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Hydroponic Cultivation of Tomato

Bartosz Markiewicz, Tomasz Kleiber and
Maciej Bosiacki

Additional information is available at the end of the chapter

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Abstract

Mineral substrates used in plant hydroponic cultures should have low contents of the solid phase and good, stable air and water properties. Rockwool is a substrate with such properties, and it has been produced for plant culture systems since 1969 by I/S H.J. Henriksen and V. Kähler (Denmark). The aim of the study is to evaluate the effect of an application of increasing manganese (Mn) and boron (B) concentrations added to a nutrient solution on the yielding, content of macro- and micronutrients in tomato leaves and fruits (*Lycopersicon esculentum* Mill., cv. Alboney F1 and Emotion F1). Plants were grown in rockwool using a nutrient solution with the following content of Mn (mg dm^{-3}): 0.06, 0.3, 0.6, and 1.2 mg dm^{-3} (Experiment I, 2008–2011) and 2.4, 4.8, 9.6, and 19.2 mg dm^{-3} (Experiment II, 2012)—designated the symbols for Mn: Mn-0, Mn-0.3, Mn-0.6, Mn-1.2, Mn-2.4, Mn-4.8, Mn-9.6, and Mn-19.2 and for B: (0.011), 0.4, 0.8, 1.6 in the form of $\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$ (Experiment I) and boric acid H_3BO_3 (Experiment II) (combinations of the designated symbols, respectively, B-I, B-II, B-III, and B-IV). The influence of Mn and B nutrition on biometric parameters and chemical composition of leaves and fruits of tomato is discussed.

Keywords: *Lycopersicon esculentum* Mill., rockwool, plant nutrition, manganese, boron

1. Introduction

Due to the quantitatively and qualitatively inferior plant yielding, conventional field cultivation of tomato using fertilizer broadcasting and irrigation is less economically viable in comparison with advanced soilless cultivation systems [1]. Such cultures may be run either applying fertigation (hydroponics) or without it [2] (**Figure 1**).

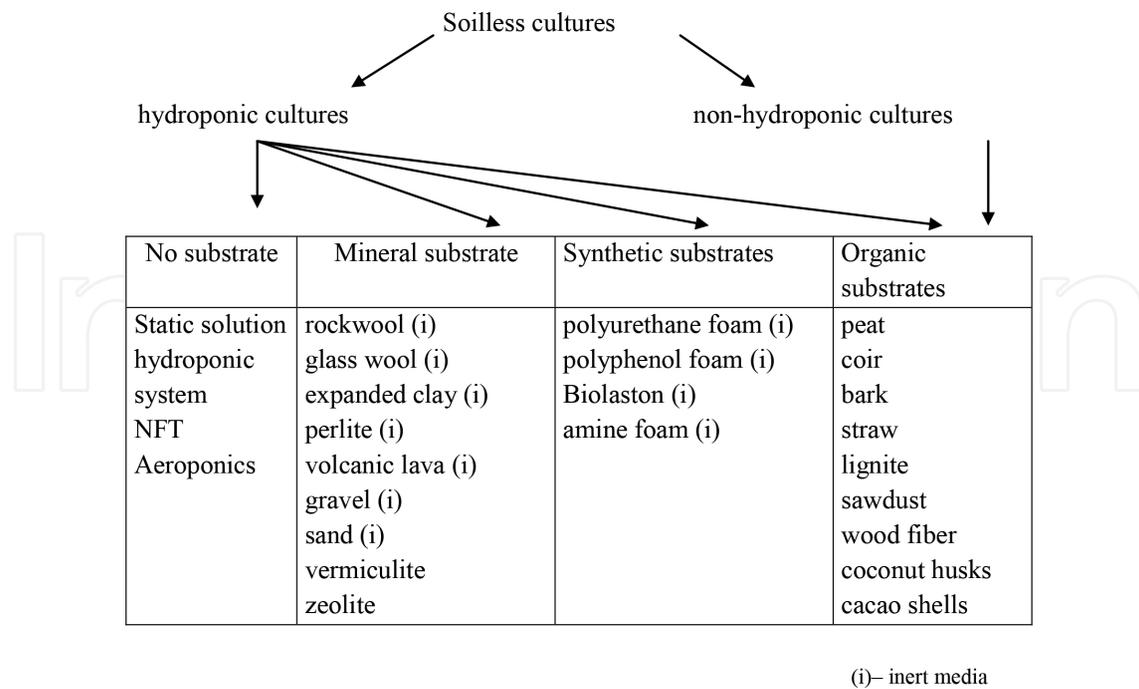


Figure 1. Classification of soilless cultures [2].

In horticultural practice, the applications of cultures without a conventional substrate are found, namely aeroponic systems (in which the air is the medium for growth of plant root systems—as the isolated space, periodically filled with injected nutrient solution) [3], the nutrient film technique (NFT; in which a thin film of the surrounding medium is the root growth medium), and the static hydroponic system [4]. In soilless cultures, mineral, synthetic, and organic substrates are used [2,5]. However, currently, mineral substrates, e.g. rockwool, are becoming increasingly popular, among other things, thanks to the precision of plant nutrition in comparison with cultures run in organic substrates, e.g. a mixture of peat and bark or sawdust [6]. Mineral substrates used in plant hydroponic cultures should have low contents of the solid phase and good, stable air and water properties. Rockwool is a substrate with such properties, and it has been produced for plant culture systems since 1969 by I/S H.J. Henriksen and V. Kähler (Denmark). Rockwool, classified to the group of mineral substrates, is produced by melting a natural rock mixture, composed of diabase (60%) and calcium (20%) with coke (20%) at a temperature of 1500–1600°C. Next from such lava rockwool of 0.5 mm in diameter is formed in spinners; it is cooled with air to 200°C; phenolic resins are added (up to 1.3 mg·10 g⁻¹ d.m. rockwool) along with binders; and compounds facilitating moisture absorption, providing it with hydrophilic properties. Such prepared rockwool is pressed to form blocks of different sizes, growing mats (e.g. 100 × 20 × 7.5—typically used in cucumber growing; 100 × 15 × 7.5—usually used in tomato culture) or culture cubes for seedling production (e.g. 10 × 10 × 10 cm). Rockwool substrate, thanks to the ultrahigh temperature at which it is produced, is free from pathogens and pests. Companies producing rockwool offer substrates composed of one and two layers, differing in their air and water properties. The fiber arrangement has a significant effect on the distribution of water and electric conductivity (EC) in the growing mat

because increasing fiber density in the upper section of the mat has an advantageous effect on nutrient medium permeation and thus facilitates a more uniform growth of plant root systems.

