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ORIGINAL PAPER

EFFECT OF DEFICIT AND OVER-STANDARD BORON CONTENT IN NUTRIENT SOLUTION ON THE BIOLOGICAL VALUE OF TOMATO FRUIT*

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Abstract

The aim of the study was to assess the effect of varying boron levels in the nutrient solution used for fertigation on the macro- and micronutrient content and antioxidative compound content such as vitamin C, lycopene and polyphenolic compounds as well as the antioxidant activity of tomato fruit (*Lycopersicon esculentum* Mill., cv. Alboney F_1 and Emotion F_1). Plants were grown in rockwool using a nutrient solution with the following content of boron (mg dm^{-3}): Control (0.011), 0.4, 0.8, 1.6 in the form of: $Na_2B_4O_7$ $10H_2O$ (treatments of the designated symbols, respectively, B-I, B-II, B-III, B-IV). Standard nutrient solution for tomato cultivation was used with the following nutrient content (mg dm^{-3}): $N\text{-}NH_4$ – 2.0, $N\text{-}NO_3$ – 230, P – 50, K – 420, Ca – 140, Mg – 60, Cl – 30, $S\text{-}SO_4$ – 120, Fe –1.80, Mn – 0.3, Zn – 0.50, Cu – 0.07. The concentration of boron in the medium modifies the mean content of nitrogen, phosphorus, magnesium (significantly the lowest content was determined in the B-IV treatment), and potassium (the lowest content in the B-I and B-IV treatments). In the range of boron concentrations of 0.011 - 1.60 mg B dm^{-3}, a decrease in the mean iron content and an increase in the content of manganese and zinc in tomato fruits were found. The variety significantly differentiated the content of potassium (B-II and B-III), magnesium (B-II), iron (B-I and B-II), manganese (B-II), copper (B-II), the antioxidant activity and lycopene content in tomato fruit. Increasing concentrations of B in the nutrient solution caused a statistically significant decrease of vitamin C in fruit. The higher content of lycopene in the Alboney F_1 variety was reported at all concentrations of boron (94.4 - 102.4 mg kg^{-1}). In the Emotion F_1 variety, the lycopene content was demonstrated to be 53.2 - 71.9 mg kg^{-1} of FW. The experiment showed that colour parameters of tomato fruits did not change significantly in response to higher boron doses.

Keyword: Borax, tomato fruit, antioxidant activity, total polyphenol content, lycopene, vitamin C, colour.

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INTRODUCTION

One of the greatest challenges in plant nutrition has been to determine the primary function of boron (B) in plants (Blevins, Lukaszewski 1998). Boron is one of 8 micronutrients essential for the plant growth and development. It is classified as a non-metal (Tomaszewska 2010). Boron plays a uniquely important role in the growth of plants (Brown et al. 2002), in phenolic metabolism (Ruiz et al. 1998) and in the ascorbate-glutathione metabolic cycle (Brown et al. 2002). It may form complex compounds with sugars, phenols, organic acids and polymers (Hu, Brown 1994). Most frequently, B is found in complex combinations with mannitol, sorbitol, glucose and fructose.

The boron content affects the metabolism of plant nitrogen, and the deficiency of this microelement increases the nitrate content of plants. In tomato deficient in B, nitrate levels rise as a consequences of reduced nitrate reductase (NR) activity (Bonilla et al. 1988). In nitrogen-fixing plants (pea and soybean), the activity of nitrogenase is sensitive to B deficiency and B toxicity (Rahman et al. 1999, Carpena et al. 2000). Boron deficiency also influences photosynthesis. According to Loomis and Durst (1992), boron is involved in the following aspects of plant life: sugar transport, cell wall synthesis and lignification, cell wall structure, carbohydrate metabolism, RNA metabolism, respiration, membrane functions, and DNA synthesis. Boron interacts with polysaccharides, pyridoxine, riboflavin and dehydroascorbic acid (Naghii, Samman 1993). Acccording to Hu, Brown (1997), boron uptake under conditions of an adequate and excessive boron supply is the result of passive absorption of undissociated boric acid.

Boron may also form complex compounds with the RG-II polysaccharide (Kobayashi et al. 1996, O'Neil et al. 1996, 2001, Goldbach et al. 2002) stabilized with calcium ions, the most important boron-binding compound in the cell wall. This micronutrient is involved in the flowering and fruiting processes of plants (Brown et al. 2002).

The optimal boron content in nutrient solution for fertigation of tomato grown in rockwool is 0.3 mg dm^{-3} (Jarosz, Dzida 2011, Kowalczyk, Gajc-Wolska 2011, Jarosz et al. 2012). Many authors recommend a dose between 0.2 and 0.7 mg B dm^{-3} (Adams 1994, Komosa et al. 2014, Markiewicz, Kleiber 2014, Markiewicz 2017). Excessive boron nutrition reduces the marketable yielding of tomato (Markiewicz et al. 2016). Boron uptake by plants is dependent on the content of other macronutrients. It is important to have a calcium content that makes it difficult to obtain calcium tetraborate by plants. Boron extraction is also limited by PO_4^{-3}, SO_4^{-2}, Cl^- (Sharma et al. 2006).

