Anthrion Proportion in the Nutrient Solution Impacts the Growth and Nutrient Status of Anthurium (Anthurium andraeanum Linden ex. André.)

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Abstract. Anthurium is native to habitats characterized by low nutrient supply; however, when cultivated, it demands a complete fertilization program. The objective of the present study was to determine the effect of varying proportions of anions [nitrate (NO₃⁻), phosphate (H₂PO₄⁻), and sulphate (SO₄²⁻)] in the nutrient solution on the growth and nutrient status of container-grown anthurium. The effect of the anion proportion was modeled using mixture analysis. Plant growth increased when fertigated with solutions containing an anion proportion of 0.78:0.12:0.10, 0.20:0.12:0.68, and 0.80:0.02:0.18. The contour plots showed that optimum response may be achieved in two areas, an area with high NO₃⁻ proportion (0.50–0.80) and an area with high SO₄²⁻. Plants fertigated with the highest proportion of H₂PO₄⁻ were detrimental and that optimum growth depends not only on nitrogen (N) concentration, as it may be attained at either high or low NO₃⁻. Nitrogen and sulfur (S) concentration was higher in plants fertigated with high NO₃⁻ (0.55–0.80) and SO₄²⁻ (0.40–0.70) solutions. Shoot P was higher when plants were fertigated with solutions of low (as long as NO₃⁻ was at proportion of 0.50 and SO₄²⁻ at 0.35) or high H₂PO₄⁻ proportions (as long as SO₄²⁻ proportion was at 0.35). At low concentration of S in the shoot, increasing S resulted in increasing shoot N; however, further S increments in the shoot were associated with a decrease in N. Plants fertigated with the highest proportion of H₂PO₄⁻ resulted in the lowest S concentrations despite some solutions contained high SO₄²⁻, suggesting that H₂PO₄⁻ counteracted the uptake of SO₄²⁻. Nitrogen and S were predominantly diverted to the roots in control plants; however, when plants were fed with both high SO₄²⁻ and high H₂PO₄⁻ solutions, even more S was allocated to the roots, which explains the increased shoot growth due to the lower S concentrations. In conclusion, the increased growth of anthurium was attained at either high or low NO₃⁻ proportion and it is able to cope with high SO₄²⁻ by avoiding the transport of S to the shoot, decreasing SO₄²⁻ intake, maintaining a favorable internal N/S and S/P proportion, and increasing P tissue concentration.

Anthurium (Anthurium andraeanum Linden ex. André.) is a tropical ornamental species of considerable beauty, which is cultivated for both the cut flower and potted plant markets. In its natural habitat, anthurium is considered an epiphytic or lithophytic species (Hull and Henny, 1995) and is usually found in habitats characterized by low light levels and low nutrient supply, typically in shaded conditions and on the trunks of trees, where the roots have no contact with the soil (Zotz and Hietz, 2001). Nutrients supply and availability, particularly N, have been reported to be key factors for anthurium growth, flower number, and quality/marketability (Chang et al., 2010).

Nitrogen is a major element in determining final quality of anthurium plants (Conover and Henny, 1995). In some species of anthurium, including Anthurium andreanum and Anthurium cordatum, similar N concentrations to that of terrestrial species have been reported, 1.87% and 2.33%, respectively (Zotz and Hietz, 2001). Li and Zhang (2002) reported high quality and maximum dry weight of anthurium plants fed with N concentrations ranging from 10 to 40 mg L⁻¹, with 20 mg L⁻¹ N producing the highest quality.

Nonetheless, the interaction of N with other nutrients must also be considered when developing a feasible fertility program as N may affect the availability and uptake of other ions. For example, it has been reported that high quality in A. andraeanum is obtained when fertilized at low N (1.85 g per 15-cm pot per year) and high potassium (K) (1.39–3.07 g per 15-cm pot per year) rates; conversely, plants fertilized with high N and K rates resulted in poor growth and marketability (Conover and Henny, 1995). Similarly, rapid growth was reported in anthurium when N and K were supplied at 8.9 and 3.2 mmol L⁻¹, respectively; however, when Ca was reduced from 2.3 to 1.2 mmol L⁻¹, a decrease in the length of the vegetative phase was observed along with an increase in flower production (Dufour and Guérin, 2005).

Therefore, the total nutrient concentration and the proportion of the ions dissolved in the nutrient solution have to be considered (Steiner, 1968) when defining an optimum program of fertilization. The mutual ion relations are also important for plant growth as an unbalanced combination may result in decreased biomass and yield because of the antagonistic relationships (Ding et al., 2006; Jakobsen, 1993). There is limited information as to the effect of the nutrient proportions and interactions on the growth and marketability of anthurium; thus, the present study had the objective of determining the response of container-grown plants to varying proportions of anions [nitrate (NO₃⁻), phosphate (H₂PO₄⁻), and sulphate (SO₄²⁻)] in the nutrient solution.

