Influence of Silicon application on agronomic and nutritional performance of container grown highbush blueberries

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Abstract

Biostimulants have been largely studied and established to improve nutrient uptake by plants, growth, productivity, fruit quality, as well as plant resilience to abiotic and biotic stresses. Among them, silicon (Si) is reported to be beneficial in mitigating stresses such as plant diseases, salinity, drought, and nutrient imbalance. Regarding organic highbush blueberries, the ability to enhance crop resilience and high-quality berries is an essential component of the success of the organic sector in international markets. Since the health-promoting compounds in fruits are often associated with secondary metabolites involved in plant defense, Si could enhance the nutritional value of berries. Indeed, it has been observed that Si increases sugar content and certain phenolic compounds. Thus, in a split-plot design over one growing season, we compared in a greenhouse complex (Laval University, Quebec) two different type of silicon sources (1) organic wollastonite (58% Si02, 23% CaO, 6% MgO) at a rate of 4g/L of growing media and (2) potassium silicate (18 % Si02, 50% K) at a rate of 1,7 mM added to the irrigation water and (3) a control receiving no Si. Eight highbush blueberry cultivars were selected for this study including early and late-maturing cultivars and were grown in 10L container supplied with organic fertilizers and into an organic peat-based growing media provided by Berger (Berger, Saint-Modeste). The application of silicon reveals that potassium silicate was absorbed in greater quantities than wollastonite as seen in the leaf Si content. The silica content in the leaves varies from one cultivar to another. Earliblue and Liberty exhibit lower leaf silica content at 34% and 35%, respectively, in comparison to the average silica content of the eight cultivars included in the study. This observation implies that there is variation in the ability of highbush blueberries to absorb silicon, and it's not consistent across all cultivars. Bluegold showed the highest content in Si with a total of 370 ppm. Potassium silicate also had a positive effect on microbial enzymatic activity by increasing the FDA contents of the samples when compared to plants without silica. When it comes to phenolic compounds, Earliblue and Liberty exhibits the lowest levels of polyphenols and anthocyanins. In contrast, Bluegold shows the highest levels of polyphenols and anthocyanins, highlighting a correlation between Si content and phenolic compounds in highbush blueberries.

Keywords: Vaccinium corymbosum, organic production, production systems, controlled environment, silicon

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INTRODUCTION

Silicon (Si) is a mineral element present in the soil, and it is the second most prevalent element after oxygen (Etesami et Maheshwari, 2018). Depending on the plant species, Si concentrations can vary from 0.1% to 10,0% of dry weight and can be equivalent to the major nutrient such as N, P and K (Liang et al, 2007). The underlying mechanisms of the biostimulant effects of silicon include increasing resistance to biotic and abiotic stress, adjusting pH, and acquiring macro-and micronutrients present in Si-fertilizers. Silicon can consequently, enhanced plant growth and yield. In regard to blueberries, it has been reported that silicon can improve yield and fruit qualities as well as photosynthetic activities while also reducing nutrient imbalance (Ferron-Carillo et al, 2021; Gallegos-Cedillo et al, 2018). A study conducted at the University of Almeria in Spain highlights that the application of silicon in blueberries significantly improves fruit yields, increases Brix content, and enhances post-harvest fruit firmness (Ferron-Carillo et al., 2021). From a physiological perspective, silicon applications may lead to a more efficient water use, improve water absorption by the roots, and increase plant drought tolerance under water stress conditions (Estami, 2018). This can be explained by the development of a cuticle-silica double layer on the epidermal tissues of the leaves, which reduces leaf transpiration and water flow in the xylem vessels (Estami, 2018).Also, the application of silica to certain horticultural plants promotes plant development in addition to reducing the presence of pathogens such as Botrytis cineria as reported by Pozo et al. (2015). Silica can be applied in various forms either by fertigation, broadcast or foliar application. Broadcast applications have been shown to further increase foliar silica concentration and are more effective in inducing stimulatory effects compared to foliar application (Haynes et al., 2014). On the other hand, foliar applications, when well calibrated, could avoid chemical or physical immobilization and allow a direct impact on certain environmental stresses (Maghsoudi et al., 2016). Ultimately, what makes the association between blueberries and silicon particularly intriguing is that blueberries are classified as high accumulators of silicon, storing 3 to 5 times more silicon than nitrogen in their leaves (Gallegos-Cedillo et al., 2018).

