Journal of Elementology ISSN 1644-2296

Kleiber T., Bosiacki M., Breś W. 2015. *The effect of choline-stabilized orthosilic acid application on tomato grown under increasing Mn stress*. J. Elem., 20(4): 897-910. DOI: 10.5601/jelem.2015.20.1.820

THE EFFECT OF CHOLINE-STABILIZED ORTHOSILIC ACID APPLICATION ON TOMATO GROWN UNDER INCREASING MN STRESS

Tomasz Kleiber, Maciej Bosiacki, Włodzimierz Breś

Chair of Plant Nutrition
Poznań University of Life Sciences

Abstract

The aim of the study has been to assess the efficiency of choline-stabilized orthosilic acid (ch-O-SA; bioavailabile form of silicon) application under increasing intensity of manganese stress on the chemical composition of plants and yielding of tomato (*Lycopersicon esculentum* Mill. cv. Alboney F_1 and cv. Emotion F_1). Plants were grown in rockwool with the application of a nutrient solution of the following chemical composition (mg dm^{-3}): N-NH_4 2.2, N-NO_3 230, P 50, K 430, Ca 145, Mg 65, Cl 35, S-SO_4 120, Fe 2.48, Zn 0.50, Cu 0.07; pH 5.50, EC 3.00 mS cm^{-1}. The following manganese levels in the nutrient solution were tested (mg dm^{-3}): 9.6 and 19.2. The effect of ch-OSA application (at a concentration of Si equal 0.3 mg dm^{-3} of the nutrient solution) was investigated at both Mn-levels. The ch-OSA application alleviated Mn toxicity by increasing the biomass production in the Mn-low variant (+ 8.2% for Alboney F_1 and 16.8% for Emotion F_1, the differences being significant for Emotion F_1), whereas the ch-OSA application in the Mn-high variant did not influence the plant yielding. All the factors affected the plant nutrient status and the chemical composition of tomato fruits. The chemical composition of leaves depended on (means of all the studied combinations): Mn (K, Na) and ch-OSA nutrition (N, Mg, Na), cultivar (for P, K, Ca, Na), but in the case of fruits significant differences were found between Mn (N, P, Ca, Mg) and ch-OSA nutrition (N, Mg, Na) and cultivar (N, P). In both Mn-levels, visual symptoms of manganese toxicity appeared on plants – in the Mn-high variant, they were observed after 4 weeks, while in the case of the Mn-low variant - after 10 weeks of exposure to strong Mn-stress. Treatment with ch-OSA at both of the studied Mn levels did not prevent the development of visual toxicity symptoms on the plants.

Keywords: ch-OSA, silicon, *Lycopersicon esculentum* Mill., fertigation, manganese, yielding, leaves, fruits, macronutrients.

---

dr inż. Tomasz Kleiber, Chair of Plants Nutrition, Poznań University of Life Sciences, Zgorzelecka 4, 60-198 Poznań, Poland, e-mail: tkleiber@up.poznan.pl

INTRODUCTION

The optimal level of Mn in the nutrient solution used for tomato fertigation ranges from 0.3 to 0.6 mg dm^{-3} and could vary from cultivar to cultivar (Kleiber et al. 2014). Most of groundwater to a depth of 100 m contains lower quantities of this micronutrient, while about 5% of water used to prepare nutrient solutions may contain 1 - 4.5 and even up to 10 mg Mn dm^{-3} (Sawiniak 1990). Precision of micro-nutrition significantly affects plant yielding (Kleiber et al. 2014).

Silicon is an element which alleviates the Mn-stress of plants (Epstein 1999, Iwasaki, Matsumura 1999, Shi et al. 2010) and may significantly change the nutrient uptake and plant yielding (Epstein 1999, Aziz et al. 2002, Jarosz 2013). The earliest studies focusing on this problem were conducted on lettuce as a model plant, using e.g. silica sol and choline- stabilized orthosilic acid (ch-OSA) as sources of Si (Kleiber 2014*a*, Kleiber et al. 2015). Ch-OSA is known as a bioavailable form of silicon (EUROPEAN FOOD SAFETY AUTHORITY 2009) and may also be used in human therapy (Spector et al. 2008): combined ch-OSA treatment with Ca/Vit D3 had a potential beneficial effect on bone collagen compared to Ca/Vit D3 alone, which suggests that this treatment is of potential use in osteoporosis.

The aim of the conducted study was to alleviate the effect of choline- stabilized orthosilic acid (ch-OSA; as sources of the bioavailable silicon form) treatment on tomato grown under varied Mn stress. Research on the alleviation of stress caused by an excessive Mn content in a nutrient solution is of particular importance in the case of tomato because of its large cultivation area and high consumption (GUS 2012).

MATERIAL AND METHODS

Plant-growing experiments were conducted in 2013-2014 in a greenhouse of the Department of Plant Nutrition, the Poznań University of Life Sciences. The aim of this study was to assess the effect of ch-OSA application under increasing Mn stress on the chemical composition of leaves and fruits and plant yielding of tomato grown in rockwool. The experiments were established using the randomized complete block design in 4 replications. Biological pest control was applied. All cultivation measures were performed in accordance with the current recommendations for tomato growing.