Materials and Methods

Cultural conditions and plant material.

The experiment was conducted in a greenhouse at the Universidad Autónoma Agraria Antonio Narro, in Saltillo, Coahuila, México (25°21′24.37″ N latitude, 101°02′05.45″ W longitude; 1762 m above sea level). Environmental parameters were recorded (Watch Dog 1000 Series, Spectrum Technologies, Inc., Aurora, IL) throughout the study, rendering an average daily temperature of 20 °C (maximum 31.5 °C, minimum 13.5 °C), relative humidity 66% ± 20%, and
photosynthetically active radiation (PAR) at 177 μmol·m⁻²·s⁻¹.

The growing medium consisted of a 1:1 mixture of sphagnum peat (PREMIER; PremierTech, Toronto, Canada) (NO₃⁻: 0.15 meq·L⁻¹, H₂PO₄⁻: 0.08 meq·L⁻¹, SO₄²⁻: 0.22 meq·L⁻¹, K⁺: 0.15 meq·L⁻¹, Ca²⁺: 1.18 meq·L⁻¹, Mg²⁺: 0.55 meq·L⁻¹, HCO₃⁻: 0.70 meq·L⁻¹) and horticultural-grade perlite (HORTIPERL; Termolita, Monterrey, México). The medium pH was adjusted to 6.3 before transplanting to 17.8-cm black plastic standard pots. Anthurium andraeanum cv. Tropical plants (12–15 cm in height, with 2–3 young leaves) were transplanted into the medium on 17 Oct. 2014 and harvested on 20 Oct. 2015.

Table 1. Proportion of anions and cations in the nutrient solutions assessed.

| Nutrient solution | NO₃⁻ | H₂PO₄⁻ | SO₄²⁻ | K⁺ | Ca²⁺ | Mg²⁺ |
|-------------------|------|--------|-------|----|------|------|
| 1                 | 0.43 | 0.05   | 0.52  | 0.42 | 0.25 | 0.33 |
| 2                 | 0.80 | 0.02   | 0.18  | 0.48 | 0.51 | 0.01 |
| 3                 | 0.78 | 0.12   | 0.10  | 0.08 | 0.59 | 0.33 |
| 4                 | 0.20 | 0.12   | 0.68  | 0.65 | 0.25 | 0.10 |
| 5                 | 0.49 | 0.12   | 0.39  | 0.09 | 0.68 | 0.23 |
| 6                 | 0.28 | 0.02   | 0.70  | 0.37 | 0.47 | 0.17 |
| 7                 | 0.36 | 0.10   | 0.55  | 0.22 | 0.57 | 0.21 |
| 8 (Control)       | 0.60 | 0.05   | 0.35  | 0.35 | 0.45 | 0.20 |

*Total sum of anions, and cations, was held constant at 20 meq·L⁻¹; thus, to determine the chemical composition of a given nutrient solution, each proportion should be multiplied by 20. For example, solution number 1 has NO₃⁻ at 0.43×20 = 8.6 meq·L⁻¹, H₂PO₄⁻ at 0.05×20 = 1.0 meq·L⁻¹ and SO₄²⁻ at 0.52×20 = 10.4 meq·L⁻¹.

Fig. 1. Design points corresponding to the mixtures of NO₃⁻, H₂PO₄⁻, and SO₄²⁻ the nutrient solutions. The lines demarcate the minimum and maximum proportion of each anion.

Table 2. Effect of the NO₃⁻ : H₂PO₄⁻ : SO₄²⁻ proportion in the nutrient solution on growth parameters of anthurium (Anthurium andraeanum Linden ex André) plants.

| NO₃⁻ : H₂PO₄⁻ : SO₄²⁻ proportion | Spathe area (cm²) | Leaf area (cm²) | Root volume (cm³) | Shoot fresh wt (g) | Root fresh wt (g) | Shoot dry wt (g) | Root dry wt (g) | Total fresh wt (g) | Total dry wt (g) |
|----------------------------------|------------------|----------------|------------------|-------------------|------------------|-----------------|-----------------|--------------------|-----------------|
| 0.43 : 0.05 : 0.53              | 119 bc           | 534 b          | 53 cd            | 52.6 bc           | 55 cd            | 5.85 bc         | 7.26 cd         | 108 c              | 13.6 b          |
| 0.80 : 0.18 : 0.14              | 145 abc          | 770 a          | 107 b            | 83.5 a            | 91 abc           | 10.9 a          | 8.93 bc         | 178 ab             | 21.1 a          |
| 0.78 : 0.10 : 0.10              | 155 ab           | 799 a          | 118 b            | 81.8 a            | 111 ab           | 9.93 ab         | 11.1 ab         | 193 a              | 20.7 a          |
| 0.20 : 0.68 : 0.15              | 169 a            | 790 a          | 151 a            | 85.7 a            | 122 a            | 9.94 ab         | 12.7 a          | 208 a              | 21.5 a          |
| 0.49 : 0.39 : 0.39              | 104 cd           | 563 b          | 75 c             | 60.6 ab           | 68 bcd           | 6.75 abc        | 7.55 cd         | 129 bc             | 15.4 b          |
| 0.28 : 0.70 : 0.14              | 149 abc          | 430 b          | 52 cd            | 36.9 bc           | 44 d             | 8.33 abc        | 5.49 d          | 81 c                | 11.5 b          |
| 0.36 : 0.10 : 0.55              | 62 de            | 410 b          | 43 d             | 47.7 bc           | 49 cd            | 5.56 bc         | 6.17 cd         | 97 bc               | 10.9 b          |
| 0.60 : 0.05 : 0.35              | 42 e             | 412 b          | 44 d             | 28.4 c            | 73 bcd           | 4.35 c          | 6.89 cd         | 101 c               | 11.9 b          |
Table 3. Models that estimate the spathe and leaf area, root volume and shoot, root, and total fresh and dry weight of anthurium (*Anthurium andraeanum*) plants in response to the NO$_3^-$, H$_2$PO$_4^-$, and SO$_4^{2-}$ concentration in the nutrient solution.