In our study, two silicon treatments and one control were investigated to assess the influence of this biostimulant on highbush blueberries grown in containers. Wollastonite (CaSiO3 – 52% SiO2) was chosen as the organic form of silicon, while potassium silicate (K2SiO3 – 25% SiO2) was selected as the inorganic form. Wollastonite is a naturally occurring mined product while potassium silicate is a liquid form of silicate and can be used as a foliar spray or through fertigation (Liang et al, 2015). To our knowledge there has not been studies reporting wollastonite application on container grown blueberries crops. However, Silva et al. (2023) observed a significant improvement in vegetative growth, fruit yield, and fruit quality when applying SiO^2 (98% silica, concentration of 1.5g/L in aqueous solution) through foliar application to three highbush blueberry cultivars ('Beckblue', 'Climax', and 'Brightwell). Through a one season trial, we investigated the influence of silicon on the microbial activity, soil nutrient content, productivity, plant growth and fruit qualities of highbush blueberries. We hypothesis that the rate of silicon (Si) absorption in the form of wollastonite is like the absorption rate of potassium silicate provided through fertigation, although some cultivars exhibit a higher Si absorption rate than others. Also, we suppose that application of silicon in the form of wollastonite enhances the photosynthetic performance, growth, productivity, and fruit quality of plants grown in pots under organic farming management.

MATERIALS AND METHODS

Study site

The experiment took place in a greenhouse that was located at Laval University QC, Canada (lat. 46°78’14’’N, long 71°27’50’’W). The experiment took place from February 2022 to June 2022. The temperature was set at 20 °C during the day and 16 °C at night. The humidity was set at 55% by day and 60% by night. A PPFD of 150 µmol m^{-2} s^{-1} was added by HPS lamps for 16 hours.

Plant material

The plants (Cv. ‘Bluecrop’. ‘Bluejay’, ‘Blueray’, ‘Duke’, ‘Earliblue’, ‘Lastcall’, ‘Liberty’, ‘Spartan’) were obtained as 2-year-old plant from a local nursery (Saint-Césaire, QC, Canada) and grown in 10 L containers with a custom organic peat-based growing media provided by Berger (Berger, Saint-Modeste, QC). The eight cultivars have different harvest date with Earliblue being the earliest and Lastcall being a late harvest cultivar. Plants were placed in hibernation for four months in a refrigerated room at 4 °C on a commercial farm (Saint-Laurent de l'île d'Orléans, QC, Canada). Nine plants per cultivars were selected and placed in a greenhouse on February 1, 2022. Plants were pruned in February with sanitized cutters and spaced at 0.75m c.t.c. distance with 2m between rows.

Experimental design

Two silicon treatment were allocated in a split-plot design with cultivars being the main plot and silicon sources as sub plot. Each treatment plot consisted of 1 plant. There was a total of 72 experimental unit splitted into three repetitions. Treatments are listed in table 1. Wollastonite (organic) was applied in two applications of 2g/L of growing media into each container and mixed thoroughly. Potassium silicate was supplied at 0.3mL L-1 via the irrigation solution. Daily irrigation was supplied with 2 drippers with pH-adjusted water using sulfuric acid. The irrigation pH of both solutions was maintained at 4.5-5.0 and electrical conductivity (EC) was at 0.7 mS $cm^{-1}$for the K_2O_3Si solution and at 0,3 mS cm^{-1} for solution destinated to plants treated with wollastonite. Plants were irrigated 8 minutes per day for a total of 2.0L per irrigation. The plants received alternating fertilization: every four weeks with a poultry manure-based fertilizer Actisol 5-3-2 (Notre-Dame-Du-Bon-Conseil, Qc, Canada) and daily with a nutrient solution provided through fertigation, on weeks without granular fertilization, using Nature’s Source 10-4-3 (Nature’s Source, TX, USA). A total of 8 g of N per plant was applied during the growing season.

