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Research Article

Nutrimental modifications in blueberry (*Vaccinium corymbosum* L.) caused by vanadium supply

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Abstract

Blueberry plants prosper in acid environments with pH 4.5, condition that enhances vanadium (V) bioavailability. In different species, literature reports nutrimental modifications caused by V, nevertheless in blueberry plants this effect remains unknown. This study assessed the impact of six vanadium (V) doses in nutrient solutions (0, 20, 40, 80, 160 µM) and as foliar sprays (20 µM) on blueberry plants, employing a completely randomized experimental design with three replicates. At 66 days after applying the treatments, nutriments concentrations in leaves, stems and roots of each plant were determinate. Except for N, V modified nutrimental concentrations in at least one plant organ. V applied to foliage benefits Mn (67%) in leaf, as Ca (56%), Mg (40%), B (26%) and Mn (46%) did in stems and P (50%) in roots. No matter V concentration in solution, P (51%), Fe (270%) and Cu (230%) in roots are enhanced, but Mo it is reduced up to 6 times. The use of 160 µM of V in solutions increases Mg (40%) concentrations in stems, the same happened in Ca (32%) and Zn (47%) in roots but reduced K (35%) in this organ. V applied from 0 to 160 µM in solution increases 3, 64, 225 times V concentration in leaf, stem and roots respectively. These results show that V applications in solution benefits P levels in leaf, Ca and Mg in stem, P, Ca and Mg in root; while foliar spray enhances K, Ca, Mg concentration in stem and Mg in root.

Keywords: heavy metal; hydroponics; macronutrients; micronutrients; toxic

Introduction

Plant growth environments encompass a range of elements beyond necessary nutrients, including heavy metals like vanadium (V), a transition metal affected by soil redox conditions. Found in minimal concentrations within plants, V impact remains uncertain due to experimental challenges in excluding it, often inadvertently introduced as a contaminant in water, and substrates (Pilbeam, 2015). Usually, greater

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concentrations than 2 mg kg^{-1} in plant tissue (Aihemaiti *et al.,* 2020) can disturb plant metabolism through the suppression of crucial enzymes, protein formation, and ion transport. Consequently, the potential benefits of this metal remain obscure (Pourret *et al*., 2018).

Plant absorb V passively and it's highly dependent in factor like soil pH, organic matter content, redox potential, iron (Fe), aluminum (Al) content and other metals which can coexist and affect its bioavailability (García-Jiménez *et al*., 2018; Aihemaiti *et al*., 2019).

Depending of V doses, the plant tissue and plant species, it has found increase and decreases in macro and micronutrients concentration. Literature reports pepper (*Capsicum annum* L.) crop with different V concentration (0-15 µM) in nutrient solution decreased K, Mg, and Mn concentration in leaves (15 µM), increased N, P, K, Ca, Mg, Cu, and B concentration in stems (5 µM) while in root P, K, Ca, Mg, Cu and B concentration were enhanced (15 µM) (García-Jiménez *et al*., 2018). *Mentha pulegium* plants treated with V (0-785.23 µM) in a hydroponic system reduced Fe, Mn, Zn, Ca, K and Mg concentrations in leaves (785.23 µM), same way did V doses (785.23 µM) Fe, Zn, and Ca concentrations in stems, while in a medium with V doses (392.6 µM) Fe and Mg were enhanced in roots (Akoumianaki-Ioannidou *et al*., 2015). V doses between 0 and 785.23 µM in sweet basil plants (*Ocimum basilicum*) decreases Fe concentration in leaves with V concentrations (98.15 -785.23 µM) and the same occurred in Fe, Zn, Ca, and Mg in roots with 785.23 µM, although nutrimental content in stems were not affected (Akoumianaki-Ioannidou *et al*., 2016).

Blueberries, perennial woody shrubs, are categorized as calcifuge plants, adapted to thrive in acidic soils with pH levels ranging from 4.2 to 5.5. These acidic conditions also enhance the availability of heavy metals, including vanadium (Retamales *et al*., 2018; Aihemaiti *et al*., 2019).