At present, rockwool is commonly used in cultivation of various plant species, both vegetables (such as cucumber and tomato) and ornamental plants (such as rose and gerbera). Its primary advantages include low bulk density (depending on the type ranging from 50 to 100 g·dm⁻³) and high overall porosity (92–98%). Rockwool, in contrast to most organic substrates, ensures uniform air and water conditions and the distribution of the nutrient solution within the root systems of plants, which is important in the case of commercial-scale production. Its important advantage is also connected with preventing the development of anaerobic conditions in the root hair zone, through retention of 20% air at total water capacity. Physical properties of growing mats are as follows: water 52%, the solid phase 3%, and air 45% [7]. However, such properties as water retention or air capacity undergo significant changes upon the completion of the plant vegetation cycle [8].

Rockwool is an inert substrate, devoid of the sorption complex, in which no ion exchange may take place. Its chemical composition may be as follows: P₂O₅ 0.2–0.9%, K₂O 0.7–1.3%, CaO 17.5–21.2%, MgO 5.2–9.0%, Fe₂O₃ 6.4–8.4%, MnO 0.1–0.5%, Na₂O 1.2–2.2%, SiO₂ 40.7–42.9%, Al₂O₃ 17.8–19.4%, TiO₂ 0.7–2.5%, As < 4 mg·kg⁻¹, Cd < 0.5 mg·kg⁻¹, Pb < 10 mg·kg⁻¹, and Hg < 0.01 mg·kg⁻¹. Rockwool also exhibits no buffer properties [9]. It is an alkaline substrate (pH in H₂O = 7.0–8.0), and its reaction is determined by high contents of alkaline elements (Ca, Mg, Na, and K). The high Ca content may cause retrogradation, i.e. chemical sorption of phosphorus. To prevent chemical sorption of nutrients by rockwool before the onset of plant culture, it is acidified with a nutrient solution with pH 5.5–6.0.

An advantage of the application of rockwool as a substrate in plant culture is connected with the limited spread of root system diseases because plants are grown in separate, foil-covered growing mats (as a rule with two plants per mat). A potential risk of diseases may be increased in the case of closed systems with nutrient solution recirculation (in which the nutrient solution leaking from the root systems is recycled for fertigation), at potential problems with its effective disinfection. Applicable nutrient solution disinfection methods in practice include thermal methods [10,11], filtration based on reverse osmosis or another type of membrane systems [12,13], UV radiation, or ozone treatment [14,15].

A disadvantage of rockwool as a homogeneous substrate for plant growing is connected with its problematic disposal and management because this substrate is not biodegradable. It is estimated that from 150 to 200 m³ rockwool remains after 1-hectare culture of greenhouse tomato [16]. However, such substrates may be used to improve physical properties of soils, particularly heavy soils [8,17], or as an additive to mixed substrates [18]. A certain drawback—in view of the problems with water quality in Europe—may also be connected with the quality requirements for the chemical composition of water for the preparation of fertigation nutrient solutions. Maximum ion concentrations in water may not exceed concentrations recommended for a given plant species (the so-called hydroponic concentrations), taking into consideration the optimal value of EC [19]. In turn, locally observed deterioration of water quality affecting its applicability in fertigation may be connected with both macro- and

micronutrients. Response of tomato grown in rockwool to varied concentrations of micronutrients (Mn and B) in nutrient media is presented in the successive chapters.

A serious problem in cultures run in open systems with no nutrient solution recirculation may also be connected with contamination of the natural environment with excess drainage water leaking from the root zone [20]. The greatest contamination is caused by intensive tomato cultures in rockwool run in open systems, which may be as follows: N-NO₃ (up to 245 kg·month·ha⁻¹), K (up to 402 kg·month·ha⁻¹), Ca (up to 145 kg·month·ha⁻¹), and S-SO₄ (up to 102 kg·month·ha⁻¹), while in the case of micronutrients: Fe (up to 2.69 kg·month·ha⁻¹), Mn (up to 0.19 kg·month·ha⁻¹), Zn (up to 0.52 kg·month·ha⁻¹), and Cu (up to 0.09 kg·month·ha⁻¹). In view of the above, apart from studies aiming at the optimization of nutrition for plants grown in rockwool, studies are also being conducted on the applicability of alternative substrates in plant growing to replace rockwool, such as coir, wood fiber, or aeroponic systems [5,21–24].

2. The influence of selected micronutrient nutrition on plant yielding

2.1. Manganese

2.1.1. *The physiological role*

Mn, similarly iron (Fe), zinc (Zn), copper (Cu), and nickel (Ni), is a heavy metal (atomic mass = 54.93) and, at the same time, a metallic micronutrient. This nutrient, similarly Fe, may be found in plant tissues at greater concentrations than necessary for appropriate functioning of the organism. Mn serves many physiological functions because it is a component of several enzymes: Mn-catalase and dehydrogenases, and it is an activator of decarboxylases, hydroxylases, acid phosphatase, and dismutase, e.g. SOD [25]. It is also found in lignins, flavonoids, and the PS II-protein complex. It plays an important role in the reactions of water splitting in the light-dependent reactions of photosynthesis. Mn is an activator of citric acid enzymes, reduction of nitrates, and metabolism of proteins, saccharides, and lipids, and it also participates in oxidation of indole-3-acetic acid (IAA) [25]. Mn indirectly controls the level of NADPH, and its extreme deficiency may cause thylakoid membrane dysfunctions. It is also involved in the tricarboxylic acid cycle, in the synthesis of chlorophyll (phosphatidic acid), and in the removal of free radicals formed in chloroplasts.

Mn is absorbed by plants as the Mn²⁺ cation, and it is passively transported through the cell membrane following the electrochemical gradient [26]. In plants, it is mainly transported in the xylem; it is scarcely reutilized; thus, the first symptoms of its deficiency are manifested in the apical parts of plants. Excessive uptake of Mn may damage the photosynthetic organs and therefore leads to reduced contents of chlorophyll and yielding of plants [27–29]. Mn tolerance of plants depends on their genome.

2.1.2. Manganese in human diet

Mn is an essential micronutrient, which has to be supplied with the diet. It plays an important role in many physiological processes, and it is required in the regulation of sugar levels, bone growth and reproduction, or proper functioning of the immune system [30]. However, there are no standards regulating the content of Mn in food. The daily allowance recommended by the National Academies' Institute of Medicine, referred to as adequate intake (AI), for this micronutrient amounts to 1.8 mg for women and 2.3 mg for men [31]. Daily intake causing no toxicity symptoms, defined as tolerable upper intake level (UL), is as high as 11 mg•day⁻¹. European nutrition standards define the optimal intake as 1–15 mg Mn•day⁻¹ [32]. No symptoms of Mn deficiency are observed in free living subjects [33], and rational nutrition fully covers the daily requirement for this nutrient [34].

