The Original

Deficit and excess of nutrients in maize crop: morphological and agronomic effects

T.A. Segatto[1], I.R. Carvalho[2], W.J.A. Bandeira[2], L.C. Pradebon[2], M.V. Loro[1], J.P. Sangiovo[2]

[1]Universidade Federal de Santa Maria, Centro de Ciência Rurais, Departamento de Fitotecnia, Avenida Roraima, Cidade Universitária, Camobi, Prédio 77, CEP 97105-900 Santa Maria, RS, Brazil.
[2]Universidade Regional do Noroeste do Rio Grande do Sul, Departamento de Estudos Agrários, Avenida do Comércio, nº3.000, Bairro Universitário, CEP 98700-000, Ijuí, RS, Brazil.

Corresponding Author: Ivan Ricardo Carvalho
Email: carvalho.irc@gmail.com

Genet. Mol. Res. 23 (4): gmr2316
Received May 14, 2024
Accepted December 26, 2024
Published December 30, 2024
DOI http://dx.doi.org/10.4238/gmr2316

ABSTRACT. Nutritional disorders can lead to a decline in plant growth due to changes in nutritional efficiency. The present study aimed to evaluate the morphological development of corn plants grown in nutrient solutions with excess and deficit of macro and micronutrients. We used 30 scenarios with different combinations of nutrient presence and absence to simulate nutrient deficits and excesses. Incandescent and fluorescent lamps connected to a timer were used to simulate the hours of light and dark, in order to meet the demand for light for the photosynthesis process of the plants. The ambient temperature was controlled, remaining close to 30°C. The laboratory remained closed in order to prevent the entry of insects and pathogens. The nutrient solutions were replaced every 15 days, in addition to replacing the water lost in the process of evapotranspiration of the plants. Linear correlation analysis between pairs of characters, cluster analysis using Euclidean distance and principal component analysis were carried out. Excess aluminum had an influence on the change in the total biomass

produced and the height of the corn plants. Sulfur, copper and zinc caused changes in the root system. Excess nitrogen and sulfur caused necrosis and yellowing of the leaves. Magnesium deficiency caused curling and chlorosis of the leaves. Nitrogen deficiency promoted lower values of root length, plant height and shoot green weight.
Key words: *Zea mays*; Nutrition; Correlation, Eucliadian distance.

INTRODUCTION

Maize (*Zea mays* L.) is one of the most cultivated crops in the world, where the grains are destined for the processing industry for human food and animal nutrition, in addition to ethanol production (Bilhalva et al., 2023). The crop requires proper fertilizer management (Oliveira et al., 2019), where knowledge of nutritional requirements during the cycle makes it possible to increase the agronomic and economic efficiency of the production system (Maranhão et al., 2018).

The availability of soil moisture and the amount of adequate nutrients can regulate root growth, delay leaf senescence, and promote grain filling and yield (Ali et al., 2018; Ali et al., 2019; Wu et al., 2022). On the other hand, problems of deficiency or excess of nutrients applied without many criteria are constantly identified (Rezende et al., 2010). Both the lack of a certain element and its excess can reflect in productivity declines caused by damage to plant metabolism, with low efficiency in the use of fertilizers (Elemer and Datnoff, 2014).

The diagnosis of nutritional disorders is complex, as the deficiency or excess of several elements can occur simultaneously in different plant tissues, in addition to the fact that the deficiency of one element can contribute to the excessive absorption of another (Taiz et al., 2017). In addition, soil heterogeneity is an intrinsic property of the same, resulting from the action of formation components, influencing the availability of nutrients and structuring for cultivation (Pavinato and Rosolem). In this context, the technique of growing plants in nutrient solution has allowed advances in the knowledge of plant nutrition and foliar diagnosis, by providing adequate control of the composition of the solution, bypassing the heterogeneity and complexity presented by the soil (Gondim et al., 2016).

Based on the above, it is evident that nutritional disorders can lead to a decline in plant growth due to changes in nutritional efficiency. In this context, the present study aimed to evaluate the morphological development of corn plants grown in nutrient solutions with excess and deficit of macro and micronutrients.

MATERIAL AND METHODS

The experiment was carried out at the Production Physiology Laboratory of the Regional University of the Northwest of the State of Rio Grande do Sul (UNIJUÍ), located in the municipality of Ijuí/RS, conducted on a bench, using glass containers with a capacity of three liters. The corn seedlings were submitted to the complete nutrient solution, allowing uniform initial development without nutritional restrictions, in a period of seven days, being relocated to other containers that received the treatments.

30 scenarios were used: I - complete (nitrogen - N, phosphorus - P, potassium - K, calcium - Ca, magnesium - Mg, sulfur - S, boron - B, chlorine - Cl, copper - Cu, iron - Fe , manganese - Mn, molybdenum - Mo and zinc - Zn); II - absence of all macro and micronutrients (water only); III - double the nutrients; IV - absence of nitrogen (-N); V - absence of phosphorus (-P); VI - absence of potassium (-K); VII - absence of calcium (-Ca); VIII - absence of magnesium (-Mg); IX - absence of sulfur (-S); X – absence of boron (-B); XI - absence of manganese (-Mn), XII - absence of zinc (-Zn) XIII - absence of copper (-Cu); XIV - absence of molybdenum (-Mo); XV - absence of iron (-Fe); XVI - excess nitrogen (+N); XVII - excess phosphorus (+P); XVIII - excess potassium (+K); XIX - excess of calcium (+Ca); XX - excess magnesium (+Mg); XX1 - excess sulfur (+S); XXII- excess boron (+B); XXIII - excess of manganese (+Mn), XXIV - excess of zinc (+Zn) XXV - excess of copper (+Cu); XXVI - excess of molybdenum (+Mo); XXVII - excess iron (+Fe); XXVIII - excess of aluminum (+Al); XXIX - excess sodium (+Na) and; XXX - absence.

The solutions were prepared based on salts, which were weighed, distributed and dissolved in different containers according to the treatment. The chemical composition of nutrient solutions (mL L^{-1}) that were used to make the solutions are: KH_2PO_4 mol L^{-1}, KNO_3 mol L^{-1}, Ca $(NO_3)_2$ $.4H_2O$ mol L^{-1}, $MgSO_4.7H_2O$ mol L^{-1}, K_2SO_4 0,50 mol L^{-1}, $CaSO_4$ 0,01 mol L^{-1}, Ca $(H_2PO_4)_2$ 0,05 mol L^{-1}, Mg $(NO_3)_2$. 6 H_2O mol L^{-1}, Micronutrientes, Fe – EDTA.

Incandescent and fluorescent lamps connected to a timer were used to simulate the hours of light and dark, in order to meet the demand for light for the photosynthesis process of the plants. The ambient temperature was controlled, remaining close to 30°C. The laboratory remained closed in order to prevent the entry of insects and pathogens. The nutrient solutions were replaced every 15 days, in addition to replacing the water lost in the process of evapotranspiration of the plants.