Over the past four years, Mexico has emerged as the eighth-largest global exporter of fresh blueberries, achieving sales abroad worth $490 million dollars with an impressive average annual growth rate of 15.5%. The country's specialization in blueberry production and trade is attributed to its diverse range of climates and favorable conditions (Secretaría de Agricultura y Desarrollo Rural, 2023), nevertheless heavy metal concentration on environment is increasing as time goes by due to anthropogenic activities, leading to severe contamination of environment (Covarrubias and Cabriales, 2017). For the above reasons, literature in this way is varied, although V could be categorized as a beneficial element, its effect in nutrimental composition modification in diverse plant species is scarce. Given the positive influence of blueberries on Mexico's economy and the necessity for their future preservation, it is convenient to investigate V exposure in blueberry plants and its effects on measurable parameters related to nutritional composition. Understanding these dynamics can contribute to sustainable blueberry production and safeguarding Mexico's economic interests. This study hypothesized both V concentration and method of application, stimulate nutrimental absorption in different organs of this crop. Hence, the work's main objective was to study the effect of V doses and method of application in nutrimental concentration of blueberry.

Materials and Methods

Description of the study site

At Colegio de Postgraduados campus Montecillo's installations, Bluberry plants cv. 'Biloxy' were treated with V in a greenhouse from March to May 2021. In this experiment, temperature and relative humidity were registered with DHT.22 (Smarg-Da®, Mexico) sensor, the following average is reported weekly (Figure 1).

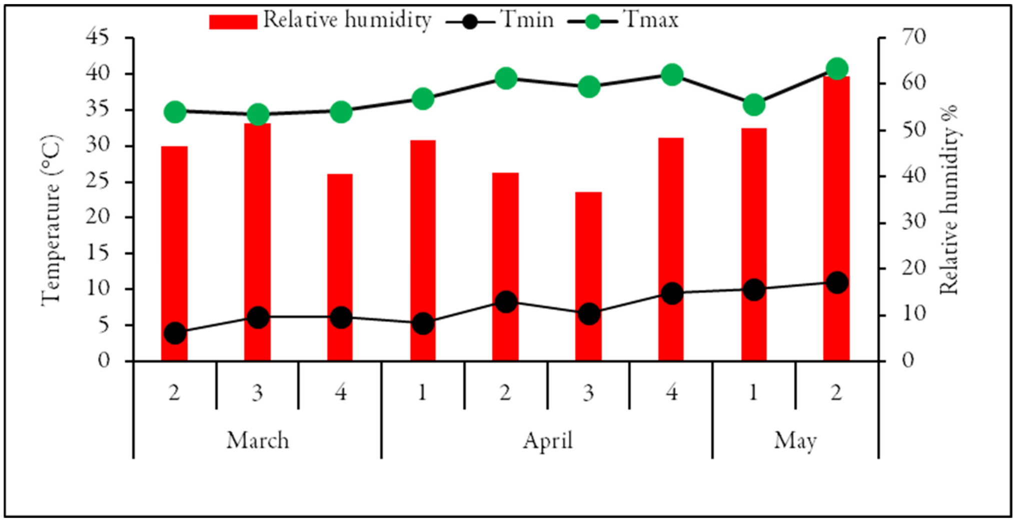

Figure 1. Weekly average of temperature maximum (Tmax), minimum (Tmin) and relative humidity, within experimental evaluation cycle from March to May 2021

Crop conditions and experimental design

This investigation was done through a completely randomized design, which evaluated V effect in doses 0 (control), 10, 20, 40, 80 and 160 µM supplied with NH_4VO_3 in nutrient solution (NS) and foliar spray 20 µM in the morning at 08:00 am each 14 days. Three repetitions per treatment were considered, using a blueberry plant in a 5 L container as an experimental unit.