Boron in excessive quantities is dangerous to human health and life (Sahin, Nagiboglou 2006). Its toxicity had not been recognized until the 1950s. Previously, borax and boric acid had been added to preserve food. Nowadays, a lethal dose of boron for an adult is 15-20 grams (Nielsen 1997).

The nutritional status is one of the factors influencing the quality of tomato fruit (Gad, Kandil 2010, Salam et al. 2010). The content of boron in the tomato fruit depends on the technology of cultivation, and ranges from 17 to 21.88 mg kg^{-1} (Komosa et al. 2011). The content of boron in tomato fruit was found to be dependent on the boron content in the nutrient solution used in fertigation (Markiewicz et al. 2016) A wide range of boron concentrations in the medium has been tested on varieties that are no longer used in cultivation. The aim of this study has been to verify and check the previously determined hydroponic concentrations of boron on the biological value of tomato fruit.

MATERIAL AND METHODS

Experiment design and plant cultivation

The study on the effect of increasing boron nutrition on tomato growth was conducted in 2011-2012 (March-September), at a specialist greenhouse of the Department of Plant Nutrition, the Poznan University of Life Sciences. The greenhouse was equipped with a modern, computer-controlled fertigation system and energy-conservation curtains. One of the steps carried out in the years 2011-2012 was to determine the relationship between the mentioned nutrient and selected biological parameters of fruits. The experiments were conducted on two cultivars of tomato (*Lycopersicon esculentum* Mill.): Alboney F_1 and Emotion F_1, and with 4 levels of boron nutrition. Plants were grown in standard rockwool (Grodan; 100 x 15 x 7.5 cm; V 11.25 dm^3; 60 kg m^{-3}) at the density of 2.5 plants m^{-2}. The experiments were set in the same design with 5 replications composed of four plants each. Biological pest control was applied. All cultivation measures were performed in accordance with the current recommendations for tomato growing (Adamicki et al. 2005). Plants were grown using fertigation in a closed system without recirculation of the nutrient solution, which contained (mg dm^{-3}): $N\text{-}NH_4$ – 2.0, $N\text{-}NO_3$ – 230, P – 50, K – 420, Ca – 140, Mg – 60, Cl – 30, $S\text{-}SO_4$ – 120, Fe –1.80, Mn – 0.3, Zn – 0.50, Cu – 0.07. The pH was 5.50 and EC was 3.00 mS cm^{-1}. The following levels of plant nutrition with boron were tested: 0.011 (as a deficit concentration), 0.40 (as a standard concentration) 0.80, 1.60 mg dm^{-3} (as over-standard concentrations), and they were denoted respectively as B-I, B-II, B-III, B-IV. The boron content in B-I corresponds to the content of this ion in water used to prepare the nutrient solution for plant fertigation. Borax ($Na_2B_4O_7$ $10H_2O$ 11,3%B) was the source of boron in the other tested treatments. The nutrient solution dose depended on the development phase of plants and climatic conditions. In the period of intensive plant yielding and high temperatures (months June – July), 3.0-3.5 dm^3 nutrient solution per plant were applied daily, in 15-20 single doses at 20-30% outflow of the drainage solution.

Samples collection

In the course of the plant-growing experiments, representative samples of fruits were collected in the last decade of August (7th cluster) for chemical analyses. A representative sample of 4 kg of fruit was obtained from each studied combination (2 cultivars x 4 levels of a variety of B = 8 combinations).

Preparation of samples

For the total polyphenol content measurements and the antioxidant activity determination, tomato fruits were homogenized for 1 min at 14000 rpm (a manual homogenizer ESGE, Bionovo, Poland). From each combination, three samples of 10 g were taken and mixed (in the dark under nitrogen) with 6 cm^3 of distilled water. This was done on a magnetic stirrer for 30 min. For the ascorbic acid determination, 10 g of fruit puree was centrifuged and the supernatant was mixed with 6 cm^3 of distilled water (Ferreira et al. 1997) in the dark under nitrogen for 3 min. Then, the samples were filtrated under vacuum (type 388 filters, Filtrak, Niederschlag Bärenstein, Germany). Each extract was prepared immediately before an analysis (Muzolf-Panek et al. 2017).

Macro- and micronutrient content in tomato fruits

The collected plant material was dried at a temperature of 45-50°C, and then ground. In order to determine the total nitrogen, phosphorus, potassium, calcium and magnesium content, the plant material was mineralized in concentrated sulfuric acid. Nutrient content was determined using the following methods: N-total – by the distillation method according to Kjeldahl in a Parnas-Wagner apparatus, P – by colorimetry with ammonium molybdate (according to Schillak), while K, Ca and Mg – by atomic absorption spectrometry (AAS). In order to determine total content of iron, manganese, zinc and copper, the plant material was mineralized in a mixture of acetic and perchloric acids (3:1 v/v). After mineralization, concentrations of Fe, Mn, Zn and Cu were determined with AAS.

