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THE EFFECT OF NUTRIENT SOLUTIONS ON YIELD AND MACRONUTRIENT STATUS OF GREENHOUSE TOMATO (*Lycopersicon esculentum* Mill.) GROWN IN AEROPONIC AND ROCKWOOL CULTURE WITH OR WITHOUT RECIRCULATION OF NUTRIENT SOLUTION

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Abstract. Aeroponics creates possibilities to cultivate plants without soil or substrate, obtaining the optimal yield, saving water and nutrient solutions and do not contaminate the environment. In a three year experiment was shown that the higher total and marketable yields of tomato cv. 'Alboney F_1' were in cultivation in rockwool with recirculating nutrient solution. Lower yields, however being in the same significance range, were in rockwool without recirculation of nutrient solution and aeroponic culture with A-1 and A-2 nutrient solutions, but the lowest in aeroponics with A-3 nutrient solution. The saving of nutrient solution in aeroponic culture, in relation to the cultivation in rockwool with non-recirculating system, was 58.1%, but comparing with recirculating system 18.8%. Plants grown in aeroponic culture with application of A-2 and A-3 nutrient solutions had higher contents of N, P and K in leaves than cultivated in rockwool with or no recirculation and in aeroponic with A-1 nutrient solution. All tested nutrient solutions (A-1, A-2 and A-3) in aeroponic culture caused the higher contents of Mg in leaves than in rockwool cultivation. The highest Ca leaves contents were in plants grown in rockwool with recirculationg nutrient solution and aeroponic culture with A-2 and A-3 nutrient solutions. Plants grown in rockwool without recirculation of nutrient solution shown the lowest Ca contents, however there was no symptoms of blossom end rot (BER) on fruits. The yield and macronutrient status of tomato in aeroponic culture with application of A-1 nutrient solution were similar to the plants grown in rockwool with non-recirculating standard nutrient solution A-2.

Key words: soilless culture, plant nutrition, nutrient contents, fertigation

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INTRODUCTION

Aeroponic method of plant cultivation was defined by International Society for Soilless Culture as „a system where roots are continuously or discontinuously exposed to an environment saturated with fine drops (a mist) of nutrient solution" [Nichols and Christie 2002]. Plant roots are developed in two-phase root environment – liquid and air. There is not solid phase, typical in soils and substrates. In aeroponic culture does not occur the antagonism between water and air in the root environment. Continuously contact with oxygen stimulates metabolic processes which have positive effect on the development of roots and nutrient uptake [Stoner and Clawson 1997]. The unsatisfied results obtained in cultivation of plants in hydroponic culture with immobile nutrient solution was mainly connected with poor aeration of root environment because in one liter of water could be solve only 8.7 mg O_2 [Soffer and Burger 1988].

The advantageous effects of aeroponic culture were found for: tomato, cucumber lettuce and strawberry [Massantini 1977, Giacomelli 1989, Repetto et al. 1994], leafy vegetables [Lim 1996, Demšar et al. 2004], muskmelon [Bode et al. 1998], potato [Sattelmacher et al. 1990, Ritter et al. 2001, Farran and Mingolo-Castel 2006], herbs and medicinal plants [Christie and Nichols 2004, Hayden 2006], chrysanthemum [Soffer and Burger1988, De Kreij and van der Hoeven 1996], anthurium [Fascella and Zizzo 2007], eustoma, lisianthus and zantedeschia [Christie and Nicholas 2004], *Ficus benjamina* L. [Soffer and Burger1988], *Acacia mangium* Willd [Martin-Laurent et al. 2000] and cranberry [Barak et al. 1996].

Intermittent injection of nutrient solution decreases temperature of root environment. This is very advantageous effect in the growing of plants in the tropical and subtropical regions as well as in the greenhouses at summer time in the moderate climatic zone [Lee 1993, He and Lee 1998]. High temperature of root environment in the range of 30–35ºC involves iron deficiency symptoms on leaves [He and Lee 1998], and have significant effect on roots morphology, nutrients absorption, enzymatic and phytohormon activities and quantitative relations between the roots and upper plant part [Tan et al. 2002].

