B A S E *Biotechnol. Agron. Soc. Environ.* 2023 **27**(1), 15-18 OPEN ACCESS **Short note**

Impact of contrasted bioavailable silicon inputs in a hydroponic system on the development of maize plants (*Zea mays* L.)

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Description of the subject. Silicon is a beneficial chemical element, considered as "quasi-essential" for plant growth and production. Seven of the top ten most important crops in the world are silicon-accumulating Poaceae species, maize being one of them. However, the beneficial role of Si for plants is still under debate.
Objectives. In this study, we evaluate the impact of three silicon concentrations in a nutrient solution on the development of maize plants.
Method. We cultivated maize plants in a hydroponic system allowing to provide three contrasted silicon fertilization: (1) a silicon-deficient medium (0.05 mM); (2) a medium silicon supply, comparable to what can be found in an agricultural soil (0.6 mM); and (3) a highly enriched silicon medium (2.0 mM), named Si-, Si+ and Si++, respectively.
Results. We found the silicon contents in aerial parts of plants to be strongly impacted by the concentration available in the growing medium: 0.247 g $Si{\cdot}kg^{-1}$ DW (Si-), 5.707 g $Si{\cdot}kg^{-1}$ DW (Si+) and 8.731 g $Si{\cdot}kg^{-1}$ DW (Si++). However, neither plant size nor phenology were impacted by silicon supplies. Both fresh leaf weight (+15.5%) and dry leaf weight (+13.5%) increased under Si++ (compared to Si-). Finally, neither root fresh weight nor root dry weight was impacted by Si fertilization.
Conclusions. We conclude that increase in the concentration of Si in nutrient solution leads to increase in fresh and dry weight of the maize leaves.
Keywords. Plant nutrition, maize, foliage, accumulation, soilless culture.

Impact d'une disponibilité contrastée en silicium sur le développement de plants de maïs (*Zea mays* L.) cultivés en système hydroponique
Description du sujet. Le silicium est un élément chimique bénéfique, considéré comme « quasi-essentiel » pour la croissance et la production de plantes. Sept des dix cultures les plus importantes au monde sont des Poaceae accumulatrices de silicium dont le maïs fait partie.
Objectifs. Dans cette étude, nous avons évalué l'impact de trois concentrations en Si disponibles dans une solution nutritive sur le développement de plants de maïs.
Méthode. Nous avons cultivé des plants de maïs dans un système hydroponique nous permettant de fournir trois fertilisations en Si différentes : (1) un milieu déficient en silicium (0,05 mM) ; (2) une concentration moyenne proche des teneurs en Si des sols agricoles (0,6 mM) ; et (3) un milieu fortement enrichi en silicium (2,0 mM), nommés respectivement Si-, Si+ et Si++.
Résultats. Nous avons trouvé que les teneurs en Si foliaire étaient fortement impactées par la concentration disponible dans le substrat de culture : 0,247 g $Si{\cdot}kg^{-1}$ MS (Si-), 5,707 g $Si{\cdot}kg^{-1}$ MS (Si+) et 8,731 g $Si{\cdot}kg^{-1}$ MS (Si++). Cependant, ni la taille ni la phénologie des plantes n'ont été affectées par la fertilisation au silicium. Le poids des feuilles fraîches (+15,5 %) et le poids des feuilles sèches (+13,5 %) ont tous deux augmenté sous Si++ (par rapport à Si-). Enfin, ni le poids frais ni le poids sec des racines n'ont été affectés par la fertilisation au Si.
Conclusions. Nous concluons que, même en maximisant les apports en Si dans le système hydroponique, l'enrichissement n'impacte pas le développement des plants de maïs.
Mots-clés. Nutrition des plantes, maïs, feuillage, accumulation, culture sans sol.

1. INTRODUCTION

Silicon (Si) is a mineral element considered as "quasi-essential" for plant development and is the fourth major nutrient element in gramineous crops (following nitrogen, phosphorous and potassium). Most graminaceous plants are known as Si-accumulators: they actively accumulate Si, the concentration of which varies from 0.5% to 10% of their dry weight (Liang et al., 2015; Kuai et al., 2017; Coskun et al., 2019). Plants absorb Si by the roots in the form of an uncharged monomeric molecule called monosilicic acid (H_4SiO_4), the only available form of Si in soil (Guo-chao et al., 2018). After Si has been transported from roots to shoots, it is deposited as amorphous hydrated silica ($SiO_2.nH_2O$) in plant epidermal tissues (Reynolds et al., 2016).