Radical scavenging activity measurements (DPPH method)

The DPPH free radical scavenging activity measurements were carried out according to the procedure of Sánchez-Moreno et al. (1998) with some modification. Briefly, 10 mm^3 of a sample were added to 990 mm^3 of DPPH in methanol (0.1 mmol) and mixed. The reaction mixture was incubated for 30 min in the dark at room temperature, and the decrease in absorbance caused in the sample was measured at 515 nm on a spectrophotometer Cary 1E (Varian, Belrose, Australia). For each sample, three separate determinations were carried out. The corresponding solvent blank readings were also taken (DPPH in methanol), and the percentage of scavenged $DPPH^{\cdot}$ radicals was

calculated from the decrease of absorbance. The percentage of scavenged DPPH$^{\cdot}$ was plotted against the concentration of the sample, and the IC50 values were estimated based on the equation curve. IC50 is a concentration of a sample which gives a 50% reduction of the initial concentration of DPPH$^{\cdot}$ radicals in a mixture. The DPPH$^{\cdot}$ radical scavenging activity of a sample was also expressed in TEAC values, i.e. as Trolox equivalent antioxidant capacity (mmol of Trolox kg^{-1} of fresh weight FW). The TEAC value was calculated as a ratio of the slope of the linear plot for scavenging of DPPH$^{\cdot}$ radicals by the sample under study to the slope of the plot for DPPH$^{\cdot}$ radicals scavenging by the water-soluble vitamin E analogue Trolox, used as an antioxidant standard.

Total polyphenol content measurements (Foli-Ciocaulteau method)

The total polyphenol content (TPC) was determined using a spectrophotometer Cary 1E. The procedure was based on using the Folin-Ciocalteu reagent (FCR) as described by Singleton and Rossi (1965) with modifications. In brief, 40 mm^3 of the sample were added to 200 mm^3 FCR, mixed and incubated for 3 min (room temperature, dark place). Then, 600 mm^3 20% (w/v) of sodium carbonate solution were added and filled up to 4 cm^3 with distilled water. The samples were again mixed and incubated for 2 h at room temperature in the dark prior to taking an absorbance reading at 765 nm against blank samples (40 mm^3 distilled water instead of the sample). Gallic acid was used as the standard, and the results were presented as mg gallic acid equivalents (GAE) per kg of the sample.

Vitamin C measurement (ascorbic acid in its reduced form – ascorbate)

Ascorbic acid was determined by a sensitive spectrophotometric method using 2-(5-bromo-2-pyridylazo)-5-diethylaminophenol (Br-PADAP), as described by Ferreira et al. (1997). A sample containing 1.0-60.0 mg of ascorbic acid was placed in a 25 cm^3 standard flask. Then, 1.0 cm^3 of (40 mg cm^{-3}) iron(III) solution, 4.0 cm^3 of 0.03% Br-PADAP solution and 2.5 mm^3 acetate buffer (pH 4.75) were added and mixed. After 5 min of incubation in the dark, 1.0 mm^3 of 0.1% EDTA solution was added and replenished to 25 cm^3 with demineralized water. Absorbance was measured after 5 min at 560 or 748 nm against an appropriate blank. The calibration curve was plotted within the ascorbic acid concentration range from 0 to 1.2 μg cm^{-3}. Data were expressed in mg of ascorbic acid per kg of fresh weight (FW).

Lycopene measurement

Lycopene was extracted from fresh tomato samples. A homogenized sample (5 g) was mixed with 50 cm^3 of the mixture of hexane/acetone/ethanol (2:1:1) in order to extract carotenoids. After 1 h, the solution was left to separate into a distinctly divided polar and non-polar layers, the latter con-

taining lycopene. Total lycopene was determined by spectrophotometric measurements at 472 nm using a spectrophotometer Cary 1E. The content of total lycopene was determined from the lycopene calibration curve (KOPEC et al. 2012). Data were expressed in mg of lycopene per kg of FW.

Instrumental colour measurements

The colour of tomato fruit was determined with a Minolta Chroma Meter CR-200b (Konica Minolta, Tokyo, Japan) in the CIE L*a*b* system. It expresses colour as three numerical values, L* for lightness and a* and b* for the green-red and blue-yellow colour components. The spectrocolourimeter was calibrated during the study by using a white ceramic reference standard. Colour measurements were performed directly on the surface of tomato fruit just after fruit harvesting.