Particularly important are studies on the application of aeroponic method for tomato growing under glass. Biddinger et al. [1998] tested the reaction of tomato on the different levels of phosphorus in the nutrient solutions applied in aeroponic culture. It was shown, that decreasing of concentration of phosphorus in the nutrient solution reduced the biomass production. There are not researches on the optimal nutrient contents in nutrient solutions for tomato growing in aeroponic system. Usually there are used the nutrient solutions recommended for soilless culture as like as NFT (Nutrient Film Technique) or cultivation in inert media – mainly in rockwool, expanded clay or perlite [Sonneveld and Straver 1994].

The main purpose of this study was a comparison of yield and nutrient status of tomato (*Lycopersicon esculentum* Mill.) grown in aeroponic culture with application of different nutrient solutions in relation to cultivation in rockwool with or not recirculation of nutrient solution.

MATERIALS AND METHODS

Experiments on cultivation of greenhouse tomato (*Lycopersicon esculentum* Mill.) cv. 'Alboney F_1' grown aeroponically and in rockwool with recirculating and non-recirculating nutrient solution systems were conducted in the years 2009–2011. In aeroponic culture were tested three nutrient solutions: A-2 the standard, commonly used in soilless culture, A-1 30% lower and A-3 30% higher concentration of nutrients than A-2. In cultivation in rockwool with or no recirculation the standard nutrient solution A-2 was tested (tab. 1).

Table 1. Nutrients and sodium contents in water and in nutrient solutions used in aeroponic culture and in rockwool culture with recirculating and non-recirculating nutrient solution for greenhouse tomato cv. 'Alboney F_1' (2009–2011)

Nutrient	H_2O			Aeroponic culture 2009–2011			Rockwool culture[b] 2009–2011
	2009	2010	2011	A-1	A-2	A-3	
	mg·dm^{-3}						
N-NH_4	tr.[a]	tr.	tr.	<14.0	<14.0	<14.0	<14.0
N-NO_3	3.7	0.3	0.3	147.0	210.0	273.0	210.0
P	0.3	0.7	0.3	49.0	70.0	91.0	70.0
K	1.8	3.6	2.4	246.0	351.0	457.0	351.0
Ca	57.3	69.7	61.4	119.0	170.0	221.0	170.0
Mg	13.4	15.3	14.2	59.0	84.0	110.0	84.0
S-SO_4	58.3	50.7	55.6	92.0	132.0	171.0	132.0
Na	22.7	22.0	22.8	22.7	22.7	22.7	22.7
Cl	42.2	37.8	42.7	42.2	42.2	42.2	42.2
Fe	0.080	0.084	0.079	1.17	1.68	2.18	1.68
Mn	0.080	0.003	0.070	0.38	0.54	0.71	0.54
Zn	1.64	1.42	1.44	1.64	1.42	1.44	1.42–1.64
B	0.011	0.011	0.008	0.26	0.38	0.49	0.38
Cu	tr.	tr.	tr.	0.055	0.079	1.03	0.079
Mo	tr.	tr.	tr.	0.044	0.048	0.062	0.048
HCO_3^-	277.5	242.8	265.8	n.d.[c]	n.d.	n.d.	n.d.
pH	7.00	7.21	7.01	5.50	5.50	5.50	5.50
EC (mS·cm^{-1})	0.73	0.71	0.72	2.60	3.00	3.40	3.00

[a] tr. – traces, [b] recirculating and non-recirculating nutrient solution system, [c] n.d. not determined

Cultivation of tomato in aeroponics was conducted in gathers which had a shape of U letter with dimensions: 11 cm width, 15 cm height and 14 m long. There were lined with black and white (outside) foil. On the bottom of the gathers the pipes (ϕ 12 mm) were placed with foggers in a distance at 50 cm. On the top of the gathers, in a distance of 50 cm between foggers, the wire hangers were put with the square holes size 10 × 10 cm, to which the rockwool cubs (10 × 10 × 7.5 cm) with tomato seedlings were placed. The gathers with the rockwool tubes from the top were covered with black and white (outside) foil to isolate influx of light to the root environment. During days the nutrient solution was injected every 15 minutes for 15 seconds (for young plants) and 30 minutes for 30 seconds (for the mature plants). At nights the nutrient solutions was applied every 60 minutes for 60 seconds to prevent drying of the roots. The excess of nutrient solution not uptake by plants, after filtration and disinfection with the UV irradiation (253.7 nm), was collected in the tank, mixed with the rest of nutrient solution and reused. There were constructed 3 separated installations for growing of tomatoes with application of 3 nutrient solutions A-1, A-2 and A-3.

