Effect of pH and Silicon in the Fertigation Solution on Vegetative Growth of Blueberry Plants in Organic Agriculture

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Abstract. The effect of pH and silicon (Si) in the nutrient solution on the vegetative development of 2-year-old blueberry plants (*Vaccinium corymbosum* L. cv. Ventura) was studied. Two independent experiments were performed on coir fiber (CF) and sand as substrates. In experiment 1, Si was applied in the nutrient solution at a dose of 0.0, 0.3, 0.6, and 1.2 mM. In experiment 2, plants were treated with nutrient solution at pH 4.00, 4.75, 5.50, and 6.25, using two sources of acidification: nitric acid and citric acid. The parameters of plant growth, foliar surface, and stem biomass were measured. With the application of 1.2 mM Si to CF, plant height registered a significant increase of 8%, and shoot dry and fresh biomass increased by 21% and 25%, respectively. The results of experiment 1 indicated that the application of Si benefits the vegetative growth of blueberry plants in CF, but no effect was observed in the sand substrate. In the results of experiment 2, the pH level of 6.25 in CF decreased the dry weight of stems and leaves by 21% and 18%, respectively. A significant increase in the pH range of 4.00 to 5.50 was recorded in both the citric acid and nitric acid treatments, but these significant effects were not found in sand. Citric acid presented a similar behavior to nitric acid, which indicates that it can be a good source of acidification in organic and ecologically friendly crops.

Blueberry cultivation has become important worldwide as a result of its high profitability (Bañados, 2006; Caspersen et al., 2016; Strik and Yarborough, 2005), organoleptic qualities, and benefits to human health (Ames et al., 1993; Kalt and Dufour, 1997; Peng et al., 2014; Prior et al., 1998). According to the Food and Agriculture Organization of the United Nations (FAO, 2017), from 2012 to 2016, the area of blueberry cultivation worldwide increased by 34.14%, from

82,696 ha to 110,928 ha, and a production of 552,505 t was recorded, with the United States and Canada as the main producers. Spain, with 6412 t, is the eighth largest producer and has become one of the most important producers worldwide. The limiting factors for the development and production of blueberry have been known for a long time (Coville, 1910). One of the main factors influencing the development and production of crops is the pH of the soil, the substrate, and the nutrient solution, which can interfere with the availability of nutrients (Adams, 2004; Arnon and Johnson, 1942; Urrestarazu, 2015). It is well known that blueberries develop well in acidic soils with a pH of 4.5 to 5.5 and with low levels of fertility (Korcak, 1988; Mainland, 2012; Retamales and Hancock, 2012). Some authors recommend nutrient

solutions with low electrical conductivity (EC) between 0.45 and 1.5 dS·m⁻¹ (Ameri et al., 2012; Bryla et al., 2010; Ingestad, 1973; Machado et al., 2014). However, the optimal EC of the nutrient solution for the cultivation of blueberries in soilless culture has not yet been determined (Voogt et al., 2014).

Adequate management of mineral nutrition and fertigation parameters in crops ensures good growth and high-quality production (Ehret et al., 2014; Keen and Slavich, 2012; Vargas and Bryla, 2015; Xu et al., 2014). However, it is necessary to develop new programs of mineral nutrition and fertigation with other nutrients and soil improvers for blueberries (Bryla and Strik, 2015; Vargas et al., 2015). Silicon is not considered an essential element, according to the traditional criteria of Arnon and Stout (1939), because many plants can complete their cycle in its absence (Marschner, 2011). However, the beneficial effects of Si have been published both in plant protection (Imtiaz et al., 2016; Luyckx et al., 2017; Urrestarazu et al., 2016; Van Bockhaven et al., 2013) and in mineral nutrition (Kaya et al., 2006; Mengel and Kirkby 2000; Zhu and Gong, 2014). During the past few decades (Heine et al., 2005; Sonneveld and Straver, 1994; Sonneveld and Voogt, 2009) and, more recently (Pozo et al., 2015), Si is considered in the nutrient solution for horticultural and ornamental crops. Both Si and citric acid are active substances accepted in organic farming in Europe (DOUE, 2008) and the United States (USDA Organic, 2015). Although blueberry is a clearly acidophilic plant, there is no possibility of using nitric or other inorganic acid in an organic agriculture by soilless culture, so citric acid is a clear alternative to achieve adequate pH levels. However, there is no information on adequate levels in fertigation. In addition, Si has been published as a plant-beneficial element associated with the mitigation of abiotic and biotic stresses (Boldt et al., 2018).