The variables Green Leaf Area Index (GLI, index), Normalized Green-Red Difference Index (NGRDI, index), Blue Green Pigment Index (BGI, index), phenological stage (STA, %), normal plants (NP, %), abnormal plants (AP, %), chlorosis (CHL, %), yellowing of leaves (YL, %), leaf edge damage (LED, %), curling (CUR, %), necrosis (NEL, %), root aggressiveness (RAG, %), root length (RLE, cm), normal roots (NR, %), thick roots (TR, %), straight roots (SR, %), deformed roots (DR, %), radicle (RAD, %), shoot green weight (SGW, g), root green weight (RGW, g), shoot dry weight (SDW, g), root dry weight (RDW, g), shoot length (SL, cm), root length (RLE, cm) and plant height (PH, cm) for each of the treatments. The indices were obtained using phenomic analysis, from the reflectance of RGB band colors, where the Green Leaf Area Index levels were calculated by the equation GLI = (2G-R-B)/(2G+R+B), the Normalized levels Green-Red Difference Index were calculated by the equation NGRDI = (G-R)/(G+R) and Blue Green Pigment Index levels were calculated by the equation BGI = B/G.

In order to organize, summarize and describe the information that was collected, descriptive analysis of the data was carried out to identify the distribution trend of values. To understand the degree of relationship between the variables studied, a simple correlation analysis was carried out to infer the linear association measures between two variables. Seeking to verify the association between one or more nutrients in the effects caused in plants, cluster analysis was used, considering the average values for individuals and using Euclidean distance to form the groupings. As a way of complementing the previous analyses, principal components analysis was used to identify the relationship between nutrients and variables, considering nutrient deficit and excess. The analyzes were conducted with the aid of the R software (R Core Team, 2022).

RESULTS AND DISCUSSION

The portion of the leaf area composed of green leaf area (GLI) consists of the photosynthetically functional component (Viña et al., 2011). For the Green Leaf Area Index, or GLI (Figure 1a) values observed, treatments with excess boron, sulfur and molybdenum presented the highest indexes, followed by treatments with a deficit of zinc, potassium and nitrogen. The lowest values for the index were identified in treatments with magnesium deficit, phosphorus deficit, excess manganese and excess zinc. Considering the values for the variable Normalized Green-Red Difference Index (NGRDI, Figure 1b), only treatments with excess manganese and excess zinc were below the general average. The highest values for this index were obtained for treatments with excess boron, calcium and iron, as well as for treatments with a deficit of copper, manganese, phosphorus and zinc. The NGRDI index is calculated by reflectance in the green and red parts of the spectrum (Jannoura et al., 2015), and can be used to determine nutrient status (Hunt et al., 2005). On the other hand, for the Blue Green Pigment Index (BGI, Figure 1c) values, most treatments were below the general average, where the deficit of phosphorus and magnesium and the excess of manganese and zinc reached the highest values for the index.

The effects of treatments that simulated both excess and deficit of nutrients did not show great contrast for the phenological stage variable (STA, Figure 1d), except for treatments with potassium and phosphorus, where the phenological stage advanced more quickly when the plants were submitted to the solution with deficit of these nutrients. Considering the number of normal and abnormal plants evaluated (NP and AP, Figure 1e; 1f), only the treatments with excess boron, iron deficit, manganese excess and phosphorus deficit showed abnormal seedlings.

Leaf chlorosis (CHL, Figure 1g) was more evident in treatments with nutrient deficit, especially when the plants were subjected to a magnesium and iron deficit, which presented 100% chlorosis, in addition to a boron, calcium and manganese deficit. Magnesium, together with nitrogen, are the only nutrients in the soil that are constituents of chlorophyll (Pereira et al., 2020), in addition to acting in phosphorylation, translocation of photoassimilates and the activation of several enzymes (Römheld and Kirby, 2007). The same behavior was identified in treatments with excess manganese and magnesium, mainly, in addition to potassium, copper, phosphorus and zinc. The characteristic of yellowing of the leaves (YL, Figure 1h) was observed largely in plants grown in nutritional solution with a deficit of iron, magnesium and sulfur and with an excess of boron and magnesium. Both the deficit and the excess of molybdenum did not cause yellowing of the leaves.

As for the edge damage variable (LED, Figure 1i), the highest percentages occurred for excess magnesium, calcium, potassium, nitrogen and sulfur and also for magnesium deficit. Values below the average were computed for nitrogen and calcium deficit, in addition to zinc and manganese excess, as well as for potassium deficit, which did not cause edge damage. Dynamically, all treatments caused curling (CUR, Figure 1j), as it is an early symptom and quite characteristic of some nutritional disorder in the plant, not being identified only for potassium deficit.

The most frequent change in leaf color is chlorosis, changing to light green or yellowish. The evolution of chlorosis is necrosis, which according to Taiz et al. (2017) are characteristic symptoms of phosphorus deficiency, in which the leaves have small points of dead tissue. The highest levels of necrosis (NEL, Figure 2a) were observed in plants that were subjected to excess calcium, potassium, magnesium and nitrogen, in addition to a deficit of calcium, magnesium, molybdenum and nitrogen. Necrosis was not identified only for plants that developed in solution with potassium and manganese deficit.

Figure 1. Mean and frequency distribution of the variables Green Leaf Index (a), Normalized Green-Red Difference Index (b), Blue Green Pigment Index (c), phenological stage (d), normal plants (e), abnormal plants (f), chlorosis (g), yellowing of leaves (h), leaf edge damage (i) and leaf curling (j) for treatments with nutrient excess and nutrient deficit in maize plants grown in different nutrient solutions. Mg: magnesium; N: nitrogen; Mn: manganese; Na: sodium; Cu: copper; Al: aluminum; Fe: iron; Mo: molybdenum; P: phosphorus; K: potassium; Ca: calcium; Zn: zinc; B: boron; S: sulfur.

The deficiency of iron, magnesium, manganese, phosphorus and sulfur and also the excess of magnesium and nitrogen were decisive for the occurrence of abnormalities in the root system. According to Khan et al., (2017), maize growth dynamics and crop grain yield are strongly associated with N, as it is one of the main constituents of chlorophyll and nucleic acid. Furthermore, the deficit of boron, molybdenum and nitrogen as well as the excess of calcium, copper and sulfur had no effect on the percentage of normal roots (NR, Figure 2b).

The root aggressiveness system (RAG, Figure 3c) did not vary significantly for the treatments in which the characteristic was observed, with the highest percentages for the deficit of boron, calcium, potassium and nitrogen and for the excess of calcium and zinc. Similar behavior occurred for the variable root length (RLE, Figure 2d), where practically all treatments exceeded, for excess calcium, phosphorus and zinc and deficit of calcium, potassium, nitrogen and zinc, or were close to 90cm. The lowest RLE values were evaluated in plants subjected to excess magnesium.