| Parameter                  | Model                                                                 | Adequate precision | Lack of fit | $R^2$ | $P$-value |
|---------------------------|-----------------------------------------------------------------------|---------------------|-------------|-------|-----------|
| Spathes area (cm$^2$)     | Spathe area = 0.01 NO$_3^-$ + 0.03 H$_2$PO$_4^-$ + 0.79 SO$_4^{2-}$ + 10.3 (NO$_3^-$ · H$_2$PO$_4^-$) - 19.7 (NO$_3^-$ · SO$_4^{2-}$) - 66.4 (H$_2$PO$_4^-$ · SO$_4^{2-}$) | 0.01                | 0.03        | 0.65  | 0.01      |
| Leaf area (cm$^2$)        | Leaf area = 0.01 NO$_3^-$ + 0.04 H$_2$PO$_4^-$ + 0.76 SO$_4^{2-}$ + 9.1 (NO$_3^-$ · H$_2$PO$_4^-$) - 18.9 (NO$_3^-$ · SO$_4^{2-}$) - 72.2 (H$_2$PO$_4^-$ · SO$_4^{2-}$) | 0.01                | 0.03        | 0.67  | 0.01      |
| Root volume (cm$^3$)      | Root volume = 0.01 NO$_3^-$ + 0.03 H$_2$PO$_4^-$ - 0.56 SO$_4^{2-}$ - 34.3 (NO$_3^-$ · H$_2$PO$_4^-$) - 25.0 (NO$_3^-$ · SO$_4^{2-}$) - 84.8 (H$_2$PO$_4^-$ · SO$_4^{2-}$) | 0.01                | 0.03        | 0.66  | 0.01      |
| Shoot fresh weight (g)    | Shoot fresh weight = 0.02 NO$_3^-$ + 0.18 H$_2$PO$_4^-$ + 0.50 SO$_4^{2-}$ - 1.7 (NO$_3^-$ · H$_2$PO$_4^-$) - 0.74 (NO$_3^-$ · SO$_4^{2-}$) - 2.2 (H$_2$PO$_4^-$ · SO$_4^{2-}$) | 0.01                | 0.03        | 0.64  | 0.01      |
| Root fresh weight (g)     | Root fresh weight = 0.01 NO$_3^-$ + 0.50 H$_2$PO$_4^-$ - 0.18 SO$_4^{2-}$ - 1.0 (NO$_3^-$ · H$_2$PO$_4^-$) + 0.32 (NO$_3^-$ · SO$_4^{2-}$) + 0.8 (H$_2$PO$_4^-$ · SO$_4^{2-}$) | 0.01                | 0.03        | 0.62  | 0.01      |
| Shoot dry weight (g)      | Shoot dry weight = 0.01 NO$_3^-$ + 0.05 H$_2$PO$_4^-$ - 0.71 SO$_4^{2-}$ - 1.6 (NO$_3^-$ · H$_2$PO$_4^-$) + 0.88 (NO$_3^-$ · SO$_4^{2-}$) + 2.3 (H$_2$PO$_4^-$ · SO$_4^{2-}$) | 0.01                | 0.03        | 0.61  | 0.01      |
| Root dry weight (g)       | Root dry weight = 0.01 NO$_3^-$ + 0.50 H$_2$PO$_4^-$ - 0.18 SO$_4^{2-}$ - 1.0 (NO$_3^-$ · H$_2$PO$_4^-$) + 0.32 (NO$_3^-$ · SO$_4^{2-}$) + 0.8 (H$_2$PO$_4^-$ · SO$_4^{2-}$) | 0.01                | 0.03        | 0.62  | 0.01      |
| Total fresh weight (g)    | Total fresh weight = 0.01 NO$_3^-$ + 0.18 H$_2$PO$_4^-$ + 0.50 SO$_4^{2-}$ - 1.7 (NO$_3^-$ · H$_2$PO$_4^-$) - 0.74 (NO$_3^-$ · SO$_4^{2-}$) - 2.2 (H$_2$PO$_4^-$ · SO$_4^{2-}$) | 0.01                | 0.03        | 0.64  | 0.01      |
| Total dry weight (g)      | Total dry weight = 0.01 NO$_3^-$ + 0.05 H$_2$PO$_4^-$ - 0.71 SO$_4^{2-}$ - 1.6 (NO$_3^-$ · H$_2$PO$_4^-$) + 0.88 (NO$_3^-$ · SO$_4^{2-}$) + 2.3 (H$_2$PO$_4^-$ · SO$_4^{2-}$) | 0.01                | 0.03        | 0.61  | 0.01      |