Chemicals

Methanol, the Folin-Ciocalteu phenol reagent (FCR), 1,1-diphenyl--2-picrylhydrazyl (DPPH), 2-(5-bromo-2-pyridylazo)-5-diethylaminophenol (Br-PADAP), iron(III) sulfate pentahydrate, ethylenediaminetetraacetic acid (EDTA), ascorbic acid were supplied from SIGM-ALDRICH (Steinheim Germany), while sodium carbonate was obtained from Poch (Gliwice, Poland).

Statistical analysis

The data were analyzed using Statistica 12.0 software (StatSoft, Kraków, Poland). All results were underwent analysis of variance (ANOVA) with B level in nutrient solution and cultivar as independent variables. The LSD test was used to analyze differences between groups within the parameter. The Pearson's correlation coefficients were calculated for the correlation between the B concentration and the measured parameters. All statistical analyses were performed at $p \leq 0.05$.

RESULTS AND DISCUSSION

Macronutrients

The nitrogen content determined in fruits of two tomato varieties was dependent on the boron content in the fertigation nutrient solution (Table 1). Both a decrease and an increase in boron levels in the medium solution considered to be standard (0.40 mg B dm^{-3}) caused a reduction in the nitrogen content in fruits of the two tomato cultivars. Significantly the smallest mean nitrogen content was recorded in treatment B-IV (19.4 g kg^{-1}). Nitrogen levels recorded in this study in tomato fruits were comparable to the values reported by NZANZA (2010), while being higher than obtained by KLEIBER

Table 1

The influence of boron nutrition on the macro- and microelement content in tomato fruit (means from 2011-2012)

Cultivar	B-level (mg dm^{-3})									
	B-I	B-II	B-III	B-IV	Mean	B-I	B-II	B-III	B-IV	Mean
	N (g kg^{-1} d.m.)					Fe (mg kg^{-1} d.m.)				
Alboney F_1	22.2 *bc*	25.3 *d*	22.1 *bc*	18.6 *a*	22.0 *A*	66.9 *d*	59.16 *c*	52.20 *b*	37.13 *a*	53.85 *A*
Emotion F_1	20.7 *ab*	23.5 *cd*	21.4 *b*	20.1 *ab*	21.4 *A*	77.70 *f*	73.66 *e*	50.46 *b*	36.63 *a*	59.61 *B*
Mean	21.4 *B*	24.4 *C*	21.7 *B*	19.4 *A*		72.30 *D*	66.41 *C*	51.33 *B*	36.88 *A*	
	P (g kg^{-1} d.m.)					Mn (mg kg^{-1} d.m.)				
Alboney F_1	4.40 *b*	6.00 *d*	5.10 *c*	3.30 *a*	4.9 *A*	13.93 *a*	14.73 *a*	16.66 *cd*	16.63 *cd*	15.49 *A*
Emotion F_1	4.40 *b*	6.20 *d*	5.40 *c*	3.70 *a*	4.7 *A*	15.00 *ab*	15.93 *bc*	17.13 *d*	17.66 *d*	16.43 *B*
Mean	4.40 *B*	6.10 *D*	5.25 *C*	3.50 *A*		14.46 *A*	15.33 *B*	16.90 *C*	17.15 *C*	
	K (g kg^{-1} d.m.)					Zn (mg kg^{-1} d.m.)				
Alboney F_1	42.0 *a*	46.7 *b*	42.0 *a*	41.4 *a*	43.1 *A*	15.20 *ab*	17.66 *bc*	23.90 *f*	24.03 *f*	20.20 *A*
Emotion F_1	40.8 *a*	42.2 *a*	47.4 *b*	42.0 *a*	43.0 *A*	14.70 *a*	18.50 *cd*	20.50 *de*	22.30 *ef*	19.00 *A*
Mean	41.4 *A*	44.5 *B*	44.7 *B*	41.7 *A*		14.95 *A*	18.08 *B*	22.20 *C*	23.16 *C*	
	Ca (g kg^{-1} d.m.)					Cu (mg kg^{-1} d.m.)				
Alboney F_1	1.90 *a*	2.20 *a*	1.70 *a*	1.50 *a*	1.80 *A*	12.66 *ab*	12.36 *ab*	12.30 *ab*	9.10 *a*	11.60 *A*
Emotion F_1	5.30 *b*	2.50 *a*	1.60 *a*	1.60 *a*	2.70 *B*	13.76 *b*	19.26 *c*	13.50 *ab*	13.30 *ab*	14.95 *B*
Mean	3.60 *A*	2.25 *A*	1.65 *A*	1.50 *A*		13.21 *AB*	15.81 *B*	12.90 *AB*	11.20 *A*	
	Mg (g kg^{-1} d.m.)									
Alboney F_1	3.50 *d*	3.10 *cd*	2.40 *bc*	1.30 *a*	2.60 *A*					
Emotion F_1	3.40 *d*	4.60 *e*	2.50 *bc*	1.70 *ab*	3.00 *B*					
Mean	3.45 *C*	3.80 *C*	2.45 *B*	1.50 *A*						

