Figure 2A.

A statistical difference was not observed for NL; however, a difference was observed in LA where the omission of either boron, magnesium or zinc resulted in the lowest averages of this variable (Tab. 1). Boron withdrawal from the nutrient

TABLE 1. Average plant height (PH), number of leaves (NL), leaf area (LA) and total dry mass (TDM) of eggplant grown under nutrient exclusion from the nutrient solution.

Nutrient solution	PH (cm)	NL	LA (cm^2)	TDM (g)
Complete	31.25^a	8.00	359.31^a	1.21^a
-Mg	26.62^b	7.00	270.68^b	0.49^b
-B	27.25^b	7.25	269.08^b	0.63^b
-Zn	31.00^a	7.50	336.33^a	1.12^a
-Mn	28.12^b	7.50	272.01^b	0.72^b
-Cu	30.37^a	7.75	318.89^a	0.83^b
P-value	0.0056**	0.3485^{ns}	0.0077**	0.0001**
CV%	6.30	8.60	12.12	19.64
OA	29.10	7.50	304.38	0.83

OA: Overall average; CV: Coefficient of variation; ** - significant at 1% probability level ($P<0.01$); * - significant at the 5% probability level ($0.01=<P<0.05$). Means followed by the same letter do not differ statistically. The Scott & Knott test was applied at a level of 5% probability of the event occurring.