Vegetables are capable of accumulating this nutrient with an increase in the concentration of Mn in nutrient solution used in fertigation. The disturbed Fe/Mn ratio in food may be potentially dangerous for consumers, including vegetables more frequently consumed in season. These micronutrients compete for the same protein in blood serum (transferrin) and the protein divalent metal transporter system DMT 1 [35]. Daily uptake of Fe with food rations is sufficient for men, but very often it does not cover the safe level recommended for women [33]. In addition, it is known that the accumulation of Mn in the human organism—when the consumed diet is one of the routes of absorption of this micronutrient—may be harmful, leading to changes in the central nervous system. However, a detailed mechanism of Mn neurotoxicity is relatively little known [30,36].

2.1.3. Tomato reaction on increasing concentration of Mn in nutrient solution

This chapter shows the multifaceted response to increase Mn concentrations in nutrient solutions, ranging from insufficient to excessive/toxic: chemical changes the root zone of plants, in leaves—focusing on chosen parameters of photosynthetic activity as well as yields of fruits and their quality. It also shows a specific potential applicability of choline-stabilized orthosilicic acid (ch-OSA) in nutrient solution to alleviate Mn stress in tomato. Described studies were conducted on cultivation of two cultivars: 'Alboney F₁' (*Enza Zaden*) and 'Emotion F₁' (*S&G*) grown in rockwool. In experiments, a standard nutrient solution with varying contents of Mn was used: Experiment I—control: 0.06 (native content in water), 0.3, 0.6, and 1.2 mg•dm⁻³ and Experiment II—2.4, 4.8, 9.6, and 19.2 mg•dm⁻³ [37].

2.1.3.1. Chemical composition of the root zone

The increase in Mn concentration in nutrient solution use in fertigation of tomato has a significant and multifaceted effect on the chemical composition of the rhizosphere [37]. Generally, Mn content in the root zone is significantly reduced in relation to that in nutrient solution applied in plants, but the response generally significantly varies between cultivars (**Table 1**).

Sampling place	Mn level							
	Experiment I				Experiment II			
	Mn-0	Mn-0.3	Mn-0.6	Mn-1.2	Mn-2.4	Mn-4.8	Mn-9.6	Mn-19.2
Dripper	0.06 c	0.31 e	0.57 i	1.16 j	2.45 b	4.88 e	9.78 g	19.91 j
'Alboney F ₁ ' ¹	0.04 b	0.06 c	0.36 f	0.53 h	1.14 a	3.92 c	6.55 f	17.98 i
'Emotion F ₁ ' ²	0.02 a	0.14 d	0.14 d	0.42 g	1.04 a	4.40 d	10.02 g	16.66 h

Notes: Results were subjected to analysis of variance, independently for each experiment; nutrient solution collected from slabs of cv.; ¹'Alboney F₁'; ²'Emotion F₁'; values described with identical letters do not differ significantly at $\alpha = 0.05$.

Table 1. The effect of increasing Mn concentration in nutrient solution ($\text{mg}\cdot\text{dm}^{-3}$) on contents of that microelement in cultivation slabs [38].

Increasing concentrations of Mn in nutrient solution significantly modifies the chemical composition of root zone, but the reaction varies depending on cultivar and Mn concentration: in the range of Mn contents up to $1.2 \text{ mg}\cdot\text{dm}^{-3}$; a significant increases: N-NO₃, Ca, Mg, S-SO₄, Zn (except for Mn-1,2), Na, and Cl; pH (alkalization) and EC, at a simultaneous reduction of contents of K (except for the control) and Fe.

2.1.3.2. Chemical composition of leaves

Mn nutrition and cultivar significantly influence on the chemical composition of leaves [39]. Mn content in tomato leaves is significantly connected with the contents of this nutrient in nutrient solution used in fertigation of plants and similarly in case of rhizosphere generally varies between cultivars (**Table 2**).

Cultivar	Experiment I				Experiment II			
	Mn-0	Mn-0.3	Mn-0.6	Mn-1.2	Mn-2.4	Mn-4.8	Mn-9.6	Mn-19.2
Mn content in leaves								
'Alboney F ₁ '	62.9 a	175.3 b	260.7 d	290.8 e	424.0 a	464.4 c	472.0 c	471.4 c
'Emotion F ₁ '	71.1 a	229.7 c	263.8 d	313.3 f	446.2 b	459.4 bc	465.9 c	489.5 d
Mn content in fruits								
'Alboney F ₁ '	7.4 a	10.7 b	19.3 e	22.8 f	73.8 a	82.5 b	83.4 b	103.8 d
'Emotion F ₁ '	6.8 a	16.0 c	17.7 d	34.5 g	97.1 c	106.5 d	110.2 d	132.6 e
Fe content in fruits								
'Alboney F ₁ '	94.2 e	89.7 d	85.9 cd	71.2 a	66.1 e	51.7 d	49.6 c	39.2 b
'Emotion F ₁ '	86.8 cd	83.1 c	76.5 b	71.4 a	57.2 d	41.3 c	37.3 b	34.6 a
Total yield of 1 tomato plant								
'Alboney F ₁ '	6.05 a	6.56 c	6.32 bc	6.21 b	5.77 e	5.51 de	5.04 cde	4.44 bc

Cultivar	Experiment I					Experiment II		
	Mn-0	Mn-0.3	Mn-0.6	Mn-1.2	Mn-2.4	Mn-4.8	Mn-9.6	Mn-19.2
'Emotion F ₁ '	5.81 a	5.82 a	6.32 bc	5.93 a	5.42 de	4.83 cd	4.04 b	2.80 a

Notes: Results were subjected to analysis of variance, independently for each experiment; nutrient solution collected from slabs of cv.: ¹'Alboney F₁'; ²'Emotion F₁'; values described with identical letters do not differ significantly at $\alpha = 0.05$.

Table 2. The influence of Mn nutrition on content of Mn in leaves, Fe and Mn in fruits (in mg kg⁻¹ d.m.) and on total yield of 1 tomato plant (kg) [40–42].

Increasing intensity of Mn nutrition may vary the plant nutrient status in the case of Mn-0 reduces the contents of macroelements with a simultaneous increase in the contents of Fe, Zn, and Cu, whereas in the case of the Mn-1.2 combination a decrease in the contents of N, Mg, Fe, and Zn with an increase in the contents of P, K, and Ca in relation to the combination of optimal yielding [37,38,43]. Kleiber et al. [38] claimed that variation in contents of micronutrients is greater than that of macronutrients. The same authors [44] also found that the contents of trace elements (Al, Ba, Co, Cr, and Ni) in leaves of tomato grown under strong Mn stress are decreasing.