The percentage of thick roots (TR, Figure 2e) was higher when plants developed in excess of boron, calcium, potassium, magnesium and zinc as well as in deficit of molybdenum and zinc. This characteristic was not so intense when in excess of iron and sulfur and in deficit of magnesium and phosphorus. For the variable straight roots (SR, Figure 2f) the excess of boron, potassium, nitrogen and sulfur did not have a negative influence, in addition to the deficit of calcium and zinc. The excess of molybdenum and the deficit of potassium, molybdenum and phosphorus negatively affected the percentage of straight roots.

Only treatments with iron, potassium, magnesium, manganese, molybdenum and phosphorus showed deformed roots (DR, Figure 2g), with emphasis on treatments with magnesium excess and iron and manganese deficit, where all evaluated plants showed the characteristic. In general, both excess and deficit of nutrients stimulated a high formation of radicle (RAD, Figure 2h), mainly for nitrogen deficit, where all plants showed a high formation of rootlets. One of the essential micronutrients for the crop is boron, where Berlezi et al., (2019), working with the application in maize silage, identified that the plants submitted to this experiment presented a greater biomass production in relation to the control, in addition to greater root growth, allowing greater access to water in drought conditions.

All treatments were above the overall average for the variable shoot green weight (SGW, Figure 2i), where the highest values were observed in treatments with an excess of molybdenum and iron, as well as with a deficit of nitrogen, boron and manganese. For the variable root green weight (RGW, Figure 2j) a behavior similar to that of the SGW was observed, with plants grown in solution with an excess of molybdenum, calcium, sulfur and zinc and with a deficit of potassium, boron, nitrogen and phosphorus showing the greatest values.

For shoot dry weight (SDW, Figure 3a) greater segregation in values was identified. Treatments with iron and molybdenum excess and nitrogen and potassium deficit showed the highest values. Excess molybdenum also did not cause root development problems, as it was the treatment with the highest value for the variable root dry weight (RDW, Figure 3b), in addition to the potassium deficit, which also demonstrated the same behavior. Gondim et al., (2010), working with the nutritional efficiency of corn in nutrient solutions, found that the omission of macronutrients promotes a decrease in the dry weight production of the aerial part and the efficiency of nutrient absorption.

Shoot length (SL, Figure 3c) was affected by excess boron and manganese, being the only treatments that were below the average for the variable. The highest values were identified for the

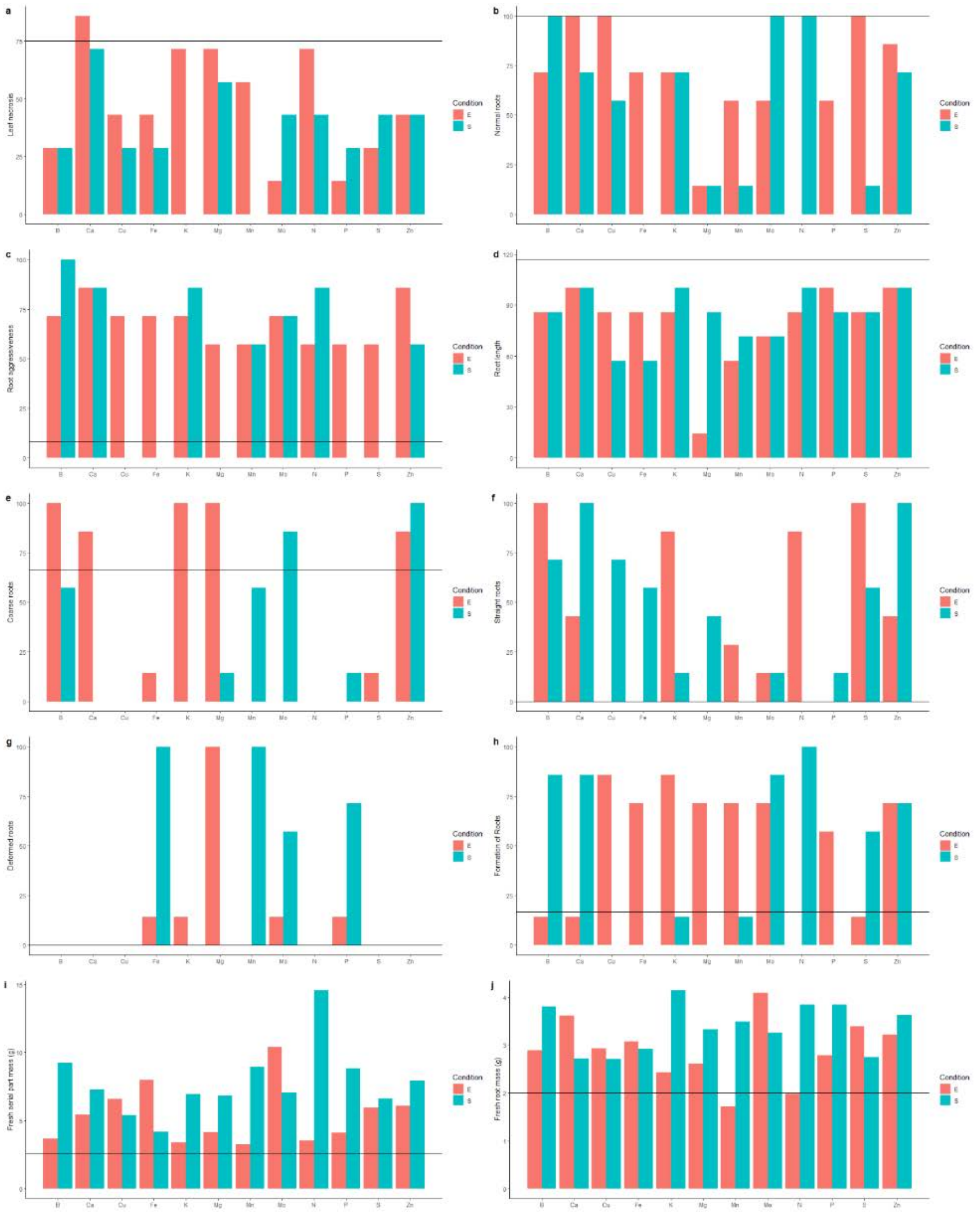

Figure 2. Mean and frequency distribution of the variables necrosis (a), normal roots (b), root aggressiveness system (c), root length (d), thick roots (e), straight roots (f), deformed roots (g) , rootlets (h), shoot green weight (i) and root green weight (j) for treatments with nutrient excess and nutrient deficit in maize plants grown in different nutrient solutions. Mg: magnesium; N: nitrogen; Mn: manganese; Na: sodium; Cu: copper; Al: aluminum; Fe: iron; Mo: molybdenum; P: phosphorus; K: potassium; Ca: calcium; Zn: zinc; B: boron; S: sulfur.