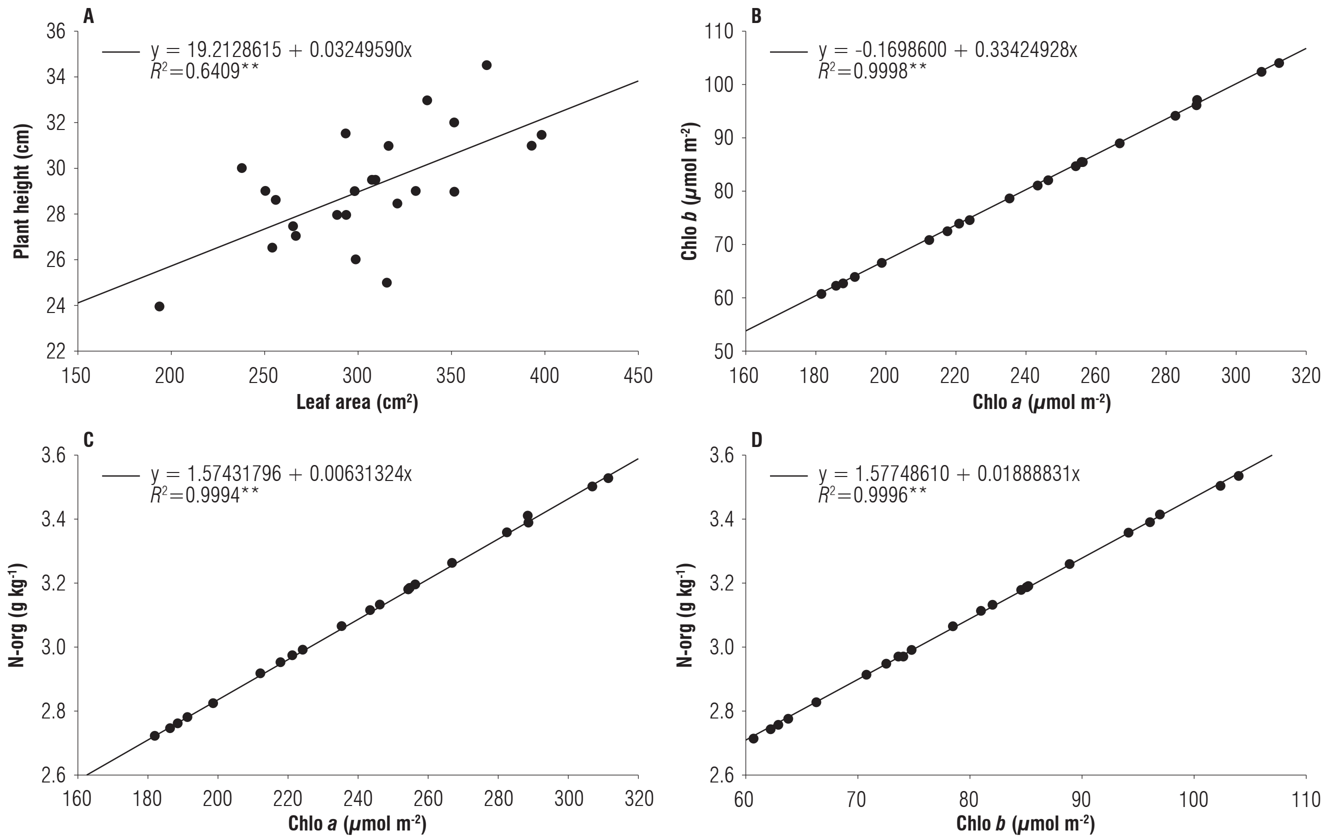

FIGURE 2. Significant linear regressions after Pearson's correlation between the variables plant height (PH), leaf area (LA), contents of chlorophylls *a* and *b* (Chlo *a* and Chlo *b*), organic nitrogen content (N-org) of eggplant grown under nutrient exclusion from the nutrient solution.

solution presented the lowest average, with a difference of approximately 25.11% in relation to the plants that received all nutrients. Notably, the poor formation of the eggplant leaves that were grown under exclusion of boron is seen in Figure 3, where the leaf blade is characterized by ribbed intervein spaces.

It is worth noting that cultivation under the restriction of magnesium, manganese and copper most contributed to the negative effects on the growth of eggplant in a nutrient solution, as shown in Figure 4.

The restriction of these elements, especially magnesium and boron, can compromise the metabolism of biomolecules such as sucrose (primary) and cellulose and lignin (secondary), which can alter morphology of leaf tissues, especially leaf size. These results corroborate with Lisboa *et al*. (2024). Furthermore, significant changes in temperature, light intensity, and water availability can further exacerbate these changes in plant morphology (Ohnishi *et al*., 2023).

Nutrient restrictions also influenced the TDM of eggplant. The crop with all nutrients and those without zinc presented the highest averages. The crop with all nutrients presented a difference of 59.20% higher in relation to the crop with magnesium restriction, which presented the lowest average total dry mass (Tab. 1).

This response to magnesium restriction was expected as similar results were reported by Lisboa *et al*. (2024) and Lisboa, Galindo *et al*. (2024), who highlighted the importance of magnesium in gas exchange and development in tomato and pepper. When the plant undergoes sudden changes in leaf gas exchange, its dry mass is compromised due to impaired carbon fixation, which is dependent on electrons captured by $NADP^+$ in the light-dependent phase of photosynthesis. This restriction affects the metabolic action of the 1,5-bisphosphate carboxylase/oxygenase, commonly known as Rubisco, crucial in the Calvin cycle (Taiz & Zeiger, 2013).

This negative response due to the restriction of nutrition in the formation of chlorophylls *a* and *b* is observed in Table 2. The absence of the Mg, Zn, and Mn resulted in lower averages, with approximately 33.76% and 33.91% lower contents of chlorophylls *a* and *b*, respectively, in relation to plants that were grown with all nutrients. Due to their same metabolic origin, chlorophylls *a* and *b* present a significant correlation, as seen in Figures 1 and 2B.