2.1.3.3. Chosen parameters of photosynthetic activity

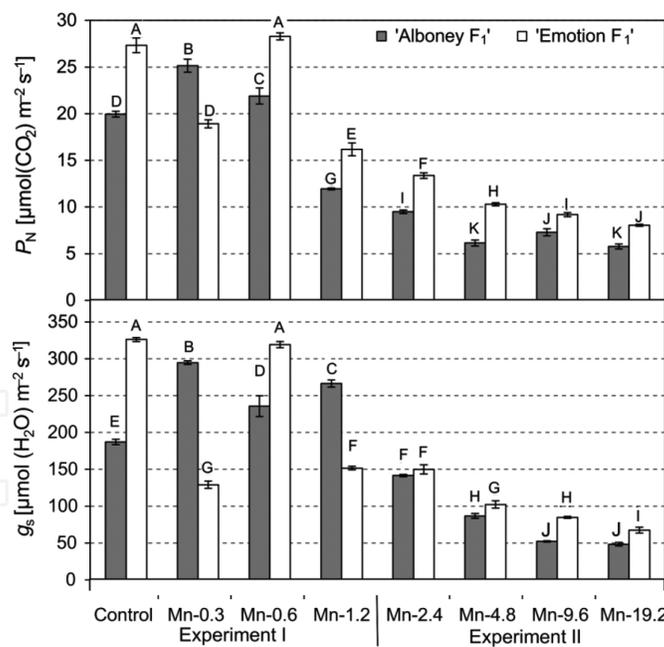


Figure 2. Means \pm SE of net photosynthesis rate (PN) and stomatal conductance (gs) in tomato cultivated with different Mn in nutrient solution. Letters denote significant differences between means at $p=0.05$ (Kleiber et al. 2014 a).

Excessive Mn nutrition causes a toxic effect, which is observed morphologically in plants at a Mn concentration in nutrient solution $\geq 4.8 \text{ mg} \cdot \text{dm}^{-3}$ (Figure 2) [38, 40]; however, already at a Mn concentration of $1.2 \text{ mg} \cdot \text{dm}^{-3}$, changes are observed in their photosynthetic activity. The

first symptom of excessive Mn nutrition in plants is a reduction of net photosynthetic activity (P_N), although plant yielding is still visually similar to that obtained at hydroponic concentrations. With an increased intensity of Mn nutrition of plants, the values of P_N and stomatal conductance (g_s) are increasing (to $0.6 \text{ mg Mn} \cdot \text{dm}^{-3}$), which indicates an adequate level of CO_2 consumption in the process of assimilation. Those parameters of photosynthetic activity significantly vary depending on the cultivar, which confirm significant variation between cultivars in relation to Mn nutrition [38].

2.1.3.4. The morphology of aboveground parts and yielding of plants

Morphological symptoms of toxic effects of Mn in the form of midrib and lateral veins browning in leaflets of a compound leaf and next necroses of compound leaves and plant apices and inflorescence withering could be observed at the earliest after 6 weeks of culture (at Mn-19.2) and 10 weeks of exposure (at Mn-9.6) to the nutrient solution (**Figure 2**) [42,43]. For those combinations, a significant reduction in the photosynthetic activity of plants is present [38]. Symptoms of Mn deficiency on leaves could be observed earlier than toxicity—after 3 weeks (in the case of control).

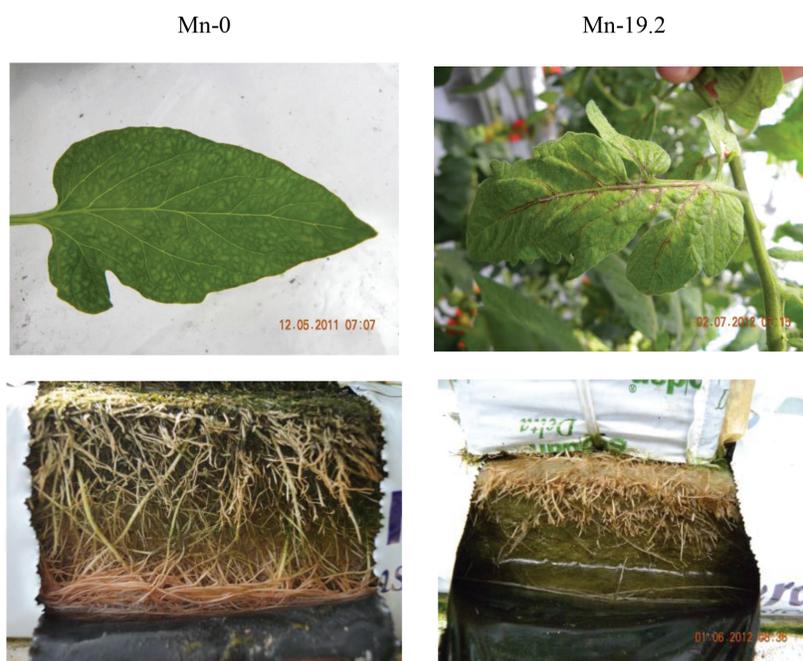


Figure 3. Morphological appearance of leaves and roots at manganese deficiency (at Mn-0) and toxicity (at Mn-19.2) Fot. Kleiber.

The hydroponic concentration of Mn for fertigation of tomato varies depending on cultivar. The greatest marketable yield of fruits in cv. 'Alboney F_1 ' is obtained at the Mn contents of $0.3\text{--}0.6 \text{ mg} \cdot \text{dm}^{-3}$ nutrient solution, but in the case of cv. 'Emotion F_1 ' yield for the range of maximum Mn-0.3 is lower than Mn-0.6 (**Table 2**). The content of Mn in nutrient solution amounting to $1.2 \text{ mg} \cdot \text{dm}^{-3}$ is excessive and contributed to a significant deterioration of yielding, at the simultaneous lack of morphological toxicity symptoms on plants. Mn stress

significantly reduces not only mass of fruits but also leaves and shoots [42]. Significantly, the greatest contents of Mn are characterized leaves, whereas lowest contents are characterized fruits. There is a marked correlation between increasing contents of Mn in nutrient solutions used in fertigation of plants and its contents in leaves, stems, and fruits ($R^2 = 0.94\text{--}0.99$). A high correlation could also be observed for Mn contents between examined plant parts ($R^2 = 0.89\text{--}0.98$).

Tomato cultivars may significantly differ in relation to the requirement and tolerance to Mn concentration in nutrient solutions used in fertigation, but, generally, those species may be classified as a medium tolerance to excessive Mn concentrations in nutrient solution.