The experiments were conducted on two tomato cultivars (*Lycopersicon esculentum* Mill. cv. Alboney F_1 and cv. Emotion F_1), with 3 studied factors: A – Mn nutrition; B – ch-OSA treatment (source of bioavailable Si); C – cultivar. Seeds were sown to cultivation cups in the 3rd decade of March in each year of the study. After 2-3 weeks, seedlings were transplanted to rockwool cubes (10 × 10 × 10 cm). Plants were transplanted to permanent beds in the first week of May. The experiment was continued until the end of August each year. Plants, after their transplantation to the permanent site, were fertigated with a standard nutrient solution of the following chemical composition (mg dm^{-3}): N-NH$_4$ 2.2, N-NO$_3$ 230, P 50, K 430, Ca 145, Mg 65, Cl 35, S-SO$_4$ 120, Fe 2.48, Zn 0.50, Cu 0.07, pH 5.50 and EC 3.00 mS cm^{-1}. Plants were grown in standard rockwool (Grodan, 100 x 15 x 7.5 cm, 60 kg m^{-3}) at a stocking of 2.5 plants m^{-2}.The following Mn nutrition levels were examined (mg dm^{-3}): 9.6 and 19.2 (denoted as Mn-9.6/Mn-low and Mn-19.2/Mn-high). In each Mn treatment, the effect of ch-OSA application (content of Si equal 0.3 mg dm^{-3} of nutrient solution) was investigated. Manganese II sulfate monohydrate pure *pro analisis* ($MnSO_4 \cdot H_2O$, 32.3% Mn) and choline-stabilized orthosilicic acid (ch-OSA; 0.6% Si; Actisil; Yara Poland) were the sources of the analyzed nutrients. The fertilizer dose in the nutrient solution depended on the development phase of plants and climatic conditions in the greenhouse. During the intensive yielding of plants and high temperatures (June – August) 3.0-3.5 dm^3 nutrient solution per plant was supplied daily in 15-20 single doses, with 20-30% effusion of drain water from the slabs.

During the plants' growth and development, material samples were collected to determine the content of N, P, K, Ca, Mg and Na. The index parts (8th-9th fully expanded leaves counting from the apex) were collected at monthly intervals (15.06, 15.07 and 16.08 each year). One bulk sample comprised 6 leaves. Every year, in the first decade of August representative samples of fruits were also collected. In order to determine the total forms of nitrogen, phosphorus, potassium, calcium, magnesium and sodium, homogenized plant material was digested in concentrated sulphuric acid. After plant material mineralization, the following determinations were made: total nitrogen – by the distillation method acc. to Kjeldahl in a Parnas-Wagner apparatus, phosphorus – colorimetrically with ammonium molybdate (acc. to Schillak), potassium, calcium, magnesium and sodium – by atomic absorption spectrometry method (on a Carl Zeiss Jena apparatus). The results were processed by Anova and the Duncan test ($\alpha = 0.05$).

RESULTS ANS DISCUSSION

Plant yielding and toxicity symptoms

The optimal level of Mn in the nutrient solution in the case of Alboney F$_1$ ranges from 0.3 to 0.6 mg dm^{-3}, while in the case of Emotion F$_1$ it equals 0.6 mg dm^{-3} (Kleiber et al. 2014). Excessive Mn nutrition caused a significant reduction of plant yielding and led to chemical problems with the nutrient status of plants. The plant yielding was found to have been decreasing under the growing manganese stress (Figure 1). At the Mn-low level for both cultivars treated with ch-OSA, an upward trend for fruit yielding was found, but

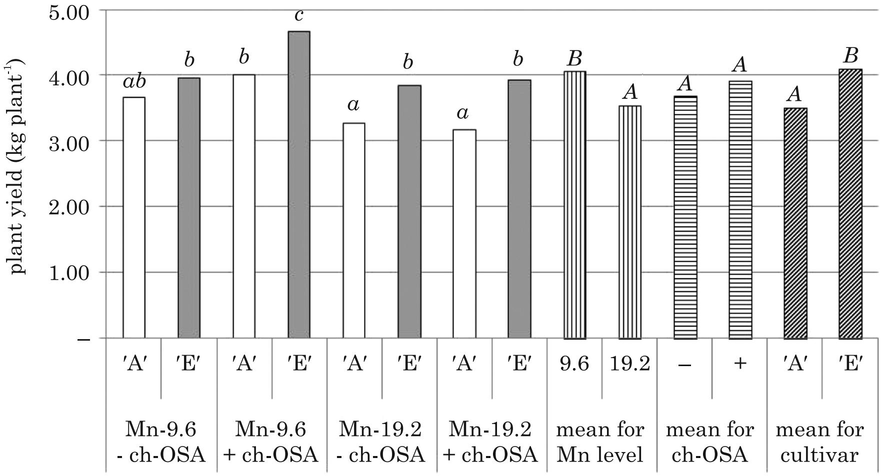

Fig. 1. The influence of manganese and choline-stabilized orthosilic acid (ch-OSA) nutrition on tomato yield (mean from the years 2013-2014, kg plant^{-1})

Key for Figures 1 and 2: means marked with different small letters differ significantly; means marked with different capital letters differ significantly (separately for each factor)

it was significant only in cv. Emotion F_1. At the Mn-high level, there was no significant influence of ch-OSA treatment on yielding. Similar findings were reported by Iwasaki et al. (2002): the alleviating effect of Si nutrition could vary depending on the severity of manganese stress. The mean yield of fruits from cv. Emotion F_1 was higher than from Alboney F_1. Shi et al. (2010) confirms that the response of plants under heavy metal stress to Si nutrition could be cultivar-specific. In terms of the mean of all the combinations, the treatment with ch-OSA did not differentiate tomato yielding. Typical and characteristic symptoms of Mn toxicity are brown spots in older leaves, which may also be followed by chlorosis and necrosis, and the browning of roots (Horst, Marschner 1978). Brown spots appear where oxidized Mn and oxidized phenolic compounds accumulate in the walls of epidermal cells (Horiguchi 1987, Wissemeier, Horst 1992). The earliest symptoms of Mn-toxicity on the plants (midrib browning and browning of leaf blade margins, as well as necrosis of leaves and decay vertex inflorescences) were manifested appeared after about 4 weeks of exposure to Mn-19.2. In the case of Mn-9.6, despite a markedly increased plant yielding for Alboney F_1 and a significantly increased plant yielding for Emotion F_1 induced by choline-stabilized orthosilicic acid, Mn toxicity symptoms were observed after 10 weeks of exposure. The application of ch-OSA did not prevent visual toxicity symptoms on the plants at either of the tested Mn-levels.