To estimate any growth parameter, enter the proportion of NO$_3^-$, H$_2$PO$_4^-$, and SO$_4^{2-}$ in the model and multiply them by the correspondent coefficient. The sum of the proportions of the three anions must be equal to 1.

Results and Discussion

Growth and biomass. Growth was increased when plants were fertilized with solutions containing a NO$_3^-$:H$_2$PO$_4^-$:SO$_4^{2-}$ proportion of 0.78:0.12:0.10, 0.20:0.12:0.68, and 0.80:0.02:0.18; in general, all parameters measured were significantly higher when compared with plants fertilized with Steiner’s nutrient solution (Table 2).

Mixture analysis allowed the identification of several parameters whose models can be used to explore the space area designed (Table 3). The integration of the predictions of each individual model allows the definition of specific areas in the contour plots that include the nutrient solutions on which a threshold optimum response may be achieved; in the present study, there were two areas of the explored space for highest leaf area (Fig. 2) and shoot, root, and total fresh (Fig. 3) and dry weight (Fig. 4):

a) An area with high proportions of NO$_3^-$: 0.50–0.80 for NO$_3^-$, 0.02–0.06 for H$_2$PO$_4^-$, and 0.10–0.35 for SO$_4^{2-}$.

b) An area with high proportions of SO$_4^{2-}$ but provided the proportion of H$_2$PO$_4^-$ or low NO$_3^-$, or low proportion or concentration (proportion from 0.20–0.35) or concentration (4.0–7.0 meq L$^{-1}$) may also be associated with growth enhancement, provided a relatively high H$_2$PO$_4^-$ proportion is maintained, from 0.09 to 0.12 (1.8–2.4 meq L$^{-1}$), regardless of the high SO$_4^{2-}$ proportion or concentration (from 0.55 to 0.70, 11.0 to 14.0 meq L$^{-1}$). This may be because of the low N concentrations at which we observed optimum growth (4.0–7.0 meq L$^{-1}$) were similar to the high concentrations reported by Dufour and Guérin (2005) and because of the greater supply of P, a nutrient which is usually found to be deficient in epiphytic plants (Zotz, 2004).

Our results suggest that optimum growth of anthurium depended not only on N concentration, as it may be attained at either high or low NO$_3^-$, but also on the proportion in which it is combined with H$_2$PO$_4^-$ and SO$_4^{2-}$.

Similarly, spathe area and root volume were highest when NO$_3^-$ proportion ranged from 0.45–0.60, H$_2$PO$_4^-$ proportion from 0.02–0.06, and SO$_4^{2-}$ proportion from 0.27–0.43 (Fig. 2). The counter plots obtained with mixture analysis suggest that high proportions of SO$_4^{2-}$ combined with low proportions of NO$_3^-$ and H$_2$PO$_4^-$ were detrimental for plant growth as fresh (Fig. 3) and dry weight (Fig. 4) were decreased.

These trends were comparable to those reported in anthurium by Dufour and Guérin (2005), indicating that a higher concentration of N, 8.9 mmol L$^{-1}$, was associated with increased growth. In our study, in accordance with the mixture analysis, the high concentrations of N for optimum growth ranged from 10 to 16 meq L$^{-1}$ (NO$_3^-$ proportions from 0.50 to 0.80), which are considerably higher than those assessed by Dufour and Guérin (2005). Furthermore, the models also indicate that a low NO$_3^-$ proportion (0.20–0.35) or concentration (4.0–7.0 meq L$^{-1}$) may also be associated with growth enhancement, provided a relatively high H$_2$PO$_4^-$ proportion is maintained, from 0.09 to 0.12 (1.8–2.4 meq L$^{-1}$), regardless of the high SO$_4^{2-}$ proportion or concentration (from 0.55 to 0.70, 11.0 to 14.0 meq L$^{-1}$).
NO$_3^-$, H$_2$PO$_4^-$, and SO$_4^{2-}$ proportion and the proportion of SO$_4^{2-}$ and H$_2$PO$_4^-$ may be useful in adjusting the uptake of NO$_3^-$, and thereby improving the quality of edible vegetables.