Nine months old blueberry plants cv. 'Biloxy' were stablished in hydroponic nutrient solution system. The nutrient solution used was based on Steiner's formulation (Steiner, 1984), with a modification in the NO_3^- : NH_4^+ ratio (60:40). The nutrient solution underwent a 20-minute oxygenation cycle at 4-hour intervals, facilitated by an air compressor installed in the container (Sunsun®, ACO-002, China) during the experimental period. In this investigation pH value was adjusted daily to five with H_2SO_4 or NaOH. The NS was renewed weekly considering the following composition in $mol_c\ m^{-3}$: Ca^{2+}= 3.48, Mg^{2+}= 1.55, K^+= 2.71, NH_4^+= 2.44, NO_3^-= 3.67, SO_4^{2-}= 5.7 and H_2PO_4-= 0.81 all previously indicated fertilizers were used as grade reagent; while micronutrients in µM were Fe (53.72), Mn (25.48), Zn (4.28), B (23.89), Cu (1.76) and Mo (1.084) (Tradecorp® Tradecorp AZ, Madrid). The macro and micronutrients were initially formulated into a 200 L stock solution. Subsequently, the fertilizers were diluted and uniformly distributed across five separate 20 L containers for each treatment. To maintain rigorous contamination controls, each 20 L container was poured into three individual 5 L containers, this process was repeated every 7 days when the NS was renewed.

Root, stem and leaf macro and micronutrients analysis

After 66 days following the application of treatment, plant samples were collected from blueberry plants. The plants were divided into root, stem, and leaf, these components were thoroughly washed with tap water and then rinsed with distilled water. Subsequently, each organ was placed in paper bags and subjected to drying in an oven (Riosa® HCF-125D, Mexico) with air circulation at 70 °C for 72 hours until a constant dry weight was achieved. After drying, each organ was pulverized using a domestic blender (Oster®, Mexico) for subsequent mineral analysis. The leaves selected for analysis were those that had recently reached maturity and were fully expanded. Phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg) concentration in g kg^{-1} of dry weight (DW) were performed. Iron (Fe), copper (Cu), zinc (Zn), manganese (Mn), molybdenum (Mo), boron (B) and vanadium (V) in mg kg^{-1} DW of leaf, stem and root were determinate. All determinations were carried out by wet digestion of dry tissue using a perchloric-sulfuric acid mixture, with 2:1 (v/v) proportion. Extracts obtained were analyzed in an inductively coupled plasma optical emission spectrometry (Agilent® 725 ICP-

OES; Mulgrave, Victoria, Australia). This instrument was calibrated with standard solutions of known concentration for each element, following recommendations stablished in this instrument's manual. N was extracted following the procedure indicated before and considering semimicro-Kjeldahl method according to Bremner (1965).

Data analysis

Utilizing R 4.2.1 software (R Core Team, 2022), statistical analysis was done. Prior to performing a one-way analysis of variance, it was assessed normality and homogeneity of variance using the Shapiro-Wilk and Levene's tests, respectively. When required, a logarithmic transformation to the data was applied. The results are presented without any transformation. Additionally, a pairwise comparisons using Tukey's test with a significance level of $p \leq 0.05$ was conducted.

Results and Discussion

The exposure of blueberry plants to V in the nutrient solution, as well as its application to leaves, resulted in distinct effects on nutrient concentrations within each plant organ evaluated. In leaf, V affected P, B, Fe, Mn and V concentrations, which will be discussed later; in stem N and P were not affected by V; while in root, V exposition affected most of nutrients, except in N, B and Mn (Table 1).

Table 1. Vanadium effect (*p*-value) in leaf, stem and root nutrimental concentrations in blueberry crop

Element	Leaf	Stem	Root
	(*p*-value)		
Nitrogen	0.08	0.09	0.55
Potassium	>0.05	<0.01*	<0.05*
Phosphorous	<0.01*	0.29	<0.01*
Calcium	0.43	<0.01*	<0.01*
Magnesium	0.12	<0.01*	<0.05*
Boron	<0.01*	<0.01*	0.81
Copper	0.37	0.05	<0.01*
Iron	<0.01*	<0.05*	<0.01*
Manganese	<0.01*	<0.01*	0.40
Zinc	0.93	<0.05*	<0.01*
Molybdenum	ND	ND	<0.01*
Vanadium	<0.01*	<0.01*	<0.01*

ND: Not detected, * Significance $p \leq 0.05$

Root, stem and leaf macro and micronutrients analysis

Vanadium supply had not significant effect on N, K, Ca, Mg, Cu and Zn in leaves, similarly, in steams V did not affect N, P, and Cu. Furthermore, concentrations of V did not affect N, B, or Mn in roots.

The application of V in the nutrient solution at a concentration of 160 µM resulted in toxic effects, as depicted in Figure 2. This toxicity hindered the growth of both leaves and plant height, making impossible to conduct chemical analysis on blueberry leaves cultivated with V 160 µM.