Silicon is involved in the metabolic or physiological changes in plants (Liang 1999). Different forms of this element, e.g. choline-stabilized orthosilicic acid and silica sol, may be used to alleviate the Mn stress of plants. Kleiber (2014*a*) proved that an increased ch-OSA concentration in a nutrient solution (within range 0.21-0.63 mg Si dm^{-3}) significantly improved the yielding of lettuce grown under strong Mn-stress. Si lowered the apoplastic Mn concentration in cowpea and may modify the cation binding capacity of the cell wall (Horst et al. 1999). One possible mechanism occurring between Si and the metals is the reduction of the activity of toxic metal ions in the medium (Hiradate et al. 1998). Benefits of silicon actuation have recently been reported in connection with physiological parameters such as stomatal conductance (Gunes et al. 2007) or photosynthesis (Sacała 2009). Lobato et al. (2013) stated that an increased Si nutrition under water deficiency caused positive and significant changes of transpiration rate and the chlorophyll (a, b and total) content. Kleiber et al. (2015) observed that higher Si concentrations in a nutrient solution (in the form of silica sol) significantly influenced plant nutrient status and alleviated the Mn stress as well as stimulating fresh matter production, RWC (Relative Water Content) and the number of leaves in lettuce. The response to Si nutrition could vary depending on a cultivar (Lobato et al. 2013). Generally, positive symptoms of Si nutrition under Mn-stress include an increase in biomass production (Maksimović et al. 2007, 2012). Manganese present in Si-treated plants is therefore less available and for this reason less toxic than in plants not treated with Si (Rogalla, Römheld 2002). Also, other authors observed a similar tendency for improved tomato yielding after Si nutrition (Stamatakis et al. 2003, Toresano-Sanchez et al. 2012, Jarosz 2014). A similar positive effect of Si nutrition on growth of horticultural plants under Mn stress was found for cucumber (Rogalla, Römheld 2002).

Plant chemical composition

The determined content of N, P, K, Ca, Mg and Na was higher in leaves than in fruits (Tables 1-2, Figure 2). Generally the content of nitrogen in

Table 1

The influence of manganese and choline-stabilized orthosilic acid (ch-OSA) nutrition on the content of N, P, K in tomato leaves (g kg^{-1} DM) and their coefficients of variation (CV, %) mean from the years 2013-2014

Mn level (A)	ch-OSA (B)	Cultivar (C)	Term				CV (%)	
			June	July	August	mean		
N								
9.6	-	Alboney F_1	35.7	33.6	31.5	33.6 *bc*	5.10	
		Emotion F_1	28.7	28.0	27.3	28.0 *a*	2.04	
	+	Alboney F_1	38.5	34.7	30.8	34.7 *bc*	9.07	
		Emotion F_1	34.1	34.2	34.6	34.3 *bc*	0.01	
19.2	-	Alboney F_1	35.0	33.3	31.5	33.3 *bc*	4.30	
		Emotion F_1	32.9	32.2	31.5	32.2 *bc*	1.77	
	+	Alboney F_1	30.1	30.8	31.5	30.8 *ab*	1.86	
		Emotion F_1	40.6	36.1	31.5	36.1 *c*	10.31	
		mean	34.5	32.8	31.3			
Mean for A	Mn-9.6	32.6 *A*	mean for B	ch-OSA -	31.8 *A*	mean for C	Alboney F_1	33.1 *A*
	Mn- 19.2	33.1 *A*		ch-OSA +	34.0 *B*		Emotion F_1	32.6 *A*

cont. Table 1

Mn level (A)	ch-OSA (B)	Cultivar (C)	Term				CV (%)	
			June	July	August	mean		
				P				
9.6	-	Alboney F$_1$	7.89	8.35	8.90	8.38 *a*	4.93	
		Emotion F$_1$	9.35	10.22	11.00	10.19 *ab*	6.61	
	+	Alboney F$_1$	8.67	9.12	9.54	9.11 *a*	3.90	
		Emotion F$_1$	11.18	11.97	12.70	11.95 *b*	5.19	
19.2	-	Alboney F$_1$	7.87	10.24	12.60	10.24 *ab*	18.86	
		Emotion F$_1$	9.80	10.22	10.50	10.17 *ab*	2.83	
	+	Alboney F$_1$	6.55	8.57	10.50	8.54 *a*	18.88	
		Emotion F$_1$	7.41	8.80	10.30	8.84 *a*	13.35	
		mean	8.59	9.69	10.76			
Mean for A	Mn-9.6	9.99 A	mean forB	ch-OSA -	9.75 *A*	mean for C	Alboney F$_1$	9.07 *A*
	Mn-19.2	9.44 A		ch-OSA +	9.61 *A*		Emotion F$_1$	10.30 *B*
				K				
9.6	-	Alboney F$_1$	48.8	48.3	45.3	47.5 *c*	3.18	
		Emotion F$_1$	40.9	42.4	42.6	42.0 *a*	1.83	
	+	Alboney F$_1$	46.0	47.5	48.8	47.4 *c*	2.43	
		Emotion F$_1$	48.9	47.5	48.0	48.1 *c*	1.19	
19.2	-	Alboney F$_1$	48.5	46.3	43.6	46.1 *bc*	4.34	
		Emotion F$_1$	45.0	43.2	42.6	43.6 *ab*	2.32	
	+	Alboney F$_1$	47.4	45.7	43.5	45.5 *bc*	3.51	
		Emotion F$_1$	40.6	43.1	45.6	43.1 *ab*	4.72	
		mean	45.8	45.5	45.0			
Mean for A	Mn-9.6	46.3 *B*	mean forB	ch-OSA -	44.9 *A*	mean for C	Alboney F$_1$	46.7 *B*
	Mn-19.2	44.6 *A*		ch-OSA +	46.0 *A*		Emotion F$_1$	44.2 *A*