Soil microbial and leaf mineral analysis

Soil samples were taken within the root regions at a depth of 20cm once for microbial activity analysis (FDA analysis; Adam and Duncan, 2001) Soil were conserved at 4 °C. During harvest, 15 mature leaves per plant: 5 from the top, 5 from the middle and 5 from the bottom were collected. These leaves were dried at 60°C for the analysis of the macro- and micro-elements. Silicon leaf content was also analyzed with the same leaf sample.

Photosynthesis and plants growth measurements

Leaf chlorophyll content was measured using a SPAD 502 Plus Chlorophyllometer (Konica Minolta Co. Ltd., Tokyo, Japan). SPAD indices were measured on a leaf at the base of the plant as well as on a leaf at the top of the plant. Chlorophyll fluorescence (Fv/Fm) values were also collected from the same leaves using a Handy PEA (Hansatech Instruments Ltd., King's Lynn, UK) after 20 min dark adaptation (Hansatech Instruments Ltd, 2006). The number of stems, height, and diameter of each stem were measured using a tape measure and digital caliper. The 72 plants of the experiment were sampled.

Yield and fruit qualities

Blueberries were harvested and weighed weekly during the harvest period that ranged from late April to Early June. Unsellable fruits were removed if they were unripe, had mold, or had physical damages. They were then weighed and constituted non-sellable fruits. The sellable fruits from each plant were also weighed. Average size per fruit was also measured. Soluble sugars in blueberries were measured on the same day of harvest. The level of soluble sugars was measured using a BRIX PAL-1 3810 portable refractometer (Atago, Tokyo, Japan). To assess the polyphenol content of blueberries, 50 halved fruits were freeze-dried twice using a Hull S30 Ultra Lyophilizer (SP Scientific, Warminster, PA, USA). The overall determination of phenolic compounds in freeze-dried blueberries was obtained by the Folin-Ciocalteu test (Singleton et al., 1999). Evaluation of anthocyanin content was also carried out from freeze-dried blueberries using differential pH methodology (Durst and Wrolstad, 2005).

Statistical analysis

Analyzes of variance were performed with the MIXED procedure of SAS (SAS® OnDemand for Academics, SAS Institute Inc., Cary, NC, USA) with a significance level of P ≤ 0.05. Data normality was checked with a Shapiro-Wilk test and homogeneity was visually interpreted on residual plots.

Table 1. Silicon treatment used for the greenhouse experimental trial on highbush blueberries grown in containers.

Silicon sources	**N-P_2O_5-K_2O content (%)**	**SiO^2 content (%)**	**Rate^z**
Control	-	0 %	0
Wollastonite ($CaSiO_3$)	-	52 %	4 g L^{-1}
Potassium Silicate (K_2O_3Si)	0-0-15	25 %	0,3 mL L^{-1}.

^{Z} Rate for $CaSiO_3$ is expressed in gram per growing media. Rate for K2O3Si is the concentration of the irrigation solution

RESULTS

Soil microbial and leaf mineral analysis

The potassium silicate (K_2O_3Si) treatment exhibited significantly higher microbial activity (+47%) than the wollastonite treatment but was similar to the control substrate (Table 3) suggesting that potassium silicate and the control had a beneficial impact on microbial activity by increasing the FDA amount per sample. Wollostonite performed poorly in regard to microbial activity and can be explained by the fact that it is considered by some research as an antimicrobial element (Cardoso et al., 2021)

Photosynthesis and plants growth measurements

The silica treatments had no impact on the efficiency of photosystem II (Fv/Fm), the performance index, and the leaf chlorophyll content. However, the chlorophyll content varied among cultivars ($P < 0.001$). Liberty (39.29 SPAD units) and Bluegold (37.97 SPAD units) exhibited the highest chlorophyll content when compared to other cultivars (34.74 SPAD units). In terms of plant growth expressed by plant height, the two Si treatments had a positive effect, increasing the average plant height by 10% and 5.6% respectively for wollastonite and potassium silicate compared to control plants (Table 3). The number of stems and stem diameter were not influenced by Si treatments. A silica treatments x cultivars interaction was observable for stem diameter (cm) ($P = 0.034$) and number of stems per plant ($P < .0001$).

