



Silicon foliar application on nutrition and growth of *Phalaenopsis* and *Dendrobium* orchids



Cibele Mantovani*, Renato de Mello Prado, Kathia Fernandes Lopes Pivetta

São Paulo State University (Unesp), School of Agricultural and Veterinarian Sciences, Jaboticabal, Path of Access Professor Paulo Donato Castellane, s/nº, Zip code 14884-900, Jaboticabal, Brazil

ARTICLE INFO

Keywords:

Orchid nutrition
C/Si ratio
Stoichiometry
Orchidaceae
Si toxicity

ABSTRACT

Foliar application of silicon can be beneficial to orchid growth, but it may also impair growth depending on the source and solution concentration. Due to the lack of information on silicon toxicity in long-term orchid nutrition, experiment with two different orchid species, *Phalaenopsis* Golden Peoker and *Dendrobium* Valentine, were performed. The plants were grown in plastic trays with dry *Sphagnum* in a greenhouse, being fed the nutrient solution without silicon in the first six months. After that, the plants were transplanted to individual plastic vessels (0.9 L). The treatments followed a completely randomized design with a 5×3 factorial consisting of five Si concentrations (control, 14.3, 28.6, 42.9 and 57.2 mmol L^{-1}) and three sources (monosilicic acid, potassium silicate, and potassium silicate and sodium silicate mixture), with five replicates. After 18 months of Si foliar application, the Si, C, N, P, K, Ca, Mg and S levels, lignin content and biometric variables were determined for both species. The application of 27 and 16 mmol L^{-1} Si (potassium silicate and monosilicic acid) resulted in the highest values for the evaluated biometric parameters for *Phalaenopsis* and *Dendrobium*, respectively. The results suggest that silicon foliar application affected nutrient absorption and green color index of *Phalaenopsis* and *Dendrobium*, and the lignin content of *Phalaenopsis*. Application of concentrations greater than 39 and 18 mmol L^{-1} Si over 18 months was toxic to *Phalaenopsis* and *Dendrobium*, respectively, since the orchid dry matter decreased by 10% (critical level due to toxicity). Applying increasing concentrations of Si sources decreased the C:N:P stoichiometric ratio of orchids.

1. Introduction

There are several studies on orchid nutrition and fertilization in the literature (Naik et al., 2009; Wang and Chang, 2017) because orchid farming represents one of the most economically important activities of the global nursery industry (Teixeira da Silva, 2013). However, to our knowledge, there are no reports on the application of Si during the entire vegetative cycle.

In plant metabolism, silicon (Si) is involved in the synthesis of lignin, increasing tissue stiffness (Epstein, 1999), but, it is not known how excess Si would affect orchid growth.

Recent study in the literature correlated Si to the C:N:P stoichiometric change in grass leaves (Schaller et al., 2012), which may imply that organic compounds are partially replaced by Si compounds in plant tissue when Si is available to the plant, reinforcing the importance of Si. However, this relationship has not been investigated for perennial plants such as orchids.

There are report on *Phalaenopsis* orchids cultivated *in vitro* indicating growth benefit when Si is present in the culture medium (Zhou,

1995). However, Si may decrease plant growth under certain cultivation conditions as reported by Soares et al. (2008) for orchids (*Hardrolaelia*) while using sodium silicate as Si source during the acclimatization phase (8 months).

Also in Maize, Si in excess forms a thick silicate layer below the cuticle on the leaf epidermis (Kochanová et al., 2014) that may reduce plant gas exchange and biomass accumulation without causing oxidative stress. Therefore, unlike other toxicity stresses, excess Si may not trigger an increase of reactive oxygen resulting in oxidation of organic compounds such as proteins and lipids, inducing membrane damage and extravasation of the cytosol to the apparent free space of the cell, causing cell death (Fridovich, 1986; Marschner, 1995).

Other studies on Si are restricted to *in vitro* orchid cultivation (Sivanesan and Park, 2014) or the initial phase during the first month of plant growth (*Phalaenopsis* hybrids) (Vendrame et al., 2010). Furthermore, there are no reports on Si foliar application during the entire vegetative cycle that can last up to 18 months depending on the growth environment.

It is important to study not only the benefits of silicon but also its

* Corresponding author.

E-mail address: orquidariomantovani@gmail.com (C. Mantovani).

possible detrimental effect on plants that absorb but do not accumulate Si such as orchids to improve the knowledge on the role that foliar Si plays on the growth of ornamental plants.

It has been hypothesized that Si *via* foliar applications can benefit the orchids, but excess can diminish nutrient absorption and plant growth without altering the leakage of cellular electrolytes and lignin contents depending on the Si source and solution concentration.

Therefore, the objective of the present study was to evaluate the response of epiphytic orchids to silicon foliar application from various sources each at several concentrations during the growth phase, from seedlings until pre-flowering.

2. Material and methods

The experiment was carried out in an orchid greenhouse located in Itapolis, São Paulo, Brazil. The used orchids, *Phalaenopsis* Golden Peoker and *Dendrobium* Valentine seedlings, were obtained *via in vitro* propagation and acclimatized in plastic trays filled with dry *Sphagnum* substrate. In the first six months, the plants were fertirrigated with the complete nutrient solution of Sarruge (1975) without Si, biweekly. Then, the seedlings were transplanted individually into black polyethylene vessels (upper diameter: 13 cm, lower diameter: 8.4 cm, height: 10.6 cm) with 0.9 L volume.

The nutrient concentrations (mg L^{-1}) in the solution was: 225 N; 31 P; 234 K; 200 Ca; 48 Mg; 64 S; 0.5 B; 0.5 Mn; 0.05 Zn; 0.02 Cu; 0.01 Mo; 5 Fe (Sarruge, 1975).

The plants were kept in a greenhouse with average Photosynthetic Photon Flux Density of $300 \mu\text{mol m}^{-2}\text{s}^{-1}$ at noon, and maximum and minimum temperatures of 34 and 15 °C, respectively. The pots were filled with a layer of expanded clay at the bottom (25% of the total volume) and with a 2:1 (v/v) mixture of pinus bark and charcoal medium, and placed on hanging tables at a height of 0.65 m. The position of the pots was randomly changed after each treatment application, every 15 day.

The plants were irrigated twice and three times a week in the winter and summer, respectively, with 100 mL of distilled water (pH = 6.8) per pot. The complete nutrient solution of Sarruge (1975) was applied separately in the substrate *via* fertirrigation, once a week.

The silicon was applied *via* foliar to two orchid species, the *Phalaenopsis* Golden Peoker and *Dendrobium* Valentine, following a 3×5 factorial scheme consisting of three sources and five Si concentrations. The treatments were as follows: control (zero), 14.3, 28.6, 42.9 and 57.2 mmol L^{-1} Si from monosilicic acid (ZumsilTM manufactured by TERRATECH CORP. in Miami, Florida, USA); potassium silicate (Sifol[®] manufactured by Diatom in Mogi das Cruzes, São Paulo, BR) and potassium silicate and sodium silicate mixture. The experiment followed a completely randomized design with five replicates, and the experimental unit consisted of three plants, with one plant per pot.