<u>Nitrogen</u>

V doses had not effect N concentration in any plant organ analyzed (Table 2), which agree with pepper leaves and roots exposed to V in solution in 0-15 µM (García-Jiménez *et al.*, 2018).

Figure 2. Phytotoxic effects induced by a 160 μM vanadium application

Table 2. Effect on leaf, stem and root macronutrient concentration in blueberry by V supply in nutrient solution and foliar application (20F)

Vanadium (μM)	N	P	K	Ca	Mg
(g kg^{-1} DW leaf)					
0	18.43a	0.82b	6.16a	4.63a	0.85a
10	19.34a	0.88b	5.05a	4.32a	0.95a
20	13.04a	0.74b	5.85a	4.87a	0.94a
40	18.20a	0.91ab	5.40a	4.21a	0.92a
80	18.67a	1.24a	6.41a	4.68a	1.07a
20F	14.18a	0.75b	5.57a	4.99a	0.98a
CV (%)	19.55	16.78	10.12	12.45	10.64
HSD	8.13	0.35	1.42	1.38	0.24
Sufficiency levels [a]	16.53 – 20.66	0.83 – 3.06	4.03 – 7.16	3.7 – 8.33	1.26 – 2.83
(g kg^{-1} DW stem)					
0	9.18a	1.76a	2.42ab	3.46c	0.53c
10	8.48a	1.67a	2.42ab	3.62bc	0.55c
20	8.75a	1.48a	2.52ab	4.61ab	0.60bc
40	9.68a	1.54a	2.26b	4.12bc	0.59c
80	10.90a	1.60a	2.22b	4.20bc	0.65abc
160	9.97a	1.68a	2.17b	4.41abc	0.74a
20F	8.92a	1.49a	2.76a	5.40a	0.75ab
CV (%)	12.13	11.43	7.16	10.92	9.49
HSD	2.70	0.42	0.39	1.07	0.14
(g kg^{-1} DW root)					
0	20.91a	2.12b	3.77a	4.81bc	1.37b
10	18.98a	3.25a	3.23ab	4.28c	1.46ab
20	20.73a	3.20a	4.02a	4.04c	1.71ab
40	20.03a	3.09a	3.13ab	4.67bc	1.72ab
80	17.93a	3.08a	2.92ab	5.54ab	1.90a
160	18.28a	3.15a	2.44b	6.40a	1.87ab
20F	17.76a	3.20a	3.40ab	4.43bc	1.41ab
CV (%)	16.35	12.17	15.85	10.07	13.69
HSD	9.44	0.91	1.33	1.17	0.51

Means with different letters in each column and organ indicate statistical differences (Tukey, $p \leq 0.05$);
CV: coefficient of variation (%); HSD: honestly significant difference.
[a] Data adapted from Retamales *et al.* (2018).
DW: Dry Weight

Phosphorus

Phosphorus accumulation in foliar tissues exhibited a significant increment of 51% at a V concentration of 80 μM in the nutrient solution, which was statistically distinguishable from the control and all other treatment, excluding 40 μM V treatment which showed similar results. In root, P concentrations were statistically elevated by V treatments at or above 10 μM in the nutrient solution as well as by foliar application of 20 μM (20F). In roots, the highest P concentration achieved was corresponded to the 10 μM V treatment as delineated in Table 2. The use of V solutions ranging from 5 to 15 μM in pepper plants, increased 2.1 times P concentration in root compared the highest V treatment (15 μM) to control treatment (García-Jiménez *et al*. 2018). The observed increment in P concentration may be attributed to the enhanced biosynthesis of chlorophyll and amino acids. (Aihemaiti *et al.,* 2019). Additionally, V and P share analogous chemical structures; however, P is preferentially and more efficiently absorbed (Imtiaz *et al.,* 2017).