Key for Tables 1 and 2: means in columns marked with different small letters differ significantly; means in columns marked with different capital letters differ significantly (separately for each factor)

leaves was stable for Alboney F$_1$, but it increased with the higher Mn concentration for Emotion F$_1$. The nitrogen content in leaves was influenced by the ch-OSA treatment, whereas no effect of a cultivar was observed. The most stable content of nitrogen during the plant growing period was recorded in Emotion F$_1$ at Mn-low treated with ch-OSA (coefficient of variation: CV 0.01%) while the biggest fluctuations were found for the same cultivar at Mn-high with ch-OSA application (CV 10.31%; Table 1). In most cases, the coefficient of variation did not exceed 10%. The mean content of nitrogen from all variants of the studied factors was lower in the last term of sampling (August; -6.48%) than in June. In the case of plants grown at Mn-low treated and un-treated with ch-OSA (separately in cv.), the N content trend during the growing season was similar. The N content trend in fruits depended on Mn (higher for Mn-19.2) and Si (higher for ch-OSA+) nutrition as well as the cultivar (higher content was determined for Alboney F$_1$). The content of phosphorus in leaves depended significantly on a cultivar. Neither Mn level nor ch-OSA nutrition influenced the content of this nutrient. The

Table 2

The influence of manganese and choline-stabilized orthosilic acid ch-OSA nutrition on the content of Ca, Mg, Na in tomato leaves (g kg^{-1} DM) and their coefficients of variation (CV, %), mean from the years 2013-2014

Mn level (A)	ch-OSA (B)	Cultivar (C)	Term				CV (%)	
			June	July	August	mean		
Ca								
9.6	-	Alboney F_1	23.6	28.5	30.4	27.5 *a*	10.51	
		Emotion F_1	25.1	28.6	32.5	28.7 *a*	10.50	
	+	Alboney F_1	21.4	28.2	37.4	29.0 *a*	22.64	
		Emotion F_1	40.0	37.3	38.1	38.4 *b*	2.95	
19.2	-	Alboney F_1	30.7	31.9	33.6	32.1 *ab*	3.63	
		Emotion F_1	23.7	33.0	45.8	34.1 *ab*	26.47	
	+	Alboney F_1	26.7	31.3	32.2	30.1 *ab*	8.08	
		Emotion F_1	37.6	38.5	39.2	38.4 *b*	1.67	
		mean	28.6	32.2	36.1			
Mean for A	Mn-9.6	30.8 *A*	mean for B	ch-OSA -	30.6 *A*	mean for C	Alboney F_1	29.7 *A*
	Mn- 19.2	33.8 *A*		ch-OSA +	33.9 *A*		Emotion F_1	34.8 *B*
Mg								
9.6	-	Alboney F_1	7.81	7.51	7.97	7.76 *a*	2.46	
		Emotion F_1	8.29	7.68	7.06	7.68 *a*	6.54	
	+	Alboney F_1	9.16	7.92	6.74	7.94 *a*	12.45	
		Emotion F_1	11.66	9.21	6.97	9.28 *ab*	20.64	
19.2	-	Alboney F_1	7.60	7.74	7.59	7.64 *a*	0.87	
		Emotion F_1	6.92	7.53	7.92	7.46 *a*	5.52	
	+	Alboney F_1	8.71	9.11	9.52	9.11 *ab*	3.63	
		Emotion F_1	11.65	10.35	8.76	10.25 *b*	11.53	
		mean	8.98	8.38	7.82			
Mean for A	Mn-9.6	8.14 *A*	mean for B	ch-OSA -	7.63 *A*	mean for C	Alboney F_1	8.10 *A*
	Mn-19.2	8.63 *A*		ch-OSA +	9.15 *B*		Emotion F_1	8.67 *A*
Na								
9.6	-	Alboney F_1	0.17	0.18	0.20	0.19 *a*	7.52	
		Emotion F_1	0.15	0.18	0.21	0.18 *a*	15.72	
	+	Alboney F_1	0.23	0.23	0.22	0.23 *ab*	2.16	
		Emotion F_1	0.35	0.32	0.29	0.32 *bc*	8.60	
19.2	-	Alboney F_1	0.19	0.18	0.16	0.18 *a*	7.71	
		Emotion F_1	0.17	0.20	0.23	0.20 *a*	12.00	
	+	Alboney F_1	0.19	0.22	0.26	0.22 *ab*	13.96	
		Emotion F_1	0.27	0.41	0.54	0.41 *c*	27.73	
		mean	0.17	0.18	0.20			
Mean for A	Mn-9.6	0.22 *A*	mean for B	ch-OSA -	0.18 *A*	mean for C	Alboney F_1	0.20 *A*
	Mn-19.2	0.25 *B*		ch-OSA +	0.29 *B*		Emotion F_1	0.28 *B*

recorded coefficients of variation in the case of phosphorus varied from 2.83 to 18.88% (respectively for Emotion F_1 at Mn-high and Alboney F_1 at the same Mn-level treated with ch-OSA). In most cases, the coefficient of varia-