The characteristics of the Si sources were density = 1.25 and $\text{Si} = 79.3 \text{ g L}^{-1}$ for monosilicic acid (ZumsilTM); density = 1.41, $\text{Si} = 168 \text{ g L}^{-1}$, and $\text{K}_2\text{O} = 211.5 \text{ g L}^{-1}$ for potassium silicate (Sifol[®]); and density = 1.15; $\text{Si} = 124 \text{ g L}^{-1}$; $\text{K}_2\text{O} = 42.3 \text{ g L}^{-1}$ and $\text{Na} = 31.6 \text{ g L}^{-1}$ for the potassium silicate with sodium silicate mixture. The pH of the Si solution was adjusted to approximately 5.7 and 5.9 for all treatments.

The potassium concentrations were balanced with potassium chloride in all treatments. On the other hand, in the potassium silicate and sodium silicate mixture treatments, the sodium concentrations were balanced with sodium chloride.

Because orchids absorb nutrients and Si *via* foliar and roots, a solution volume sufficient to cover the total leaf area was applied on each plant using a micro-sprayer. This volume increased as plant developed (ranging from 30 to 50 mL per plant) while application frequency depended on the vegetative growth. The Si solution was sprayed every 30 days in the first six months and every 15 days in the last 12 months.

Eighteen months after Si application had started and the plants

began flowering (the first stem emerged), the following parameters were measured: stem diameter (mm) measured at 2 cm from the stem base using a digital caliper (Starrett[®]727-2001 manufactured in Itu, São Paulo, BR); root length (cm) measured the longer of aerial root in each plant; root volume (mL) determined by the volumetric test method (Carrigan and Frey, 1980); leaf area (cm^2) obtained from all plant leaves using a digital meter (Li-Color, model L1-3000[®]); electrolyte leakage (Dionisio-Sese and Tobita, 1998), and green color index (using the portable OptiScience[®] chlorophyll meter model CCM-200, in the central part of the adaxial surface of the last fully developed leaf of each plant). The number of pseudobulbs and plant height (cm) were determined only for *Dendrobium* Valentine while the number of leaves and plant width (corresponding to the distance between the apex of the last two fully expanded leaves, cm) were measured only for *Phalaenopsis* Golden Peoker.

The orchids were divided into aerial part/shoot and root and dried in forced circulation oven at 65–70 °C temperature, until constant weight. The dry matter was determined. The plant material was ground to determine the N, P, K, Ca, Mg and S contents following the methodology described by Bataglia et al. (1983) and the C content by the Dumas method using the LECO[®] CN628 carbon analyzer. The accumulation of C, N, P, K, Ca, Mg and S in the aerial shoot was calculated based on the nutrient concentration and dry matter.

The silicon content in the leaf tissue was determined following the method proposed by Korndörfer et al. (2004), and multiplied by the dry matter to obtain Si levels in the shoot whereas the lignin content was determined by the Klason method (Silva and Queiroz, 2002).

The results were analyzed by the F-test at 1% and 5% probability. The polynomial regression was applied when significant for doses (D) while the means were compared by Tukey at 5%, for sources (F), in which the same letters indicate that the values do differ for the same dosage among the sources (a, b, and c). The calculations were carried using the AgroEstat software (Barbosa and Maldonado, 2014).

3. Results

3.1. Levels of nutrients and silicon

In *Phalaenopsis*, the C levels decreased linearly in relation to monosilicic acid application (Si_Mono); increased quadratically with potassium silicate (Si_K) maximizing at 946.8 mg per plant for 26.7 mmol L^{-1} Si; and, decreased quadratically with the potassium and sodium silicate mixture (Si_K/Na) reaching a minimum at 235.2 mg per plant for 77.3 mmol L^{-1} Si (Fig. 1A). The N, K, Ca and Mg levels increased quadratically with increasing Si from the potassium silicate and the potassium and sodium silicate mixture. However, Si from the monosilicic acid did not affect N, K, Ca and Mg levels (Fig. 1B–F). The K levels were affected by the applied Si, reaching a maximum of 564.5 mg per plant for the 27.6 mmol L^{-1} Si (potassium silicate). The P, S, and Si levels increased quadratically with increasing Si levels, regardless of the source (Fig. 1C, G, and H).

The highest Si levels in *Phalaenopsis* were obtained for the 33.7 mmol L^{-1} Si from the potassium and sodium silicate mixture, followed by 30.9 mmol L^{-1} Si from potassium silicate, and 29.6 mmol L^{-1} Si from monosilicic acid (Fig. 1H).

In *Dendrobium*, the C, N, K and S levels increased quadratically with increasing Si from monosilicic acid, and potassium and sodium silicate mixture while decreasing linearly with increasing Si from silicate potassium (Fig. 2A, B, D, and G). The K level reached up to 244.1 mg per plant for 23.4 mmol L^{-1} Si (Si_K/Na). The highest C levels were 1193.6 and 1155.7 mg per plant recorded for monosilicic acid (14.2 mmol L^{-1} Si) and potassium and sodium silicate mixture (24.2 mmol L^{-1} Si), respectively. The P, Ca and Mg levels increased quadratically with increasing Si from monosilicic acid; decreased linearly with potassium silicate, and remained unchanged for the potassium and sodium silicate mixture (Fig. 2C, E, and F).