2.1.3.5. Chemical composition of fruits

Increasing intensity in Mn nutrition causes increasing in Mn concentration in fruits—but the response similarly in case of leaves generally significantly varies between cultivars (except Mn-0; Table 2) [41,44]. The range of hydroponic concentrations of Mn in fruits that are determined for cv. 'Alboney F₁' is 10.7–19.3 mg Mn•kg⁻¹ d.m., whereas for cv. 'Emotion F₁' it is 17.7 mg Mn•kg⁻¹ d.m. At the greatest tested concentration of Mn for these cultivars, they are 103.8 and 132.6 mg Mn•kg⁻¹ d.m. Mean Fe/Mn ratios in fruits recorded at the applied hydroponic concentrations are 1.00 : 0.15–0.22, while at the application of 19.2 mg Mn•dm⁻³, it is 1.00 : 3.20, whereas at the nutrient solution of Mn-1.2, these ratios are 1.00 : 0.40. This indicates a marked and adverse reduction in relative Fe contents. In view of the recommended daily allowances for Mn in the human diet, it seems potentially undesirable to consume tomato fruits from plants supplied excessive or toxic levels of this nutrient.

Mn nutrition significantly impacts on the nutritive value of tomato fruits. A significant reduction is generally recorded for the contents of P, K, Ca, and Mg and the other metallic micronutrients (Fe, Zn, and Cu). Significant variation, depending on the cultivar, is shown generally for N, Ca, Mg Fe, Zn, and Cu. The greatest contents of N, Ca, and Mg in fruits are in the control, while those of P and K—at 0.3 mg Mn dm⁻³, whereas the lowest contents of nutrients (except for N) are in the case of Mn-19.2.

The increasing intensity in Mn nutrition significantly modifies contents of trace elements (Al, Ba, Co, and Pb) in fruits, at the same time, having no effect on Cr and Cd [41]. A series of those metals in tomato fruits within the range of hydroponic concentrations of Mn are in the following: Ba 4.340–6.180 mg•kg⁻¹ d.m. > Ni 4.746–5.198 mg•kg⁻¹ d.m. > Co 1.014–1.064 mg•kg⁻¹ d.m. > Pb 0.854–0.887 mg•kg⁻¹ d.m. > Cd 0.379–0.395 mg•kg⁻¹ d.m. > Cr 0.120 mg•kg⁻¹ d.m. > Al 0.066–0.081 mg•kg⁻¹ d.m. In the range of hydroponic Mn concentrations, contents of analyzed trace elements generally did not vary significantly between cultivars.

2.1.3.6. Use of choline-stabilized orthosilicic acid (ch-OSA) in nutrient solution to alleviate Mn stress

Studies conducted so far have indicated a significant role of silicon (Si) as an element alleviating the toxic effect of Mn [27,45–50]. Previous studies on that subject are concerned with various species, e.g. beans, barley, cucumber, rice, and cowpea. The highest Mn concentrations in nutrient solution (9.6 and 19.2 mg•dm⁻³) cause the strongest Mn stress of tomato. One of the

available forms of Si, which may be used in fertigation, is ch-OSA. Ch-OSA is also used in medicine; e.g. in combination therapy, ch-OSA/vitamin D₃ is used as a preparation affecting bone collagen in the treatment of osteoporosis [51].

The application of the tested bioavailable Si compound (ch-OSA at a scaled concentration of 0.3 mg Si•dm⁻³) improves photosynthetic activity (**Table 3**) and results in improving plant yielding—especially for lower levels of Mn. All the factors—(i) content of Mn in nutrient solution, (ii) the application of ch-OSA, and (iii) the cultivar—significantly affect the chemical composition of leaves and tomato fruits [45,46]. Increasing in Mn stress modifies the concentration of microelements and Si in tomato leaves. Application of ch-OSA also influences the concentration of nutrients, but the determined changes were generally multidirectional and vary depending on Mn level and cultivar. Ch-OSA treatment does not influence on the Mn concentrations in fruits.

Mn level	Ch-OSA treatment			Ch-OSA treatment		
	-	+	Mean	-	+	Mean
	'Alboney F ₁ '			'Emotion F ₁ '		
	<i>P_N</i> [μmol (CO ₂) m ⁻² s ⁻¹]					
9.6	8.46 a	11.58 c	10.02 A	8.14 a	17.03 c	13.11 A
19.2	6.92 b	10.38 d	8.65 B	9.44 b	13.16 d	11.47 A
	<i>g_s</i> [μmol (H ₂ O) m ⁻² s ⁻¹]					
9.6	80.05 b	113.83 b	96.94 A	80.26 a	151.31 c	119.00 A
19.2	69.77 a	114.40 b	92.09 A	99.50 b	122.97 d	112.31 A
	Marketable yield of 1 tomato plant					
9.6	4.88 a	5.80 b	5.35 A	4.53 b	4.89 c	4.71 B
19.2	4.78 a	4.85 a	4.80 A	4.06 a	3.85 a	3.96 A

Notes: Means in rows marked with various big letters differ significantly; means in columns marked with various big letters differ significantly; means in rows and columns marked with various small letters differ significantly.

Table 3. The influence of Mn and ch-OSA nutrition on the photosynthetic activity in leaves (*P_N*—net photosynthetic rate, *g_s*—stomatal conductance) and marketable yield of 1 tomato plant (kg) [46].

2.2. Boron

2.2.1. Physiological role of boron

B is an essential micronutrient for plant growth and development. It is classified as a biophilic non-metal [52]. It participates in the formation of cell-wall structures and cell divisions [53], pollen tube development [54], and saccharide metabolism [55]. Plants accumulate B through their root system [56] or through leaves [54]. B content affects nitrogen metabolism of plants, although a deficit of this micronutrient results in an increased content in nitrates in plants. Boron also plays a role in phenolic metabolism [57] and in the ascorbate–glutathione metabolic

cycle [53]. It also participates in the formation and functioning of the cell wall [58]. B deficit results in the inhibition of cell-wall synthesis and affects cell elasticity [59], leading to an increase in pore size, resulting in cell-wall rupture [53]. B may form complex compounds with sugars, phenols, organic acids, and polymers [60]. Most frequently, B is found in complex combinations with mannitol, sorbitol, glucose, and fructose [60]. B may also form complex compounds with the RG-II polysaccharide [61–64] stabilized with calcium ions [53,61], the most important boron-binding compound in the cell wall. This complex is found in mono- and dicotyledonous plants [65,66].