Yield and fruit qualities

In terms of yield expressed in grams of fresh fruit per plant, no significant difference between Si treatments was observed, with productivity ranging from 386 to 428 grams per plant (Table 2). Similarly, Si treatments had no effect on fruit size, which averaged 2.31 grams per fruit. Furthermore, fruit yield varied among cultivars, with Duke (599 grams per plant) and Liberty (672 grams per plant) being the most productive compared to other cultivars, except for Spartan (513 grams per plant), which was similar. The largest fruit sizes were observed in Spartan (2.93 g/fruit) and Blueray (2.69 g/fruit), while the smallest sizes were found in Bluejay (1.49 g/fruit), Bluegold (2.08 g/fruit), Earliblue (2.24 g/fruit), and Last call (2.29 g/fruit).

Si treatments had no significant effect on the concentration of soluble sugars (°Brix), anthocyanins, and polyphenols, while significant differences were observed among the studied cultivars. The highest concentration of soluble sugars was found in the Last call cultivar (13 °Brix), while the lowest was in the Duke cultivar (7.7 °Brix), with other cultivars having intermediate values ranging from 8.8 to 10.3 °Brix. Additionally, concentrations of anthocyanins and polyphenols in fruits were highest for the Bluegold cultivar (6.20 and 15.94 mg g-1 dry weight, respectively) and lowest for the Earliblue cultivar (3.83 and 9.27 mg g-1 dry weight, respectively), with other cultivars having intermediate values ranging from 4.28 to 5.88 mg g-1 dry weight and 10.17 to 11.78 mg g-1 dry weight, respectively (Fig. 1)

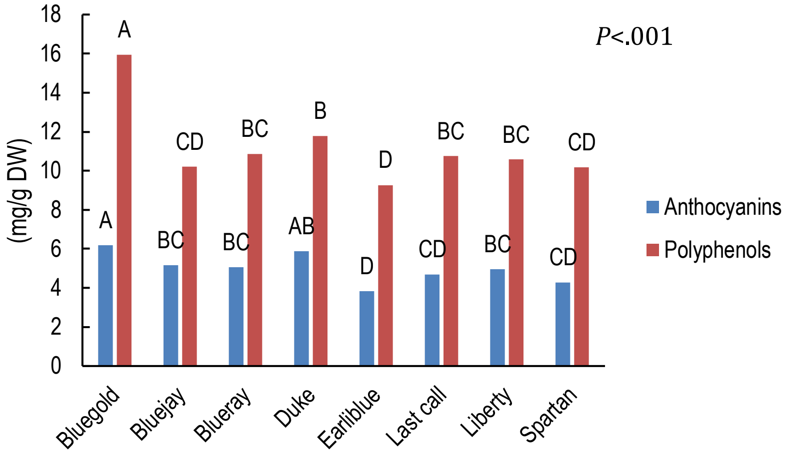

Figure 1 Anthocyanins and Polyphenols content in berries of eight cultivars. *Distinct letters indicate significant differences in anthocyanin or polyphenol content between cultivars.*

Table 2. Analysis of variance and comparisons of means (when the effect is significant) of different agronomic parameters relating to yields and quality measured at harvest according to eight highbush blueberry cultivars and three silica treatments for the 2022 season (yield and fruit size n=90, brix n=270)

		Yield		**Fruit size**		**Solubles sugars**	
		(g of berries plant^{-1})		(g fruit^{-1})		(ºBrix)	
Cultivar	Bluegold	219,1	C^{z}	2,08	C	9,0	BC
	Bluejay	202,8	C	1,49	C	10,0	B
	Blueray	430,6	B	2,69	A	8,8	BC
	Duke	598,2	A	2,31	BC	7,7	C
	Earliblue	207,2	C	2,24	C	9,1	BC
	Last call	386,7	B	2,29	C	13,0	A
	Liberty	672,4	A	2,49	AB	10,0	B
	Spartan	513,4	AB	2,93	A	10,3	B
Treatment	Wollastonite	385,8		2,40		10,0	
	Potassium silicate	397,2		2,23		9,8	
	Control	428,4		2,31		9,4	
ANOVA- P values							
Cultivar (C)		<0,001		<0,001		0,005	
Treatment (T)		0,348		0,560		0,450	
C × T		0,361		0,522		0,780	