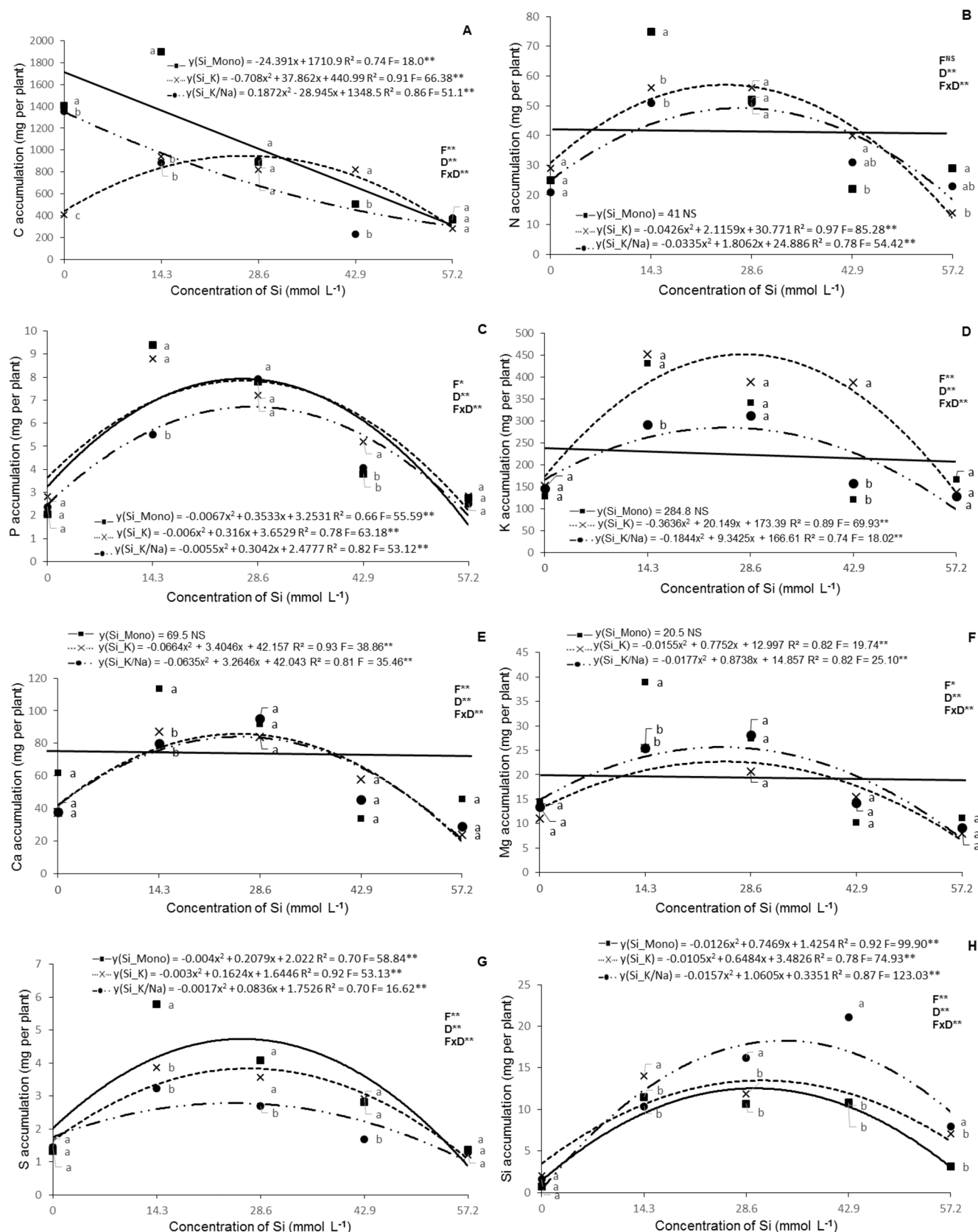


Fig. 1. Accumulation of C (A), N (B), P (C), K (D), Ca (E), Mg (F), S (G) and Si (H) in aerial part of *Phalaenopsis* Golden Pecker with increasing concentrations of monosilicic acid (Si_Mono), potassium silicate (Si_K) and potassium and sodium silicate mixture (Si_K/Na) after 18 months from the start of Si application. * $p < 0,05$; ** $p < 0,01$; ^{NS} not significant by the F test. F to Si source, D to Si concentration and FxD to interaction.

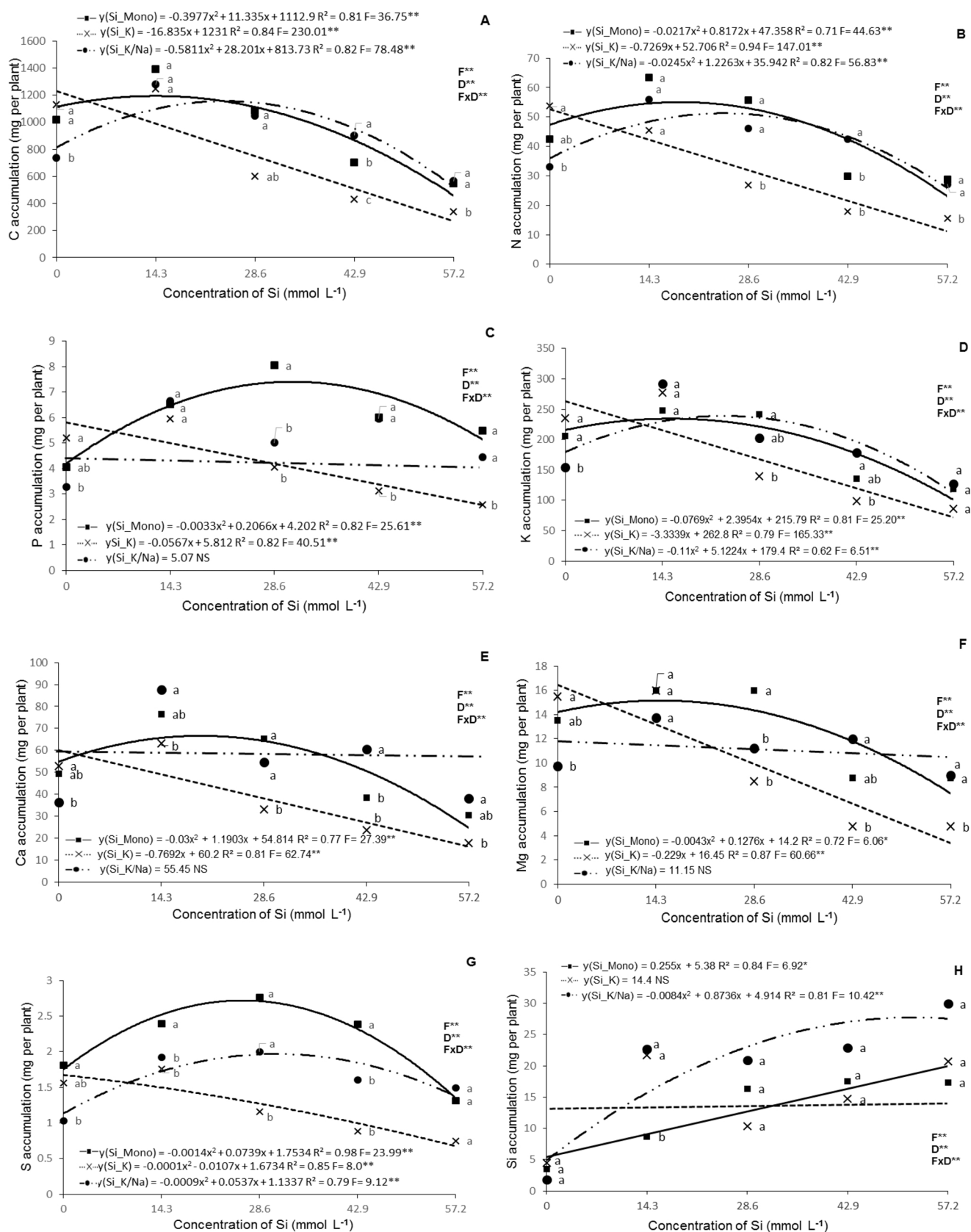


Fig. 2. Accumulation of C (A), N (B), P (C), K (D), Ca (E), Mg (F), S (G) and Si (H) in aerial part of *Dendrobium Valentinum* with increasing concentrations of monosilicic acid (Si_Mono), potassium silicate (Si_K) and potassium and sodium silicate mixture (Si_K/Na) after 18 months from the start of Si application. $^{**} p < 0,01$; NS not significant by the F test. F to Si source, D to Si concentration and FxD to interaction.