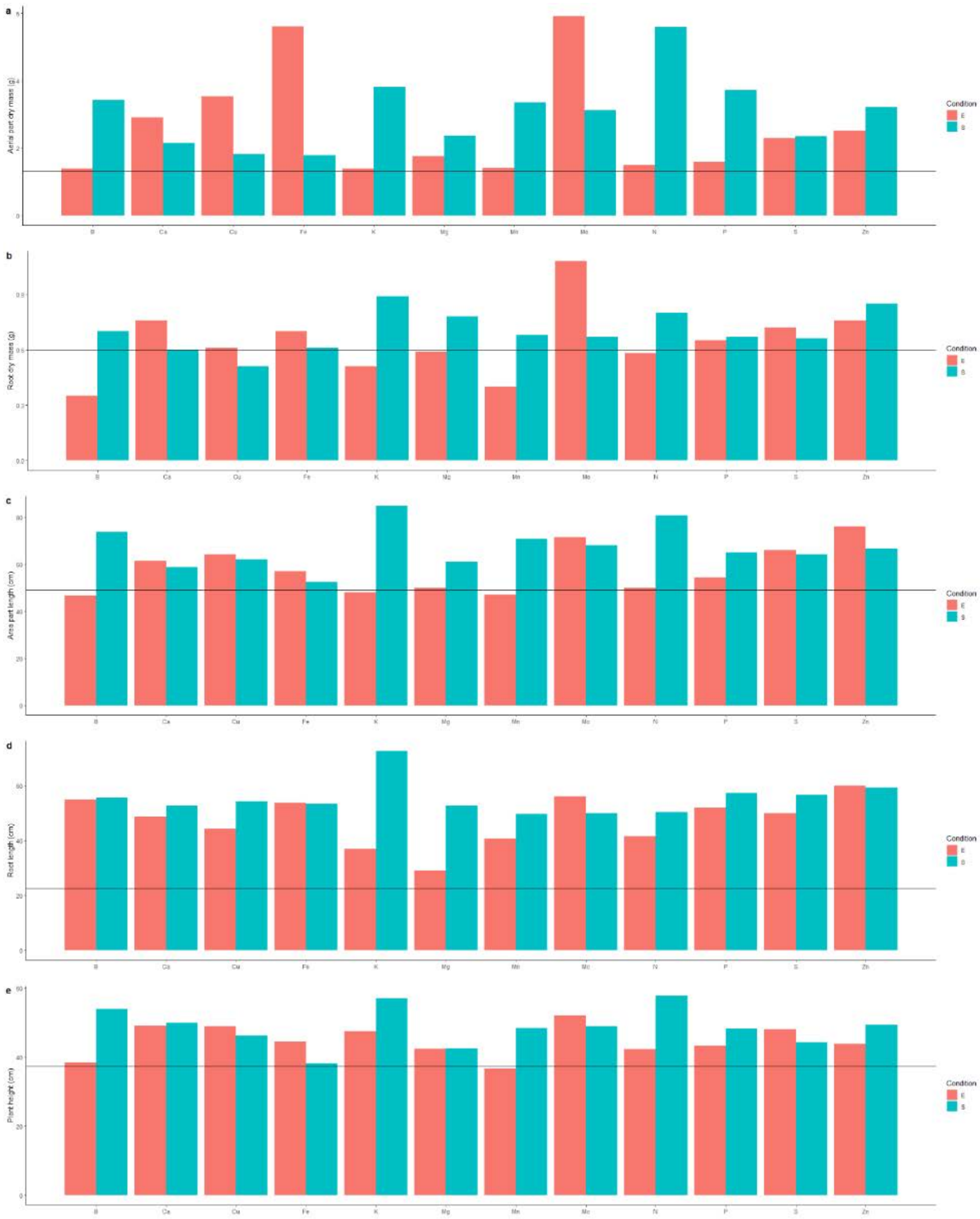

Figure 3. Considering the linear correlations for excess nutrients (Figure 4), a positive correlation of very strong magnitude (r between 0.90 and 1) was identified between the variables shoot green weight (SGW) and root green weight (RGW), shoot dry weight (SDW) and root green weight (RGW), root dry weight (RDW) and root green weight (RGW), root dry weight (RDW) and shoot green weight (SGW), as well as plant height (PH) and root dry weight (RDW). The relationships between these variables were already expected, as they are directly linked to the growth and development of plants.