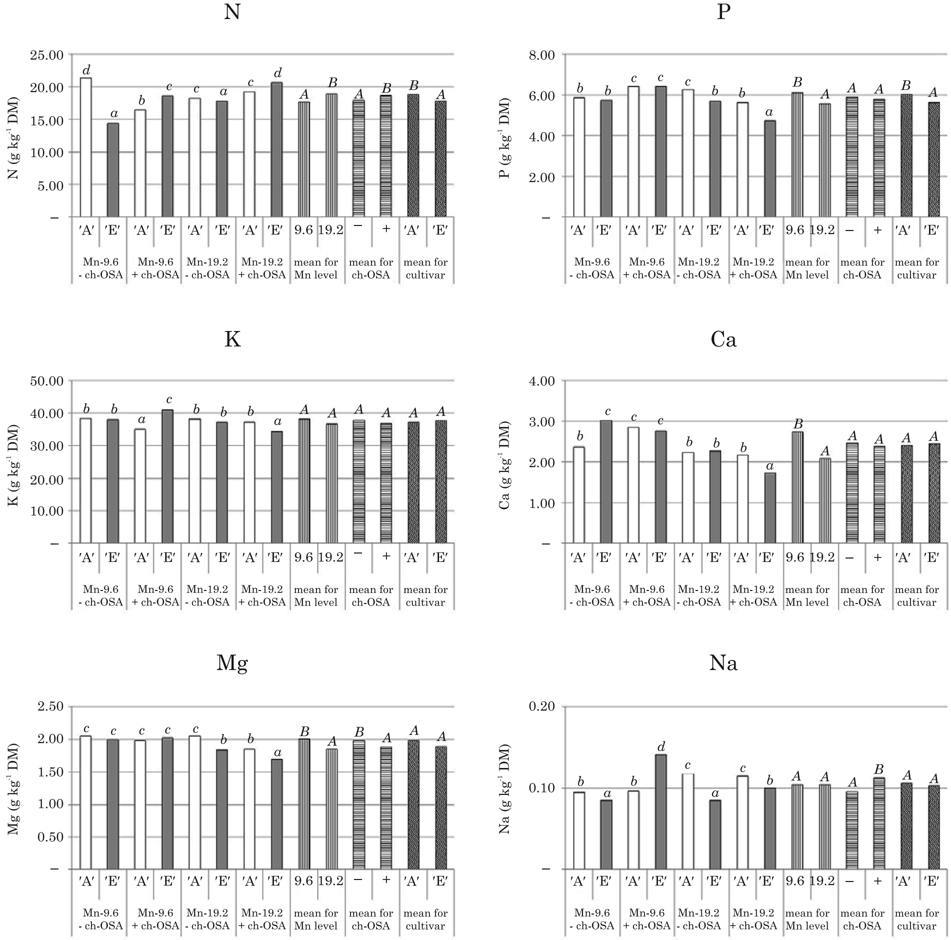

Fig. 2. The influence of manganese and choline-stabilized orthosilic acid (ch-OSA) nutrition on macronutrient and sodium content in tomato fruits (mean from the years 2013-2014, g kg^{-1} DM)

tion did not exceed 10%. During the plant growing period, the mean content of P in leaves increased by about 25.3% (from June to August). A similar trend was found in every combination. In fruits, the mean P content varied, depending on the Mn-level and cultivar. At the low-Mn variant, ch-OSA application caused a significant increase in the fruit P content, but a reverse trend was determined in the Mn-high variant. At the Mn-low combination, ch-OSA application caused a significant increase in the content of potassium in cv. Emotion F$_1$ (both in leaves and fruits), while in the case of Alboney F$_1$ the above treatment decreased the K content in fruits. In the Mn-high variant, the content of potassium in leaves was stable, but decreased significantly in fruits of cv. Emotion F$_1$ under the ch-OSA treatment. For mean values, a significant influence of the Mn-level and cultivar was found in the case of the K content in leaves, but the effect on the fruit K content was non-significant. Generally, the content of potassium in leaves was stable comparing with N and P – the coefficient of variation ranged from 1.19 to 4.72% (for Emotion F_1 at Mn-low/ch-OSA+ and Mn-high treated with ch-OSA). The mean content of K in the subsequent months was similar (Table 1).