In agricultural soils, Si concentration may vary from 0.1 to 0.6 mM (Epstein, 1994). Silicon amendment enhances plant performance, fruit yield or grain quality (Cooke & Leishman, 2016; Frew et al., 2018; Devanna et al., 2021; Leroy et al., 2022a). Silicon fertilization is widely used, especially on soils with low Si availability (Ma & Takahashi, 2002). Maize is considered as one of the most important crop species and an important source of food (Sun et al., 2021). Hydroponics make it possible to isolate the effect of Si by eliminating the effects of the soil matrix (macro and micronutrients, soil microbiota, etc.). Therefore, in this study, we provide information on the effect of Si on maize plant development by growing maize plants in hydroponics using three very contrasted levels: an average soil Si concentration (0.6 mM), and two extremes in Si availability, one mimicking a complete deficiency (0.05 mM) and at solubility limit of 2 mM (Exley, 2015).

2. MATERIALS AND METHODS

2.1. Hydroponic system

Maize plants (*Zea mays* L. var Delprim) were grown using a hydroponic production system under the same cultivation parameters as those previously described in Leroy et al. (2022b). All assays were performed in Gembloux in 2019. In brief, 16 corn seedlings were transplanted into hydroponic plastic pots (5 cm diameter) containing rockwool substrate. Plants were held on a raft floating on a 20-litre plastic bucket containing a nutrient solution (HY-PRO© A&B, Bladel, Netherlands) and placed in a room at 23 ± 2 °C (day), 19 ± 2 °C (night), 55-70% relative humidity (RH) and uniform light intensity set at 300 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Starting on the day following seedling transplantation, all plants were cultivated under one of the three Si concentrations: (a) deficient solution without Si addition, named Si- [0.05 mM Si]; (b) medium level of Si, named Si+ [0.6 mM Si]; (c) a highly-enriched solution, named Si++ [2.0 mM Si]. Silicon was supplied as monosilicic acid (H_4SiO_4) in the nutrient solution.

2.2. Foliar Si content

Foliar Si content was quantified on maize plants that were grown for 24-26 days in the hydroponic system (until plants reached the 16^{th} BBCH growth stage). The entire plant was collected (stem and leaves), dried at 50 °C for 72 h, ground in a plant shredder and left for 24 h at 450 °C for calcination. One hundred milligrams of ash were melted at 1,000 °C for 5 min in a graphite crucible containing 0.4 g Li-tetraborate and 1.6 g Li-metaborate (Chao & Sanzolone, 1992). The fusion bead was then dissolved in 10% HNO_3 before quantifying Si concentrations by ICP-OES (De Tombeur et al., 2021).

2.3. Maize growth and physiological parameters

During growing period, eight measurements of plant size (cm) and phenological stage (BBCH growth stage) were performed. At the end of the cultivation (16 BBCH), different physiological parameters were also measured including fresh leaf weight, dry leaf weight, fresh root weight, dry root weight and the length of seminal root.

2.4. Statistical analysis

R studio software (v 1.2.1.1335) was used for all statistical analyses (R core team 2019). Some data had to be transformed to reach a normal distribution before being subjected to analysis of variance (ANOVA) and Tukey's post-hoc test ($\alpha = 0.05$). Data on plant Si content had to be transformed using (rn)transform (GenAbel package), while data on dry roots weight had to be transformed using a log function. Data on leaf fresh and dry weights, fresh root weight and the length of seminal root were not transformed. Data on measurements and phenological stages were subjected to generalized linear models.

3. RESULTS

We found the silicon contents in aerial parts of plants to be strongly impacted by the concentration available in the growing medium: 0.247 g $Si \cdot kg^{-1}$ DW (Si-), 5.707 g $Si \cdot kg^{-1}$ DW (Si+) and 8.731 g $Si \cdot kg^{-1}$ DW (Si++). The statistical analysis concluded on the impact of Si concentration in the culture medium on the Si content in the plant ($F_{2,45} = 86.39$; $p < 0.001$)

(**Figure 1C**). Neither plant growth (cm) ($F_{2,381}$ = 2.254; p = 0.106) nor phenological stage (BBCH) ($F_{2,381}$ = 1.160; p = 0.203) were impacted (**Table 1**). We also observed significant differences among leaves fresh weight (8.13 ± 1.38 [Si-]; 8.66 ± 1.29 [Si+]; 9.62 ± 1.77) (mean ± SE) ($F_{2,45}$ = 4.1; p = 0.023) and leaves dry weight (0.75 ± 0.15 [Si-]; 0.76 ± 0.12 [Si+]; 0.88 ± 0.16 [Si++]) (mean ± SE) ($F_{2,45}$ = 3.641; p = 0.034) (**Figure 1**). In contrast, we found no significant impact of Si fertilization on roots fresh weight (2.19 ± 0.71 [Si-]; 2.01 ± 0.52 [Si+]; 2.18 ± 0.47 [Si++]) (mean ± SE) ($F_{2,45}$ = 0.446; p = 0.643) nor roots dry weight (0.12 ± 0.03 [Si-]; 0.12 ± 0.03 [Si+]; 0.14 ± 0.03 [Si++]) (mean ± SE) ($F_{2,45}$ = 1.53; p = 0.226) and the length of seminal roots (48.65 ± 5.75 [Si-]; 48.74 ± 8.36 [Si+]; 48.93 ± 5.60 [Si++]) (mean ± SE) ($F_{2,45}$ = 0.007; p = 0.993).