There is little information regarding either conventional or organic agriculture on the adjustment of pH level or on the use of different acids for the acidification of the rhizosphere. In addition, there is no information on the potential benefits of Si in blueberry cultivation. Therefore, the objectives of this work were to evaluate the effect of the use of Si in the nutrient solution and to compare citric acid, as a source of acidification, to nitric acid in the nutrient solution for the cultivation of blueberry in organic agriculture.

Materials and Methods

Treatments and growth conditions. Two independent experiments (Expts. 1 and 2) were carried out at the University of Almería, Spain, in a multispan greenhouse with characteristics that have been described by Valera et al. (2016). On 1 Apr. 2017, 2-year-old blueberry plants (*Vaccinium corymbosum* L. cv. Ventura) were transplanted from 1-L containers to 22-L containers with Pelemix®

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CF substrate, the physical characteristics of which have been described by Rodríguez et al. (2014), and silica sand with a granulometry of 0.5 to 1.0 mm in diameter. Vegetative development was evaluated on 1 Sept. 2017. The planting density was 2.5 plants/m².

Expt. 1: Application of silicon in the nutrient solution. The plants were fertigated with a nutrient solution similar to that proposed by Sonneveld and Straver (1994), as shown in Table 1. The Si treatments were 0.0, 0.3, 0.6, and 1.2 mM. The Si source used was Siliforte® (CAPA Ecosystems®, Valencia, Spain) (CAPA Ecosystems, 2012). The pH of the nutrient solutions was adjusted to 5.5 with dilute nitric acid.

Fertigation scheduling. Each new fertigation was performed when 10% of the readily available water was used up (Rodríguez et al., 2014; Urrestarazu, 2015; Urrestarazu et al., 2017). The pH and EC of the supplied nutrient solution and the drainages were monitored daily using a Crison MM40+ Conductivitymeter and pH meter (LPV2500.98.0002; Hach®, Vizcaya, Spain), and the volume (measured in liters) was determined with a graduated cylinder with 100 mL of precision. Based on the irrigation and drainage volumes, the water uptake was estimated according to Pozo et al. (2014).

Parameters of vegetative growth. Training pruning was performed 180 d after the application of the treatments, which were used to evaluate vegetative development. The parameters of vegetative growth measured were plant height (measured in meters), shoot biomass (leaves and stems), and leaf area (measured in square meters per plant), as measured with an AM350 Area Meter (ADC BioScientific Ltd., Hertfordshire, UK). The plants were divided by their different organs, and stem and leaf fresh weights were obtained. The dry weight was obtained by placing the material in a convection oven (Thermo Scientific Heratherm®, Germany) at 75 °C until constant weight and then measured using an OHAUS Adventurer® Analytical Precision Analytical Balance (model AX 124/E).

Expt. 2: pH of the nutrient solution. The nutrient solution used was the same as that used in Expt. 1. The pH was adjusted with nitric acid and citric acid manufactured by Nortem® Biotechnology (Cádiz, Spain). The pH values of the solutions after adjustment were 4.00, 4.75, 5.50, and 6.25. For each acid source, an acidification curve was generated, and the increase in EC was determined (Fig. 1). The EC of the nutrient solutions always remained between 1.5 and 1.6 dS·m⁻¹. Fertigation management and growth parameters were performed according to the description for Expt. 1.

