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ORIGINAL PAPER

Effect of fertilization on the mineral composition of leaves and fruits of highbush blueberry (*Vaccinium corymbosum* L.) in container cultivation*

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Abstract

The study was carried out at the Agricultural Experimental Station in Felin affiliated with the University of Life Science in Lublin. The experimental material consisted of 5-year-old plants of cv. Bluecrop highbush blueberry growing in a mixture of sphagnum peat, sand and finely ground pine bark (v/v: 2:1:1) in 35 dm^3 containers. Two factors were taken into account in the experiment: A – form of nitrogen: 1) ammonium, 2) nitrate, 3) amide; B – fertilization level corresponding to the content in the substrate: 0, 100, 200, 400 mg N dm^{-3}. The following fertilizers were used: ammonium sulphate (21% N-NH_4, 24% S), magnesium nitrate (11% N-NO_3, 9.5% Mg), urea (46% N), monopotassium phosphate (22.3% P, 28.2% K), potassium sulphate (44.8% K, 17.0% S) and magnesium sulphate (9.5% Mg, 12.7% S). In leaves and fruits, total nitrogen was determined using the Kjeldahl method on a Foss Tecator apparatus, phosphorus was measured colorimetrically with ammonium vanadomolybdate (Thermo Evolution 300), while potassium, magnesium and calcium, and also manganese, iron, zinc and copper in leaves were determined with the ASA method (Perkin-Elmer, AAnalyst 300). The study found that the N-form had no effect on the content of nitrogen and phosphorus in leaves. The N-form had a significant effect on the content of potassium, magnesium, and calcium. The tested fertilization levels influenced significantly the concentration of nitrogen, phosphorus, and magnesium, whose values increased in direct proportion to the mineral fertilizer doses, while the opposite relationship was observed for Ca. The macronutrient contents in leaves (except for N in the control) corresponded to optimal values for the limit values, indicating proper nutrition of the highbush blueberries in this experiment. The highbush blueberry leaves were characterized by optimal contents of Mn, Fe, Zn, and Cu, with the exception of Fe and Cu in the control. The N form significantly influenced the content of Mn, Zn, and Cu, in addition to Fe.

Keywords: macronutrient, micronutrient, N-form, doses of fertilizer, cv. Bluecrop

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INTRODUCTION

Blueberry fruits have excellent nutritional, health promoting, dietary and technological values, which makes them suitable for direct consumption, drying, freezing and making various products (Milivijević, Miletić 2022). With its largest area of highbush blueberry cultivation in Europe, Poland is the second largest producer of this fruit globally (FAOSTAT 2025).

Blueberries are a plant with specific soil requirements. They prefer very acidic, light soils with a high humus content. Polish soils rarely meet all these criteria simultaneously, so it is commonly recommended to lower the soil pH before planting by applying sulfur and amending it with organic materials, which increase the amount of humus and improve physical and chemical properties of the soils (Hart et al. 2006). In the 20^{th} century, highbush blueberry was considered a plant with low nutritional requirements (Smolarz, Mercik 1992), but the results of studies by Bal (1997), Glonek and Komosa (2013) suggest that they are higher than commonly believed. Fertilization should be based on observations of plant growth, assessment of nutritional status based on leaf analysis, and soil fertility. New cultivation technologies (NGS, soilless cultivation, and covered cultivation) are often conducted in containers (Schreiber et al. 2020). Container production is suitable over a limited space, such as a high tunnel that enables moving plant pots and adjusting growing density depending on plant growth (Li, Bi 2019).

For this purpose, substrates that meet the soil requirements of blueberries (pH, physical and chemical properties) are used, consisting of mixtures in various proportions, e.g., sphagnum peat, pine bark, sawdust, perlite, and coconut fiber (Ochmian et al. 2010, Kingston et al. 2017, Strik et al. 2017, Kingston et al. 2020, Milivijević, Miletić 2022). Due to the limited volume of the substrate, the possibility of changes in pH, salinity, or flooding, fertilization is very important. The literature contains research results on the impact of nitrogen form, fertilization doses, and substrate types on the growth, yield, and mineral status of leaves and fruits, and substrate in container-grown blueberries (Wilber, Williamson 2008, Jiang et al. 2017, Tamir et al. 2020).

It turns out that highbush blueberries have high nitrogen requirements (Hanson 2006) and also prefer ammonium nitrogen (Hart et al. 2006, Banados et al. 2012). Some researchers believe that the NH^{4+} content, which is absorbed more quickly by blueberry plants, limits the uptake of NO_3, which explains the weaker effect of NO_3 – fertilization (Williamson, Miller 2009, Imler et al. 2019).

Mineral fertilization is still widely used, based on soil fertility and plant nutrient requirements, and often using granular fertilizers. Fertilization combined with irrigation (fertigation) relies on the use of highly soluble fertilizers such as ammonium nitrate, potassium nitrate, and magnesium nitrate, resulting in the predominance of nitrate in the nutrient solution.

Studies by Smolarz (1996), Glonek and Komosa (2006, 2013) suggest that this is acceptable for highbush blueberries, confirming their good yields under production conditions. The limiting values for nitrogen content in leaves of well-nourished plants are 1.80-2.10% (Wach et al. 2023). Another very important nutrient for highbush blueberries is potassium. Its optimal content is 0.35-0.65%, and the fruit contains a large amount of potassium (Wach et al. 2023). Increasing potassium doses raises its content in leaves and soil (sorption), but may limit magnesium uptake (Sardans, Peñuelas 2021).

The availability of calcium in blueberry leaves is limited mainly by its optimal content of 0.4-0.8% (Hart et al. 2006). Proper calcium nutrition of blueberries is difficult to achieve due to the highly acidic pH of the substrate and leaching, which is why it is recommended to apply calcium by spraying (Ochmian 2012). Calcium affects fruit hardness and shelf life (Ochmian et al. 2007, Ochmian, Kozos 2014). Highbush blueberries have low phosphorus requirements and respond poorly to fertilization (Eaton et al. 1997), but a study by Smagula et al. (1995) indicates an increased phosphorus content in leaves and enhanced vegetative growth, including the root system.

The optimal magnesium content in highbush blueberry leaves is 0.12-0.25% (Hart et al. 2006). Light and acidic mineral soils contain little of this important nutrient (Komosa et al. 2017). Smolarz (1996) observed an increase in Mg and Ca content owing to its supply in irrigation water. A quick way to correct deficiencies is foliar fertilization (Ochmian 2012, Ochmian, Kozos 2014).