^{z}*Different letters indicate a significant difference between the means for the same factor in the same column at P ≤ 0.05 (protected Fisher's LSD test).*

Table 3. Analysis of variance and mean comparisons (when the effect is significant) for the growth (number of stems, height (cm), diameter (cm)), leaf mineral concentration (% of dry leaf weight), and microbial activity (FDA, μg g-1 h-1) of the growing media for eight highbush blueberry cultivars and three silicon treatments (growth n=180, foliar n=90, FDA n = 180).

		Nb stems	**Height (cm)**	**Diameter (cm)**	**N (%)**	**P (%)**	**K (%)**	**Si (ppm)**	**FDA (μg g^{-1} h^{-1})**
Cultivar	Bluegold	6,90	37,58	5,77	1,89 A	0,126 AB	0,77 B	370,5 A	174,1
	Bluejay	5,54	34,79	6,78	1,45 BC	0,086 C	0,63 BC	294,6 AB	141,0
	Blueray	6,90	41,81	5,85	1,67 ABC	0,102 BC	0,53 C	266,4 B	116,4
	Duke	5,80	34,31	7,52	1,71 ABC	0,120 AB	0,67 BC	288,2 AB	181,7
	Earliblue	2,71	50,36	7,40	1,86 A	0,149 AB	0,67 BC	179,5 C	160,7
	Last call	6,55	53,17	6,04	1,60 BC	0,120 AB	0,67 BC	249,4 B	158,6
	Liberty	5,96	32,89	6,25	1,84 A	0,128 AB	0,57 C	175,7 C	144,1
	Spartan	9,04	29,94	5,22	1,61 BC	0,111 B	1,05 A	371,1 A	157,9
Treatment	Wollastonite	6,00	41,16 A[z]	6,48	1,68	0,12	0,72	239,6 B	99,9 B
	Potassium Silicate	6,18	39,68 A	6,42	1,77	0,12	0,70	387,1 A	190,1 A
	Control	6,34	37,23 B	6,19	1,66	0,11	0,67	196,5 C	173,0 A
ANOVA – P values									
Cultivar (C)		0,001	0,044	0,059	0,008	0,001	0,003	<0,001	0,900
Treatment (T)		0,559	0,004	0,203	0,186	0,534	0,610	<0,001	<0,001
C × T		<,0001	0,067	0,034	0,921	0,835	0,551	0,579	0,414

[z] *Different letters indicate a significant difference between the means for the same factor in the same column at P ≤ 0.05 (protected Fisher's LSD test).*

DISCUSSION

The silica experiment partially invalidated our hypotheses about silica absorption, revealing variable absorption rates among cultivars. Wollastonite was less absorbed than potassium silicate, and although some cultivars showed increased absorption of silica, this did not have a significant impact on photosynthetic performance, productivity, or fruit quality, except an increase in plant height and modulation of microbial activity which may be linked to the pH of the rhizosphere. Indeed, wollastonite had a negative effect on microbial activity. It is also possible to state that blueberries, even though they are categorized as large accumulators of silica (Morikawa and Saigusa, 2004), do not all have the same absorption capacity and certain cultivars seem to have a greater affinity for silica than others. The disproportionality of foliar silica concentrations among the eight cultivars in the study explains this fact as well as the data compiled by Morikawa and Saigusa (2004) who observed a large disparity between the foliar concentrations of blueberry cuttings subject to silicon application. As a result, the average foliar concentration for plants supplemented with silica was 0.310 mg g-1 m.s. This closely resembles the results obtained by Carnelli et al. (2002) for the analysis of Ericaceous leaves of V. myrtillus and V. vitis-idaea who observed Si concentrations of 0.3 mg g-1 m.s. and 0.4 mg g-1 m.s., respectively. The polyphenol concentration was significantly higher for some cultivars, including Bluegold and Duke. A study focusing on the chemical variations of dried grapes from 4 cultivars of vines discovered an increase in the concentration of anthocyanins following foliar applications of silica realizing that silica induces specific modifications in the composition of the fruits of a plant at the scale of a cultivar without abiotic or biotic stress (Sut et al., 2022).