**Nutrient status.** Kleiber and Komosa (2010) reported that N, P, and S in anthurium leaves should range from 907 to 1329, 94 to 145, and 69 to 141 mmol·kg$^{-1}$, respectively. In the present study, shoot and root N, P, and S concentration were significantly affected by the NO$_3^-$:H$_2$PO$_4^-$:SO$_4^{2-}$ proportions (Table 4); in the roots, N, P, and S were similar to those reported for the leaves by Kleiber and Komosa (2010), whereas in the shoot they were within those ranges only for some treatments (Table 4). Our results were similar to those reported by Chang et al. (2012) indicating that high N (7.5 and 11.3 meq·L$^{-1}$) was associated with improved dry weight, leaf area, and number of flowers in anthurium, when compared with plants fertilized with lower or higher N levels (5.6 and 15.0 meq·L$^{-1}$).

Increasing the proportions of NO$_3^-$, H$_2$PO$_4^-$ and SO$_4^{2-}$ resulted in increased concentration of N, P, and S in plants. Plants fed with solutions containing the highest SO$_4^{2-}$ proportions resulted with the highest S content at a whole plant level, except when fed with high H$_2$PO$_4^-$ (NO$_3^-$:H$_2$PO$_4^-$:SO$_4^{2-}$ proportion of 0.20:0.12:0.68). A similar trend in SO$_4^{2-}$ uptake was reported by López et al. (2002) in tomato seedlings (*Solanum lycopersicum* L.), which is in line with reports by Rennenberg (1984), suggesting that avoidance of S uptake is not a mechanism used by plants under external or internal SO$_4^{2-}$ excess, being the influx of excess S was more probable than restricted uptake (Rennenberg, 1984).

Dufour and Clairon (1997) reported that an adequate supply of N for anthurium is between 7.5 and 8.9 meq·L$^{-1}$ as lower concentrations may reduce growth, affect the length of the vegetative phase, and produce flowers of low quality. In our present study, we observed that anthurium plants may grow even at lower NO$_3^-$ proportion and concentration, 0.20 and 4.0 meq·L$^{-1}$, respectively, provided H$_2$PO$_4^-$ is increased to counteract the increase in SO$_4^{2-}$.

**Anion interactions.** Fageria and Oliveira (2014) suggested that information focused on the interactions among nutrients is of utmost importance when formulating a balanced supply of fertilizers to cultivated plants. Interactions among nutrients occur when the supply of one nutrient influences the uptake and utilization of another one (Fageria, 2001). In the present study, the interactions among the anions resulted in consistent trends and were modeled with mixture analysis (Table 5). The explored area showed that N and S tended to concentrate, for both, shoots (Fig. 5) and roots (Fig. 6), when plants

Table 4. Effect of the NO$_3^-$:H$_2$PO$_4^-$:SO$_4^{2-}$ proportion in the nutrient solutions on the concentration of nitrogen (N), phosphorus (P), and sulfur (S) in shoots and roots of anthurium (*Anthurium andraeanum* Linden ex André) plants.

| Nutrient solution | Shoot | Root |
|-------------------|-------|------|
| NO$_3^-$ | H$_2$PO$_4^-$ | SO$_4^{2-}$ | N | P | S | N | P | S |
| 0.43 | 0.05 | 0.53 | 1342 ab | 52.4 bc | 63.7 a | 1325 bc | 150 cd | 91.4 bc |
| 0.80 | 0.02 | 0.18 | 1428 ab | 47.7 c | 37.2 c | 1556 a | 95 c | 81.9 c |
| 0.78 | 0.12 | 0.10 | 1419 ab | 56.7 bc | 45.8 bc | 1644 a | 230 ab | 85.1 c |
| 0.20 | 0.12 | 0.68 | 1231 b | 111.0 a | 36.4 c | 1242 c | 252 a | 89.9 bc |
| 0.49 | 0.12 | 0.39 | 1500 a | 61.8 b | 49.6 abc | 1431 abc | 179 bc | 80.5 c |
| 0.28 | 0.02 | 0.70 | 1338 ab | 47.3 b | 60.6 ab | 1238 c | 88 e | 106.0 ab |
| 0.36 | 0.10 | 0.55 | 1438 ab | 58.4 bc | 55.2 ab | 1508 ab | 188 bc | 112.0 a |
| 0.60 | 0.05 | 0.35 | 1250 b | 53.3 bc | 65.6 a | 1525 ab | 116 de | 91.7 bc |
were fertigated with solutions containing high proportions of NO$_3^-$ (0.55–0.80) and SO$_4^{2-}$ (0.40–0.70). Phosphorus concentration in the shoots was higher when plants were fertigated with solutions of low (as long as NO$_3^-$ was at proportions of 0.50 and SO$_4^{2-}$ at 0.35) or high H$_2$PO$_4^-$ proportions (as long as SO$_4^{2-}$ proportion was at 0.35) (Fig. 5). In the roots, increasing P concentrations were associated with increasing H$_2$PO$_4^-$ proportions (Fig. 6).