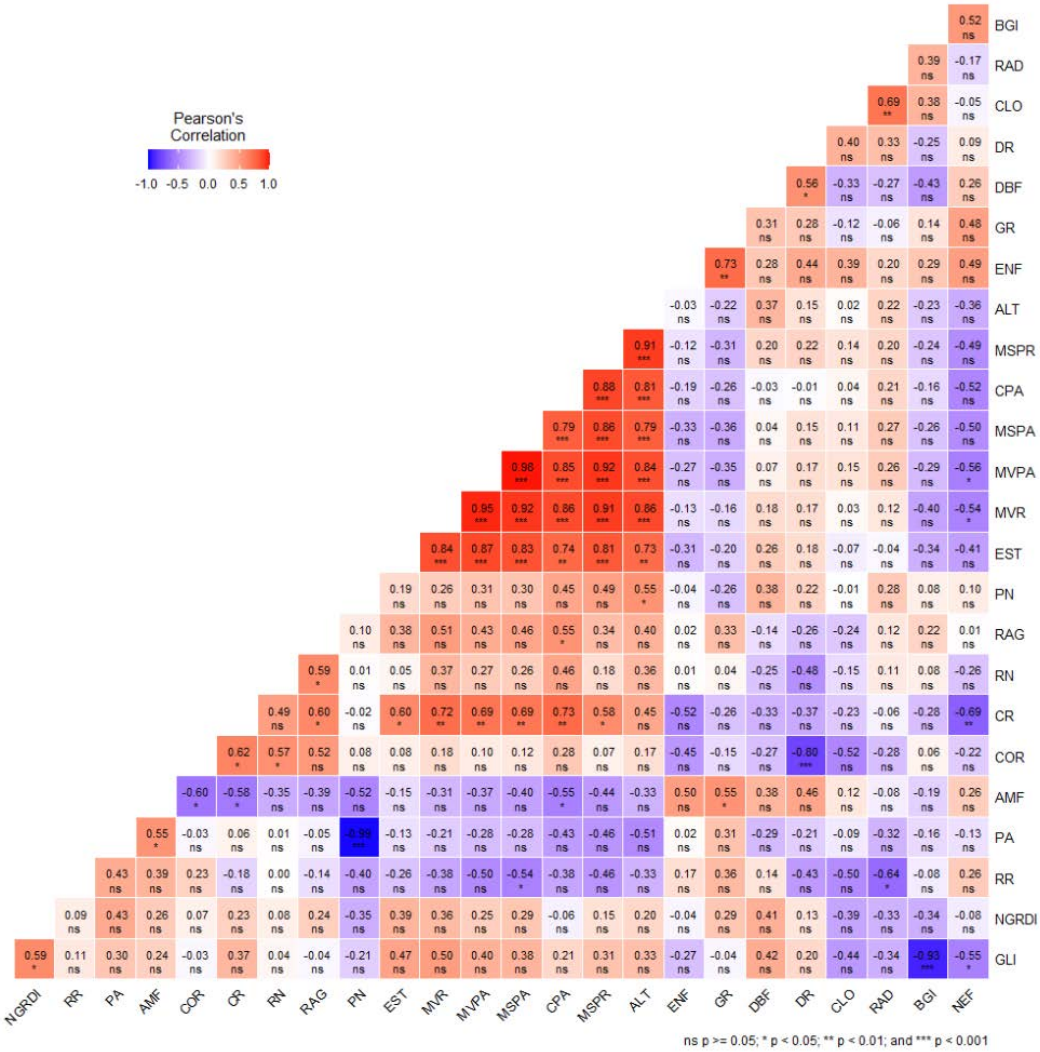

Figure 4. Simple linear correlation between the variables Green Leaf Area Index (GLI), Normalized Green-Red Difference Index (NGRDI), Blue Green Pigment Index (BGI), phenological stage (STA), normal plants (NP), abnormal plants (AP), chlorosis (CHL), yellowing of leaves (YL), leaf edge damage (LED), curling (CUR), necrosis (NEL), root aggressiveness (RAG), root length (RLE), normal roots (NR), thick roots (TR), straight roots (SR), deformed roots (DR), radicle (RAD), shoot green weight (SGW), root green weight (RGW), shoot dry weight (SDW), root dry weight (RDW), shoot length (SL), root length (RL) and plant height (PH) for corn plants grown in a solution with excess nutrients.

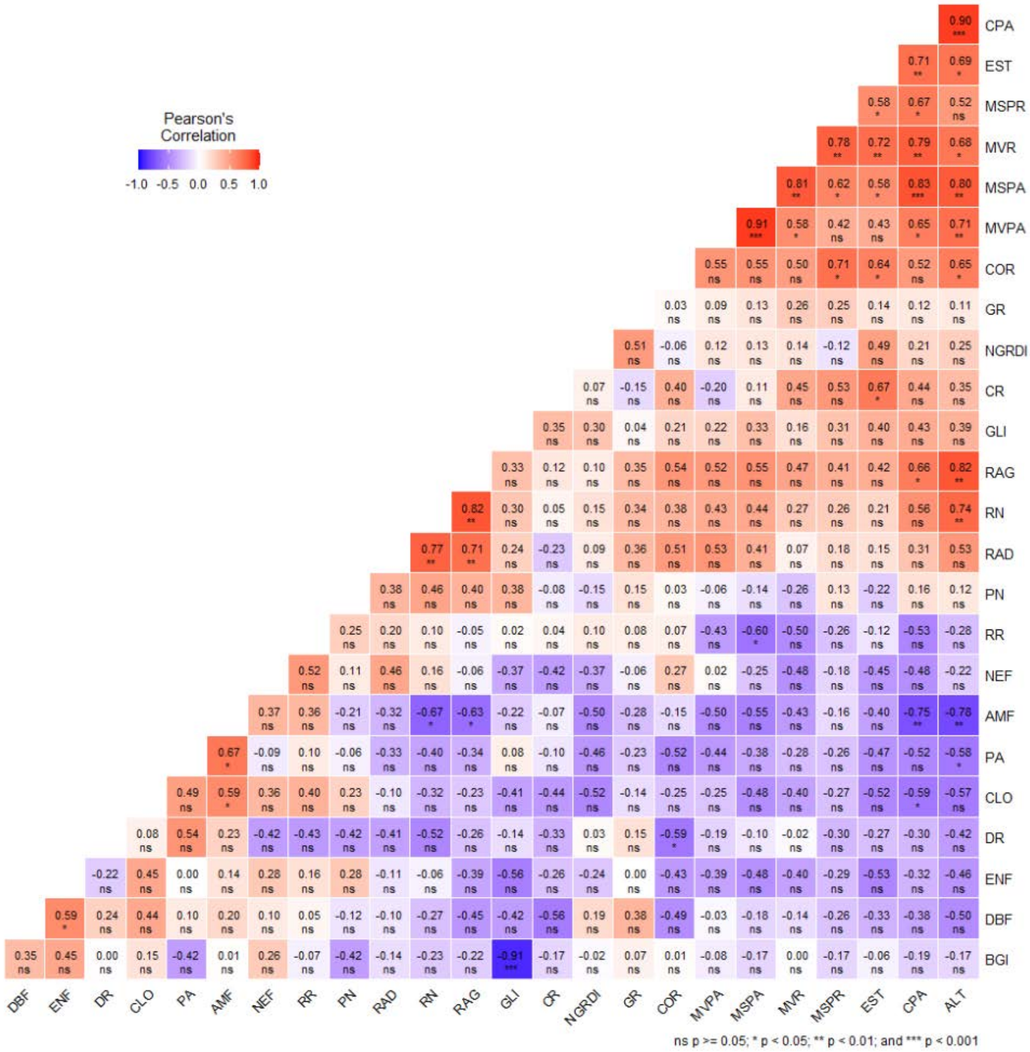

Figure 5. Simple linear correlation between the variables Green Leaf Area Index (GLI), Normalized Green-Red Difference Index (NGRDI), Blue Green Pigment Index (BGI), phenological stage (STA), normal plants (NP), abnormal plants (AP), chlorosis (CHL), yellowing of leaves (YL), leaf edge damage (LED), curling (CUR), necrosis (NEL), root aggressiveness (RAG), root length (RLE), normal roots (NR), thick roots (TR), straight roots (SR), deformed roots (DR), radicle (RAD), shoot green weight (SGW), root green weight (RGW), shoot dry weight (SDW), root dry weight (RDW), shoot length (SL), root length (RLE) and plant height (PH) for corn plants grown in nutrient deficit solution.

deficit of nitrogen, boron and potassium. Plant height (PH, Figure 3e) was similar for nutrient excess as well as nutrient deficit, being negatively affected by boron and manganese excess. The highest plant height measurements were obtained when the plants were subjected to a boron, potassium and nitrogen deficit.

There was a strong correlation (r between 0.60 and 0.89) between the variable plant height (PH) and the variables stature (STA), root green weight (RGW), shoot green weight (SGW), shoot dry weight (SDW) and shoot length (SL). Likewise, a strong positive correlation was observed between root dry weight (RDW) and the variables stature (STA), shoot dry weight (SDW) and shoot length, as well as between the variable shoot length (SL) and the variables stature (STA), root green weight (RGW), shoot green weight (SGW) and shoot dry weight (SDW). The variable stature (STA) still showed a strong correlation with the variables shoot dry weight (SDW), shoot green weight (SGW) and root green weight. The height and number of leaves are important characteristics for maize, as they are directly related to the plant's potential to obtain sufficient light energy to produce the photoassimilates necessary for its development and production (Lima et al., 2020).