The aim of the study was to determine the effect of mineral fertilization and nitrogen form on the mineral composition of leaves and fruits of highbush blueberries grown in container.

MATERIALS AND METHODS

The study was carried out at the Agricultural Experimental Stadion in Felin affiliated with the University of Life Science in Lublin. The experimental material consisted of 5-year-old plants of cv. Bluecrop highbush blueberry plants growing in a mixture of sphagnum peat, sand and finely ground pine bark (v/v: 2:1:1) in 35 dm^3 containers. The bushes were placed on stands positioned on black agro-textile (110g m^2) and kept outdoors. Irrigation was based on tensiometer readings.

Two factors were included in the experiment: A – nitrogen form: 1) ammonium, 2) nitrate, 3) amide; B – fertilization level corresponding to the content in the substrate: 0, 100, 200, 400 mg N dm^{-3}.

The experiment included 10 combinations of six plants each, with one shrub as a replicate. The experimental design and fertilization regimen are presented in Table 1. Doses of phosphorus, potassium, and magnesium fertilizers increased with nitrogen fertilization to maintain a 1:0.25:0.75:0.3 ratio. The fertilizers were divided into 2 parts: 0.5 dose applied in mid-April, the remaining amount – in mid-June.

The following fertilizers were used: ammonium sulphate (21% $N\text{-}NH_4$, 24% S), magnesium nitrate (11% $N\text{-}NO_3$, 9.5% Mg), urea (46% N), monopotassium phosphate (22.3% P, 28.2% K), potassium sulphate (44.8% K, 17.0% S) and magnesium sulphate (9.5% Mg, 12.7% S).

Table 1

The scheme and fertilization of highbush blueberry with the nutrients N:P:K:Mg in a (1:0.25:0.75:0.3) ratio (g plant^{-1}) in the experiment

No.	N – form	Level of fertilization (mg dm^{-3})	N	P	K	Mg
1.	control	0	–	1.05	2.125	0.875
2.	$N\text{-}NH_4$	100	3.5	1.05	2.125	0.875
3.	$N\text{-}NH_4$	200	7.0	2.1	5.25	1.75
4.	$N\text{-}NH_4$	400	10.5	3.15	7.375	3.5
5.	$N\text{-}NO_3$	100	3.5	1.05	2.125	0.875
6.	$N\text{-}NO_3$	200	7.0	2.1	5.25	1.75
7.	$N\text{-}NO_3$	400	10.5	3.15	7.375	3.5
8.	$N\text{-}NH_2$	100	3.5	1.05	2.125	0.875
9.	$N\text{-}NH_2$	200	7.0	2.1	5.25	1.75
10.	$N\text{-}NH_2$	400	10.5	3.15	7.375	3.5

Leaf samples (3th-5th on the top) were collected in each year of the study from the current year's long shoots; the sampling took place in the last ten days of July (after the first fruit harvest). The content of macronutrients was determined in the fruits of the second harvest (the largest). Leaf and fruit samples were initially dried at a temp. of 60-70°C and then ground. Next, after they were dried at 105°C, total nitrogen was determined by the Kjeldahl method using the Foss Tecator digestion system. After dry mineralization of the plant material at 550°C, the following were determined: phosphorus by colorimetry with ammonium-vanadium-molybdate (Thermo, Evolution 300), potassium, calcium, magnesium and (for leaf only) manganese, iron, zinc and copper by AAS (Perkin-Elmer, AAnalyst 300) – Ostrowska et al. (1991).

The results were statistically analyzed by two-way analysis of variance (ANOVA) with the Statistica 13.3 software (StatSoft Inc., Tulsa, OK, USA), using the Tukey's test to evaluate the differences at a significance level of p=0.05.

RESULTS AND DISCUSSION

Fertilization adjusted to plant requirements ensures optimal nutrition, and determines proper growth and yield (Banados et al. 2012). The macronutrient content of highbush blueberry leaves grown in containers is presented in Table 2. Statistical analysis revealed significant differences between individual combinations.

Table 2

The content of macronutrients in leaves of cv. Bluecrop highbush blueberry plants cultivated in containers

N – form	Level of fertilization (mg dm^{-3})	Macronutrient (g kg^{-1} d.m.)				
		N	P	K	Mg	Ca
Control	0	12.79 ^{a}*	1.12 ^{a}	4.15 ^{cd}	2.24 ^{b}	5.70 ^{e}
$N\text{-}NH_4$	100	16.44 ^{b}	1.21 ^{abc}	3.68 ^{abc}	2.29 ^{bc}	5.16 ^{d}
	200	18.08 ^{c}	1.29 ^{cd}	3.63 ^{ab}	2.25 ^{bc}	3.91 ^{b}
	400	20.58 ^{e}	1.46 ^{e}	3.73 ^{abc}	1.90 ^{a}	3.26 ^{a}
$N\text{-}NO_3$	100	17.35 ^{c}	1.15 ^{ab}	3.43 ^{a}	2.41 ^{cd}	4.50 ^{c}
	200	19.23 ^{d}	1.27 ^{bcd}	4.67 ^{e}	2.53 ^{d}	3.26 ^{a}
	400	19.48 ^{d}	1.30 ^{cd}	4.27 ^{de}	3.10 ^{f}	3.00 ^{a}
$N\text{-}NH_2$	100	16.45 ^{b}	1.14 ^{ab}	3.53 ^{a}	2.03 ^{a}	4.69 ^{c}
	200	19.30 ^{d}	1.26 ^{bcd}	3.75 ^{abc}	2.36 ^{bc}	4.35 ^{c}
	400	21.86 ^{f}	1.39 ^{de}	4.02 ^{bcd}	2.80 ^{e}	4.35 ^{c}

* Values followed by the same letters do not differ significantly at $\alpha = 0.05$

The content of nitrogen in highbush blueberry leaves was the lowest in the control treatment (12.79 g kg^{-1} d.m.), which confirms the importance of this most important nutrient for blueberries (Hart et al. 2006, Vargas and Bryla 2015). In combinations fertilized with nitrogen, the N concentration ranged from 16.44 to 21.86 g kg^{-1} d.m., and blueberry nutrition in this experiment was at an optimal level (Wach et al. 2023) even under the influence of medium doses of nitrogen in each form.