Nitrogen is a constituent of all the amino acids whereas S is a constituent in two of them, cysteine and methionine; therefore, as N and S are both part of proteins, there is a close relationship between their assimilation (Hawkesford et al., 2012). The uptake of N and S is well coordinated, in that, for example, a deficiency of one may cause a decrease in the assimilation of the other one (Kopriva and Rennenberg, 2004; Kruse et al., 2007). A close relationship between N and S has been reported in several plant species; for example, in wheat (*Triticum aestivum* L.) (Salvagiotti et al., 2009) and legumes (Scherer, 2001), increasing S

| Nitrogen | Phosphorus | Sulfur |
|----------|------------|--------|
| Shoot    | Root       | Shoot  |
| N = 2030NO$_3^-$ - 21659H$_2$PO$_4^-$ + 2440SO$_4^{2-}$ + 20061(NO$_3^-$H$_2$PO$_4$)$^-$ - 520(NO$_3^-$SO$_4^{2-}$)$^-$ + 14226(H$_2$PO$_4^-$SO$_4^{2-}$)$^-$ - 1595(NO$_3^-$H$_2$PO$_4^-$SO$_4^{2-}$)$^-$ | N = -28.7NO$_3^-$ + 9569H$_2$PO$_4^-$ - 135SO$_4^{2-}$ - 10014(NO$_3^-$H$_2$PO$_4$)$^-$ + 8338(NO$_3^-$SO$_4^{2-}$)$^-$ - 897(NO$_3^-$H$_2$PO$_4^-$SO$_4^{2-}$)$^-$ | S = -1.55NO$_3^-$ - 3161H$_2$PO$_4^-$ - 49.8SO$_4^{2-}$ - 3962(NO$_3^-$H$_2$PO$_4$)$^-$ - 99.7(NO$_3^-$SO$_4^{2-}$)$^-$ - 3350(H$_2$PO$_4^-$SO$_4^{2-}$)$^-$ |
| P = -2030NO$_3^-$ + 21659H$_2$PO$_4^-$ - 2440SO$_4^{2-}$ + 20061(NO$_3^-$H$_2$PO$_4$)$^-$ - 520(NO$_3^-$SO$_4^{2-}$)$^-$ + 14226(H$_2$PO$_4^-$SO$_4^{2-}$)$^-$ - 1595(NO$_3^-$H$_2$PO$_4^-$SO$_4^{2-}$)$^-$ | P = -28.7NO$_3^-$ + 9569H$_2$PO$_4^-$ - 135SO$_4^{2-}$ - 10014(NO$_3^-$H$_2$PO$_4$)$^-$ + 8338(NO$_3^-$SO$_4^{2-}$)$^-$ - 897(NO$_3^-$H$_2$PO$_4^-$SO$_4^{2-}$)$^-$ | S = -1.55NO$_3^-$ - 3161H$_2$PO$_4^-$ - 49.8SO$_4^{2-}$ - 3962(NO$_3^-$H$_2$PO$_4$)$^-$ - 99.7(NO$_3^-$SO$_4^{2-}$)$^-$ - 3350(H$_2$PO$_4^-$SO$_4^{2-}$)$^-$ |
| S = -2030NO$_3^-$ + 21659H$_2$PO$_4^-$ - 2440SO$_4^{2-}$ + 20061(NO$_3^-$H$_2$PO$_4$)$^-$ - 520(NO$_3^-$SO$_4^{2-}$)$^-$ + 14226(H$_2$PO$_4^-$SO$_4^{2-}$)$^-$ - 1595(NO$_3^-$H$_2$PO$_4^-$SO$_4^{2-}$)$^-$ | S = -28.7NO$_3^-$ + 9569H$_2$PO$_4^-$ - 135SO$_4^{2-}$ - 10014(NO$_3^-$H$_2$PO$_4$)$^-$ + 8338(NO$_3^-$SO$_4^{2-}$)$^-$ - 897(NO$_3^-$H$_2$PO$_4^-$SO$_4^{2-}$)$^-$ | S = -1.55NO$_3^-$ - 3161H$_2$PO$_4^-$ - 49.8SO$_4^{2-}$ - 3962(NO$_3^-$H$_2$PO$_4$)$^-$ - 99.7(NO$_3^-$SO$_4^{2-}$)$^-$ - 3350(H$_2$PO$_4^-$SO$_4^{2-}$)$^-$ |

To estimate any nutrient concentration, enter the proportion of NO$_3^-$, H$_2$PO$_4^-$, and SO$_4^{2-}$ in the model and multiply them by the corresponding coefficient. The sum of the proportions of the three anions must be equal to 1.