The calcium content in leaves in the Mn-low variant significantly increased for Emotion F_1 after ch-OSA application to the nutrient solution used for plant fertigation, but the other determined changes were non-significant (Table 2). In turn, in the case of fruits, a significant upward trend was found after ch-OSA in cv. Alboney F_1 in the Mn-low variant (Figure 2). At the Mn-high level, ch-OSA+ caused a significant reduction in the content of Ca in cv. Emotion F_1. In terms of the mean values, the cultivar's Ca content in leaves changed, but a significant impact of the Mn-level was observed in fruits. The coefficient of variation (CV) ranged from 1.67 to 26.47 (for cv. Emotion F_1 at Mn-high, treated and un-treated with ch-OSA). Generally, the content of calcium in leaves increased during the plant growing period (mean about 26.2%; except cv. Emotion at Mn-low treated with ch-OSA, where the content of Ca decreased). The mean content of magnesium in leaves was significantly higher under the application of choline-stabilized orthosilic acid. At Mn-high, in cv. Emotion F_1 treated with ch-OSA as a source of Si the Mg status of leaves improved significantly. In fruits, both Mn and ch-OSA nutrition significantly influenced the content of magnesium. For the Mn-high variant, a significant decrease of the Mg content in both cultivars was observed in ch-OSA-treated plants. The most stable content of magnesium was recorded in Alboney F_1 at Mn-high un-treated with ch-OSA (CV 0.87%), while the highest fluctuations (CV 20.64%) were found for cv. Emotion F_1 at Mn-low with ch-OSA application. Nonetheless, in most cases, the coefficient of variation did not exceed 10%. The mean content of Mg during the growing season decreased by about 14.8%, although some discrepancies were found (Alboney F_1: at Mn-low untreated with ch-OSA and Mn-high untreated/treated with ch-OSA; Emotion F_1 at Mn-high ch-OSA-). The treatment of plants with ch-OSA caused a significant upward trend for the sodium content in leaves and fruits of cv. Emotion F_1 (both in Mn-low and Mn-high). The content of Na in leaves was significantly influenced by all the studied factors, while in fruits it was only modified by ch-OSA application. The recorded coefficients of variation (CV) of the Na content were highly varied: from 2.16% (Alboney F_1 at Mn-low treated with ch-OSA) to 27.73% (Emotion F_1 at Mn-high treated with ch-OSA). The mean content of sodium in leaves increased by about 15%, from 0.17 to 0.20 g kg^{-1} DM (June – August), except Alboney F_1/Emotion F_1 at Mn-low treated with ch-OSA, Alboney F_1 at Mn-high untreated with ch-OSA).

The research results showed a significant influence of manganese and ch-OSA (as a source of silicon) nutrition on the chemical composition of leaves. Silicon promotes modifications of nitrogen metabolism (Watanabe et al. 2001). In studies conducted with a fertilizer containing choline-stabilized orthosilic acid as a source of Si, Kleiber (2014*a*) reported significant changes of macro- and micronutrient content in aerial parts of lettuce grown under Mn-stress: a downward trend for N (for 0.21 and 0.63 mg Si dm^{-3}), an upward trend for P (for 0.42 and 0.63 mg Si dm^{-3}), K (for 0.21 and 0.42 mg Si dm^{-3}), Ca (for all the Si-treatments) and Mg (only for 0.21 mg Si dm^{-3}), while no significant changes were observed in the Na content when compared with the control. Lee et al. (2000) claimed that Si addition to the nutrient solution had a positive effect on the P uptake. The content of Si in the plant root zone significantly influenced the potassium content in leaves (Jarosz 2013), which was also detected in oour experiments, *albeit* only in cv. Emotion F_1 grown in the Mn-low variant. Silicon treatment may increase the Ca concentration in plant tissues and hence restore membrane integrity (Kaya et al. 2006). Silicon also significantly improves RWC. Potassium and sodium are important nutrients in the osmotic adjustment of plants. In the current study, significant changes in the content of those nutrients (especially sodium) were found in combinations including ch-OSA application. Kaya et al. (2006) reported that under drought stress Si nutrition may result in an improved supply of potassium. Aziz et al. (2002) found a decrease in the content of N and K in plants with a simultaneous increase in the content of Ca and Mg in plants under Si nutrition. Silicon nutrition has a limited effect on calcium concentrations in plants (Liang 1999), but the actual response could vary from cultivar to cultivar. Many authors found a decrease in the content of calcium in plants under increasing Si nutrition (Ma, Takahashi 1993, Epstein 1999, Chen et al. 2011, Jarosz 2013). In the current study, the Na content was found to increase under ch-OSA application, whereas some authors (Matoh et al. 1986, Liang 1999) found an opposite trend for the sodium content. Matoh et al. (1986) reported also a positive influence of Si on dry matter production in salinity stressed plants.

The chemical composition of fruit harvested from plants of the Si treatment with a standard level of manganese in the nutrient solution (0.54 mg dm^{-3}) showed similar levels of elements to those in the control, except for manganese (Jarosz 2014). Kleiber (2014*b*) found similar nitrogen content in tomato fruits stressed by an increasing intensity of manganese nutrition (9.6 and 19.2 mg dm^{-3} of nutrient solution) and a similar trend for the phosphorus content, although the concentrations determined by this author were two-fold higher. Jarosz (2013) showed a positive influence of Si (in the form of silica sol) manifested by a decreasing N content in cucumber fruits. The K content in fruit determined in the present study was similar to that found by Kleiber (2014*b*). The content of K and Ca in cucumber fruits varied depending on a Si concentration in the root zone of plants (Jarosz 2013). It is known that increased Mn nutrition causes a significant reduction of Ca and Mg levels in tomato fruits (Kleiber 2014*b*).

Notably, the response of the two tomato cultivars in the Mn-low variant was a varied, with a positive influence of ch-OSA application to the nutrient solution on plant yielding. In the case of cv. Emotion F_1, the application of Si significantly increased the content of N, K, Ca and Na in leaves when compared with the un-treated plants. Simultaneously, an upward trend was found for N, P, K and Na in tomato fruits, which coincided with the stable levels of Ca and Mg. The response of cv. Alboney F_1 was different, with no changes of N, P, K, Ca, Mg and Na levels in leaves and an increasing content of P and Ca, decreasing content of N and K and no significant changes of Mg and Na levels in tomato fruits. The chemical composition of tomato leaves depended on (means for all the studied combinations): Mn (K, Na) and ch-OSA nutrition (N, Mg, Na), cultivar (for P, K, Ca, Na). In the case of fruits, significant differences were found between Mn (N, P, Ca, Mg) and ch-OSA nutrition (N, Mg, Na) and cultivar (N, P). The coefficients of variation (CV) of nutrients in leaves ranged from (in %): N 0.01-10.31; P 2.83-18.88; K 1.19-3.72; Ca 1.67-26.47; Mg 0.87-20.64; Na 2.16-27.73. A coefficient of variation in the range of 0-20% indicates low diversity, while in the range of 20-40% suggests average variation between the sampling dates. In many cases, the variability of the nutrients should be considered to be low. Given all the factors, greater variability (CV) was demonstrated in the case of cv. Emotion F_1' than cv. Alboney F_1. Also the increasing Mn nutrition and ch-OSA application caused higher variability.