The study did not show any significant differences between the effects produced by the tested nitrogen forms, which differed significantly in the N content from the control (Figure 1). The leaves of blueberries fertilized with urea contained the highest levels of nitrogen (17.6 g kg^{-1} d.m.). Studies by other authors (Vargas, Bryla 2015) indicate that the ammonium form is preferred and best absorbed by blueberries.

Regardless of the form of nitrogen, increasing doses caused a significant and directly proportional increase in the content of this nutrient in highbush blueberry leaves (Figure 2). The highest nitrogen content was observed at the highest fertilizer dose (20.64 g kg^{-1} dm), which is consistent with the results of Glonek and Komosa (2013), Strik and Vance (2015), Vargas and

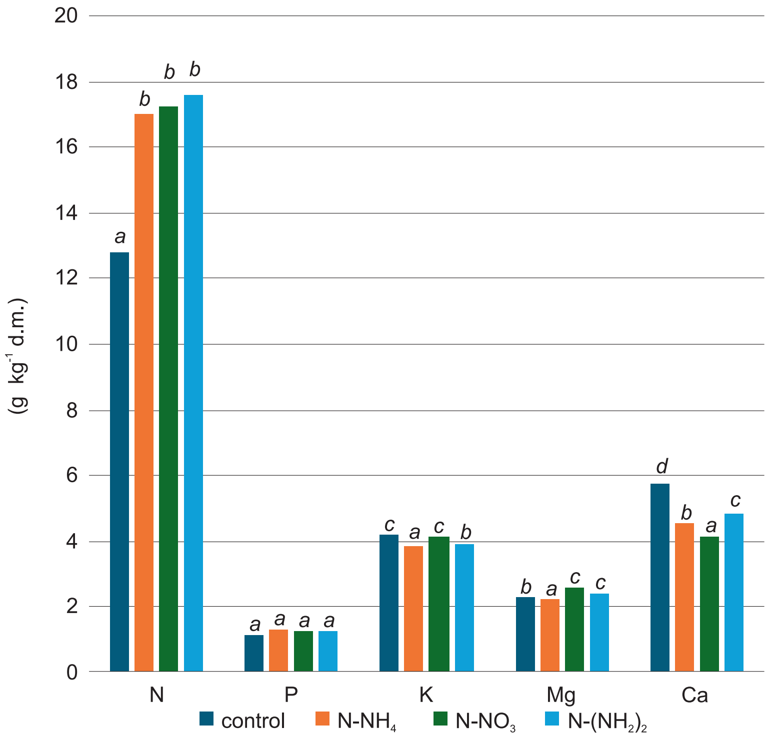

Fig. 1. The effect of N-form on macronutrient content in leaves of cv.
Bluecrop highbush blueberry plants cultivated in containers.
* Values followed by the same letters do not differ significantly at $\alpha = 0.05$

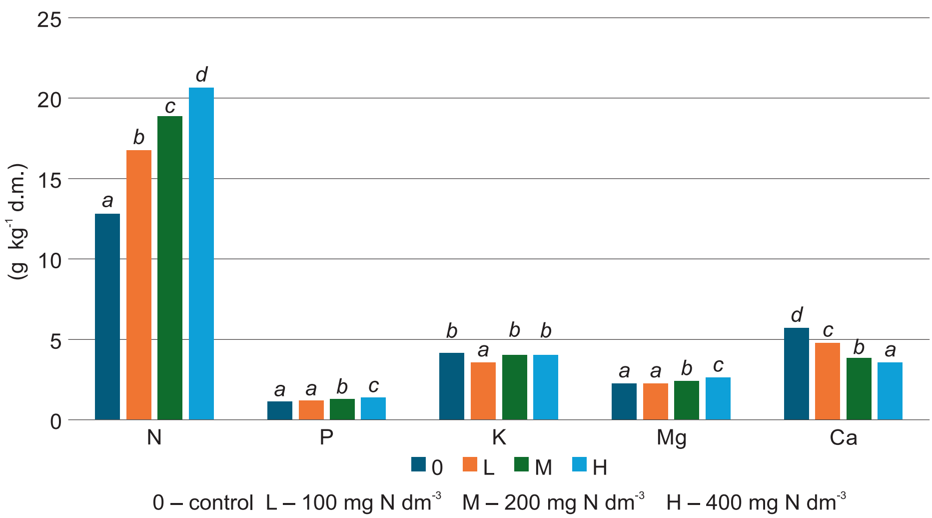

Fig. 2. The effect of doses of fertilizers on macronutrients content in leaves of cv.
Bluecrop highbush blueberry plants cultivated in containers.
* Values followed by the same letters do not differ significantly at $\alpha = 0.05$

Bryla (2015) and Davis and Strik (2022). Some authors (Smolarz, Mercik 1992, Smolarz 1996) report that high doses (>100 kg N) limit growth, yield, and reduce frost resistance. They also observed an increase in the content of this nutrient in leaves. They found no significant differences between fertilization levels: 0; 50; and 100 kg N, and believe that using high doses is pointless.

In the current experiment, phosphorus content in highbush blueberry leaves was optimal according to Hart et al. (2006). The lowest phosphorus content was in the leaves of the control treatment (1.12 g kg^{-1} d.m.), and the highest – in the treatment fertilized with the amide form (1.46 g kg^{-1} d.m.) – Table 2.

Increasing doses also caused a significant increase in the content of this nutrient in leaves (Figure 1). Similarly, Smagula et al. (1995) demonstrated the effect of increasing phosphorus doses on its content in leaves. This study showed that the nitrogen form did not significantly affect the amount of P, although the highest content (1.27 g kg^{-1} d.m.) was in leaves fertilized with the ammonium form (Figure 2).

The effect of nitrogen form and fertilization doses on potassium content in highbush blueberry leaves was varied (Table 2). Statistical analysis showed a significant interaction between the nitrogen form and dose on potassium content, which ranged from 3.53 (N-NH_2 – 100 mg dm^{-3} d.m.) to 4.67 g kg^{-1} d.m. (N-NO_3 – 200 mg dm^{-3}). According to Wach et al. (2023), the nutritional status of highbush blueberries was optimal, but in one case it was deficient (3.43 g K kg^{-1} - N-NO_3 – 100 mg dm^{-3}).