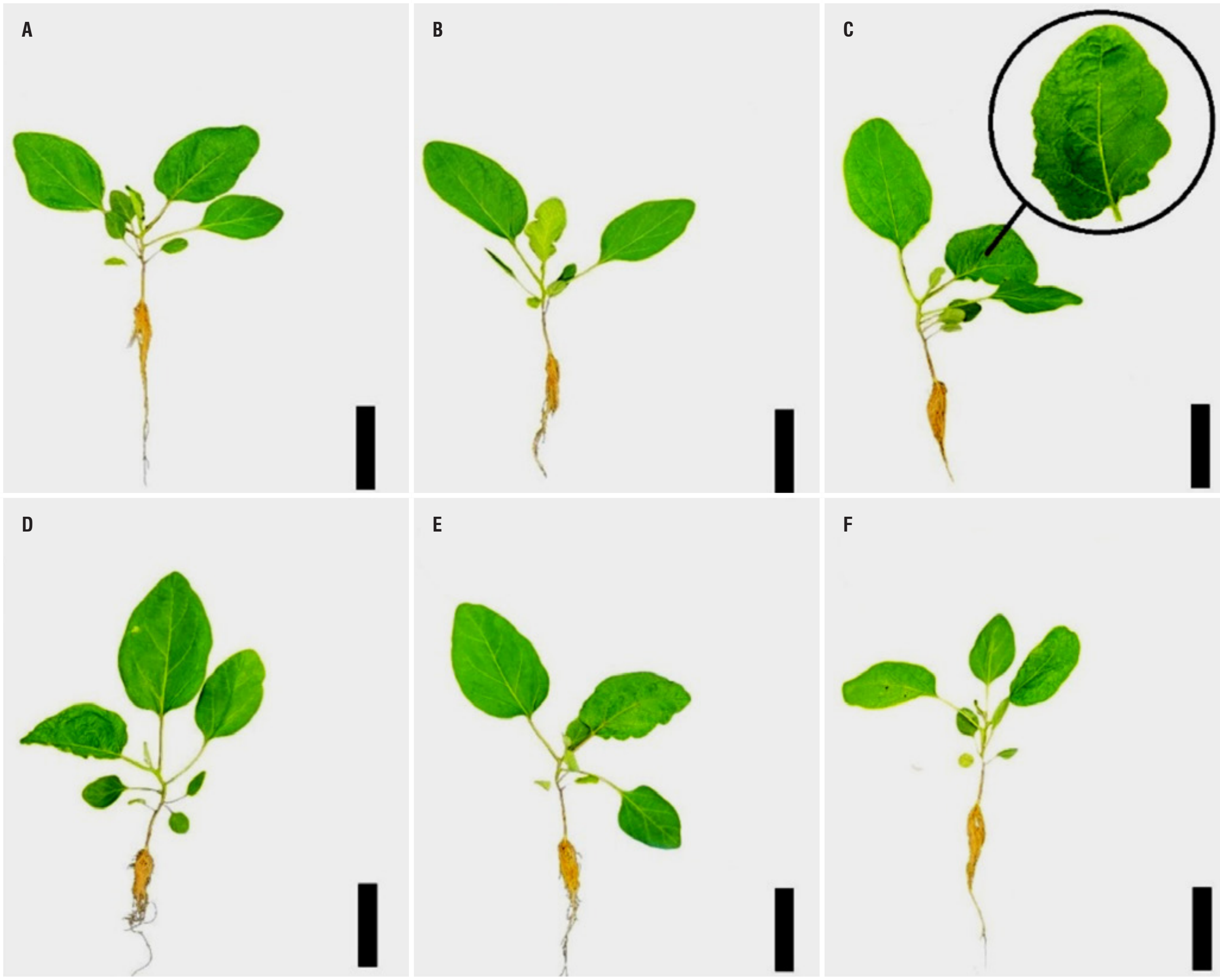

FIGURE 3. Eggplant plants grown under nutrient exclusion from the nutrient solution: A = Complete nutrient solution; B = absence of Mg; C = absence of B; D: absence of Mn; E = absence of Cu, and F = absence of Zn. Bar = 10 cm.

TABLE 2. Average contents of chlorophyll *a* and *b* (Chlo *a* and Chlo *a*, μmol m^{-2}) and organic nitrogen content (N-org, g kg^{-1}) in leaves of egg-plant grown under nutrient exclusion from nutrient solution.

Nutrient solution	Chlo *a*	Chlo *b*	N-org
Complete	294.32[a]	98.32[a]	3.43[a]
-Mg	194.93[c]	64.97[c]	2.80[c]
-B	249.78[b]	83.26[b]	3.15[b]
-Zn	206.62[c]	68.87[c]	2.87[c]
-Mn	232.94[c]	77.64[c]	3.04[c]
-Cu	259.85[b]	86.61[b]	3.21[b]
P-value	0.0003**	0.0003**	0.0003**
CV%	10.54	10.51	5.14
AO	239.74	79.96	3.08

OA: Overall average; CV: Coefficient of variation. ** - significant at 1% probability level ($P<0.01$); * - significant at the 5% probability level ($0.01=<P<0.05$). Means followed by the same letter do not differ statistically. The Scott & Knott test was applied at a level of 5% probability of the event occurring.

Due to the low concentration of nutrients in the leaves, particularly magnesium, which is a critical component of chlorophyll molecules (Pranckietienė *et al*., 2020), where it is linked with four nitrogen atoms (N), the biochemical phase of photosynthesis is compromised. This restriction reduces the assimilation of atmospheric carbon dioxide, which is necessary for conversion into glucose. Magnesium is also required for the activation of the Rubisco enzyme, which is present in chloroplasts (Taiz & Zeiger, 2013).

When plants are under stress, they experience the production of reactive oxygen species (ROS), which increases the concentrations of antioxidant enzymes. If the stress is for a long period and/or high intensity, ROS can cause serious damage to the cell structures, mainly DNA, lipids, cell membranes, and proteins (Reis *et al*., 2018).