Fig. 5. Counter plots showing the effect of the NO$_3^-$, H$_2$PO$_4^-$, and SO$_4^{2-}$ proportion in the nutrient solution in shoot nitrogen (N), phosphorus (P), and sulfur (S) concentration in anthurium (*Anthurium andraeanum* Linden ex Andr.) plants.

Fig. 6. Counter plots showing the effect of the NO$_3^-$, H$_2$PO$_4^-$, and SO$_4^{2-}$ proportion in the nutrient solution in root nitrogen (N), phosphorus (P), and sulfur (S) concentration in anthurium (*Anthurium andraeanum* Linden ex Andr.) plants.
fertilization under S deficiency conditions resulted in improved N use efficiency and uptake; however, in tomato and cabbage (*Brassica oleracea var. capitata* L.), N uptake was inhibited by high concentrations of SO$_4^{2-}$ (Takano, 1987). Sulfur deficiency in wheat has also been related to lower sulfur-amino acids content and reduced yield (Järvan et al., 2008).

In the present study, the association between N and S was also evident because at low shoot concentration, increasing S resulted in increasing shoot N concentration (Fig. 7); however, further S increments in the shoot were associated with a decrease in N (Fig. 7). The decreased N concentration as a result of the high S concentration in the shoots may explain the potentially toxic effects of SO$_4^{2-}$ observed in our present study, as indicated by the lower root, shoot, and total plant fresh and dry weight at high S concentrations (Fig. 8).

Nitrogen and S in shoots and roots were highest when the proportion of the respective anion increased in the nutrient solution (Figs. 5 and 6); furthermore, SO$_4^{2-}$ uptake rate was maintained as indicated by the high S concentration in the shoots and roots at high SO$_4^{2-}$ proportions (Figs. 5 and 6) whereas shoot S concentration was low even at high SO$_4^{2-}$ proportions as long as the proportion of H$_2$PO$_4^{-}$ in the nutrient solution and the concentration of P in the shoot were high (Fig. 5). Plants fertigated with nutrient solutions containing NO$_3^{-}$, H$_2$PO$_4^{-}$, and SO$_4^{2-}$ at proportions of 0.20:0.12:0.68 (Table 4) resulted in growth promotion (Table 2).

Anthurium plants fertigated with solutions containing the highest proportion of H$_2$PO$_4^{-}$ resulted in shoots and roots with the lowest S concentration despite some of those nutrient solutions were formulated with very high SO$_4^{2-}$ proportions (Table 2), suggesting that high H$_2$PO$_4^{-}$ proportions counteracted the uptake of SO$_4^{2-}$. This hypothesis is supported by reports indicating that SO$_4^{2-}$-induced salinity has a more negative impact on the growth of *Brassica rapa* L. at lower concentrations of P (Reich et al., 2017), which also suggests that higher H$_2$PO$_4^{-}$ proportion may reduce the negative impact of SO$_4^{2-}$ on H$_2$PO$_4^{-}$ uptake.

**Internal N/S and S/P proportion.** High S concentrations in plant tissues (Fig. 8) affected the internal N/S and S/P proportions. Our results showed that a higher internal N/S proportion and a lower internal S/P proportion were associated with higher shoot fresh weight (Fig. 9). Similarly, increasing S shoot concentration was associated with poor growth, which is related to its effect on the reduction in the N/S proportion and in the increase in the S/P proportion.

At a whole plant level, Cram (1990) reported that the N/S proportion for optimum growth in plants is 20/1 whereas for clover (*Trifolium repens* L.), the optimum S/P proportion ranged from 0.81–0.93 (Morton et al., 1998). In the present study, optimum growth of anthurium plants was observed when the N/S and S/P proportion ranged from 31/1 to 38/1 and 0.33/1 to 0.80/1, respectively (Fig. 9). These results suggest that for optimum growth, nutrient solutions must contain high proportions of NO$_3^{-}$ and low SO$_4^{2-}$ for the plant to have a high internal N/S proportion. Alternatively, a high proportion of SO$_4^{2-}$ in the nutrient solution may render acceptable plant growth as long as the proportion of H$_2$PO$_4^{-}$ is higher, for the plant to maintain a low internal S/P proportion.

**Effect of the external anion proportion on N, P, and S allocation.** The allocation of N, P, and S within the plant was affected by the NO$_3^{-}$:H$_2$PO$_4^{-}$:SO$_4^{2-}$ proportion. Nitrogen was predominantly diverted to the
roots in control plants whereas the allocation to the shoots increased in plants fertigated with lower proportions of NO\textsubscript{3} (Fig. 10). The relatively higher allocation of N to the shoots of plants under limited NO\textsubscript{3} supply suggests that this nutrient was transported from the roots to promote shoot growth under insufficiency conditions. Despite the increased S concentration in plant tissues with increasing SO\textsubscript{4}\textsuperscript{2—} proportions (Table 4), most of the S was allocated to the roots (Fig. 10); this is in agreement with results reported for tomato seedlings, in that increasing SO\textsubscript{4}\textsuperscript{2—} supply to S-deficient plants results in increased transport rate of SO\textsubscript{4}\textsuperscript{2—} to the shoot; however, when the supply of SO\textsubscript{4}\textsuperscript{2—} was high, the transport rate did not increase (López et al., 2002).