Key for Table 1: within rows means marked with different capital letters differ significantly, within rows and columns means marked with different small letters differ significantly

(2014) in a study on manganese nutrition of tomato, conducted on the same varieties. Boron concentrations increasing in the nutrient solution in our study caused significant differences in the phosphorus content in fruits. Significantly the highest mean phosphorus level in fruits (6.10 g kg^{-1}) was recorded in treatment B-II. In the range of boron concentrations from 0.011 to 1.60 mg B dm^{-3} a significant effect was found regarding the content of phosphorus in tomato fruit. According to literature references, the content of phosphorus in tomato fruit is a varietal trait (Fanasca et al. 2006, Olaniyi et al. 2010). The biggest mean potassium content in fruit was recorded in treatments B-II and B-III (at 44.5 and 44.7 g kg^{-1}, respectively). Varietal differences in the potassium content were observed only in treatments B-II and B-III. Apart from varietal differences, the level of potassium in fruits may have also been affected by phosphorus nutrition (Gad et al. 2010). The potassium content recorded in this study in tomato fruits was comparable to data reported by others (Pivot et al. 1998, Kleiber 2014). Calcium is a nutrient having a di-

rect effect on the formation of dry end rot of tomato fruit. The concentration of boron in the nutrient solution did not cause any significant differences in the calcium content in fruit. The only observed trend consisted of a reduction in the calcium content in fruit with an increase in boron levels in the fertigation nutrient solution. The highest content of calcium (5.30 g kg^{-1}) was determined in fruits of the variety Emotion F_1 with the concentration of boron in the medium equal 0.011 mg B dm^{-3}. The calcium content in fruits may be modified by the effect of the substrate (Premuzic et al. 1998, Kleiber et al. 2012) and by a variety (Olaniyi et al. 2010). Significantly the greatest mean content of magnesium in fruit was recorded in B-I (3.45 g kg^{-1}) and B-II (3.80 g kg^{-1}). In the standard nutrient solution (0,40 mg B dm^{-3}), the highest content of magnesium was found in var. Emotion F_1 fruits (4.60 g kg^{-1}). The increasing concentration of boron in the medium significantly reduced the mean content of magnesium in fruits. Significantly the lowest mean magnesium level was recorded in B-IV (1.50 g kg^{-1}). Our analyses showed significant varietal differences in the mean magnesium content in fruits. Same as other macronutrients, the level of magnesium in tomato fruits is a varietal trait (Olaniyi et al. 2010).

Micronutrients

Increasing boron doses in the nutrient solution were found to influence the iron content in tomato fruits. Significantly the highest mean iron content in fruits was recorded in the control treatment B-I (72.30 mg kg^{-1}). Significantly the highest iron level in fruits (77.70 g kg^{-1}) was recorded in treatments B-I (Emotion F_1). Varietal differences in the iron content were shown in treatments B-I and B-II. The effect of a variety differentiated the mean iron content in tomato fruits. The level of iron recorded in this study was lower than the content reported by Kleiber (2014). while being comparable to the values given by Olaniyi et al. (2010). The manganese content in fruits increased with an increase of the boron content in the fertigation nutrient solution. Significantly the greatest mean manganese content was found in treatments B-III (16.90 mg kg^{-1}) and B-IV (17.15 mg kg^{-1}). Varietal differences were shown only in treatment B-II; however, a variety significantly differentiated the mean manganese content in fruits. No significant differences were found in the content of manganese in fruit between the concentrations of boron denoted as B-I and B-II; B-III and B-IV. Identical trends were observed for the zinc content in tomato fruits. In this case, varietal differences were found only in treatment B-III. Significantly the greatest mean zinc content was recorded in treatments B-III (22.20 mg kg^{-1}) and B-IV (23.16 mg kg^{-1}). No significant differences were found in the content of zinc in the fruit between the concentrations of boron B-I and B-II; B-III and B-IV (Alboney F_1). Increasing boron concentrations in the medium were found to have no effect on the copper content in fruits of tomato cv. Alboney F_1. Trends were only observed for a decrease in the copper content in fruits with an increase in boron content in the nutrient solution. In fruits of cv. Emotion F_1, signifi-

cantly the highest copper content was recorded in treatment B-II (19.26 mg kg^{-1}). A variety significantly differentiated the mean copper level in fruits. In this study, the boron content in tomato fruits was dependent on the level of boron in the nutrient solution. In all the treatments, significant varietal differences were found in terms of the boron content. Significantly higher boron levels were recorded in fruits of cv. Emotion F_1. The highest mean boron content in fruits was determined in treatment B-IV (16.86 mg kg^{-1}) – Table 2. According to other authors the level of boron in tomato fruits is significantly lower in comparison to its content recorded in leaves (Gupta 1979, Garate et al. 1984).