Statistical analysis and experimental design. Each experiment was performed independently using a randomized complete block design, with four repetitions and four plants per repetition for each treatment in CF and sand (Montgomery, 2004). The results were subjected to an analysis of variance and a comparison of means with a Tukey test ($P \leq 0.05$), and to linear and quadratic correlations

Table 1. Nutrient solution supplied in potted plants of 'Ventura' blueberry.^z

EC (dS·m ⁻¹)	pH	Macronutrients (mm)							Micronutrients (μM)						
		NO ₃ ⁻	H ₂ PO ₄ ⁻	SO ₄ ²⁻	K ⁺	NH ₄ ⁺	Ca ²⁺	Mg ²⁺	Fe	Mn	Cu	Zn	B	Mo	
1.6 ^z	5.8	10.5	1.5	2.0	6.0	2.0	3.5	1.0	15	10	0.75	5.0	30	0.5	

^zBased on Sonneveld and Straver (1994).

Electrical conductivity = EC.

Fig. 1. pH and electrical conductivity (EC) of a complete nutrient solution as a function of the dose of nitric or citric acid. Means (n = 4).

using the statistical package Statgraphics Centurion® X.V.I.I (2018).

Results and Discussion

The drainage parameters of the resulting pH, EC, and percentage of volume of fertigation and drainage are commonly used in the practical control of soilless culture (Gorbe and Calatayud, 2010; Moya et al., 2017; Rodríguez et al., 2015; Urrestarazu, 2015; Urrestarazu et al., 2008).

Figure 1 shows a graph of the pH and EC values as a function of the acid dose added to a standard nutrient solution with 2.0 mM bicarbonate from the irrigation water. To lower the pH from 6.2 to 4.0, 1.86 to 2.36 mM nitric acid is required, which assumes an increase in the EC of the nutrient solution from 1.34 to 1.38 dS·m⁻¹. However, if these same acid levels are observed, the citric acid curve would require between 0.51 and 1.60 mM, which would increase the EC to 1.17 to 1.24 dS·m⁻¹. This would assume that the EC of the nutrient solution is between 9% and 7% lower when using citric acid than when using nitric acid at a pH level of 6.2 or 4.0, respectively. Consequently, for a plant that is sensitive to salinity, such as blueberries (Machado et al., 2014), citric acid is preferable.

Expt. 1: Application of silicon in the nutrient solution

Fertigation and water uptake parameters. There were no significant differences in the

levels of Si in the nutrient solution the fertigation parameter of drainage, nor were there significant differences between the levels of Si in the nutrient solutions (data not shown). The pH mean values in the drainages were similar for both substrates (Table 2). The percentage of drained volume was less for CF, whereas EC and water uptake were greater for CF. In relation to EC as a fertigation management reference value, a maximum of 1 to 1.5 units (measured in decisiemens per meter) of EC was established for drainages greater than the input values (nutrient solution) (Urrestarazu, 2004, 2015). With this set value, 40% and 30% drainage of the blueberries was observed throughout the crop cycle in CF and sand, respectively. The drainage EC of the obtained data was, on average, 2.13 and 1.93 units greater than the desired fertigation reference value in CF and sand, respectively.

Parameters of vegetative growth. Except for height, all parameters of vegetative growth had greater values in CF than when sand was used as a substrate (Table 3). In sand, no growth parameter registered a clear improvement with the application of Si in the nutrient solution (Fig. 2). The biomass, both fresh and dry, showed a clear and significant improvement in the organic CF substrate, but this was not observed in sand. Biomass improvement of 16% to 20% was reached at a concentration of 1.2 mM Si. The poor response to Si application in the nutrient

Table 2. Effects of substrate type on leachate pH and electric conductivity (EC), drainage, and water uptake in potted plants of 'Ventura' blueberry.^z

Characteristic	Coir	Sand	Difference
pH	5.8	5.6	0.2
EC (dS·m ⁻¹)	4.8	3.6	1.2*
Drainage (%)	32	41	-9*
Water uptake (L·week ⁻¹)	5.0	4.3	0.7*

^zData are pooled across four levels of Si in the nutrient solution.