4. DISCUSSION

We found no impact of Si inputs in the hydroponic system on maize development. However, an important Si fertilization allowed to significantly increase the Si content in the aerial parts of the plant, which consequently increased their fresh and dry weight. We believe these differences would have been even greater if plants were grown in hydroponics for a longer period of time. Unfortunately, although hydroponics is a production technique perfectly suited to laboratory studies, it does not easily allow the cultivation of mature corn plants. The difference in leaf fresh and dry weight is mainly explained by Si deposition in leaf tissues. Silicon accumulates and forms physical structures called phytoliths. Silicon could also fill actively specialized epidermal cells associated in

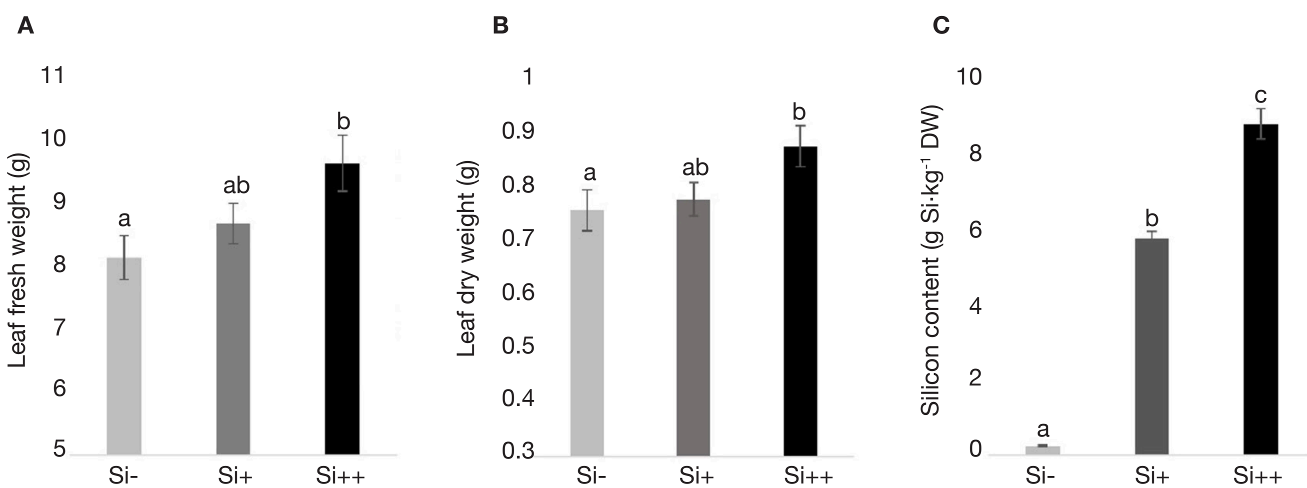

Figure 1. Impact of contrasted silicon fertilization on leaf fresh weight (A), leaf dry weight (B) and silicon content in leaves (C) (n = 16) — *Impact de la fertilisation contrastée en silicium sur le poids des feuilles fraîches (A), le poids des feuilles sèches (B) et le contenu en silicium des feuilles (C) (n = 16).*

Values are means ± SD — *les valeurs sont les moyennes ± écart-type*.

Table 1. Maize plants height measurements (cm) and phenological stages (BBCH) (means ± SE) cultivated in the three silicon supplies [Si-; Si+; Si++] at an interval of three days (first measurement taking place three days after first silicon supply in the hydroponic system) (n = 16) — *Mesures de la hauteur des plants de maïs (cm) et des stades phénologiques (BBCH) (moyennes ± SE) cultivés avec les trois apports de silicium [Si- ; Si+ ; Si++] à un intervalle de trois jours (la première mesure ayant lieu trois jours après le premier apport de silicium dans le système hydroponique) (n = 16).*