2.2.2. *The effect of boron on human health*

The role of B in the human organism has not been fully clarified. This micronutrient determines appropriate bone development, preventing osteoporosis. An adequate B uptake with the human diet prevents arthritis [61]. B was shown to affect the activity of brain cells, the metabolism of calcium and magnesium, and the immune system [67,68]. According to Kurtoğlu et al. [69] and Li et al. [70], the interaction of B and calcium influences hormonal functions in the human. The daily dose of B absorbed by humans through the respiratory and the alimentary systems as well as the skin varies, ranging from 0.25 to 20 mg a day [71–73]. B is not accumulated in tissues, and it is excreted with urine [72], but its excess is dangerous for human health [52]. The most important sources of B in the human diet include drinks, vegetables, and fruits [74]. According to Castillo et al. [75], the greatest amounts of B are contained in beets (250 mg kg⁻¹), lemons (150 mg kg⁻¹), and apples (110 mg kg⁻¹).

2.2.3. *Boron content in water*

Natural and anthropogenic factors are sources of B in underground waters. Natural concentrations of B in fresh water result from the contents of borates in soils and rocks, mixing of waters at different aquifer levels as well as the effect of marine intrusion. During rock weathering, B penetrates to the solution forming a series of anions: BO_2^- , $\text{B}_4\text{O}_7^{-2}$, BO_3^{-3} , H_2BO_3^- , and H_4BO_4^- [76]. Most frequently, B is found in water in the form of boric acid [77], less commonly in anions and organic compounds [71]. B content in surface and underground waters may range from 5 to 100 mg dm⁻³ [78]. Natural B content in underground waters in Poland amounts to 0.01–0.5 mg dm⁻³ [79]. According to Breś et al. [19], B content in water used in horticulture does not exceed 0.1 mg dm⁻³; however, in areas with high intensity of horticultural production, the content of B may exceed 0.6 mg dm⁻³ [80]. Many authors [81–84] recommend an optimal B content in the nutrient solution for fertigation of tomato at 0.3 mg dm⁻³. In studies presented by other authors, the recommended B content in the nutrient solution for tomato growing is 0.2–0.7 mg dm⁻³ [3,85–91].

2.2.4. *Material and methods*

The vegetation experiment was conducted in the years 2009–2012 (Experiment I) and 2013–2014 (Experiment II). Analyses were conducted on the effect of B fertigation on yielding and macronutrient content in leaves and fruits of tomato grown on rockwool. Vegetation experiments were run in a specialist culture greenhouse equipped with the modern climate control

system. Climate parameters (such as temperature, CO₂ content, and % RH) were recorded using the Synopta software. The facilities were equipped with a modern computer-controlled fertigation system and energy-conservation curtains. Plants were grown at a density of 2.7 plants·m⁻².

The experiment was conducted on two tomato cv. Alboney F₁ and Emotion F₁. Plants were grown in standard rockwool (density of 60 kg·m⁻³, mats of 100 × 15 × 7.5 cm). Experiment was established in a completely randomized system, in six replications with two plants in each. Biological pest control was applied in that culture. All cultivation measures were performed in accordance with the current recommendations for tomato growing [92]. Seeds were sown to cultivation plugs in the first half of March in each year of the study. After 2 weeks, seedlings were transplanted to rockwool cubes (10 × 10 × 10 cm). Plants were transplanted to permanent beds in the second half of April in each year of the study. The experiment was concluded on 30 September in each year of the study. The experiments were conducted in two factors (factor A—B concentration and factor B—cultivar) in five replications with four plants in each.

Plants were grown using fertigation in the closed system with no recirculation of the nutrient solution. A standard nutrient solution for tomato growing was used with the following nutrient contents: N-NH₄—2.0 mg·dm⁻³, N-NO₃—230 mg·dm⁻³, P—50 mg·dm⁻³, K—420 mg·dm⁻³, Ca—140 mg·dm⁻³, Mg—60 mg·dm⁻³, Cl—30 mg·dm⁻³, S-SO₄—120 mg·dm⁻³, Fe—1.80 mg·dm⁻³, Mn—0.3 mg·dm⁻³, Zn—0.50 mg·dm⁻³, and Cu—0.07 mg·dm⁻³. The nutrient solution of B was prepared and added individually to the respective tanks with a capacity of 1000 dm⁻³ in the following combinations: control (0.011), 0.4, 0.8, and 1.6 mg·dm⁻³ in the form of Na₂B₄O₇·10H₂O (Experiment I) and boric acid H₃BO₃ (Experiment II; combinations of the designated symbols, respectively, B-I, B-II, B-III, and B-IV). 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 dm³ nutrient solutions per plant were applied daily, in 15–20 single doses at 20–30% drip from mats.

In the vegetation period, the yield of fruits was recorded in terms of fruit quality grades: I—over 10.2 cm; II—10.2–8.2 cm; III—8.2–6.7 cm, IV—6.7–5.7 cm, V—5.7–4.7 cm, and VI—less than 4.7 cm. Marketable yield comprises fruits classified to Grades I–V.

Samples of nutrient solutions from the drippers and rockwool slabs representing the root zone of plants were collected at the same time of the day, using a syringe in the middle of the distance between plants, in the median axis of the slab, inserting the needle to half slab thickness, at the following dates: 15.05, 15.06, 15.07, and 16.08 of each year of the study. The average sample was collected from eight slabs. Chemical analyses of nutrient solutions were conducted directly in the tested solutions (without their stabilization) using the following methods: N-NH₄, N-NO₃—by distillation according to Bremner modified by Starck, P—colorimetrically with ammonium vanadium molybdate, K, Ca, Na—by flame photometry, Cl—nephelometrically with AgNO₃, S-SO₄—nephelometrically with BaCl₂, B—colorimetrically with curcumin; Mg, Fe, Mn, Zn, Cu—by atomic absorption spectrometry (AAS, on apparatus Carl Zeiss Jena); EC—conductometrically and pH—potentiometrically.

Leaf samples for chemical analyses were collected on 15.06, 15.07, and 16.08 in each of the years of the study. Index parts comprised 8–9 leaves counting from the top of the plant. One bulk sample was composed of 12 leaves collected from plants within a given combination. Representative samples of fruits were harvested in the second half of August in each year of the study. Collected plant material was dried at a temperature of 45–50°C and then ground. To determine total nitrogen, phosphorus, potassium, calcium, and magnesium contents, plant material was mineralized in concentrated sulfuric acid. Nutrient contents were 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). To determine total contents of iron, manganese, zinc, and copper, the plant material was mineralized in a mixture of acetic and perchloric acids (3:1 v/v), B—dry mineralization with calcium oxide (CaO). After mineralization, Fe, Mn, Zn, and Cu were determined according to AAS and B colorimetrically with curcum.

Results of biometric measurements and laboratory analyses were analyzed statistically using the Duncan test, with inference at $\alpha = 0.05$.