Of the negative correlations, relationships of very strong magnitude were observed between the variables normal plants (NP) and abnormal plants (AP) and between Blue Green Pigment Index (BGI) and Green Leaf Index (GLI), in addition to a strong negative correlation between the variables deformed roots (DR) and root length (RLE), radicle (RAD) and straight roots (SR) and between necrosis (NEL) and root length (RLE).

Similar to what was shown for the correlations between the variables sampled for plants that were subjected to excess nutrients, the nutrient deficit also caused correlations of strong magnitude between variables related to plant growth and development, and some relationships should be highlighted. A very strong positive correlation was identified between the variables shoot dry weight (SDW) and shoot green weight (SGW), between shoot length (SL) and plant height PH), in addition to a very strong negative correlation between the variables Green Leaf Index (GLI) and Blue Green Pigment Index (BGI). Positive correlations of strong magnitude (r between 0.60 and 0.89) were also observed between plant height (PH) and root aggressiveness (RAG), plant height (PH) and normal roots (NR), root aggressiveness (RAG) and normal roots (NR), radicle (RAD) and normal roots (NR) and between radicle (RAD) and root aggressiveness (RAG). On the other hand, strong negative correlations were identified between the variables plant height (PH) and yellowing of leaves (YL), shoot length (SL) and yellowing of leaves (YL), normal roots (NR) and yellowing of leaves (YL), root aggressiveness (RAG) and yellowing of leaves and between shoot dry weight (SDW) and straight roots (SR).

The cluster dendrogram considering excess nutrients (Figure 6) shows the formation of two initial groups, one of which is composed of the nutrient magnesium (Mg) only, suggesting that this nutrient, when in excess, caused changes in plants in isolation, not depending on other nutrients. A similar behavior was identified for nitrogen (N), but for the second group, showing that, in general, the changes caused by the excess of this nutrient were not dependent on the effects of excess Mg, mainly, but were also not related to the excess of other nutrients.

It is observed the formation of a subgroup formed between the nutrients manganese (Mn), sodium (Na), copper (Cu), aluminum (Al), iron (Fe), molybdenum (Mo) and phosphorus (P) and a subgroup formed by the nutrients potassium (K), calcium (Ca), zinc (Zn), boron (B) and sulfur (S). The most interdependent effects were observed for the nutrients Al and Fe and also for Mo and P, as they present the smallest Euclidean distance among all the groups. In other words, when excess

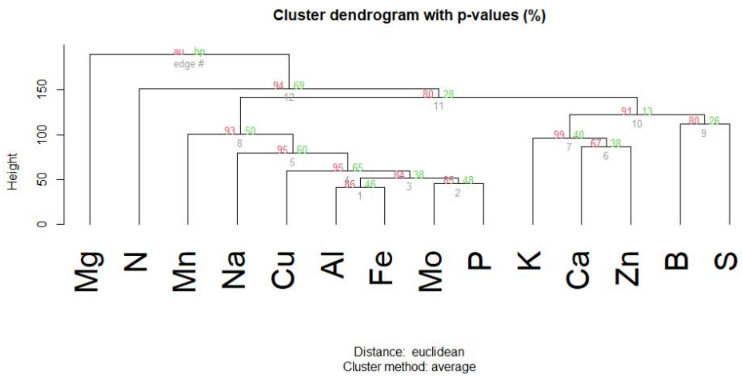

Figure 6. Cluster dendrogram considering the Euclidean distance for the average of the evaluations considering the excess of nutrients. Mg: magnesium; N: nitrogen; Mn: manganese; Na: sodium; Cu: copper; Al: aluminum; Fe: iron; Mo: molybdenum; P: phosphorus; K: potassium; Ca: calcium; Zn: zinc; B: boron; S: sulfur.

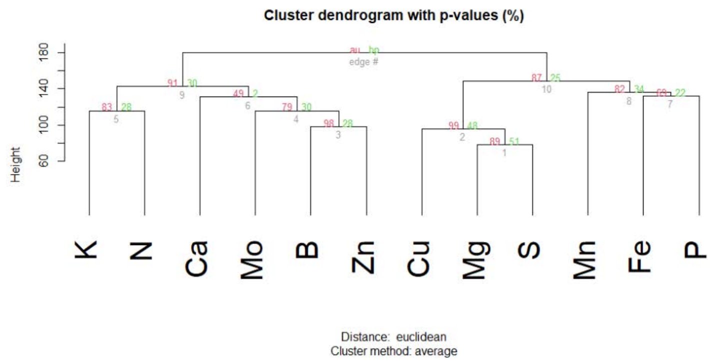

Figure 7. Cluster dendrogram considering the Euclidean distance for the average of the assessments considering the nutrient deficit. Mg: magnesium; N: nitrogen; Mn: manganese; Na: sodium; Cu: copper; Al: aluminum; Fe: iron; Mo: molybdenum; P: phosphorus; K: potassium; Ca: calcium; Zn: zinc; B: boron; S: sulfur.

aluminum changed some characteristic evaluated, there was the same tendency for change caused by excess iron, with the same behavior occurring between molybdenum and phosphorus.

The isolated effects identified for excess magnesium (Mg) were not repeated when the nutrient deficit was evaluated (Figure 7), where the cluster dendrogram shows the formation of two large groups. The first group was formed by the deficit of potassium (K), nitrogen (N), calcium (Ca), molybdenum (Mo), boron (B) and zinc (Zn). The second group was formed by the deficit of copper (Cu), magnesium (Mg), sulfur (S), manganese (Mn), iron (Fe) and phosphorus (P). Similar effects observed for the K deficit also occurred for the N deficit, with the same behavior being observed for the Mo, B and Zn deficit, differing only for the Ca deficit. The characteristics observed for the Mg deficit and for the S deficit formed the group with the greatest proximity.

Seeking to understand the relationship between nutrients and the variables studied, an analysis of main components was carried out considering excess nutrients (Figure 8). The main components are linear combinations of the original variables capable of satisfactorily explaining the variance of all variables (Greenacre et al., 2023). Using two PCAs (Principal Component Analysis), it was possible to explain 34.88% (PCA1) and 16.79% (PCA2) of the total variance of the information. The sulfur element was decisive for the variation in the characters thick roots (TR), yellowing of leaves (YL), with some influence on straight roots (SR) and abnormal plants (AP), where the boron element also influenced. Nitrogen was decisive for the occurrence of necrosis (NEL). A relationship between phosphorus, copper and zinc is observed in the Blue Green Pigment Index (BGI) and curling (CUR) values. The elements copper and zinc, together with iron, also influenced the occurrence of chlorosis (CHL), deformed roots (DR) and radicle (RAD).