Regardless of the fertilization level, significantly higher potassium contents were found in the control and under the influence of nitrate fertilization (Figure 1). High K contents in combinations with the nitrate form confirm that its uptake is not blocked. Regardless of the form of nitrogen fertilizer, higher fertilization levels significantly affected potassium concentrations in leaves compared to the lowest dose (Figure 2); however, the leaves of control plants contained the most K – 4.15 g kg^{-1} d.m. It is so because blueberry fruits contain much potassium (Ochmian, Kozos 2014, Sardans, Peñuelas 2021).

In this study on the fertilization of highbush blueberries grown in containers, magnesium nutrition was determined to be optimal according to the adopted limit values (Hart et al. 2006).

Magnesium content in leaves differed significantly between treatments and ranged from 1.9 to 3.10 g kg^{-1} d.m., and when blueberries were fertilized with the nitrate form of nitrogen at medium and high doses, it corresponded to a luxurious level of nutrition (>2.5 g kg^{-1} d.m). The experiment demonstrated a significant effect of the nitrogen form (Figure 1) and fertilization levels (Figure 2) on magnesium concentrations in highbush blueberry leaves. The highest ones were obtained for the nitrate form and the highest fertilization level (2.57 and 2.60 g kg^{-1} d.m., respectively). Leaf Ca concentrations were similar to the results of a study on conventional and organic highbush blueberry cultivation (Strik, Vance 2015)

The effect of nitrogen form and fertilization level on calcium content in leaves of highbush blueberries grown in containers is presented in Table 2. Statistical analyses of the results showed significant interactions between the studied factors. The leaves of control plants contained the most calcium (5.70 g kg^{-1} d.m.), while the lowest Ca content was found in the leaves of plants treated with the nitrate form of nitrogen and a fertilization level of 400 mg dm^{-3} (3.00 g kg^{-1} d.m.), which was below the optimal value for the limiting values (Hart et al. 2006). The highest content of this element was found in leaves of blueberries fertilized with the amide form of nitrogen (urea).

Regardless of the fertilizer doses used in the experiment, a significant effect of the form of nitrogen fertilizer was demonstrated (Figure 1). Blueberry leaves nourished with nitrate nitrogen contained significantly the least calcium (4.12 g kg^{-1} d.m.), while the highest calcium was in the control (5.70 g kg^{-1} d.m.). The experiment showed a significant decrease in calcium concentrations in leaves under the influence of increasing fertilizer doses, regardless of their form (Figure 2).

Moderate and high levels of fertilization resulted in insufficient plant supply of this nutrient (Wach et al. 2023). Sulfate fertilizers and urea cause acidification of soils and horticultural substrates (Ochmian et al. 2021), which hinders calcium uptake by acidophilic plants (Vargas, Bryla 2015). High levels of ammonium nitrogen and potassium fertilization also hinder calcium uptake (Wilber, Williamson 2008, Sardans, Peñuelas 2021).

Micronutrients

Hart et al. (2006) reports that the optimal micronutrient contents in highbush blueberry leaves are (mg kg^{-1} d.m.): Mn 50-350, Fe 60-200, Zn 8-30, and Cu 5-20. Chemical analyses showed optimal manganese and zinc contents for each experimental combination, as well as iron and copper deficiency in the control treatment and at low levels of ammonium nitrogen fertilization. The study showed a significant effect of the nitrogen form and fertilization level on micronutrient concentrations in cv. Bluecrop highbush blueberry leaves (Table 3).

The manganese content ranged from 59.31 to 68.97 mg kg^{-1} d.m. A significant effect of the nitrogen form on the manganese content was found, but no effect of the fertilization level was demonstrated. The study revealed interactions between the studied factors affecting the iron content. Significantly, the Fe content was the lowest in the combination with low levels of ammonium nitrogen fertilization (58.34 mg kg dm^{-1}), and the highest when the amide form was applied at the highest dose (70.59 mg kg^{-1} dm). Fe content increased directly with fertilization but was independent from the form of nitrogen used in the fertilizer.

Table 3

The content of micronutrients in leaves of cv. Bluecrop highbush blueberry cultivated in containers

N – form	Level of fertilization (mg dm^{-3})	Micronutrient (mg kg^{-1} d.m.)			
		Mn	Fe	Zn	Cu
Control	0	63.49 ^{ab}*	58.68 ^{a}	22.57 ^{b}	4.52 ^{a}
$N-NH_4$	100 200 400	63.72 ^{b} 64.23 ^{b} 59.31 ^{a}	58.34 ^{a} 65.13 ^{ab} 64.20 ^{ab}	24.81 ^{cd} 23.19 ^{bc} 22.41 ^{b}	4.87 ^{a} 7.63 ^{bcd} 6.96 ^{b}
$N-NO_3$	100 200 400	65.61 ^{bc} 63.83 ^{ab} 68.97 ^{c}	64.93 ^{ab} 65.26 ^{ab} 70.12 ^{b}	22.09 ^{b} 18.63 ^{a} 26.14 ^{de}	7.38 ^{bc} 7.49 ^{bc} 8.34 ^{cde}
$N-NH_2$	100 200 400	63.18 ^{ab} 63.83 ^{b} 62.55 ^{ab}	64.03 ^{ab} 63.33 ^{ab} 70.59 ^{b}	33.92 ^{g} 27.03 ^{e} 31.35 ^{f}	7.87 ^{bcd} 8.63 ^{de} 9.02 ^{e}

* Values followed by the same letters do not differ significantly at α = 0.05.

The experimental factors had a combined effect on the zinc content in blueberry leaves (Table 3). Significantly, the lowest zinc content was found in plant leaves in the variant with the nitrate form applied at a level of 200 mg N dm^{-3} (18.63 mg kg^{-1} dm), and the highest – under the influence of the amide form at the lowest fertilization level (33.92 mg kg^{-1} d.m.). Regardless of the dose, the amide form promoted the best supply of this element to blueberries (28.72 mg Zn kg^{-1} dm) – Figure 3. Low and high fertilization levels, regardless of the nitrogen form, provided the best zinc nutrition