Potassium

Foliar application of V at a concentration of 20 μM (denoted as 20F) resulted in the maximal K accumulation in the stem (2.76 mg kg^{-1} DW). Conversely, in roots, V dose of 160 μM in the nutrient solution caused a reduction of K levels by 35% compared to the control, as show in Table 2. These differences could be explained as a dose-effect response in which 20 μM stimulates K absorption due to its role in counterbalancing anions (Aihemaiti *et al.,* 2019) but at high doses causes a K deficiency (Figure 2). The introduction of V 15 μM in nutrient solution increased 83% K concentration in pepper roots when compared to control treatment (García-Jiménez *et al*., 2018). In contrast to the previously mentioned findings, this study suggests that the high levels of V might lead to toxic effects, as shown in Figure 2. Elevated concentrations of V are known to generate reactive oxygen species, (Wu *et al*., 2021) which have the potential to activate both selective and non-selective K channels, facilitating K efflux from the root. Additionally, such oxidative stress can result in the degradation of cellular membranes through lipid peroxidation (Demidchik, 2014).

Calcium

Compared to control treatment, V application of 20 μM aimed to both root and leaf, increased 33% and 56% Ca concentration in stem, respectively. In root, V maximum doses (160 μM) statically increased 32% Ca concentration respectively when compared to control treatment (Table 2). Applications between 5 and 15 μM of V in nutrient solution enhanced up to 81% Ca concentration in pepper stems; while in root, Ca concentration increases 2.3 times in relation to control treatment, when V is applied in dose of 15 μM (García-Jiménez *et al*., 2018) the fact that pepper plants could enhances Ca concentrations at lower V concentrations (5 – 15 μM) than blueberries (20 μM), could potentially be attributed to the natural habitat preferences of these plants. Blueberries thrive best in low-acidic conditions, with an optimal pH range of approximately 4.5 to 5.5. It is in these acidic conditions that heavy metals, including V, tend to be more bioavailable (Retamales *et al.,* 2018). This characteristic could explain why blueberries may benefit from a higher concentration of V for their nutritional needs. In the stem, Ca transport predominantly occurs through the xylem, facilitated by the transpiration stream. This mechanism is typically more efficient to elevate Ca concentrations in fruits rather than increasing the element's availability in the substrate. However, due to the higher transpiration rates in leaves compared to fruits, a high transpiration flow tends to direct the movement of Ca preferentially towards the foliage (Rengel *et al.*, 2023).

Magnesium

V doses of 160 μM applied on root zone, increased 40% Mg concentration in stem, compared to control treatment, without observing significant differences compared to foliar treatment (Table 2). Compared to control treatment, when V was supplied 80 μM in nutrient solution, increased 39% Mg concentration in blueberry root (Table 2). Pepper crop exposed to V doses from 5-15 μM, increased 133% Mg concentration in root (García-Jiménez *et al*., 2018). *Mentha pulegium* L. plants added with 392.61 μM of V in nutrient solution caused an increase of 20% in Mg concentration in roots (Akoumianaki-Ioannidou *et al*., 2015) although this concentration is 2.4 times higher than the one used in this experiment, this response is very similar to the one we obtained with 160 μM. It has been documented that V at a concentration of 5 μM enhances chlorophyll content in pepper plants; however, a 15 μM concentration does not elicit the same response (García-Jiménez *et al*., 2018). Additionally, exposure of this plant species to V concentrations of 392.6 μM or greater results in a reduction of chlorophyll content (Altaf *et al*. 2021).

Photosynthesis is the principal metabolic pathway by which plants assimilate atmospheric carbon dioxide, leading to the synthesis of sugars and ultimately biomass, playing a critical role in plant development and potentially increasing agricultural productivity (Jahan *et al*., 2021).

Boron

Compared to the control treatment, the application of V yielded similar response in B concentrations in both leaves and roots of blueberry plants. However, when V was applied to the leaves, a 26% increment in B concentration was observed in the stems relative to the control (refer to Table 3). V doses between 5-10 μM supplied to pepper crop, increased up to 2 times B concentration in stem (García-Jiménez *et al*., 2018). Different studies have shown an interaction between B and essential elements, like activation or deactivation of transporters, induction of genes involved in element-starvation, modulates H^+-ATPase-mediated plasma membrane nutrient uptake (Vera-Maldonado *et al.,* 2024), which could explain a higher nutrient absorption.

Copper

Based on control treatment, Cu concentration in radical zone increased up to 1.3 times by increasing doses of V in blueberry crop, although maximum concentration of this element was obtained in V levels between 40 and 80 μM. In blueberry leaves and stems, Cu levels remain without significant changes by V supply (Table 3). Similar work with V doses between 5 and 15 μM in pepper crop increased Cu concentration up to 2.3 times (García-Jiménez *et al*., 2018), similar tendency found in this study.