The quantity of normal plants (NP) was influenced by molybdenum (Figure 8), which according to Santos et al. (2020), it is important for plant metabolism, being fundamental in the assimilation of nitrate, acting on the nitrate reductase enzyme, where deficiency can compromise nitrogen metabolism, reducing crop yield. Aluminum was decisive for the variations observed for the variables root dry weight (RDW), plant height (PH), shoot length (SL), shoot green weight

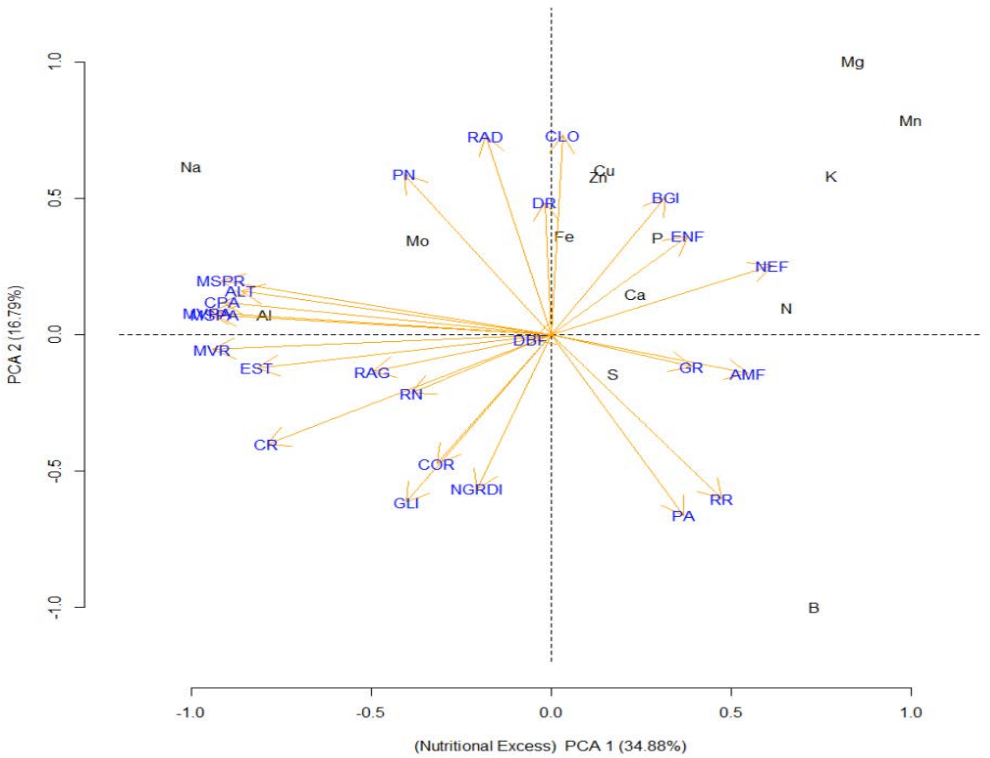

Figure 8. Principal component analysis (PCA), using the Biplot method, considering excess nutrients. Green Leaf Area Index (GLI), Normalized Green-Red Difference Index (NGRDI), Blue Green Pigment Index (BGI), phenological stage (STA), normal plants (NP), abnormal plants (AP), chlorosis (CHL), yellowing of leaves (YL), leaf edge damage (LED), curling (CUR), necrosis (NEL), root aggressiveness (RAG), root length (RLE), normal roots (NR), thick roots (TR), straight roots (SR), deformed roots (DR), radicle (RAD), shoot green weight (SGW), root green weight (RGW), shoot dry weight (SDW), root dry weight (RDW), shoot length (SL), root length (RLE) and plant height (PH) for corn plants grown in nutrient deficit solution. Mg: magnesium; N: nitrogen; Mn: manganese; Na: sodium; Cu: copper; Al: aluminum; Fe: iron; Mo: molybdenum; P: phosphorus; K: potassium; Ca: calcium; Zn: zinc; B: boron; S: sulfur.

(SGW) and shoot dry weight (SDW). No proximity was identified between the evaluated nutrients and the variables root green weight (RGW), phenological stage (STA), root aggressiveness (RAG), root length (RLE), normal roots (NR), root length (RLE), Green Leaf Index (GLI) and Normalized Green-Red Difference Index (NGRDI), and it can be inferred that the excess of any of the nutrients did not alter the values in isolation.

For the analysis of main components of the scenario in which plants were subjected to nutritional deficit (Figure 9), it was possible to explain a total of 50.75% of the total variation in information (PCA1: 36.39%; PCA2: 14. 36%). The iron element was decisive for the yellowing of leaves (YL), abnormal plants (AP) and deformed roots (DR). The sulfur and copper deficit had a strong influence on the levels of Blue Green Pigment Index (BGI) and leaf edge damage (LED). The occurrence of curling (CUR) and chlorosis (CHL) were linked to magnesium deficiency.