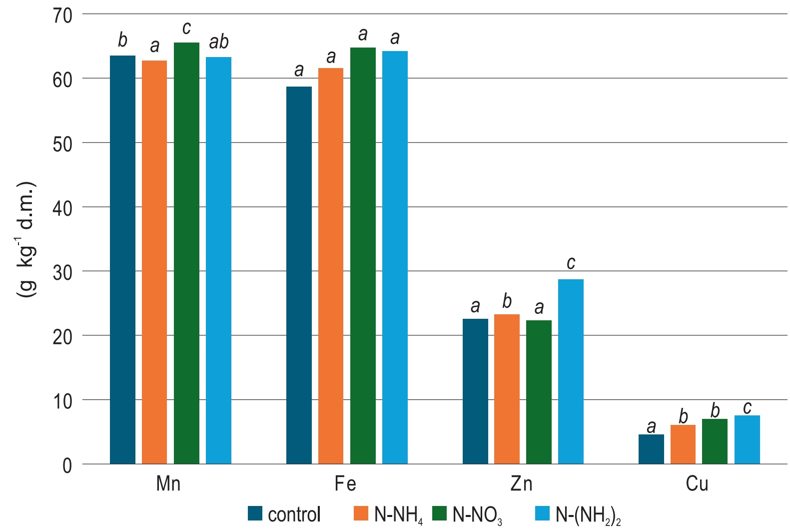

Fig. 3. The effect of N-form on micronutrient content in leaves of cv. Bluecrop highbush blueberry plants cultivated in containers.
* Values followed by the same letters do not differ significantly at α = 0.05

(26-27 mg kg^{-1} dm) – Figure 4). The Zn content was higher in this experiment than in the study of Jiang et al. (2019).

Under the conditions of this research, significantly the lowest copper content was found in leaves of the control treatment, and the highest one – in plants treated with the amide form of nitrogen used at the highest dose (4.52 and 9.02 mg kg^{-1} d.m., respectively) – Table 3. Statistical analysis showed a significant effect of the nitrogen form on copper concentrations (Figure 3). The Cu content increased in direct proportion to the fertilizer doses used in the experiment (Figure 4). The study by Jiang et al. (2019),

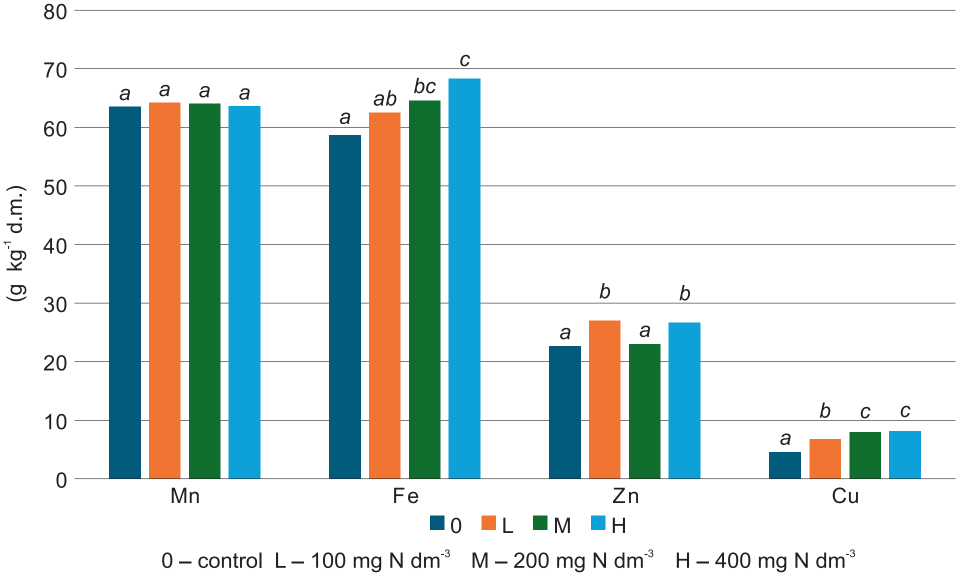

Fig. 4. The effect of doses of fertilizers on micronutrient content in leaves of cv. Bluecrop highbush blueberry plants cultivated in containers.
* Values followed by the same letters do not differ significantly at $\alpha = 0.05$

assessing the effect of pH on the content of microelements in highbush blueberry leaves, conducted on the Climax and Chaoyue No. 1 cultivars, showed lower Mn, Zn, and Cu contents than in the current experiment involving cv. Bluecrop highbush blueberries grown in containers.

Fruit Mineral Composition

Highbush blueberry fruits are rich in macronutrients: potassium, calcium, phosphorus, and magnesium, and contain a large amount of iron. Milivijević and Miletić (2022) reported that highbush blueberries had significant amounts of potassium (585-1350 mg kg^{-1}), phosphorus (114-291 mg kg^{-1}), calcium (95-255 mg kg^{-1}), and magnesium (46-80 mg kg^{-1}). Bryla and Strik (2015) reported that 1 ton of blueberry fruit contains (kg): 0.59-1.04 N, 0.05-0.14 P, 0.36-0.77 K, 0.05-0.09 Ca and 0.02-0.05 Mg.

The forms of nitrogen and fertilization levels used in the experiment had a significant effect on the macronutrient content in fruit of highbush blueberries grown in containers (Table 4). Highbush blueberry fruits contained the most total N, in amounts similar to ones reported by Ochmian (2012), but less than in other studies by Ochmian et al. (2009). Under the conditions of this experiment, the highest total nitrogen content was found in highbush blueberry fruits from plants treated with urea applied at the highest dose (7.888 g kg^{-1} d.m.), while the lowest N content was in the control (4.026 g kg^{-1} d.m.).

Table 4

The content of macronutrients in fruits of cv. Bluecrop highbush blueberry plants cultivated in containers

N – form	Level of fertilization (mg dm^{-3})	Macronutrient (g kg^{-1} d.m.)				
		N	P	K	Mg	Ca
Control	0	4.026 ^{a*}	0.472 ^{a}	3.786 ^{ab}	0.693 ^{a}	0.676 ^{cd}
$N\text{-}NH_4$	100	5.668 ^{bc}	0.542 ^{abc}	4.261 ^{ab}	0.738 ^{ab}	0.586 ^{bcd}
	200	6.487 ^{d}	0.534 ^{abc}	3.486 ^{a}	0.718 ^{ab}	0.529 ^{abc}
	400	6.802 ^{d}	0.488 ^{ab}	4.033 ^{ab}	0.856 ^{bc}	0.751 ^{d}
$N\text{-}NO_3$	100	5.158 ^{b}	0.566 ^{bc}	4.927 ^{b}	0.911 ^{cd}	0.629 ^{bcd}
	200	6.417 ^{cd}	0.546 ^{abc}	4.692 ^{ab}	0.985 ^{d}	0.448 ^{ab}
	400	6.338 ^{cd}	0.485 ^{ab}	3.884 ^{ab}	0.751 ^{ab}	0.672 ^{cd}
$N\text{-}NH_2$	100	5.026 ^{b}	0.537 ^{abc}	4.323 ^{ab}	0.759 ^{ab}	0.453 ^{ab}
	200	5.280 ^{b}	0.651 ^{d}	5.108 ^{b}	0.769 ^{ab}	0.366 ^{a}
	400	7.888 ^{e}	0.605 ^{cd}	4.160 ^{ab}	0.755 ^{ab}	0.688 cd

* Values followed by the same letters do not differ significantly at $\alpha = 0.05$

Nitrogen forms did not cause significant differences in the total N content in comparison with the control (Figure 5). However, the fertilization level had a significant and directly proportional effect on the concentration of total nitrogen in the fruit (Figure 6). The total N content ranged from 4.026 to 7.009 g kg^{-1} d.m.