Iron

Foliar applications of V in blueberry plants resulted in a higher Fe concentration in leaves showing a 43% increase on 80 μM V treatment when applied via nutrient solution. V doses ranging from 10 to 80 μM in the nutrient solution statistically increased Fe concentration in roots by 1.7 times, though no significant differences were observed when compared to the foliar treatment. In stems, evaluated treatments did not maintain a trend in Fe concentration, observing its best values when V was applied in 40 μM or applied to leaves (20F) (Table 3). V supply between 196.3 and 785.23 μM within nutrient solution in *Mentha pulegium* L plants, raise Fe concentration from 25% to 62% in roots (Akoumianak *et al*., 2015), responses that show similar trends to those found in this research. Interactions between V and Fe has been studied by Warington (1956) who found that increasing Fe concentration in nutrient solution overcome V toxicity in peas (*Pisum sativum* L.) and soybean (*Glycine max*), also Warington (1954) found that soybean plants in high V concentrations (98.5 μM) in nutrient solution, injured soybean, aspect that could limit plant growth by radical damage. This finding could explain why Fe concentration, increased in roots.

Table 3. Effect on leaf, stem and root micronutrient concentration in blueberry by V supply in nutrient solution and foliar application (20F)

Vanadium (μM)	B	Cu	Fe	Mn	Zn
(mg kg^{-1} DW leaf)					
0	76.21ab	2.67a	128.42ab	335.31bc	11.99a
10	56.33b	2.61a	139.00a	322.09bc	12.57a
20	70.84ab	2.46a	108.4ab	498.19ab	12.76a
40	67.13ab	2.94a	116.09ab	419.80abc	11.59a
80	67.72ab	3.43a	99.36b	266.61c	12.13a
20F	89.93a	2.69a	141.92a	560.93a	12.48a
CV (%)	13.28	20.70	10.74	18.38	13.58
HSD	24.36	1.43	35.08	205.70	4.11
Sufficiency levels [a]	25.6 – 66.66	5 – 17.5	53.66 – 156.66	40 – 283.33	8 - 30
(mg kg^{-1} DW stem)					
0	23.98bc	5.74a	82.26ab	963.79bc	25.30ab
10	21.72c	4.22a	69.59ab	907.44bc	20.86b
20	25.67b	4.75a	75.49ab	1176.01ab	24.81ab
40	27.41ab	6.16a	85.76a	1025.01bc	27.95ab
80	27.07ab	4.88a	57.46b	836.39c	28.90ab
160	27.24ab	5.49a	60.15ab	1167.31ab	37.42a
20F	30.32a	4.52a	84.91a	1411.23a	29.66ab
CV (%)	5.71	15.55	14.64	9.47	20.72
HSD	3.73	2.27	26.94	273.35	13.26
(mg kg^{-1} DW root)					
0	23.26a	43.25d	1035.07b	328.52a	47.63c
10	26.34a	71.06bc	2132.94a	230.12a	52.28bc
20	22.16a	82.17ab	2392.17a	354.64a	58.59abc
40	25.68a	100.67a	2652.22a	379.82a	58.22abc
80	23.27a	100.78a	2125.78a	289.91a	63.44ab
160	23.57a	89.29ab	2795.34a	368.30a	70.19a
20F	22.92a	51.01cd	1884.87ab	293.57a	48.59c
CV (%)	6.59	11.61	17.96	27.88	9.37
HSD	3.91	21.15	955.32	230.38	13.05

Means with different letters in each column and organ indicate statistical differences (Tukey, $p \leq 0.05$);
CV: coefficient of variation (%); HSD: honestly significant difference.
[a] Data adapted from Retamales *et al.* (2018).
DW: Dry Weight

Manganese

Compared with the control treatment, foliar V applications increased 67% Mn concentration in leaf and 46% in stem, whereas at root this element was not affected by V exposure in blueberry plants (Table 3). Mn has multiple function in several plant processes like photosynthesis, respiration, reactive species scavenging, plant defense against pathogens and hormone signaling, among these, photolysis of water and Mn-superoxide dismutase (Mn-SOD) enzyme are the most studied (Alejandro *et al*., 2020). Hence, an increment in Mn concentration could impact in a positive way different processes like photosynthesis or scavenge reactive species nevertheless more investigation is needed.