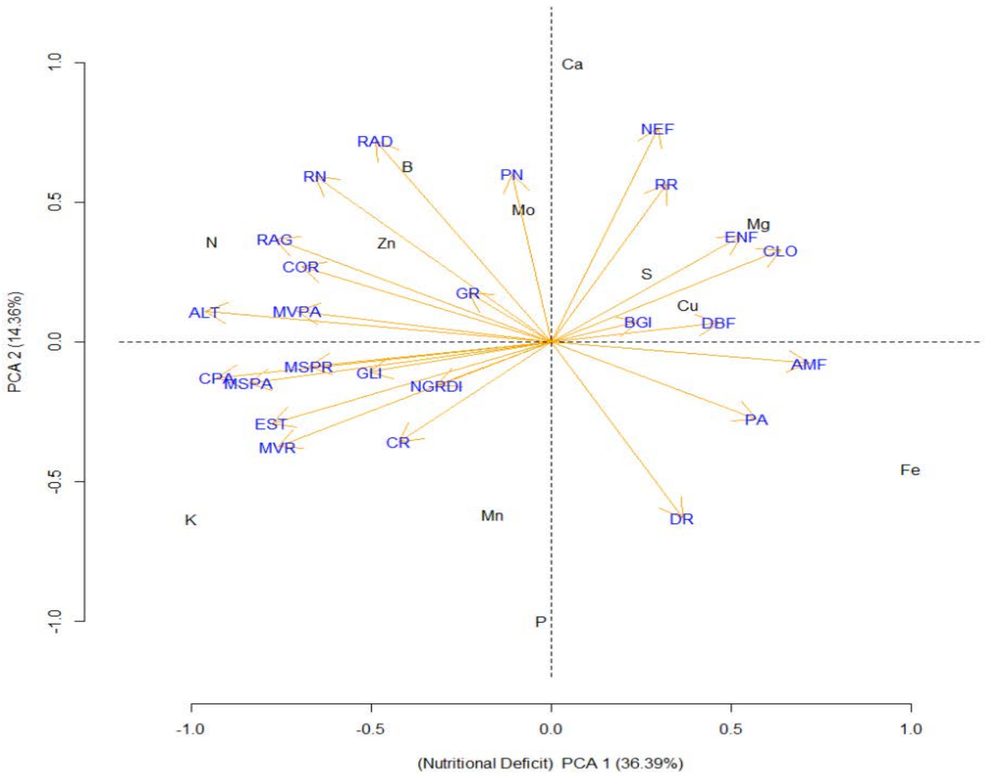

Figure 9. Principal component analysis (PCA), using the Biplot method, considering nutrient deficit. Green Leaf Area Index (GLI), Normalized Green-Red Difference Index (NGRDI), Blue Green Pigment Index (BGI), phenological stage (STA), normal plants (NP), abnormal plants (AP), chlorosis (CHL), yellowing of leaves (YL), leaf edge damage (LED), curling (CUR), necrosis (NEL), root aggressiveness (RAG), root length (RLE), normal roots (NR), thick roots (TR), straight roots (SR), deformed roots (DR), radicle (RAD), shoot green weight (SGW), root green weight (RGW), shoot dry weight (SDW), root dry weight (RDW), shoot length (SL), root length (RL) and plant height (PH) for corn plants grown in nutrient deficit solution. Mg: magnesium; N: nitrogen; Mn: manganese; Na: sodium; Cu: copper; Al: aluminum; Fe: iron; Mo: molybdenum; P: phosphorus; K: potassium; Ca: calcium; Zn: zinc; B: boron; S: sulfur.

The nutrient complex formed by molybdenum, boron and zinc (Figure 9) was important for the values observed for normal plants (NP), radicle (RAD) and normal roots (NR), For thick roots (TR), root length (RLE), plant height (PH) and shoot green weight (SGW), nitrogen deficit was the factor with the greatest weight. Potassium and manganese deficiency had some influence on the traits shoot length (SL), shoot dry weight (SDW), root dry weight (RDW), Green Leaf Pigment Index (GLI) and Normalized Green-Red Difference Index (NGRDI), with greater weight for changes in phenological stage (STA), root green weight (RGW) and root length (RL) values.

CONCLUSIONS

Excess aluminum had an influence on the change in the total biomass produced and the height of the corn plants.

Sulfur, copper and zinc caused changes in the root system.

Excess nitrogen and sulfur caused necrosis and yellowing of the leaves.

Magnesium deficiency caused curling and chlorosis of the leaves.

Nitrogen deficiency promoted lower values of root length, plant height and shoot green weight.

REFERENCES

Ali S, Ma X, Jia Q, Ahmad I, et al. (2019). Supplemental irrigation strategy for improving grain filling economic return and production in winter wheat under the ridge and furrow rainwater harvesting system. *Agricultural Water Management*. 226: 105842.

Ali S, Xu Y, Jia Q, Ahmad I, et al. (2018). Ridge-furrow mulched with plastic film improves the anti-oxidative defence system and photosysthesis in the leaves of winter wheat under deficit irrigation. *PLoS One*. 13: e0200277.

Berlezi AJ, Pavan D, Feldmann AN, Mühl RF, et al. (2019). Interferência da aplicação de boro na produtividade do milho silagem e na produção de leite.

Bilhalva NS, Coradi PC, Biduski B, Mallmann CA, et al. (2023). Early detection of quality alterations in corn grains stored in vertical prototype silos using real-time monitoring of carbon dioxide and equilibrium moisture content. *Food and Bioproducts Processing*. 140: 242-258.

Elemer WH, Datnoff LE. (2014). Mineral nutrition and suppression of plant disease. *Encyclopedia of Agriculture and Food Systems*. 4: 231-244.

Gondim ARO, Prado RM, Alveus AU, Fonseca IM. (2010). Nutritional efficiency of corn cv. BRS 1030 subjected to omission of macronutrients in nutrient solution. *Revista Ceres*. 57: 539-544.

Greenacre M, Groenen PJF, Hastie T, D'enza AI, et al. (2017). Principal Component Analysis. *Nature Reviews Methods Primers*. 2: 1-24.

Hunt ER, Cavigelli M, Daughtry CST, Mcmurtrey JE, et al. (2005). Evaluation of digital photography from model aircraft for remote sensins of crop biomass and nitrogen status. *Precision Agriculture.* 6: 359-378.

Khan ZH, Khalil SK, Shah F, Iqbal A, et al. (2017). Plant density and nitrogen doses can affect growth of sweet corn. *Amjad Iqbal Department of Agriculture Abdul Wali Khan University Marda*. 26: 3872-3879.

Lima JC, Nascimento MN, Jesus RS, Silva AL, et al. (2020). Crescimento inicial e diagnose nutricional de plantas de milho cultivadas com omissão de macronutrientes em argissolo. *Nativa*. 8: 567-571.

Maranhão TD, Cândido MJD, Soares I, Lopes MN, et al. (2018). Accumulation and partition of macronutrients in *Pennisetum purpureum* cv. Roxo managed under different growth ages and seasons. *Brazilian Journal of Animal Health and Production*. 19: 223-240.

Oliveira TF, Oliveira VJB, Clemente JM, Aquino LA, et al. (2019). Extração e exportação de macronutrientes em lavouras de milho de alta produtividade. *Revista em Agronegócio e Meio Ambiente*. 12: 837-854.

Pavinato PS, Rosolem CA. (2008). Disponibilidade de nutrientes no solo: decomposição e liberação de compostos orgânicos de resíduos vegetais. *Brazilian Journal of Soil Science*. 32: 911-920.

Pereira EG, Saraiva AG, Dias AC, Ferreira NDS, et al. (2020). O metabolismo de nitrogênio em plantas de arroz é severamente afetado pela deficiência de cálcio e magnésio. *Brazilian Journal of Development*. 6: 15353-15361.

R Core Team. (2022). R: A language and environment for statistical computing. R Foundation for Statistical Computing Vienna Austria 2022.

Rezende CFA, Fernandes EP, Silva MF, Leandro WM. (2010). Crescimento e acúmulo de nutrientes em mudas cítricas cultivadas em ambiente protegido. *Bioscience Journal*. 26: 367-375.

Römheld V, Kirkby EA. (2007). Magnesium functions in crop nutrition and yield. Cambridge: International Fertiliser Society.

Santos CM, Junior LAL, Buso DHW. (2020). Cultivo de milho com diferentes doses e épocas de aplicação de molibdênio. *Brazilian Journal of Development.* 6: 5393-5402.

Taiz L, Zeiger E, Moller IM, Murphy A. (2017). *Plant physiology and development*. 6. ed. Porto Alegre: Artmed.

Viña A, Gitelson AA, Nguy-Robertson AL, Pieng Y. (2011). Comparison of different vegetation indices for the remote assessment of green leaf area index of crops. *Remote Sensing of Environment*. 115: 3468-3478.

Wu P, Liu F, Li H, Tie C, et al. (2017). Suitable fertilizer application depth can increase nitrogen use efficiency and maize yield by reducing gaseous nitrogen losses. *Sceince of The Total Environment*. 781: 146787.