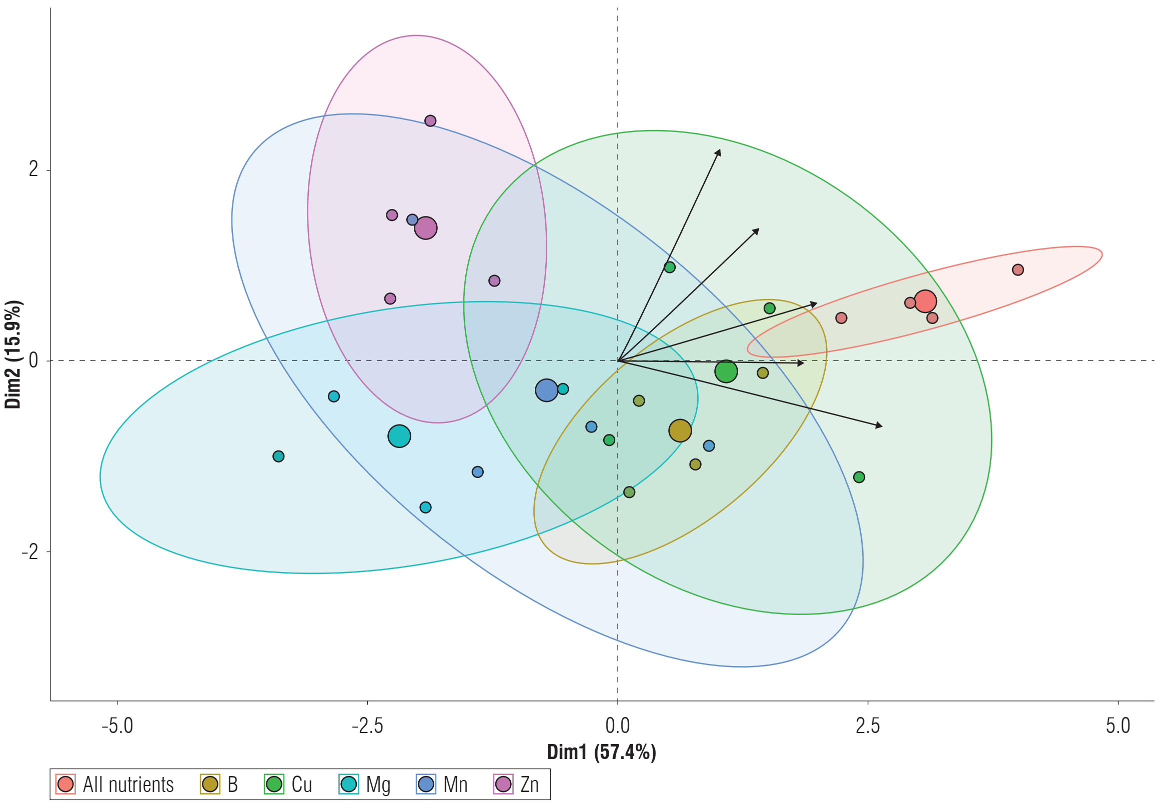

FIGURE 4. Biplot chart of the significant principal component analysis of eggplant grown under nutrient exclusion from the nutrient solution.

With this bond between the magnesium atom and nitrogen (Mg-4N) in the chlorophyll molecule, the magnesium restriction may have caused a lower concentration of N-org in eggplant leaves. This effect is well illustrated in Figures 1 and 2D, demonstrating this correlation between chlorophyll contents and N-org concentration.

Therefore, due to this correlation, nitrogen deficiency in the leaves caused by magnesium restriction (Fig. 1) starts to influence the intensity of the green color in the leaves. Many studies have already reported the correlation between the intensity of the green color and nitrogen concentrations, which can be an important factor when calculating fertilization in crops (Chang & Troughton, 1972; Silva *et al*., 2014).

Conclusions

Magnesium exclusion from the nutrient solution causes significant damage to the initial growth of eggplant grown in nutrient solution, resulting in a 33.76% reduction in the concentrations of chlorophylls *a* and *b*. The contents of these pigments correlated with the concentration of organic nitrogen in the leaves. Boron exclusion from the nutrient solution caused deformations in the leaf blades.

Conflict of interest statement

The authors declare that there is no conflict of interests regarding the publication of this article.

Author's contributions

LAML: conceptualization, research, writing - original draft, visualization, writing, and editing. MHRP: conceptualization, writing, and supervision editing. MAS: conceptualization, visualization, writing, and editing. MCF: conceptualization, writing, and editing supervision. All authors have read and approved the final version of the manuscript.

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