Table 2

The influence of B nutrition on marketable yield of 1 tomato plant (kg) and B content in fruits (Markiewicz et al. 2016) (means from 2009-2012)

Variety	B-I	B-II	B-III	B-IV	Mean
Marketable yield (kg $plant^{-1}$)					
Alboney F_1	5.55 *c*	5.52 *c*	5.09 *ab*	5.18 *b*	5.34 *A*
Emotion F_1	5.00 *a*	5.57 *c*	4.92 *a*	4.74 *a*	5.06 *A*
Średnia Mean	5.28 *AB*	5.55 *B*	5.01 *A*	4.96 *A*	
B content in fruits (mg kg^{-1} d.m.)					
Alboney F_1	11.66 *a*	13.10 *b*	16.30 *de*	16.43 *de*	14.60 *A*
Emotion F_1	11.56 *a*	14.26 *c*	15.30 *cd*	17.30 *e*	14.37 *A*
Mean	11.61 *A*	13.68 *B*	15.80 *C*	16,86 *D*	

Key for Table 2

Vitamin C

A statistically significant effect was demonstrated of both: a cultivar and a B concentration ($p \leq 0.05$). Increasing concentrations of B in the nutrient solution caused a statistically significant ($p \leq 0.05$) decrease in vitamin C in fruit (ascorbic acid in its reduced form) – Figure 1. The vitamin C decrease varied between the cultivars and was more pronounced in Alboney F_1 than in Emotion F_1. In the variety Emotion F_1, the vitamin C content equalled about 8.40 mg per kg FW under the optimal B level (sample B-II) in the nutrient solution, and decreased by about 1.8% in the B-III samples. When tomato plants were exposed to B deficit (sample B-I), the concentration of this antioxidant active compound increased by about 16% compared to samples B-II with the B concentration optimal for the plant growth. A similar tendency was observed in the Alboney F_1 cultivar. The vitamin C content reached the value of 96.0 mg kg^{-1} FW under the optimal concentration of B (sample B-II) for this plant. When the concentration of B in the nutrient solution increased up to 0.8 mg dm^{-3}, the vitamin C content decreased by about 8%, and when the plant was exposed to a deficient amount of B (sample B-I), the concentration of vitamin C increased by about 13% compared to samples B-II. Ascorbate scavenges directly the excess of reactive oxygen species generated

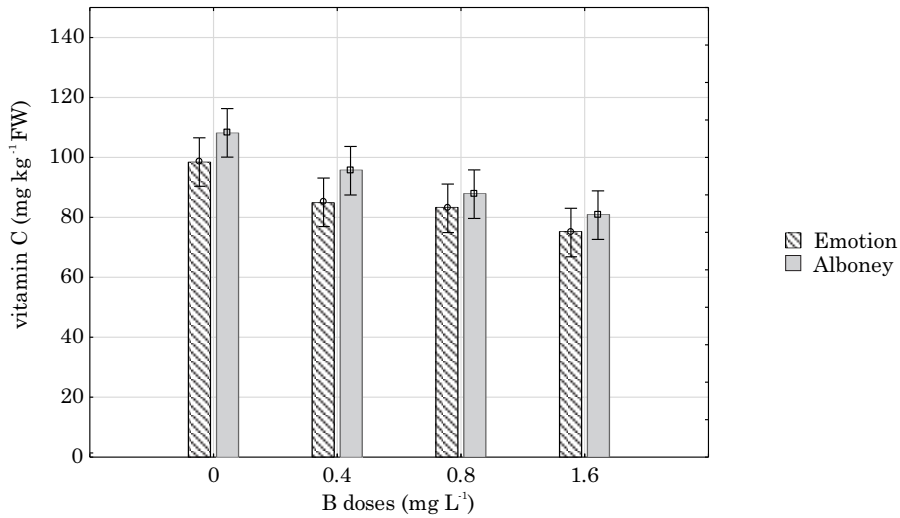

Fig. 1. Ascorbid acid (vitamin C reduced form) content in tomato fruit after plant exposure to increasing concentrations of B in the nutrient solution. Vertical bars represent standard deviation

in response to the stress induced by high doses of micronutrients and heavy metals (Hatata, Abdel-Aal 2008, Magdy, Mohamed 2013, Muzolf-Panek et al. 2017).