2.2.5. Results and discussion

2.2.5.1. Yielding

The effect of B fertigation on the marketable yield of tomato fruit was found in a vegetation experiment conducted in the years 2009–2012 (Experiment I) and 2013–2014 (Experiment II; Table 4). The mean marketable yield differed significantly depending on the level of B in the nutrient solution. The largest yield marketable varieties Alboney F₁ (Experiment I) obtained in combinations of B-I and B-II (5.55 and 5.52 kg · plant⁻¹). Increasing the B content of the medium had a significant effect on reducing the commercial yield in combinations of B-III and B-IV (5.09 and 5.18 kg · plant⁻¹) when compared to combinations of B-I and B-II. The highest yield of marketable varieties obtained Emotion F₁ in combination of B-II (5.57 kg plant⁻¹). There were no significant differences in yield trading between combinations of B-I, B-III, and B-IV, average marketable yield of these varieties did not differ significantly. In the conducted in the years 2013 – 2014 found the experience of growing influence of fertigation boron on the marketable yield of tomato fruit. The resulting average yield commercial differ significantly depending on the level of B in the medium. In the performed experiment, no significant changes were found in the shares of the marketable yield in the total yield (99.6–100.0%). When analyzing the produced marketable yield, it needs to be stressed that the optimal level of B in the nutrient solution for cv. Alboney F₁ amounts to 0.011–0.40 mg dm⁻³, whereas for cv. Emotion F₁ 0.40 mg B · dm⁻³. Increased B content in the nutrient solution caused a significant reduction of the marketable yield in both cultivars. Cultivar Emotion F₁ responded with a decrease in the marketable yield both to a deficit and excess B in the nutrient solution. Recorded results indicate a greater optimal content range in cv. Alboney F₁ for this micronutrient in the nutrient solution used in fertigation. In this study, when applying a nutrient solution considered to be standard (0.40 mg dm⁻³), a similar marketable yield was found for cv. Emotion F₁

(5.85 kg plant⁻¹) to that obtained by Kleiber [43] when using a standard nutrient solution (5.82 kg plant⁻¹). No differences were observed between cultivars, and the produced marketable yield of cv. Alboney F₁ was lower by ±0.7 kg plant⁻¹. The effect of B on yielding in tomato was confirmed by a study conducted by Oyinlola [93]. In comparison with the experiment carried out by Piróg and Komosa [94], the produced marketable yield in both cultivars in this experiment at B contents in the nutrient solution of 0.0, 0.4, and 0.8 mg dm⁻³ was greater, it may have a significant effect at mass-scale tomato production. In an experiment conducted by Jarosz and Dzida [81], the greatest total yield of cv. 'Cunero F1' was 14.7 kg m⁻² (2.7 plant m⁻²), whereas studies carried out in 2004 on the same cultivar showed a yield of 4.39 kg plant⁻¹ [9].

Variety	B-I	B-II	B-III	B-IV	Mean
Experiment I					
Marketable field (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	
Contribution of marketable yield in total yield (%)					
Alboney F ₁	99.5	99.5	99.2	99.4	99.4
Emotion F ₁	99.6	99.1	99.2	99.4	99.3
Średnia Mean	99.6	99.3	99.2	99.4	
Experiment II					
Marketable field (kg plant ⁻¹)					
Alboney F ₁	5.73 bc	5.87 c	5.65 b	5.46 a	5.68 A
Emotion F ₁	5.24 a	5.85 c	5.60 b	5.41 a	5.52 A
Mean	5.48 A	5.86 C	5.63 B	5.43 A	
Contribution of marketable yield in total yield (%)					
Alboney F ₁	99.8	100.0	99.8	99.6	99.8
Emotion F ₁	99.8	99.7	99.8	99.6	99.7
Mean	99.8	99.8	99.8	99.6	

Notes: Means in rows marked with various big letters differ significantly; means in columns marked with various big letters differ significantly; means in rows and columns marked with various small letters differ significantly.

Table 4. The influence of B nutrition on total yield of 1 tomato plant (kg).

2.2.5.2. Chemical composition of the root zone

The effect of increasing B concentrations in nutrient solutions is shown (**Table 5**). In all the combinations, an increase was shown for B contents in nutrient solutions absorbed from mats in comparison with the nutrient solution applied to plants. The greatest B content in nutrient

solutions for both cultivars was recorded in mats applying B at 1.60 mg dm⁻³. Differences between cultivars were shown in terms of B content in nutrient solutions collected from mats in combinations of B-I and B-IV (Experiment I) and B-II and B-IV (Experiment II). An increase in B content in the nutrient solution in combinations of B-III and B-IV caused a significant decrease in the marketable yield, which may have been caused by the toxic individual effect of this ion on plants [95]. In this experiment, the phenomenon of B condensation was observed in growing mats, confirming the results reported by other authors [24]. It needs to be stated that B content in growing mats exceeding 0.93 mg dm⁻³ (Experiment I) causes a significant reduction of plant yielding. However, a further increase in the content of B in nutrient solutions in the rhizosphere up to 1.87 mg dm⁻³ does not cause a significant reduction of the marketable yield between these combinations. The conducted Experiment II using boric acid as a source of B in the nutrient solution showed identical dependencies in the case of the greatest marketable yield; however, the content of B in mats close to 2.00 mg dm⁻³ caused a significant reduction of yielding in comparison with combination of B-III (±1.00 mg·dm⁻³). The highest marketable yield varieties Emotion F1 obtained when the boron content of mats 0.58 (Experiment I) and 0.67 mg·dm⁻³ (Experiment II). At the application of the same B levels in hydroponic culture of butter lettuce, a yield-modifying effect of increasing B concentrations in the nutrient solution was found for the mean weight of lettuce heads. The greatest weight of lettuce heads was produced using B content in the nutrient solution within the range of 0.40–1.60 mg dm⁻³ [96].

Sampling place	B-I	B-II	B-III	B-IV	B-I	B-II	B-III	B-IV
	Experiment I				Experiment II			
Dripper	0.11 a	0.41 d	0.80 f	1.57 h	0.11 a	0.41 c	0.82 f	1.63 h
Alboney	0.21 b	0.58 e	0.93 g	1.87 i	0.27 b	0.59 d	0.99 g	1.92 i
Emotion	0.26 c	0.58 e	0.96 g	2.00 j	0.32 b	0.67 e	1.01 g	2.11 j

Notes: Results were subjected to analysis of variance, independently for each experiment; nutrient solution collected from slabs of cv.: ¹Alboney F₁; ²Emotion F₁; values described with identical letters do not differ significantly at $\alpha = 0.05$.

Table 5. The effect of increasing B concentration in nutrient solution (mg·dm⁻³) on contents of that microelement in cultivation slabs.