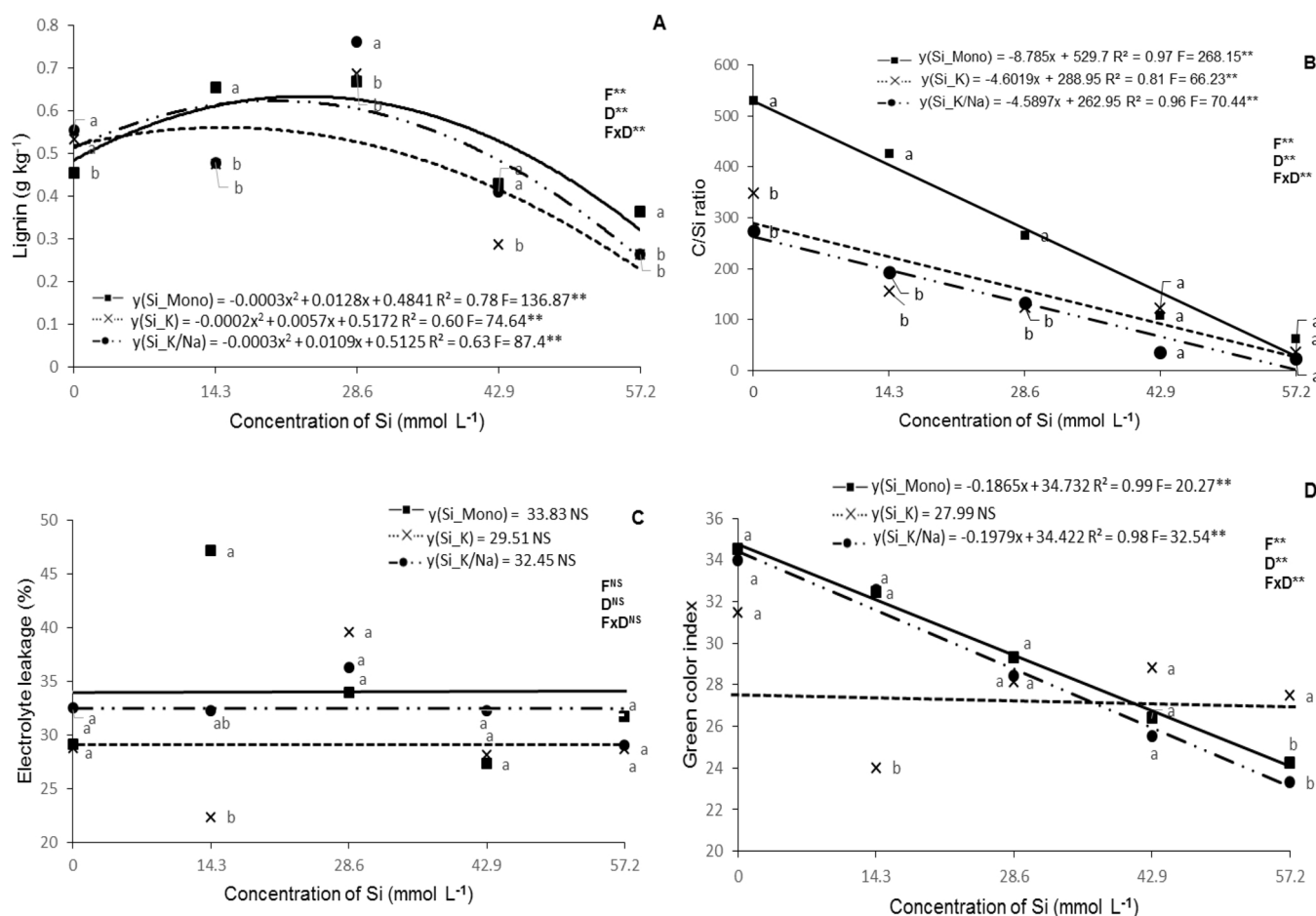


Fig. 3. Lignin content (A), C/Si ratio (B), electrolyte leakage (C) and green color index (D) in *Phalaenopsis* Golden Pecker with increasing concentrations of monosilicic acid (Si_Mono), potassium silicate (Si_K) and potassium and sodium silicate mixture (Si_K/Na) after 18 months from the start of Si application. ** $p < 0,01$; ^{NS} not significant by the F test. F to Si source, D to Si concentration and FxD to interaction.

The Si levels in *Dendrobium* increased linearly with increasing monosilicic acid, and quadratically with increasing potassium and sodium silicate mixture, reaching up to 27.62 mg per plant for 52 mmol L⁻¹ Si while remaining unchanged for increasing Si from potassium silicate (Fig. 2H).

3.2. Lignin content, electrolyte leakage, stoichiometric ratio and green color index

Phalaenopsis lignin content increased quadratically with increasing Si reaching 0.62, 0.55 and 0.61 g kg⁻¹ for the 25, 12.5 and 18.2 mmol L⁻¹ Si from monosilicic acid, potassium silicate, and potassium and sodium silicate mixture, respectively (Fig. 3A).

On the other hand, *Dendrobium* lignin content was affected by neither Si sources nor concentrations (Fig. 4A).

The C/Si ratio decreased linearly and quadratically in the foliar tissue of *Phalaenopsis* (Fig. 3B) and *Dendrobium* (Fig. 4B), respectively, with increasing Si concentration from all sources tested. The C:N:P stoichiometric ratios decreased in the foliar tissue of *Phalaenopsis* and *Dendrobium* with increasing Si concentrations (Table 1).

The leakage of electrolytes in *Phalaenopsis* was not influenced by the different silicon sources or concentrations (Fig. 3C). In *Dendrobium*, electrolyte leakage increased quadratically reaching a maximum (34.8) for the 28.5 mmol L⁻¹ Si from the potassium and sodium silicate mixture (Fig. 4C).

Phalaenopsis green color index (GCI) decreased linearly with increasing Si from monosilicic acid, and potassium and sodium silicate mixture. However, it remained unchanged (27.99) with the potassium

silicate application (Fig. 3D).

Dendrobium green color index decreased linearly with increasing Si from monosilicic acid and potassium and sodium silicate mixture. Furthermore, it increased quadratically with increasing potassium silicate concentrations, peaking at 32 for 16 mmol L⁻¹ Si (Fig. 4D).

3.3. Effect of silicon on plant growth and development

In *Phalaenopsis*, plant width, stem diameter, root length and number of leaves decreased linearly with increasing Si from monosilicic acid, and potassium and sodium silicate mixture. However, these parameters increased quadratically with increasing concentrations of potassium silicate reaching up to 35.5, 16, 22, and 6 for 15, 19, 21 and 23 mmol L⁻¹ Si, respectively (Fig. 5A–C, and E).

The root volume decreased linearly with increasing Si concentrations and sources (Fig. 5D). The leaf area decreased linearly with the Si concentrations from monosilicic acid while increased quadratically with increasing Si from potassium silicate, and potassium and sodium silicate mixture (Fig. 5F).

Phalaenopsis dry matter increased quadratically for the Si sources and concentrations tested. The dry matter reached up to 3.4, 4.1 and 3.3 g for the application of 26, 27.4, and 21.8 mmol L⁻¹ Si from monosilicic acid, potassium silicate, and potassium and sodium silicate mixture, respectively. On the other hand, dry matter decreased 10% for the 39, 39.6 and 40.1 mmol L⁻¹ Si concentrations from the monosilicic acid, potassium silicate, and sodium and potassium silicate mixture sources, respectively (Fig. 5G).