Depending on the nitrogen form and fertilization level, the phosphorus content in fruits ranged from 0.472 (control) to 0.651 g kg^{-1} d.m. ($N\text{-}NH_2$ - 200 mg N dm^{-3}) – Table 4. These differences were significant.

The analysis showed a significant effect of the fertilization level and nitrogen form on the P content in fruit (Figures 5 and 6). The highest P content was found in fruits from plants fertilized with amide nitrogen. Ochmian et al. (2010) showed higher P content in plants treated with each of the three tested substrates, and the highest P content was achieved after using coconut husk.

Potassium was the second most abundant macronutrient in blueberry fruits (Table 4). Statistical analyses showed a significant effect of nitrogen form and fertilization level on potassium concentration in highbush blueberry berries, with its content ranging from 3.486 to 5.108 g kg^{-1} d.m. (N-NH_4 – 200 mg dm^{-3} and N-NH_2 – 200 mg dm^{-3}, respectively). The study did not show significant differences in potassium content in fruits depending on the nitrogen form or fertilization level (Figures 5 and 6). The concentrations determined were lower than reported in the studies conducted by Ochmian et al. (2009, 2010).

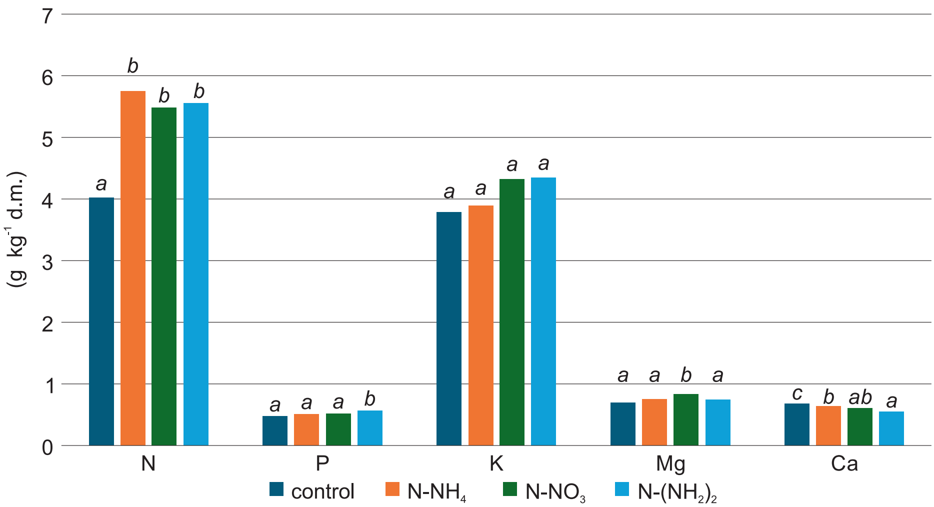

Fig. 5. The effect of N-form on macronutrient content in fruits of cv. Bluecrop highbush blueberry plants cultivated in container.
* Values followed by the same letters do not differ significantly at α = 0.05

The third most abundant macronutrient in highbush blueberry fruits was magnesium (Table 4). Statistical analyses showed a significant interaction between the nitrogen form and fertilization level on magnesium content in fruits. The concentration of this macronutrient ranged from 0.693 (control) to 0.9856 g kg^{-1} d.m. (N-NO_3 – 200 mg dm^{-3}).

Studies involving fertilization of highbush blueberries grown in containers with several forms of nitrogen yielded higher magnesium contents, as reported by Ochmian et al. (2009) and Ochmian and Kozos (2014). Regardless of the dose used, fruits from plants fertilized with nitrate fertilization contained significantly more magnesium than in the other combinations (Figure 5). However, no significant differences were found between the doses of fertilizers used in the studies, which differed significantly only from the control (Figure 6).

Calcium is a macronutrient important for fruit shelf life and storage capacity (Ochmian et al. 2007). The study showed significant differences in calcium content in highbush blueberry fruits (Table 4). The lowest calcium content was found in fruits from plants treated with the amide form of nitro-

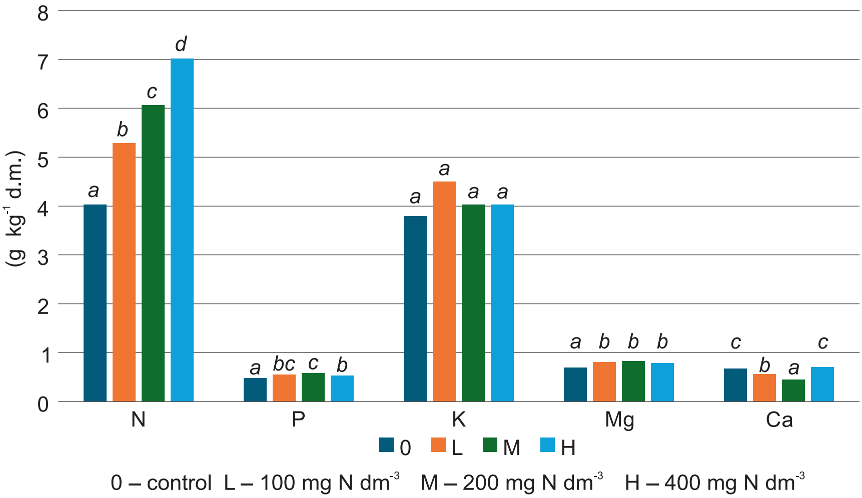

Fig. 6. The effect of doses of fertilizers on macronutrient content in fruits of cv. Bluecrop highbush blueberry plants cultivated in containers.
* Values followed by the same letters do not differ significantly at $\alpha = 0.05$

gen and a medium level of fertilization (0.366 g kg^{-1} d.m.), while the highest calcium content was found in fruits from plants treated with the ammonium form and a high level of fertilization (0.751 g kg^{-1} d.m.).