2.2.5.3. Chemical composition of leaves

An increase in B contents in the nutrient solution applied in fertigation had a significant effect on the content of this micronutrient in indicator parts of tomato (**Table 6**). In combinations of B-II and B-III, an increase in B contents in the nutrient solution caused an increase in B content by ±100%. Significantly, the greatest mean B content was assayed using the nutrient solution of 1.60 (207.07 mg·kg⁻¹). Significant differences in the mean B content in leaves were observed between cultivars. According to the studies conducted by other authors, an increase in the content of B in the nutrient solution has a significant effect on contents of this micronutrient in tomato leaves [93]. [79] when growing tomato at a toxic level of boron in the nu-

trient solution assayed $155 \text{ mg B}\cdot\text{kg}^{-1}$ in tomato leaves. Results in this study for B contents in indicator parts of tomato at 0.80 and 1.60 indicate a toxic state of nutrition of plants in the case of the investigated micronutrient. According to Kabata-Pendias and Pendias [71], an admissible B content for tomato plants is $100 \text{ mg}\cdot\text{kg}^{-1}$ B in d.m. In turn, according to De Kreij et al. [97], an optimal content of B in tomato leaves should be $54.0\text{--}75.6 \text{ mg}\cdot\text{kg}^{-1}$ B d.m. When analyzing the state of nutrition of plants in the case of boron, we need to state that in this study (Experiment I) plants of cv. Alboney F_1 yielded best at B contents in indicator parts of $33.24\text{--}78.58 \text{ mg}\cdot\text{kg}^{-1}$, whereas for cv. Emotion F_1 it was at $79.44 \text{ mg}\cdot\text{kg}^{-1}$. In analyses with the use of boric acid (Experiment II), cv. Alboney F_1 yielded best at B contents in indicator parts of $32.80\text{--}80.62 \text{ mg}\cdot\text{kg}^{-1}$, whereas for cv. Emotion F_1 at $83.89 \text{ mg}\cdot\text{kg}^{-1}$. Recorded B contents were lower than those reported by Komosa et al. [23] in their studies on yielding of cv. Emotion F_1 in closed systems with recirculation and without recirculation of the nutrient solution.

Variety	B-I	B-II	B-III	B-IV	Mean
Experiment I					
B content in leaves					
Alboney F_1	33.24 a	78.58 b	167.46 d	207.02 f	121.57 B
Emotion F_1	37.94 a	79.44 b	139.83 c	188.68 e	111.47 A
Mean	35.59 A	79.01 B	153.65 C	197.85 D	
Experiment II					
B content in leaves					
Alboney F_1	32.80 a	80.62 c	173.56 e	218.30 g	126.32 B
Emotion F_1	45.17 b	83.89 c	148.61 d	195.83 f	118.37 A
Mean	38.98 A	82.25 B	161.09 C	207.07 D	

Notes: Means in rows marked with various big letters differ significantly; means in columns marked with various big letters differ significantly; means in rows and columns marked with various small letters differ significantly.

Table 6. The influence of boron nutrition on content of B in leaves (in mg kg^{-1} d.m.).

2.2.5.4. Chemical composition of fruits

In this study, the content of B in tomato fruits was dependent on B content in the nutrient solution used in fertigation (**Table 7**). The greatest B content in fruits of tomato cv. Alboney F_1 was recorded in combinations B-III ($16.30 \text{ mg}\cdot\text{kg}^{-1}$) and B-IV ($16.43 \text{ mg}\cdot\text{kg}^{-1}$), while for cv. Emotion F_1 in combination B-IV ($17.30 \text{ mg}\cdot\text{kg}^{-1}$). Differences in B contents in fruits were shown only in the B-II combination (Experiment I). In all the combinations, significant differences were observed between cultivars in terms of B contents (Experiment II). Significantly greater B contents were assayed in fruits of cv. Emotion F_1 . The greatest mean B content in fruits was recorded in combination B-IV ($26.50 \text{ mg}\cdot\text{kg}^{-1}$). According to other authors, the content of B in tomato fruits is significantly lower in comparison with those recorded in leaves [98,99]. Results obtained in studies on the application of borax for B contents in fruits were lower than those

reported by Komosa et al. [24]. Using boric acid, greater boron levels were found in fruits, while differences were found between cultivars in the mean B content in tomato fruits.

Variety	B-I	B-II	B-III	B-IV	Mean
Experiment I					
B content in fruits					
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	
Experiment II					
B content in fruits					
Alboney F ₁	11.66 a	16.70 b	19.90 c	24.26 d	18.13 A
Emotion F ₁	15.33 b	19.56 c	24.10 d	28.73 e	21.93 B
Mean	13.49 A	18.31 B	22.00 C	26.50 D	

Notes: Means in rows marked with various big letters differ significantly; means in columns marked with various big letters differ significantly; means in rows and columns marked with various small letters differ significantly.

Table 7. The influence of boron nutrition on content of B in fruits (in mg kg⁻¹ d.m.).

3. Conclusions

1. When analyzing the produced marketable yield, it needs to be stressed that the optimal level of B in the nutrient solution for cv. Alboney F₁ amounts to 0.011–0.40 mg dm⁻³, while for cv. Emotion F₁ 0.40 mg B dm⁻³. Increased B content in the nutrient solution caused a significant reduction of the marketable yield in both cultivars. Cultivar Emotion F₁ responded with a decrease in the marketable yield both to a deficit and excess B in the nutrient solution.
2. It needs to be stated that B content in growing mats exceeding 0.93 mg dm⁻³ (Experiment I) causes a significant reduction of plant yielding. However, a further increase in the content of B in nutrient solutions in the rhizosphere up to 1.87 mg dm⁻³ does not cause a significant reduction of the marketable yield between these combinations. The conducted Experiment II using boric acid as a source of B in the nutrient solution showed identical dependencies in the case of the greatest marketable yield; however, the content of B in mats close to 2.00 mg dm⁻³ caused a significant reduction of yielding in comparison with combination B-III (±1.00 mg·dm⁻³).
3. An increase in B contents in the nutrient solution applied in fertigation had a significant effect on the content of this micronutrient in indicator parts of tomato. Results in this study for B contents in indicator parts of tomato at 0.80 and 1.60 indicate a toxic state of nutrition of plants in the case of the investigated micronutrient.

4. In this study, the content of B in tomato fruits was dependent on B content in the nutrient solution used in fertigation. Using boric acid, greater boron levels were found in fruits, while differences were found between cultivars in the mean B content in tomato fruits.

Author details

Bartosz Markiewicz, Tomasz Kleiber and Maciej Bosiacki

Department of Plant Nutrition, University of Life Sciences, Poznan, Poland

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