Dendrobium mean plant height, root length and root volume

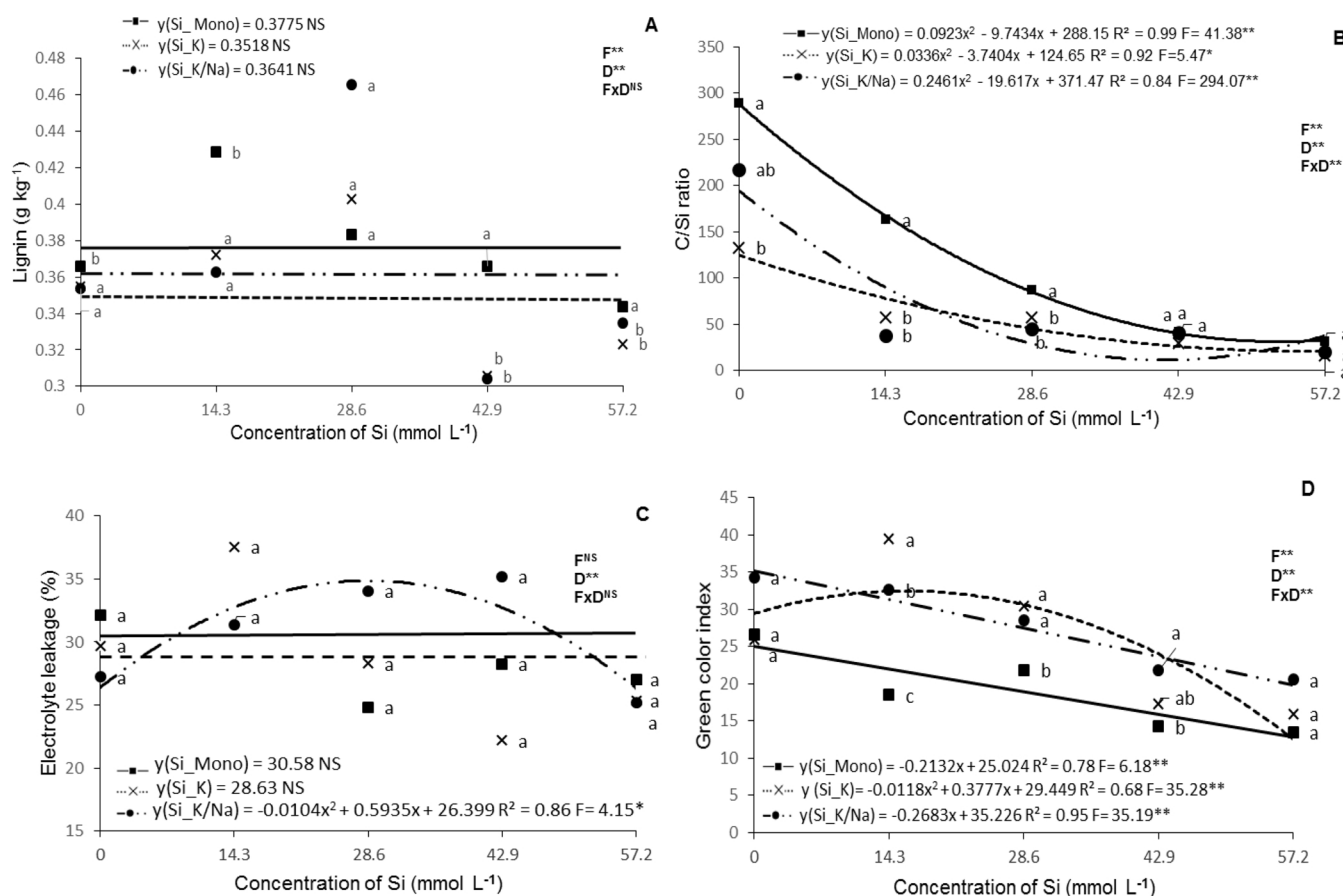


Fig. 4. Lignin content (A), C/Si ratio (B), electrolyte leakage (C) and green color index (D) in *Dendrobium Valentine* with increasing concentrations of monosilicic acid (Si_Mono), potassium silicate (Si_K) and potassium and sodium silicate mixture (Si_K/Na) after 18 months from the start of Si application. ** $p < 0,01$; ^{NS} not significant by the F test. F to Si source, D to Si concentration and FxD to interaction.

Table 1

C:N:P ratio for *Phalaenopsis Golden Peoker* and *Dendrobium Valentine* submitted to the application of monosilicic acid, potassium silicate, and potassium and sodium silicate mixture, after 18 months from the start of Si application.

| Concentrations of Si (mmol L ⁻¹) | Monosilicic acid | Potassium silicate | Potassium and sodium silicate mixture |
|--|------------------|--------------------|---------------------------------------|
| <i>Phalaenopsis Golden Peoker</i> | | | |
| 0 | 199:12:1 | 148:11:1 | 177:9:1 |
| 14.3 | 151:8:1 | 136:8:1 | 158:9:1 |
| 28.6 | 133:7:1 | 114:8:1 | 116:7:1 |
| 42.9 | 132:8:1 | 108:5:1 | 105:6:1 |
| 57.2 | 133:8:1 | 103:5:1 | 126:7:1 |
| <i>Dendrobium Valentine</i> | | | |
| 0 | 252:11:1 | 220:9:1 | 229:10:1 |
| 14.3 | 216:10:1 | 157:7:1 | 222:8:1 |
| 28.6 | 134:7:1 | 149:7:1 | 195:10:1 |
| 42.9 | 118:5:1 | 137:6:1 | 152:7:1 |
| 57.2 | 99:5:1 | 132:6:1 | 128:6:1 |

decreased linearly with the increasing Si concentrations of the tested sources (Fig. 6A and C).

The *Dendrobium* stem diameter remained unchanged for the Si concentrations from the potassium and sodium silicate mixture, but decreased linearly with Si from monosilicic acid, and decreased quadratically with increasing Si concentrations from the potassium silicate (Fig. 6B).

The highest number of pseudobulbs in *Dendrobium* (5.6) was observed for the application of 25.4 mmol L⁻¹ Si from the potassium and sodium silicate mixture. The monosilicic acid and silicate potassium Si

sources resulted in 4.1 and 4.4 pseudobulbs on average, for 11 and 9.1 mmol L⁻¹ Si, respectively (Fig. 6E).

Dendrobium leaf area decreased linearly with increasing Si from monosilicic acid and potassium silicate while increasing quadratically for the potassium and sodium silicate mixture, reaching up to 57.9 for the 25 mmol L⁻¹ Si (Fig. 6F).

Dendrobium total dry matter decreased linearly with increasing Si concentrations from potassium silicate, and potassium and sodium silicate mixture, while increasing quadratically with increasing monosilicic acid concentrations (Fig. 6G).

The maximum dry matter (3.1, 3.16 and 2.9 g) contents were observed for 16.4, 0 and 0 mmol L⁻¹ Si from the monosilicic acid, potassium silicate, and potassium and sodium silicate mixture sources, respectively. On the other hand, the maximum dry matter content dropped 10% for the 17.6, 8.2 and 13 mmol L⁻¹ Si concentrations from monosilicic acid, potassium silicate, and potassium and sodium silicate mixture sources, respectively.