Total polyphenol content and the antioxidant activity

Polyphenols are characterized by strong antineoplastic properties. They inhibit inflammatory processes in the blood vessels, increase their relaxation, improve blood flow, reduce the formation of blood clots (Yen, Chen 1995, Balasundram et al. 2006). Based on the results obtained in this study, it could be concluded that increasing concentrations of B in the nutrient solution caused an increase of the total polyphenol content (TPC) in cv. Emotion F_1 and a decrease of these compounds in cv. Alboney F_1 (Figure 2). However, the ANOVA analysis showed no statistically significant effect of B doses on TPC values. There was only a significant effect of a cultivar on the TPC. In Emotion F_1, the phenolic compound content increased from 69.0 mg GAE kg^{-1} FW at a B dose of 0.011 mg dm^{-3} to 112.0 mg GAE kg^{-1} FW at 1.6 mg B dm^{-3}. In Alboney F_1, a decrease was observed from 125.0 mg GAE kg^{-1} FW for the B-I sample to 74.0 mg GAE kg^{-1} FW for the B-IV sample. The change of TPC values was more pronounced in the Emotion F_1 cultivar. Since the phenolic content is often positively correlated with the antioxidant activity, DPPH radical scavenging properties of tomato fruit were examined and expressed as TEAC values (Figure 3). The Pearson's correlation coefficient r for TEAC values and total polyphenol content is very high and equals 0.89 for cv. Emotion F_1 and 0.96 for cv Alboney F_1, which indicates that polyphenolic compounds predominantly affect the antioxidant activity. The antioxidant

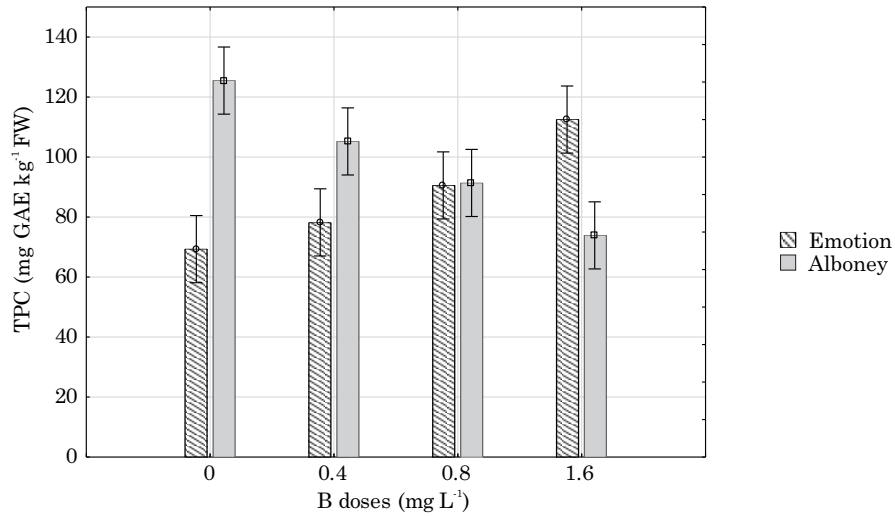

Fig. 2. Total polyphenol content (TPC) in tomato fruit after plant exposure to increasing concentrations of B in the nutrient solution. Vertical bars represent standard deviation

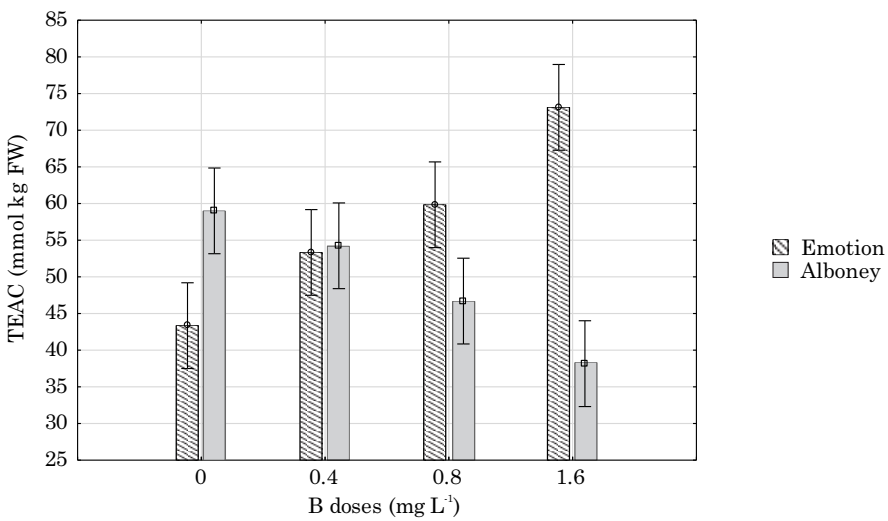

Fig. 3. Trolox equivalent antioxidant capacity (TEAC) of tomato fruit after plant exposure to increasing concentrations of B in the nutrient solution. Vertical bars represent standard deviation

activity of cv. Emotion F_1 fruits increased from 43 mmol kg^{-1} FW at a B level of 0.011 mg dm^{-3} to 73 mmol kg^{-1} FW at a B dose of 1.6 mg dm^{-3} whereas TEAC values of cv. Alboney F_1 fruits decreased from 59 mmol kg^{-1} FW in the B-I sample to 38 mmol kg^{-1} FW at the highest concentration of B in the nutrient solution (1.6 mg B dm^{-3}). As for TPC values, the antioxidant activity was significantly affected by the cultivar, not by the B doses. In this study, it was shown that boron, which is a non-metal, has less influence on

the analyzed parameters than heavy metals do (Márquez-García et al. 2012, Muzolf-Panek et al. 2017).