	Day 3	**Day 6**	**Day 9**	**Day 12**	**Day 15**	**Day 18**	**Day 21**	**Day 24**
Si -	31.8 ± 2.9	40.5 ± 5.6	53.1 ± 5.6	59.1 ± 5.9	71.0 ± 7.2	81.6 ± 5.7	88.4 ± 7.2	96.7 ± 7.5
Si +	32.0 ± 1.9	42.5 ± 6.1	54.9 ± 2.6	61.0 ± 7.3	71.2 ± 7.8	83.2 ± 6.6	88.5 ± 8.1	97.4 ± 5.0
Si ++	33.0 ± 4.6	42.4 ± 6.4	55.0 ± 5.9	63.6 ± 10.4	71.1 ± 7.8	84.4 ± 8.1	88.5 ± 11.0	96.7 ± 9.6
Si -	12 ± 0	12 ± 1	13 ± 0	13 ± 1	14 ± 0	14 ± 1	15 ± 0	16 ± 1
Si +	12 ± 0	13 ± 1	13 ± 0	13 ± 1	14 ± 0	15 ± 1	15 ± 0	16 ± 1
Si ++	12 ± 0	13 ± 1	13 ± 0	14 ± 1	14 ± 1	15 ± 1	15 ± 1	16 ± 1

Si-based antiherbivore structure (Waterman et al., 2021).

5. CONCLUSIONS

Future studies should evaluate the impact of Si accumulation in maize tissues on herbivory under different Si concentrations (more than three). This would allow for the delineation of a tipping point above which a Si amendment is no longer beneficial for maize plants.

Bibliography

Chao T.T. & Sanzolone R.F., 1992. Decomposition techniques. *J. Geochem. Explor.*, **44**(1-3), 65-106, doi.org/10.1016/0375-6742(92)90048-D

Cooke J. & Leishman M.R., 2016. Consistent alleviation of abiotic stress with silicon addition: a meta-analysis. *Funct. Ecol.*, **30**, 1340-1357, doi.org/10.1111/1365-2435.12713

Coskun D. et al., 2019. The controversies of silicon's role in plant biology. *New Phytol.*, **211**(1), 67-85, doi.org/10.1111/nph.15343

De Tombeur F. et al., 2021. Biochar affects silicification patterns and physical traits of rice leaves cultivated in a desilicated soil (Ferric lixisol). *Plant Soil*, **460**, 375-390, doi.org/10.1007/s11104-020-04816-6

Devanna B.N. et al., 2021. Versatile role of silicon in cereals: health benefits, uptake mechanism, and evolution. *Plant Physiol. Biochem.*, **165**, 173-186, doi: 10.1016/j.plaphy.2021.03.060

Epstein E., 1994. The anomaly of silicon in plant biology. *Proc. Natl. Acad. Sci. U.S.A.*, **91**(1), 11-17, doi.org/10.1073/pnas.91.1.11

Exley C., 2015. A possible mechanism of biological silification in plants. *Front. Plant Sci.*, **6**, 853, doi:10.3389/fpls.2015.00853

Frew A., Weston L.A., Reynolds O.L. & Gurr G.M., 2018. The role of silicon in plant biology: a paradigm shift in research approach. *Ann. Bot.*, **121**, 1265-1273, doi.org/10.1093/aob/mcy009

Guo-chao Y.A.N. et al., 2018. Silicon acquisition and accumulation in plant and its significance for agriculture. *J. Integr. Agric.*, **17**, 2138-2150, doi.org/10.1016/S2095-3119(18)62037-4

Kuai J. et al., 2017. Root-applied silicon in the early bud stage increases the rapeseed yield and optimizes the mechanical harvesting characteristics. *Field Crops Res.*, **200**, 88-97, doi.org/10.1016/j.fcr.2016.10.007

Leroy N. et al., 2022a. If all else fails: impact of silicon accumulation in maize leaves on volatile emissions and oviposition site selection of *Spodoptera exigua* Hübner. *J. Chem. Ecol.*, **48**, 841–849, doi.org/10.1007/s10886-022-01386-y

Leroy N., Hanciaux N., Cornélis J.-T. & Verheggen F.J., 2022b. Silicon accumulation in maize negatively impacts the feeding and life history traits of *Spodoptera exigua* Hübner. *Entomol. Gen.*, **42**(3), 413-420, doi.org/10.1127/entomologia/2021/1357

Liang Y. et al., 2015. Silicon in agriculture. From theory to practice. In: *Silicon in agriculture*. Berlin, Germany: Springer, Vol. 22, 115-131.

Ma J.F. & Takahashi E., 2002. *Soil, fertilizer and plant silicon research in Japan*. Amsterdam: Elsevier.

Reynolds O.L., Padula M.P., Zeng R. & Gurr G.M., 2016. Silicon: potential to promote direct and indirect effects on plant defense against arthropod pests in agriculture. *Front. Plant Sci.*, **7**, 1-13, doi: 10.3389/fpls.2016.00744

Sun Y. et al., 2021. Effects of exogenous silicon on maize seed germination and seedling growth. *Sci. Rep.*, **11**, 1-13, doi.org/10.1038/s41598-020-79723-y

Waterman J.M. et al., 2021. Short-term exposure to silicon rapidly enhances plant resistance to herbivory. *Ecology*, **102**(9), 1-8, doi.org/10.1002/ecy.3438

(17 ref.)