*Significant at $P \leq 0.05$

Table 3. Effects of substrate type on vegetative growth in potted plants of 'Ventura' blueberry.^z

Characteristic	Coir	Sand	Difference
Height (m)	1.1	0.9	0.2 ^{NS}
Fresh weight (g/plant)			
Stem	71	44	18*
Leaf	106	73	33*
Dry weight (g/plant)			
Stem	29	19	10*
Leaf	32	25	7*
Leaf area (m ² /plant)	0.46	0.32	0.12*

^zData are pooled across four levels of Si in the nutrient solution.

^{NS}. Nonsignificant and significant at $P \leq 0.05$.

Fig. 2. Growth response of 'Ventura' blueberry to an increasing concentration of Si in the nutrient solution. The plants were grown in pots filled with coir or sand.

solution in sand was probably a result of the potential availability of this extraction from the root zone in the silica sand substrate, because Si is not an essential component in organic matter such as CF. Xie and Wu (2009) found that sand affected the growth of blueberry plants negatively, but that mixtures of peat and sawdust increased the number of leaves, the average leaf surface, stem length, and stem diameter. Similarly, Tasa et al. (2012) reported that a mixture of peat and soil provided a greater amount of nutrients than mineral soil, which resulting in better growth and greater production of blueberries. On the other hand, Heiberg and Lunde (2006) found no significant differences in vegetative development when evaluating different types of substrates and their mixtures in greenhouses. Similarly, Pinto et al. (2017) evaluated two types of substrates

[commercial substrate Siro® and a mixture of CF, composted pine bark, and perlite (3:2:1 v/v/v)] and the size of the container used for blueberry plants and concluded there was no impact on the growth of blueberry plants. In suboptimal soil conditions with a high pH, it is advisable to use organic substrates to stabilize the pH of the root zone in blueberry cultivation (Schmid et al., 2009) and to improve the physical properties of the soil (e.g., structure, aeration, water-holding capacity) to improve growth and increase plant production (Retamales and Hancock, 2012). The buffer capacity of the organic matter that constitutes the CF was likely the reason that, despite the lower EC and pH, the CF was more suitable for blueberry plants compared with sand.

These data corroborate the growth benefits found by Pozo et al. (2015), who applied 0.65 mM Si in the nutrient solution and found, in addition to increased protection against *Botrytis cinerea*, a significant increase in the growth parameters of five families of plants grown in CF. On the other hand, Morikawa and Saigusa (2004), using river water containing between 0.66 and 1 mol·m⁻³ Si for irrigation, found that blueberry plants accumulated 3.1 and 5.4 times more Si than N in young and old leaves, respectively, thus classifying blueberry as an Si accumulator plant. These same authors noted that this accumulation may be a response to stress by heavy metals (Al, Zn, and Mn) and may serve as protection against diseases. In addition, authors such as Miyake and Takahashi (1986) observed benefits on growth, flowering, and production during strawberry cultivation with the application of Si in the nutrient solution.

Expt. 2: pH of the nutrient solution/Parameters of fertigation and water uptake

Effect on pH of drainages. Comparison of substrate. At all pH levels, ranging from 4.00 to 6.25, and for all the variables (two substrates and two types of acids), the pH values in the drainages varied without significant differences (pH 5.45–6.15, data not shown). As observed for Expt. 1, and with the exception of the treatment of pH 6.25 and nitric acid, within the same treatment and substrate, the acidity levels were relatively the same in the rhizosphere. This allows us to state that, in general, both acids are adequate to maintain the necessary acidification in the rhizosphere of blueberry plants (Table 4).

Comparison of the type of acid application. Only for pH 6.25 (greater or close to the optimum pH described for blueberry plants; data not shown) and in CF was a significant difference observed, in favor of using nitric acid with respect to citric acid. Therefore, and in general for this parameter, both acids can be used as a source of acidification.