Lycopene

According to Abushita et al. (2000), lycopene is regarded as antioxidant with high biological activity. Lycopene, the red pigment of tomato, constitutes about 80-90% of the total carotenoid content (Shi, Le Maguer 2000) In human diet, tomatoes and tomato products are the predominant sources of lycopene (Stahl, Sies 1996). Lycopene has also been shown to induce cell-to--cell communications and modulate hormones, immune systems and other metabolic pathways (Rao, Agarwal 1999). In this study, the lycopene content of tomatoes ranged from 53.2 to 71.9 mg kg^{-1} of FW for cv. Emotion, and from 94.4 to 102.4 mg kg^{-1} of FW for cv. Alboney (Table 3). The data obtained

Table 3

Effect of B doses in the nutrient solution on the colorimetric coordinates (L*, a*, b*) in tomato fruit (means from 2011-2012)

Cultivar	Parameter	B-level (mg dm^{-3})			
		B-I	B-II	B-III	B-IV
Alboney F_1	L*	41.42 ± 0.45^{aA}	40.75 ± 0.46^{aA}	41.08 ± 0.33^{aA}	41.2 ± 1.08^{aA}
	a*	22.91 ± 0.9^{aA}	22.99 ± 0.04^{aA}	22.51 ± 1.14^{aA}	23.12 ± 0.1^{aA}
	b*	21.58 ± 1.08^{aA}	21.37 ± 0.77^{aA}	21.75 ± 1.75^{aA}	21.79 ± 1.32^{aA}
	lycopene	98.7 ± 9.4^{aA}	102.4 ± 7.2^{aA}	94.4 ± 5.8^{aA}	99.4 ± 9.9^{aA}
Emotion F_1	L*	42.57 ± 0.33^{aB}	39.77 ± 0.45^{bA}	42.4 ± 0.31^{aB}	42.33 ± 0.2^{aA}
	a*	21.95 ± 0.8^{aA}	21.9 ± 2.17^{aA}	21.38 ± 1.29^{aA}	23.2 ± 1.22^{aA}
	b*	27.28 ± 0.99^{aB}	24.08 ± 1.92^{bA}	27.43 ± 0.6^{aB}	27.51 ± 0.4^{aB}
	lycopene	56.3 ± 0.3^{aB}	71.9 ± 4.4^{bB}	53.2 ± 8.1^{aB}	61.9 ± 4.7^{abB}

Letters indicate statistically significant differences (at $p\leq0.05$) between groups in columns (samples with different levels of B).

for cv. Emotion are in agreement with the results of studies performed by other authors (Hart, Scott 1995, Clinton 1998, Nguyen, Schwartz 1998, Pelz et al. 1998, Rao, Agarwal 1999, O'Neill et al. 2001, Lugasi et al. 2003), who found that the lycopene content of fresh tomatoes ranged from 8.80 to 77.4 mg kg^{-1} The higher content of lycopene in the Alboney F_1 variety was reported at all concentrations of boron. The experiment also showed that colour parameters of tomato fruits did not change significantly with increased boron doses. It was only for the Emotion F_1 cultivar that parameters L *and b* were lower for tomatoes grown at a boron concentration of 0.4 mg dm^{-3}. As shown in Table 3, significant differences in some colour parameters between the cultivars were noted.

CONLUSIONS

The effect of boron concentrations on the nutrient content in tomato fruits was demonstrated and the following conclusions were drawn:

1. The concentration of boron in the medium modifies the mean content of nitrogen, phosphorus, magnesium (significantly the lowest content was determined in the B-IV combination), and potassium (the lowest content in the B-I and B-IV combination). In the range of boron concentrations of 0.011 to 1.60 mg dm^{-3}, a decrease in the average iron content and an increase in the content of manganese and zinc in tomato fruits were found.

2. The variety significantly differentiated the content of potassium (B-II and B-III), magnesium (B-II), iron (BI and B-II), manganese (B-II), copper (B-II), and the mean content of calcium, magnesium, iron, manganese and copper.

3. Increasing concentrations of boron in the nutrient solution caused a statistically significant decrease of vitamin C in fruit. The decrease of vitamin C varied between the cultivars, and was more pronounced in Alboney F_1 than in Emotion F_1.

4. The analysis showed no statistically significant effect of the B doses on the total polyphenol content. The TPC was significantly affected by the cultivar, not by the boron doses. Moreover, the antioxidant activity was highly correlated with the content of phenolic compounds.

5. The higher content of lycopene in the Alboney F_1 variety was reported in all concentrations of boron (94.4 - 102.4 mg kg^{-1}). In the case of Emotion F_1, the lycopene content was demonstrated to be 53.2 - 71.9 mg kg^{-1} of FW. The experiment showed that colour parameters of tomato fruits did not change significantly with increased boron doses.

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