4. Discussion

4.1. Nutrition

In general, as the Si concentrations increased the level of nutrients decreased in *Phalaenopsis* and *Dendrobium* because the mineral content in the orchid tissue depends on fertilization (Naik et al., 2009) and probably Si competed with the other ions during absorption.

The present study demonstrated that *Phalaenopsis* and *Dendrobium* orchids absorbed and accumulated Si applied via foliar. However, studies involving foliar application of Si in orchids are incipient in the

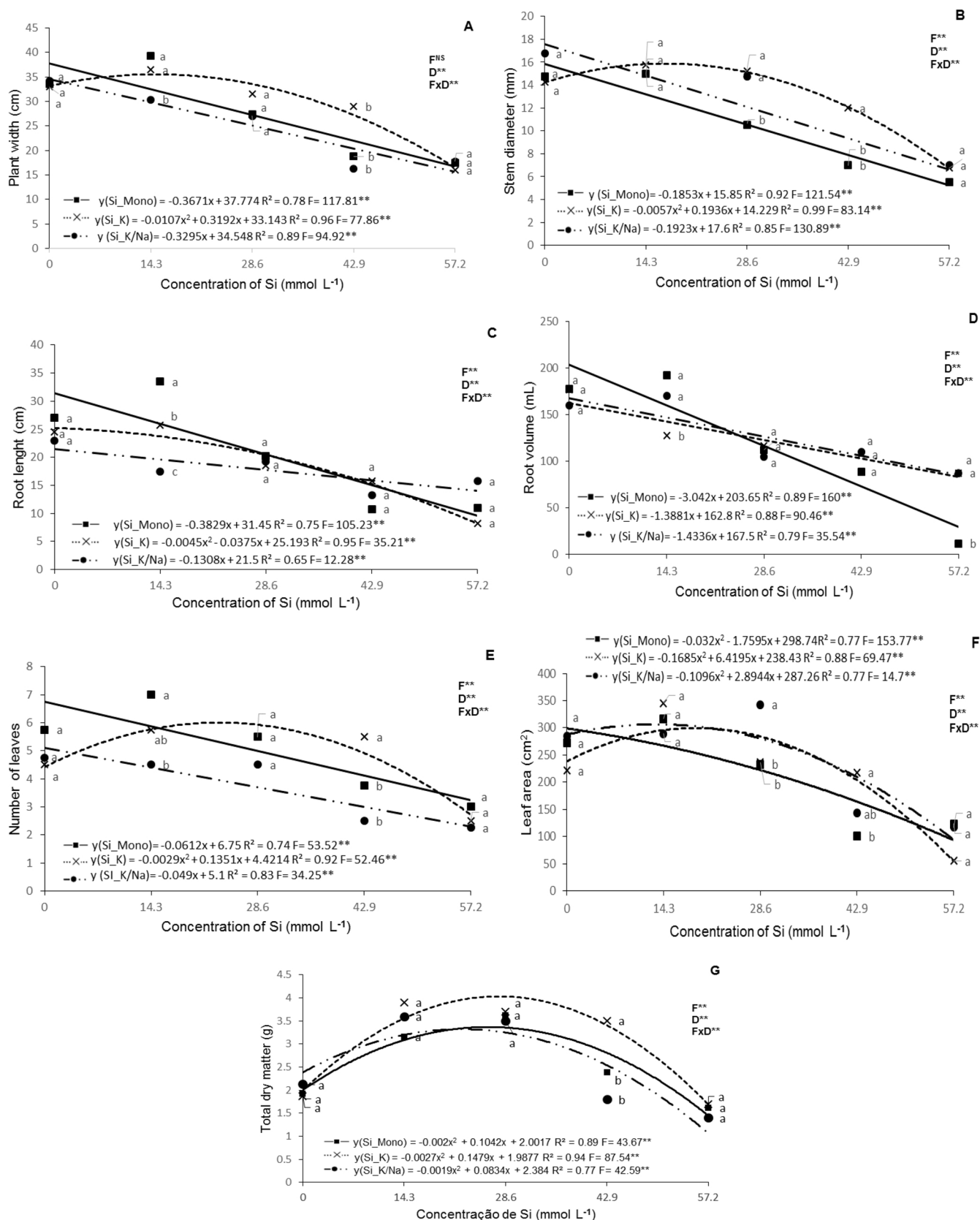


Fig. 5. Plant width (A), stem diameter (B), root length (C), root volume (D), number of leaves (E), leaf area (F) and total dry matter (G) of *Phalaenopsis* Golden Pecker with increasing concentrations of monosilicic acid (Si_Mono), potassium silicate (Si_K) and potassium and sodium silicate mixture (Si_K/Na) after 18 months from the start of Si application. ** p < 0,01; NS not significant by the F test. F to Si source, D to Si concentration and FxD to interaction.