It is well known that pH variations of the rhizosphere are strongly influenced by the ratio of ammonium nitrogen (N-NH₄⁺) to

nitric nitrogen (N-NO₃⁻). In addition, in sand, Merhaut and Darnell (1996, 1995) found that the pH decreased from ≈4.5 to 3.0 when blueberries were supplemented with only N-NH₄⁺ for 140 d but increased to 6.0 when the plants were supplemented with only N-NO₃⁻. Here, we used an average ratio of ammonium to nitric composition similar to the literature in this regard (e.g., Claussen and Lenz, 1999; Crisóstomo-Crisóstomo et al., 2014), and the pH of the drainages compared with the nutrient solution stayed within the desired limits (Urrestarazu, 2004, 2015).

Effect on EC of the drainages. Comparison of substrate. There was a significant decrease in EC for citric acid, whereas this difference was not recorded in sand.

There were significant differences in EC for the acid treatments within both substrates and pH levels (data not shown). However, for all levels of treatments, when comparing the recorded ECs for all acid–substrate combinations, greater values, between 7% and 20% more, were recorded in CF than in the sand with nitric acid, and values between 8% and 13% more were recorded with citric acid.

Comparison of the application of the type of acid. In CF, the application of nitric acid caused a significant increase in EC in lower pH treatments, which could have been the result of the greater EC value resulting from the same pH value being used in the fertigation with nitric acid (Fig. 1). In contrast, EC was not lower in sand when citric acid was applied as a source of acidification, except at a pH of 4.0, probably because it is more rapidly degraded in a better aerated substrate (the aeration capacity of sand is much greater than that of CF).

Considering the two previous points, including the observation of lower average EC values when using citric acid, we could conclude that citric acid is a more favorable agent of acidification for crops that require a very low pH, such as blueberry.

Effect on the volume percentage of drainage. Within each substrate, there was no clear variation in drainage EC, but the drainage volumes were much higher in sand.

Effect on uptake volume. Comparison of substrate. With the use of nitric acid, a clear increase in absorbed water volume was obtained. This was not observed for sand, although there was better absorption at different levels of pH (data not shown).

Comparison of acid type. At a low pH (4.00–4.75), both acids showed similar water absorption volumes in CF and sand. However, for the increase at a greater pH, there was a significant difference between the acids, favoring nitric acid in the CF substrate and citric acid in sand.

Effect on vegetative growth. Effect on height and foliar surface. There were no significant differences in plant height, neither with the progressive application of acidity (data not shown) nor in the average data (Table 5).

The averages were significantly greater, by 20%, for CF compared with sand.

There were no significant differences in leaf surface area. The average leaf area of CF in relation to sand was also greater by more than 10%.

Effect on biomass. The average biomass data did not show a clear and significant tendency when nitric acid or citric acid was used in both substrates. The average biomass of CF was greater by more than 10%. The total shoot dry weight recorded a clear and significant or highly significant linear or quadratic R^2 value of 0.99 and 0.95 for CF with nitric acid and citric acid, respectively (Fig. 3). There was no clear effect in sand. Nitric acid increase more than 20% the pH level (6.25). In contrast, when applying citric acid, the maximum was achieved at pH 4.00, with a greater increase than at pH 4.75. This increase was 13% when the pH decreased from 6.25 to 4.00, and was 8% when it

decreased from pH 4.75 to 4.00. These results allow us to conclude that in these conditions, the optimum application levels are between 4.00 and 4.75. This finding suggests that more specific trials should be conducted for levels ranging from pH 4.00 (or even less) to 4.75. It is suggested that the levels for cv. Ventura and substrate be lowered to those published by other authors, who noted the desirable pH interval was between 4.5 and 5.5 (Korcak, 1988; Mainland, 2012; Retamales and Hancock, 2012). Other authors working with soilless culture, such as Townsend (1971), adjusted the pH of the nutrient solution with sulfuric acid and sodium hydroxide for two cultivars of blueberry and found that the maximum vegetative growth occurred at pH 4.0 and 4.5, but that there was no significant growth at pH 2.5 and 3.0. However, Schmid et al. (2009) used sulfur to acidify pine sawdust to a pH range of 3.8 and 4.2, and observed increases in growth and production of 48% and 55%, respectively.