Both the form of nitrogen and the level of fertilization had a significant effect on calcium concentration in blueberry fruits (Figures 5 and 6). Regardless of the form of nitrogen, the lowest calcium content was found in the fruits of plants fertilized with medium doses of fertilizers (0.448 g kg^{-1} d.m.), while, regardless of the doses used, the lowest calcium content was found in fruits from plants fertilized with urea (0.546 g kg^{-1} d.m.). Calcium content in fruits determined in this study was higher than the data presented by Ochmian et al. (2009) and Ochmian (2012).

CONCLUSIONS

A study examining the effect of nitrogen form and fertilization doses on the mineral composition of leaves and fruits in container-grown cv. Bluecrop highbush blueberries found that the nitrogen form had no effect on the content of total N and phosphorus in leaves. The nitrogen form had a significant effect on the content of potassium, magnesium, and calcium. Fertilization levels significantly influenced the concentration of total N, phosphorus, and magnesium, whose values increased in direct proportion to the level of mineral fertilizer application, while the opposite relationship was observed for Ca.

Leaf macronutrient contents (except for N in the control) corresponded to optimal values, indicating adequate nutrition of the highbush blueberries in this experiment. Highbush blueberry leaves were characterized by optimal Mn, Fe, Zn, and Cu contents, except for Fe and Cu in the control. The form of N significantly influenced the content of Mn, Zn, and Cu, in addition to affecting Fe. Statistical analysis of the results of the impact of fertilizer doses revealed significant differences in the content of Fe, Cu, and Zn, but not in the case of Mn. The content of iron and copper in leaves increased in direct proportion to the applied fertilizer doses.

Among the tested nutrients, the cv. Bluecrop highbush blueberry fruits contained the most nitrogen and potassium, followed by magnesium, calcium, and the least phosphorus. The nitrogen forms tested caused significant differences in total N content only from the control. A significant effect of N forms was demonstrated for P, Mg, and Ca concentrations. As with leaves, blueberry fruit had significantly different N content, which increased in direct proportion to fertilizer application. A significant effect of fertilization level on P, Ca, and Mg content in fruits was observed, but this was not observed for potassium.

The fruits of cv. Bluecrop highbush blueberry plants contained the most nitrogen and potassium among the analyzed elements, followed by magnesium, calcium, and the least phosphorus. The nitrogen forms tested caused significant differences in total N content only in the control. A significant effect of N forms was demonstrated on P, Mg, and Ca concentrations. As with leaves, blueberry fruits had significantly different N content, which increased in direct proportion to fertilizer application. A significant effect of the fertilization level on P, Ca, and Mg content in fruits was observed, but no such effect was observed for potassium.

Author contributions

Conceptualization – D.W.., methodology – D.W., P.Sz., material preparation, data collection and analysis were performed – D.W., P.Sz. and A.S., chemical analysis – D.W. and P.Sz., data curation – D.W., P.Sz., writing – original draft preparation – D.W., P.Sz. and A.S., writing – review and editing: D.W., P.Sz.

All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

REFERENCES

Bal, J.J.M. (1997) ‘Blueberry culture in greenhouses, tunnels, and under raincovers’, *Acta Horticulturae*, 446, 327–331, available: https://doi.org/10.17660/ActaHortic.1997.446.48

Banados, M.P., Strik, B.C., Bryla, D.R. and Righetti, T.L. (2012) ‘Response of highbush blueberry to nitrogen fertilizer during field establishment, I. Accumulation and allocation of fertilizer nitrogen and biomass’, *HortScience,* 47(5), 648-655.

Bryla, D.R., Strik, B.C. (2015) ‘Nutrient requirements, leaf tissue standards, and new options for fertigation of northern highbush blueberry’, *HortTechnology*, 25(4), 464-470.

Davis, A.J., Strik, B.C. (2022) ‘Long-term effects of pre-plant incorporation with sawdust, sawdust mulch, and nitrogen fertilizer rate on ‘Elliot’ highbush blueberry’, *HortScience,* 57(3), 414-421, available: https://doi.org/10.21273/HORTSCI1659-21

Eaton, L.J., Stratto, G.W. and Sanderson, K.R. (1997) ‘Fertilizer phosphorus in lowbush blueberries: effects and fate’, *Acta Horticulturae*, 446, 477-486, available: https://doi.org/10.17660/ActaHortic.1997.446.68

FAOSTAT 2025, available: http://www.fao.org (date of access – 13.09.2025)

Glonek, J., Komosa, A. (2006) ‘The effect of fertigation on the nutrient status and yield of highbush blueberry cv. Bluecrop’, *Acta Horticulturae,* 715, 371–374, available: https://doi.org/10.17660/ActaHortic. 2006.715.55

Glonek, J., Komosa, A. (2013) ‘Fertigation of highbush blueberry (*Vaccinium corymbosum* L.). Part III. The effect on nutrient contents in leaves’, *Acta Scientiarum Polonorum Hortorum Cultus,* 12(3), 69–78.

Hanson E.J. (2006) ‘Nitrogen fertilization of highbush blueberry’, Acta Horticulturae, 715, 347–352.

Hart, J., Strik, B., White, L. and Yang, W.Q. (2006) ‘Nutrient management for blueberries in Oregon’, *Oregon State University. Ext. Serv. Publ.* Em 8918, available: http://ir.library.oregonstate.edu/xmlui/bitstream/handle/1957/20444/em8918.

Imler, C.S., Arzola, C.I., Nunez, G.H. (2019) ‘Ammonium uptake is the main driver of rhizosphere pH in southern highbush blueberry’, *HortScience*, 54, 955–959, available: https://doi.org/10.21273/HORTSCI13764-18

Jiang, Y., Li, Y., Zeng, Q., Wei, J. and Yu, H. (2017) ‘The effect of soil pH on plant growth. leaf chloro-phyll fluorescence and mineral element content of two blueberries’, *Acta Horticulturae*, 1180, 269–276, available: https://doi.org/10.17660/ActaHortic.2017.1180.36

Jiang, Y., Zeng, Q., Wei, J., Jiang J., Li Y., Chen, J. and Yu, H. (2019) ‘Growth, fruit yield, photosynthetic characteristics, and leaf microelement concentration of two blueberry cultivars under different long-term soil pH treatments’, *Agronomy*, 9, 35, available: https://doi.org/10.3390/agronomy9070357

Kingston, P.H., Scagel, C.F., Bryla, D.R., Strik, B.C. (2017) ‘Suitability of sphagnum moss, coir, and douglas fir bark as soilless substrates for container production of highbush blueberry’, *HortScience*, 52, 1692–1699, available: https://doi: 10.21273/HORTSCI12374-17

Kingston, P.H., Scagel, C.F., Bryla, D.R., Strik, B.C. (2020) ‘Influence of perlite in peat- and coir-based media on vegetative growth and mineral nutrition of highbush blueberry’, *HortScience*, 55, 658–663.