Zinc

Zinc concentration in leaf and stem, did not affect in comparation with control treatment; while utilizing V up to 160 µM in nutrient solution increased Zn concentration 47% in roots compared to control treatment (Table 3). In this way, literature is controversial because on one hand Zn in radical zone is reduced significantly when V supply is augmented (392.6-782.23 µM) in *Ocimum basilicum* L. plants (Akoumianaki-Ioannidou *et al*., 2016); On the other side pepper plants exposed to V levels ranging from 5 to 15 µM, raise 1.07 times Zn concentration in root (García-Jiménez *et al*., 2018), this controversy might be due to V range concentration.

The variation in plant responses to V could be related to the plant's inherent tolerance to the metal. For example*, Setaria viridis*, which is often found in mining areas contaminated with V, demonstrated that concentrations of 782.23 µM or below can promote plant growth. In contrast, levels exceeding this threshold led to growth inhibition. This suggests that different plants have specific tolerance ranges to V, which can crucially influence their growth and physiological responses to metal exposure (Aihemaiti *et al* 2019). A more recent article has shown that pepper plants exposed with different V concentration (196.3-981.5 µM) reduced plant height, leaf area, root length, root volume, root tips, root average diameter, photosynthetic rate, transpiration rate, intercellular CO_2, stomatal conductance at concentration higher than 588.9 µM without improving any of these variables at lower values when compared to control (Altaf *et al.,* 2021), these could explain different responses between plant species.

Molybdenum

Raising V doses from 10 to 160 µM in nutrient solution, reduced up to 5 times Mo concentration in root (Figure 3 yellow) while foliar sprays (20F) did not affect statically Mo concentrations in roots. Among Mo major roles, its function in nitrate reductase (NR) is highlighted, enzyme involved in N assimilation (Bittner *et al*., 2014); thus, a decrement in Mo concentration can result in a low enzymatic rate of NR enzyme, hence it could be important to study enzymatic behavior when V is present and Mo reduced, although Warington (1954) found that high Fe concentration (30 mg L^{-1}) reduced Mo uptake when this was in normal concentration (0.01 mg L^{-1}) in a condition where Mn was toxic in nutrient solution (20 mg L^{-1}) in soybean. Extrapolating these findings to the current experiment, it is possible that the accumulation of Fe in the roots of blueberry plants, due to toxic V concentrations, can inhibit the uptake of Mo.

Vanadium

Application of V ranging 0-160 µM within blueberry crop growth, raised 4, 59 and 217 times V concentration in leaf (when V levels were 80 µM), stem and root (Figure 3 green, blue and orange) respectively. Pepper plants applied with V doses from 0 to 15 µM in nutrient solution increased 19 times V concentration in root (García-Jiménez *et al.,* 2018). In tobacco plants, V increasing doses (1.96-78.52 µM) in nutrient solution augmented differentially this cation concentration 19 times in root (V 272.5 mg kg^{-1} DW), while stem this increment was 110 times greater and 32 times in leaf (Wu *et al*., 2021), similar trend was observed in this investigation.