Table 4. Effects of substrate and acid type on leachate pH and electrical conductivity (EC), drainage, and water uptake in potted plants of 'Ventura' blueberry.^z

Characteristic	Coir			Sand		
	Nitric acid	Citric acid	Difference	Nitric acid	Citric acid	Difference
pH	5.8	6.0	-0.2 ^{NS}	5.6	5.6	0.0 ^{NS}
EC (dS·m ⁻¹)	4.4	3.9	0.5*	3.5	3.7	-0.2 ^{NS}
Drainage (%)	36	34	2 ^{NS}	46	42	4 ^{NS}
Water uptake (L·week ⁻¹)	4.8	5.2	-0.4*	3.8	4.2	-0.4 ^{NS}

^zData are pooled across four levels of pH in the nutrient solution.

^{NS}. *Nonsignificant and significant at $P \leq 0.05$.

Table 5. Effects of substrate and acid type on vegetative growth in potted plant of 'Ventura' blueberry.^z

Characteristic	Coir			Sand		
	Nitric acid	Citric acid	Difference	Nitric acid	Citric acid	Difference
Height (m)	0.96	0.94	0.04 ^{NS}	0.71	0.69	0.03 ^{NS}
Fresh weight (g/plant)						
Stem	80	76	4 ^{NS}	49	46	3*
Leaf	110	100	10*	69	63	6*
Dry weight (g/plant)						
Stem	30	31	-1 ^{NS}	20	20	0 ^{NS}
Leaf	33	30	3 ^{NS}	22	21	1 ^{NS}
Leaf area (m ² /plant)	0.49	0.45	0.04 ^{NS}	0.30	0.29	0.01 ^{NS}

^zData are pooled across four levels of pH in the nutrient solution.

^{NS}. *Nonsignificant and significant at $P \leq 0.05$.

Fig. 3. Growth response of 'Ventura' blueberry to increasing levels of pH in the nutrient solution. The plants were grown in pots filled with coir or sand, and pH was adjusted using nitric or citric acid.

Nevertheless, they obtained negative results when they used citric acid to acidify the irrigation water, probably resulting from volatilization, leaching, or mineralization. In addition, using soilless culture, Rosen et al. (1990), with frequent adjustments of the pH of the nutrient solution, found the maximum vegetative growth and total dry weight at pH 4.5, regardless of the form of nitrogen used ($N-NH_4^+$, $N-NO_3^-$, or NH_4NO_3).

Our results in sand were not significant in any case. The statistical dispersion of the data in sand was much greater than in CF. These results can be justified by the recent results published by Payá-Milans et al. (2017), who indicated there are wild species of *Vaccinium arboreum* that are capable of adapting to a wider range of soil pH. As our data are only from one cultivar, it would be advisable to perform these same studies in several cultivars of blueberry species.

Similar to our results, authors such as Hall et al. (1964) also observed disparities in their results, finding a positive effect on clonal varieties of blueberry in mixtures of substrates at a pH of 4.2 (soil plus sawdust); however, in other mixtures (with compost, peat, and sand), the best results were obtained at pH values ranging from 4.9 to 5.5.

Conclusions

The application of Si benefits the vegetative growth of blueberry plants by between 8% and 25% in CF. In contrast, in sand, there was no clear benefit following the application of Si.

In general, the use of citric acid maintains the pH in the rhizosphere at the same level as nitric acid (<6.25). Therefore, citric acid can be an adequate acidifier in organic agriculture and is as suitable as nitric acid in conventional agriculture.

Maximum vegetative development was obtained at pH values ranging from 4.00 to 5.50 in both the nitric acid and citric acid treatments in CF. The results were not conclusive for sand. A pH of 5.50 to 6.25 is not advisable because of the negative effects on growth parameters. Recent and more detailed studies of the optimum pH to use in soilless culture suggest a pH range of 3.50 to 4.50, which is also recommended for other blueberry cultivars.

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