CONCLUSIONS

1. The increasing manganese nutrition and tomato cultivar significantly influenced plant yielding.

2. The response of tomato plants to the application of choline-stabilized orthosilic acid (ch-OSA) as a bioavailable form of silicon varied: ch-OSA treatment improved plant yielding at Mn-low (significant for cv. Emotion F_1) but did not influence the yielding of either cultivar at Mn-high level.

3. All the experimental factors affected the plant nutrient status and chemical composition of tomato fruits.

4. The treatment with ch-OSA increased the N and Na content and decreased the Mg content, while Mn nutrition significantly increased the content of N and decreased the content of P, Ca and Mg in tomato fruits. A significantly higher content of N and P in fruits was determined for cv. Alboney F_1.

5. The chemical composition of leaves depends on (means of all the studied combinations): Mn (K, Na) and ch-OSA nutrition (N, Mg, Na) and cultivar (for P, K, Ca, Na).

6. The ccoefficients of variation (CV) of the nutrients in leaves ranged from (in %): N 0.01-10.31; P 2.83-18.88; K 1.19-3.72; Ca 1.67-26.47; Mg 0.87-20.64; Na 2.16-27.73.

7. Despite the improved yielding of plants treated with ch-OSA in the Mn-low variant, visual symptoms of manganese toxicity appeared on the plants. Visual symptoms were also noticed in the Mn-high variant.

ACKNOWLEDGMENTS

The authors wish to thank the Yara Poland company for their assistance in conducting this experiment.

REFERENCES

Aziz T., Ahmad M., Rahmatullach M. 2002. *Silicon nutrition and crop production: a review*. Pak. J. Agri. Sci., 39(3): 181-187.

Chen W., Yao X., Cai K., Chen J. 2011. *Silicon alleviated drought stress of rice plants by improving plant water status, photosynthesis and mineral nutrient absorption*. Biol., Trace Elem. Res., 141(1): 67-76. DOI: 10.1007/s12011-010-8742-x

Epstein E. 1999. *Silicon*. Annu. Rev. Plant Physiol. Plant Mol. Biol. 50: 641-664.

EUROPEAN FOOD SAFETY AUTHORITY (EFSA) 2009. *Scientific opinion of the panel on food additives and nutrient sources added to food on choline-stabilised orthosilicic acid added for nutritional purposes to food supplements following a request from the European Commission*. EFSA J., 948: 1-23.

Gunes A., Inal A., Bagci E.G., Coban S., Pilbeam D.J. 2007. *Silicon mediates changes to some physiological and enzymatic parameters symptomatic for oxidative stress in spinach (Spinacia oleracea* L.*) grown under B toxicity*. Sci Hort., 113: 113-119.

GUS 2012. *Condition of households in 2011, in the light of the results of the household budget survey*. The Main Statistical Office in Poland (GUS), Warszawa. [http://www.stat.gov.pl / cps/rde/xbcr/gus/WZ_budzety_gospodarstw_domowych_w_2011.pdf]

Hiradate S., Taniguchi S., Sakurai K. 1998. *Aluminum speciation in aluminum-silica solutions and potassium chloride extracts of acidic soils*. Soil Sci. Soc. Am. J., 62: 630-636. DOI: 10.2136/sssaj1998.03615995006200030012x

Horiguchi T. 1987. *Mechanism of manganese toxicity and tolerance of plants*. II. *Deposition of oxidized manganese in plant tissue*. Soil Sci. Plant Nutr., 33: 595-606. DOI: 10.1080/00380768.1987.10557608

Horst W.J., Marschner H. 1978. *Effect of silicon on manganese tolerance of bean plants (Phaseolus vulgaris* L.). Plant Soil, 50: 287-303. DOI: 10.1007/BF02107179

Horst W.J., Fecht, M., Naumann, A., Wissemeier, A.H., Maier, P. 1999. *Physiology of manganese toxicity and tolerance in Vigna unguiculata (*L.*)* Walp. J. Plant Nutr Soil Sci., 162: 263-274.

Iwasaki K., Maier P., Fecht M., Horst W.J. 2002. *Effects of silicon supply on apoplastic manganese concentrations in leaves and their relation to manganese tolerance in cowpea (Vigna unguiculata (*L.*)* Walp.*)*. Plant Soil, 238: 281-288. DOI: 10.1023/A: 1014482911196

Iwasaki K., Matsumura A. 1999. *Effect of silicon on alleviation of manganese toxicity in pumpkin (Cucurbita moschata* Duch cv. Shintosa). Soil Sci. Plant Nutr., 45: 909-920. DOI: 10.1080/00380768.1999.10414340

Jarosz Z. 2013. *The effect of silicon application and type of substrate on yield and chemical composition of leaves and fruit of cucumber*. J. Elem., 18(3): 403-414. DOI: 10.5601/jelem.2013.18.3.05

Jarosz Z. 2014. *The effect of silicon application and type of medium on yielding and chemical composition of tomato*. Acta Sci. Pol., Hort. Cult., 13(4): 171-183.