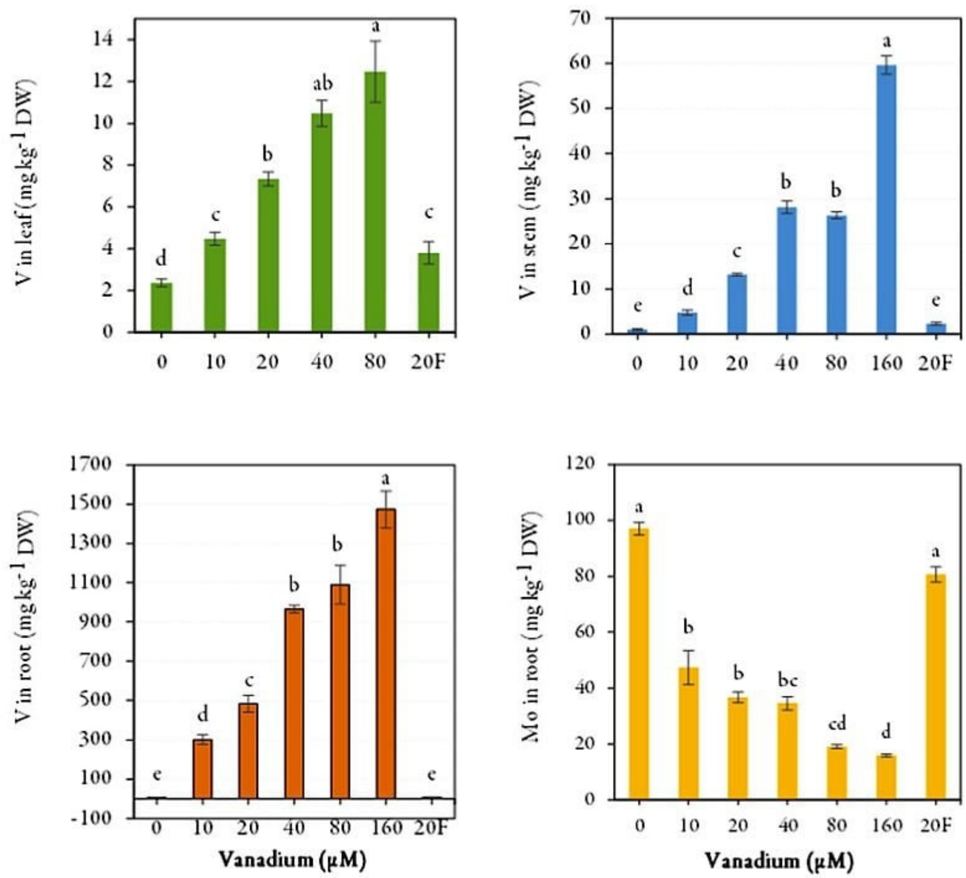

Figure 3. Vanadium concentration in dry weight (DW) of leaf (GREEN), stem (BLUE), root (ORANGE); and molibdenum (Mo) concentration in roots (YELLOW) of blueberry plants treated with V in solution or 20 µM applied to foliage (20F)

Values are means ± S.D. Different letters above bars indicate significant differences (Tukey, p ≤0.05)

The research conducted enabled the evaluation of nutritional sufficiency levels for blueberry plants when exposed to varying concentrations of V extending from 0 to 160 µM. In general, mineral composition in leaves had a variable behavior based on sufficiency levels reported by Retamales *et al.* (2018) denoted in Tables 2 and 3.

The concentrations of K, Ca, and Zn remain unaffected by V treatment, yet these cations stayed within the sufficiency range. N did not modify significatively by V addition, although this essential element resulted below the sufficiency interval in V doses of 20 µM in both solution and foliar spray. The P augmented significatively its concentration in the highest's V doses, but this remains within sufficiency levels, except for V application in doses of 20 µM both foliar and in nutrient solution where both forms kept P below sufficiency range. Fe concentrations always kept within optimum levels for this element although existed significative difference. Mg and Cu concentration were below sufficiency range and without significatively difference among V treatments. The Mn concentration maintained inside optimum levels in 80 µM treatment of V while lower V doses kept Mn levels above of sufficiency interval.

Conclusions

Blueberry plant exposed to different V concentration and method of application stimulate several nutrient uptakes in different organs, although this did not occur in K and Mo concentrations. Ranging V doses 10-160 µM supplied in nutrient solution increased P, Fe and Cu concentrations in root while, Mo diminished in this plant species. V concentration of 160 µM led to visible toxic effects on blueberry plants, enhances Mg concentrations in stems, Ca and Zn in roots but reduces K concentrations in roots. V foliar application (20F) stimulate concentrations of Mn in leaf, Ca, Mg, B and Mn in stem and P in roots, thus this method and application level could be an option in this crop management since generates increments on mineral concentrations previously mentioned.

Authors' Contributions

Data curation: RCA; Formal analysis: RCA and CSMH; Funding acquisition: PSG; Investigation: RCA; Methodology: RCA, PSG, MSV and ARA; Resources: PSG and NCH; Supervision: RCA, PSG, MSV and NCH; Writing - original draft: RCA. Writing - review and editing: RCA, CSMH and MSV.

All authors read and approved the final manuscript.

Ethical approval (for researches involving animals or humans)

Not applicable.

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Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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