Komosa, A., Roszyk, J. and Mieloch, M. (2017) ‘Content of nutrients in soils of highbush blueberry (*Vaccinium corymbosum* L.) plantations in Poland in a long-term study’, *Journal of Elementology*, 22(4), 1193-1207, available: https://doi.org/10.5601/jelem.2016.21.4.1329

Li, T., Bi, G. (2019) ‘Container production of southern highbush blueberries using high tunnels’, *HortScience,* 54(2), 267-274, available: https://doi.org/10.21273/HORTSCI13639-18

Milivojević, J., Miletović, N. (2022) ‘Nutritional, health-promoting and usable value of blueberries’, In: *The Blueberry*. Monograph. University of Belgrade, AgroNET – Center for Education and Research.

Ochmian, I. (2012) 'The impact of foliar application of calcium fertilizers on the quality of highbush blueberry fruits belonging to the duke cultivar', *Notulae Botanicae Horti Agrobotanici – Napoca*, 40(2), 163-169, available online at: https://www.notuleabotanicae.ro

Ochmian, I., Grajkowski, J., Ostrowska, K. and Mikiciuk, G. (2007). 'Wzrost, plonowanie oraz jędrność owoców dwóch odmian borówki wysokiej (*Vaccinium corymbosum* L.) uprawianej w trzech typach podłoży organicznych', *Zeszyty Naukowe Instytutu Sadownictwa i Kwiaciarstwa,* 15, 47–54. (in Polish)

Ochmian, I., Grajkowski, J., Mikiciuk, G., Ostrowska, K. and Chełpiński, P. (2009) 'Mineral composition of highbush blueberry leaves and fruits depending on substrate type used for cultivation', *Journal of Elementology*, 14(3), 509-516.

Ochmian, I., Grajkowski, J. and Skupień, K. (2010) 'Effect of substrate type on the field performance and chemical composition of highbush blueberry cv. Patriot', *Agricultural and Food Science*, (19), 69-80.

Ochmian, I., Kozos, K. (2014) 'Influence of foliar fertilization with calcium fertilizers on the firmness and chemical composition of two highbush blueberry cultivars', *Journal of Elementology*, 19(4), 185–201, available: https://doi.org/10.5601/jelem.2014.19.4.782

Ochmian, I., Kozos, K., Jaroszewska, A. and Malinowski, R. (2021) 'Chemical and enzymatic changes of different soils during their acidification to adapt them to the cultivation of highbush blueberry', *Agronomy*, 11, 44, available: https://doi.org/10.3390/agronomy11010044

Ostrowska, A., Gawliński, S. and Szczubiałka, Z. (1991) 'Metody analizy i oceny właściwości gleb i roślin', *Instytut Ochrony Środowiska. Warszawa.* (in Polish)

Sardans, J., Peñuelas, J. (2021) 'Potassium control of plant functions: ecological and agricultural implications', *Plants*, 10, 419, available: https://doi.org/10.3390/plants10020419

Schreiber, M.J., Nunez, G.H. (2021) 'Calcium carbonate can be used to manage soilless substrate pH for blueberry production', *Horticulturae*, 7, 74. https://doi.org/10.3390/horticulturae7040074

Smagula, J.M., Dunham S. and Gough R.E. (1995) 'Diamonium phosphate corrects phosphate deficiency in lowbush blueberry', *Journal of Small Fruit and Viticulture,* 3(4), 183-191.

Smolarz, K. (1996) 'Wpływ wieloletniego nawożenia mineralnego na wzrost i plonowanie kilku gatunków roślin jagodowych', *Zeszyty Naukowe Instytutu Sadownictwa i Kwiaciarstwa,* Monografie i rozprawy, 28-53.

Smolarz, K., Mercik, S. (1992) 'Wpływ zróżnicowanego nawożenia azotowego na plonowanie borówki wysokiej odmiany Bluecrop', *Prace Instytutu Sadownictwa i Kwiaciarstwa* – Seria C, (3–4), 46–48.

Strik, B.C., Vance, A.J. (2015) 'Seasonal variation in leaf nutrient concentration of northern highbush blueberry cultivars grown in conventional and organic production system', *HortScience*, 50(10), 1453-1466.

Strik, B., Vance, A.J. and Finn, C.E. (2017) 'Northern highbush blueberry cultivars differed in yield and fruit quality in two organic production systems from planting to maturity', *HortScience*, 52(6), 844–851, available: https://doi: 10.21273/HORTSCI11972-17

Tamir, G., Zilkah, S., Dai, N., Shawahna, R., Cohen, S. and Bar-Tal, A. (2020) 'Combined effects of CaCO3 and the proportion of N-NH4+ among the total applied inorganic N on the growth and mineral uptake of Rabbiteye blueberry', *Journal of Soil Science and Plant Nutrition*, 21,35–48.

Vargas, O.L., Bryla, D.R. (2015) 'Growth and fruit production of highbush blueberry fertilized with ammonium sulfate and urea applied by fertigation or as granular fertilizer', *HortScience*, 50(30), 479-485.

Wach, D., Błażewicz-Woźniak, M. and Kamiński, S. (2023). 'Zmiany zawartości wybranych składników mineralnych w liściach borówki wysokiej (*Vaccinium corymbosum* L.) w okresie wegetacji', *Annales Horticulturae,* 32(2), 53–65. https://doi.org/10.24326/ah.2023.5312

Wilber, W.L., Williamson, J.G. (2008) 'Effects of fertilizer rate on growth and fruiting of containerized southern highbush blueberry', *HortScience*, 43(1), 143-145.

Williamson, J.G., Miller, E.P. (2009) 'Effects of fertilizer rate and form on vegetative growth and yield of southern blueberry in pine bark culture', *HortTechnology,* 19(1), 152–157.