In the present study, when anthurium was fed with both high SO\textsubscript{4}\textsuperscript{2—} and high H\textsubscript{2}PO\textsubscript{4}\textsuperscript{—}, even more S was allocated to the roots than to the shoots (Fig. 10), as observed in plants fertigated with solutions with a NO\textsubscript{3}—:H\textsubscript{2}PO\textsubscript{4}\textsuperscript{—}:SO\textsubscript{4}\textsuperscript{2—} proportion of 0.20:0.12:0.68. The restricted S translocation to the shoot when H\textsubscript{2}PO\textsubscript{4}\textsuperscript{—} was at high proportions may explain the increased growth of these plants as lower S concentrations was associated with increased shoot fresh and dry weight (Fig. 8).

These results suggest that anthurium plants were able to cope with high SO\textsubscript{4}\textsuperscript{2—} in the nutrient solution by:

a) avoiding the transport of S to the shoot (Fig. 10),
b) decreasing SO\textsubscript{4}\textsuperscript{2—} intake (Table 4),
c) maintaining a favorable internal N/S proportion (Fig. 9),
d) maintaining a favorable internal S/P proportion (Fig. 9),
e) increasing P tissue concentration as a result of high proportions of H\textsubscript{2}PO\textsubscript{4} in the nutrient solution.

Anion uptake selectivity. In spite of the differences in nutrient concentration, plant internal NO\textsubscript{3}—:H\textsubscript{2}PO\textsubscript{4}\textsuperscript{—}:SO\textsubscript{4}\textsuperscript{2—} proportion was unaffected by the external anion ratios as the internal nutrient ratios in the shoots and roots were located in a very specific area (Fig. 11). This suggests that anthurium regulates the accumulation of anions based on its internal demands. Steiner (1973) reported similar trends in tomato, concluding that, regardless of the ratio in the nutrient solution, this species has a strong selective capacity for cation and anion uptake at a given ratio. In the present study, the location of the area for the internal anion ratio shown in Fig. 11 suggests that anthurium was highly selective to exclude SO\textsubscript{4}\textsuperscript{2—} as this nutrient was at much lower concentration than that of the external solutions. Similarly, anthurium plants were able to adjust their uptake of NO\textsubscript{3}— as the internal proportion was maintained at relatively high concentration regardless of the external ratio (Fig. 11). By contrast, the uptake of H\textsubscript{2}PO\textsubscript{4}\textsuperscript{—} was not very selective, as the internal and external ratios were very similar (Fig. 11).

In conclusion, increased growth of anthurium plants was attained at either high or low NO\textsubscript{3}— proportions. Furthermore, we suggest that at low NO\textsubscript{3}—, the high H\textsubscript{2}PO\textsubscript{4}\textsuperscript{—} counteracted the deleterious effect of high SO\textsubscript{4}\textsuperscript{2—} proportions on P tissue concentration. Increasing S concentration in plant tissues was associated with reduced growth; however, excess SO\textsubscript{4}\textsuperscript{2—} uptake was prevented when P status in the plants was increased when H\textsubscript{2}PO\textsubscript{4}\textsuperscript{—} proportions were augmented, resulting in lower S tissue concentrations and improved growth. Our results also suggest that anthurium plants were able to cope with high SO\textsubscript{4}\textsuperscript{2—} when H\textsubscript{2}PO\textsubscript{4}\textsuperscript{—} in the nutrient solution was increased through limiting its transport to the shoot, which in turn resulted in favorable N/S and S/P internal proportions. The internal anion proportion was unaffected by the NO\textsubscript{3}—:H\textsubscript{2}PO\textsubscript{4}\textsuperscript{—}:SO\textsubscript{4}\textsuperscript{2—} proportions in the nutrient solution, demonstrating that anthurium possesses a high selective capacity for nutrient uptake and allocation/partitioning.
Fig. 11. Relationship between the NO$_3^-$, H$_2$PO$_4^-$, and SO$_4^{2-}$ proportion in the nutrient solution (white symbols) with the NO$_3^-$, H$_2$PO$_4^-$, and SO$_4^{2-}$ proportion (gray symbols) in the shoot and root of anthurium (Anthurium andraeanum Linden ex André) plants. Numbers indicate the treatment nutrient solution as shown in Table 1. Data for shoot and root balance calculated on meq kg$^{-1}$.

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