Kaya C., Tuna L., Higgs D. 2006. *Effect of silicon on plant growth and mineral nutrition of maize grown under water-stress conditions.* J. Plant Nutr., 29: 1469-1480. DOI: 10.1080/01904160600837238

Kleiber T., Borowiak K., Budka A., Kayzer D. 2014. *Relations between yield, nutrient and water status, and gas exchange parameters of tomato at various Mn concentrations.* Acta Biol. Cracov. Ser. Bot., 56(2): 1-9. DOI: 10.2478/abcsb-2014-0030

Kleiber T. 2014*a*. *The effect of choline-stabilized orthosilicic acid application under Mn excessive nutrition on yielding of hydroponically grown lettuce* (*Lactuca sativa* L.). Aparatura Badawcza i Dydaktyczna, 3: 219-226.

Kleiber T. 2014*b*. *Changes of nutrient contents in tomato fruits under the influence of increasing intensity of manganese nutrition.* Ecol. Chem. Eng. S., 21(2): 297-307. DOI: 10.2478/eces-2014-0023

Kleiber T., Krzesiński W., Przygocka-Cyna K., Spiżewski T. 2015. *The response of hydroponically grown lettuce under Mn stress on differentiated application of silica sol.* J. Elem., 20(3). DOI: 10.5601/jelem.2015.20.1.806

Lee J. S., Park J.H., Suk Han K. 2000. *Effects of potassium silicate on growth, photosynthesis and inorganic ion absorption in cucumber hydroponics.* J. Kor. Soc. Hort. Sci., 45(5): 480-484.

Liang Y.C. 1999. *Effects of silicon on enzyme activity, and sodium, potassium and calcium concentration in barley under salt stress.* Plant Soil, 209: 217-224. DOI: 10.1023/A:1004526604913

Lobato A.K.S., Silva Guedes E.M., D. J. Marques, de Oliveira Neto C.F. 2013. *Silicon: a benefic element to improve tolerance in plants exposed to water deficiency. responses of organisms to water stress.* DOI: http://dx.doi.org/10.5772/53765

Ma J., Takahashi E. 1993. *Interaction between calcium and silicon in water-cultured rice plants.* Plant Soil, 148: 107-113. DOI: 10.1007/BF02185390

Maksimović D.J., Bogdanovic J., Maksimović V., Nikolic M. 2007. *Silicon modulates the metabolism and utilization of phenolic compounds in cucumber (Cucumis sativus* L.*) grown at excess manganese.* J. Plant Nutr. Soil Sci., 170: 739-744. DOI: 10.1002/jpln.200700101

Maksimović D.J., Mojović M., Maksimović V., Römheld V., Nikolic M. 2012. *Silicon ameliorates manganese toxicity in cucumber by decreasing hydroxyl radical accumulation in the leaf apoplast.* J. Exp. Bot., 63(7): 2411-2420. DOI: 10.1093/jxb/err359

Matoh T, Kairusmee P, Takahashi E. 1986. *Salt-induced damage to rice plants and alleviation effect of silicate.* Soil Sci. Plant Nutr., 32: 295-304. DOI: 10.1080/00380768 .1986.10557506

Rogalla H., Römheld V. 2002. *Role of leaf apoplast in silicon-mediated manganese tolerance of Cucumis sativus* L. Plant Cell Environ., 25(4): 549-555. DOI: 10.1046/j.1365-3040.2002.00835.x

Sacała E. 2009. *Role of silicon in plant resistance to water stress.* J. Elem., 14: 619-630.

Sawiniak W. 1990. *Study on the application of iron(III0 hydroxide in removal of large quantities of iron and manganese from groundwater.* Zesz. Nauk. P. Śl. 1053, Inż. Środ., 34. (in Polish)

Shi G., Qingsheng C., Liu C., Li Wu 2010. *Silicon alleviates cadmium toxicity in peanut plants in relation to cadmium distribution and stimulation of antioxidative enzymes.* Plant Growth Regul., 61: 45-52. DOI: 10.1007/s10725-010-9447-z

Spector T.D, Calomme M.R., Anderson S.H., Clement G., Bevan L., Demeester N., Swaminathan R., Jugdaohsingh R., Vanden Berghe D.A., Powell J.J. 2008. *Choline-stabilized orthosilicic acid supplementation as an adjunct to Calcium/Vitamin D3 stimulates markers of bone formation in osteopenic females: a randomized, placebo-controlled trial.* BMC Musculoskeletal Disorders, 9:85. DOI:10.1186/1471-2474-9-85

Stamatakis A., Papadantonakis N., Savvas D. 2003. *Effects of silicone and salinity on fruit yield and quality of tomato grown hydroponically*. Acta Hort., 609: 141-149.

Toresano-Sanchez T.F., Garcia A.V., Ferre F.C. 2012. *Effect of the application of silicon hydrox-*

ide on yield and quality of cherry tomato. J. Plant Nutr., 35(4): 567-590. DOI:10.1080/01904167.2012.644375

WATANABE S., FUJIWARA T., YONEYAMA T., HAYASHI H. 2001. *Effects of silicon nutrition on metabolism and translocation of nutrients in rice plants*. Develop. Plant Soil Sci., 92: 174-175. DOI: 10.1007/0-306-47624-X_84

WISSEMEIER A.H., HORST W. J. 1992. *Effect of light intensity on manganese toxicity symptoms and callose formation in cowpea (Vigna unguiculata (*L.*)* Walp.*)*. Plant Soil, 143: 299-309. DOI: 10.1007/BF00007886