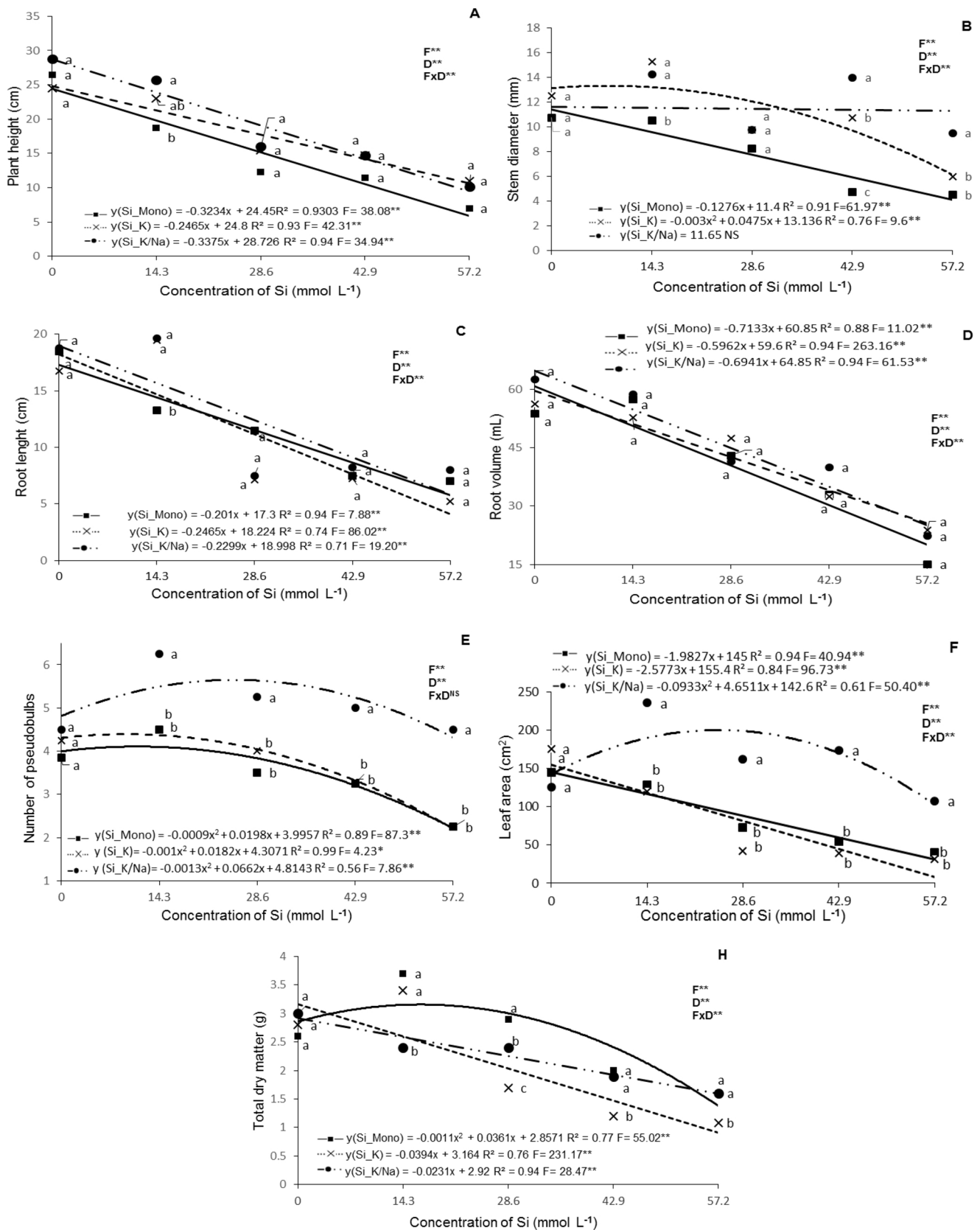


Fig. 6. Plant height (A), stem diameter (B), root length (C), root volume (D), number of pseudobulbs (E), leaf area (F) and total dry matter (G) for *Dendrobium Valentine* with increasing concentrations of monosilicic acid (Si_Mono), potassium silicate (Si_K) and a mixture of potassium silicate and sodium silicate (Si_K/Na), after 18 months from the start of Si application. ** p < 0,01; NS not significant by the F test. F to Si source, D to Si concentration and FxD to interaction.

literature and, therefore, there is no information to compare the nutritional status of the orchids that have absorbed the Si with other works performed with orchids under different cultivation conditions and age.

The applied Si did not change the lignin content of *Dendrobium*. Likewise, Radomski (2006) studied the ornamental plant *Maytenus ilicifolia* and reported similar result after applying between 0 and 600 kg Si ha⁻¹ in the soil for one year. Also, Fleck et al. (2015) evaluated the lignin content of rice, corn, and onion in the presence (1.07 mmol L⁻¹) and absence of Si and reported similar conclusion.

However, for *Phalaenopsis*, the highest silicon concentrations resulted in lower Si accumulation in the aerial part and, consequently, the lowest lignin contents (Fig. 3A). Therefore, the effect of Si on the lignin content depends on the genotype and the accumulation of Si in the aerial part, being different for plants of the genus *Phalaenopsis* and *Dendrobium*.

Among others, Si is beneficial to plant metabolism since it contributes to keep the leaves photosynthetically active, increasing the chlorophyll synthesis and the green color index (GCI) only when supplying the ammonium N source (Campos et al., 2016). However, as observed in this work, under normal conditions of cultivation (without stress), the GCI decreased for both *Phalaenopsis* and *Dendrobium* for Si addition since Si can affect the protective effects of photosynthetic mechanisms, and nutrient balance, especially N (Mateos-Naranjo et al., 2013).

In the presence of this beneficial element there was increased activity of enzymes acting in the N metabolism, such as nitrate reductase, glutamine synthetase, glutamate synthetase and glutamate dehydrogenase (Bybordi, 2012; Feng et al., 2010). Nevertheless, the excess of Si impaired the N absorption by the orchids; likewise, Botelho et al. (2005) also demonstrated that Si application decreased N absorption.

Schaller et al. (2012) studied the *Pragmites australis* gramineous treated with increasing Si doses (0, 4.66 and 46.6 g amorphous Si) and reported modifications in the C:N:P stoichiometric ratios, as well. This result may be due to a partial substitution of organic compounds by Si compounds in the plant tissue, which is advantageous to the plant since silicon deposits require less energy to form and can confer lignin-like defenses (Schoelynck et al., 2010).

Therefore, the decreasing C, N, P contents observed for high Si doses may reflect the plant shifting to a defense mechanism that uses less energy in the presence of high Si concentrations (Schaller et al., 2012). This fact influenced the accumulation of other nutrients (K, Ca, Mg and S) such as the decreasing C/Si ratio observed in the foliar tissue.

4.2. Growth and development

Foliar application of Si at low concentrations had a positive effect on the growth of *Phalaenopsis* and *Dendrobium* possibly due to the better Si distribution and absorption compared to high concentration applications.

The physical parameters evaluated for both species of orchids had the worst results for the highest Si concentration evaluated, showing that Si toxicity decreased plant growth and development. This result corroborates the results reported by Soares et al. (2008) for a biweekly application of foliar potassium silicate and sodium silicate in the acclimatization of a hybrid *Hadrolaelia lobata* × *Hadrolaelia purpurata* steel orchid for eight months.

The mineral requirements of orchids vary with plant species and growth stages, therefore, the presented results show that *Dendrobium* Valentine Orchid is more sensitive to Si foliar application than *Phalaenopsis* Golden Peoker.

The highest Si concentrations applied to the leaf corresponded to the lowest average dry matter. Similar Si negative effect was verified by Vendrame et al. (2010) with the foliar application of potassium silicate to two *Phalaenopsis* cultivars.

Si concentrations higher than 39 and 18 mmol L⁻¹ Si (monosilicic

acid) were considered as toxic critical levels for *Phalaenopsis* and *Dendrobium*, respectively, since the dry matter of orchids decreased by 10% (critical level due to toxicity).

In this study, the largest plant width (35.5 cm) for *Phalaenopsis* was obtained for 14.9 mmol L⁻¹ Si from potassium silicate during the *ex vitro* growth until the flowering. On the other hand, Zhou (1995) also observed increased size of *Phalaenopsis* leaves but with the addition of 0.1–1.0 mg L⁻¹ calcium silicate to the culture medium during the *in vitro* culture phase.

Si toxicity decreased the number of pseudobulbs in *Dendrobium*, which according to Ng and Hew (2000), play an essential role in the growth and survival of orchids, accumulating water, mineral nutrients and carbohydrates, aiding the flowering and sprouting.

Si is accumulated as H₄SiO₄ (monosilicic acid) in the epidermal cells and walls of the stomata, but when the plant begins to lose water (water stress), this monomeric form becomes polymeric forms. Therefore, Si begins to form larger polysilicic acid chains, decreasing the flexibility of the stoma walls that tend to remain closed. The closed stomata decrease transpiration and water loss, which according to Faria (2000) decreases photosynthesis, possibly leading to lower development and, consequent, lower mass of orchids cultivated with high Si doses, as verified by Luz et al. (2006) for lettuce cultivation.

Another hypothesis regarding Si toxic effect would be that excess Si forms a thick silicate layer below the cuticle on the leaf epidermis (Kochanová et al., 2014). This layer may reduce plant gas exchange and biomass accumulation without causing oxidative stress, so that orchids submitted to the highest Si concentrations had lower accumulation of Si and nutrients, as well as lower performance of all biometric parameters evaluated.