CONCLUSION

In this study, we showed that eight highbush blueberry cultivars accumulated Si at three different levels with a preference for the K2SiO3 form. K2SiO3 had a positive impact on microbial enzymatic activity suggesting that it may create optimal growth conditions for microorganism. The application of silicon had a negative impact on yield, necessitating a more thorough evaluation to understand the unfavorable growth conditions that resulted in lower yields when silicon was applied. Silicon could be used as a biostimulant with the additional role of increasing beneficial antioxidant levels as seen by the increased levels of anthocyanins and polyphenols in fruits. This could provide better fruits qualities for customers and have a positive impact on health conditions**.**

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Literature cited

Carnelli AL, Madella M, Theurillat JP & Ammann B. 2002. Aluminum in the opal silica reticule of phytoliths: a new tool in palaeoecological studies. American Journal of Botany *89*, 346–351. https://doi.org/10.3732/ajb.89.2.346

Etesami, H. & Maheshwari, D. K. (2018). Use of plant growth promoting rhizobacteria (PGPRs) with multiple plant growth promoting traits in stress agriculture: Action mechanisms and future prospects. Ecotoxicology and Environmental Safety, *156*, 225– 246. https://doi.org/10.1016/j.ecoenv.2018.03.013

Etesami, H. (2018). Can interaction between silicon and plant growth promoting rhizobacteria benefit in alleviating abiotic and biotic stresses in crop plants?. Agriculture, ecosystems and environment, *253*, 98-112. https://doi.org/10.1016/j.agee.2017.11.007

Ferrón-Carrillo, F., da Cunha-Chiamolera, T. P. L., Peña, A. A. & Urrestarazu, M. (2022). Silicon enhances production and quality of blueberry fruits (Vaccinium corymbosum L.). Journal of Plant Nutrition, *45*(10), 1563-1571. https://doi.org/10.1080/01904167.2021.2014874

Gallegos-Cedillo, V. M., Álvaro, J. E., Capatos, T., Hachmann, T. L., Carrasco, G. & Urrestarazu, M. (2018). Effect of pH and silicon in the fertigation solution on vegetative growth of blueberry plants in organic agriculture. HortScience, *53*(10), 1423-1428. https://doi.org/10.21273/HORTSCI13342-18

Liang, Y., Nikolic, M., Bélanger, R., Gong, H., & Song, A. (2015). Silicon in agriculture. LIANG, Y. et al. Silicon-mediated tolerance to salt stress. Springer Science, 123-142. https://doi.org/10.1007/978-94-017-9978-2

Maghsoudi, K., Emam, Y. & Ashraf, M. (2016). Foliar application of silicon at different growth stages alters growth and yield of selected wheat cultivars. Journal of Plant Nutrition, *39*(8), 1194-1203. https://doi.org/10.1080/01904167.2015.1115876

Morikawa, C. et Saigusa, M. (2004) Mineral composition and accumulation of silicon in tissues of blueberry (Vaccinum corymbosus cv. Bluecrop) cuttings. Plant and Soil *258*, 1–8. https://doi.org/10.1023/B:PLSO.0000016489.69114.55

Silva, T., Umburanas, R. C., Garcia, C., Bennemann, G. D., Giloni-Lima, P. C., Rusin, C., ... & Botelho, R. V. (2023). Agronomic, Physiological, and Post-Harvest Aspects of Different Blueberry Cultivars Treated with Silicon. Comunicata Scientiae, *14*, e4043. https://doi.org/10.14295/cs.v14.4043

Sut, S., Malagoli, M.& Dall'Acqua, S. (2022). Foliar application of silicon in Vitis vinifera: Targeted metabolomics analysis as a tool to investigate the chemical variations in berries of four grapevine cultivars. Plants, *11*(21), 2998. https://doi.org/10.3390/plants11212998