5. Conclusions

Si concentrations of 27 and 16 mmol L⁻¹ from potassium silicate and monosilicic acid sources are beneficial to growth of *Phalaenopsis* and *Dendrobium*, respectively.

The Si foliar application at concentrations higher than 39 and 18 mmol L⁻¹ in *Phalaenopsis* and *Dendrobium* orchids, respectively, for 18 consecutive months caused Si toxicity in the plants without altering the electrolyte leakage.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.scienta.2018.06.088>.

References

- Barbosa, J.C., Maldonado, J.R.W., 2014. AgroEstat - System for Statistical Analysis of Agronomic Trials - Version 1.1.0.711. Jaboticabal: Faculty of Agrarian and Veterinary Sciences, Universidade Estadual Paulista.
- Bataglia, O.C., Furlani, A.M.C., Teixeira, J.P.F., Furlani, P.R., Gallo, J.R., 1983. Methods of chemical analysis of plants. Campinas: Instituto Agrônomico de Campinas. Tech. Bull. 78, 48.
- Botelho, D.M.S., Pozza, E.A., Pozza, A.A.A., Carvalho, J.G., Botelho, C.E., Souza, P.E., 2005. Intensity of cercosporiosis in coffee seedlings due to sources and doses of silicon. Fitopatologia Brasileira 30, 582–588.
- Bybordi, A., 2012. Effect of ascorbic acid and silicium on photosynthesis, antioxidant enzyme activity, and fatty acid contents in canola exposure to salt stress. J. Integr. Agric. 11, 1610–1620.
- Campos, C.N.S., Prado, R.M., Caione, G., de Lima Neto, A.J., Mingotte, F.A.L.C., 2016. Silicon and excess ammonium and nitrate in cucumber plants. Afr. J. Agric. Res. 11, 276–283.
- Carrigan, L., Frey, K.J., 1980. Root volumes of *Avena* species. Crop Science 20, 407–408.
- Dionisio-Sese, M.L., Tobita, S., 1998. Antioxidant responses of rice seedlings to salinity stress. Plant Sci. 135, 1–9.
- Epstein, E., 1999. Silicon. Annu. Rev. Plant Physiol. Plant Mol. Biol. 50, 641–664.
- Faria, R.J., 2000. Influence of Calcium Silicate on the Tolerance of Rainfed Rice to Soil Water Deficit. Master'S Thesis. Federal University of Lavras, Lavras, Brasil 47p.
- Feng, J., Shi, Q., Wanga, X., Wei, M., Yang, F., Xu, H., 2010. Silicon supplementation ameliorated the inhibition of photosynthesis and nitrate metabolism by cadmium (Cd) toxicity in *Cucumis sativus* L. Scientia Hort. 123, 521–530.

- Fleck, A.T., Schulze, S., Hinrichs, M., Specht, A., Wafsmann, F., Schreiber, L., Schenk, M.K., 2015. Silicon promotes exodermal casparian band formation in Si-accumulating and Si-excluding species by forming phenol complexes. *PLoS One* 10, e0138555.
- Fridovich, I., 1986. Biological effects of the superoxide radical. *Arch. Biochem. Biophys.* 247, 1–11.
- Kochanová, Z., Jašková, K., Sedláková, B., Luxová, M., 2014. Silicon improves salinity tolerance and affects ammonia assimilation in maize roots. *Biologia* 69, 1164–1171.
- Korndörfer, G.H., Pereira, H.S., Nolla, A., 2004. Silicon analysis: soil, plant and fertilizer. Technical Bulletin. Institute of Agrarian Sciences. Federal University of Uberlândia, Uberlândia MG, pp. 2.
- Luz, J.M.Q., Guimarães, S.T.M.R., Korndörfer, G.H., 2006. Hydroponic production of lettuce in nutritive solution with and without silicon. *Horticultura Brasileira* 24, 295–300.
- Marschner, H., 1995. Part I. Nutritional physiology. In: Marschner, H. (Ed.), *Mineral Nutrition of Higher Plants* Vol. 313–363. Academic Press Limited, London, pp. 18–30.
- Mateos-Naranjo, E., Andrades-Moreno, L., Davy, A.J., 2013. Silicon alleviates deleterious effects of high salinity on the halophytic grass *Spartina densiflora*. *Plant Physiol. Biochem.* 63, 115–121.
- Naik, S.K., Ush, T., Arathi, D.B., Devadas, R., Pal, R., Medhi, R.P., 2009. Status of mineral nutrition of orchid—a review. *J. Ornament. Hortic.* 1, 1–14.
- Ng, C.K.Y., Hew, C.S., 2000. Orchid pseudobulbs—false bulbs with a genuine importance in orchid growth and survival. *Scientia Horticult.* 83, 165–172.
- Radomski, M.I., 2006. Foliar Contents of Silicon, Tannins and Lignin, in *Maytenus ilicifolia* Martius ex Reiss. (Espinheira-Santa), According to Environmental and Genetic Variables. Doctoral Thesis. Paulista State University, Botucatu, Brasil.
- Sarruge, J.R., 1975. Nutrition solutions. *Summa Phytopathol.* 1, 231–233.
- Schaller, J., Brackhage, C., Gessner, M.O., Bäuker, E., Gertdudel, E., 2012. Silicon supply modifies C:N:P stoichiometry and growth of *Phragmites australis*. *Plant Biol.* 14, 392–396.
- Schoelynck, J., Bal, K., Backx, H., Okruszko, T., Meire, P., Struyf, E., 2010. Silica uptake in aquatic and wetland macrophytes: a strategic choice between silica, lignin and cellulose? *New Phytol.* 186, 385–391.
- Silva, D., Queiroz, A.D., 2002. *Food Analysis: (Chemical and Biological Methods)*, 3 ed. UFV, Impr. Univ. 235 pp.
- Sivanesan, I., Park, S., 2014. The role of silicon in plant tissue culture. *Front. Plant Sci.* 5, 571.
- Soares, J.D.R., Pasqual, M., Rodrigues, F.A., Villa, F., Carvalho, J.D., 2008. Fertilization with foliar silicon in the acclimatization of an orchid hybrid. *Ciência e Agrotecnologia* 32, 626–629.
- Teixeira da Silva, J., 2013. Orchids: advances in tissue culture, genetics, phytochemistry and transgenic biotechnology. *Floricult. Ornament. Biotechnol.* 7, 1–52.
- Vendrame, W.A., Palmateer, A.J., Pinares, A., Moore, K.A., Datnoff, L.E., 2010. Silicon fertilization affects growth of hybrid *Phalaenopsis* orchid liners. *HortTechnology* 20, 603–607.
- Wang, Y.T., Chang, Y.C.A., 2017. Effects of nitrogen and the various forms of nitrogen on *Phalaenopsis* Orchid—a review. *HortTechnology* 27, 144–149.
- Zhou, T., 1995. The detection of the accumulation of silicon in *Phalaenopsis* (Orchidaceae). *Annu. Bot.* 75, 605–607.