Nutrient solutions for aeroponic cultivation were prepared in 1000 liters tanks from the 100-times concentrated stock solutions A and B using proportional diluter "Dosatron" in concentrations pointed out in table 1. For preparing the nutrient solutions were used the following fertilizers, tank A: HNO_3 (38%), KNO_3 (13% N-NO_3, 38.2% K), $Ca(NO_3 \cdot 2H_2O + NH_4NO_3$ (0.8% N-NH_4, 14.7% N-NO_3, 19.6% Ca), $Mg(NO_3)_2 \cdot 6H_2O$ (11.0% N-NO_3, 9.5% Mg), Fe-DTPA (Librel FeDP7 7% Fe), tank B: HNO_3 (38%), KH_2PO_4 (22.3% P, 28.2% K), K_2SO_4 (44.8% K, 17.0% S-SO_4), $MgSO_4 \cdot 7H_2O$ (9.5% Mg, 12.7% S), $MnSO_4 \cdot H_2O$ (32.3% Mn), $CuSO_4 \cdot 5H_2O$ (25.6% Cu), $Na_2B_4O_7 \cdot 10H_2O$ (11.3% B) and $Na_2MoO_4 \cdot 2H_2O$ (39.6% Mo) (zinc from water 1.42–1.64 mg $Zn \cdot dm^{-3}$, tab. 1). Nutrient solutions were acidified to pH 5.50.

In cultivation of tomato in rockwool two systems were tested – with recirculating and non-recirculating nutrient solution. Plants were grown in rockwool slabs (100 × 15 × 7.5 cm). The standard nutrient solution (A-2) recommended for tomato growing in rockwool was used (tab. 1). In the non-recirculating system the nutrient solution was prepared from the stock solutions being in containers A and B with nitric acid acidifying to pH 5.50 (similar as in the aeroponic system). Dilution of 100-folt nutrient stock solution was done by diluter (Dosatron). In the recirculating system, the nutrient solution was prepared with the use of a fertilizer mixer (ScanGrow 10). Drain water flowing out from the rockwool slabs was collected in a container and disinfected by UV irradiation (253.7 nm), diluted with tap water (36–44% disinfected drain water and 56–64% of tap water) and enriched with the lacking macro and micronutrients, which were in A and B stock solutions in a 100-fold concentration. Nutrient reaction was adjusted to pH 5.50 with nitric acid (38%) from the tank C.

The same fertilizers were used in growing of plants in rockwool with and without recirculation as like as in aeroponic culture. Nutrient solution in recirculting and non-recirculating systems were applied 10–15 times per day in the rates of 135 to 210 $ml \cdot plant^{-1}$, depending on the growing season and plant development. The first fertigation rate was applied 2 hours after sunrise and the last one 2 hours before sunset, with intervals 60–120 minutes. The saving of nutrient solution, both in rockwool and aeroponic cultures, was estimated by the measuring of water and nutrient solutions expenditure using water meters. In one rockwool slab, in both systems, were grown 2 plants. Density of plants grown in rockwool and in aeroponic culture was 2.7 plants per m^2. Plants were cultivated on 17 clusters. The experiments were done in 7 replications, with 8 plants in one replication.

Seeds of tomato cv. 'Alboney F_1' were sown into „multiblocks" of rockwool on the March 1 each year. After 2–3 weeks plants were set to the cubes of the rockwool (10 × 10 × 7.5 cm) and 3–4 weeks later (around April 15 each year) they were grown in the main experiment. During cultivation of seedlings the A-1 nutrient solution was applied. Experiments were terminated on the end of September each year.

Biological protection was applied with the using of predacious insects *Encarsia formosa* (Gahan) and *Macrolophus melanothoma* (Costa). Pollination was supported by *Bombus terrestris* L. Once a week, fruits were collected and sorted into classes (ϕ in cm): I > 10.2, II 10.2–8.2, III 8.2–6.7, IV 6.7–5.7, V 5.7–4.7, <4.7 and separately invalid fruits. The marketable yield included classes I–V.

In the mid of June, July and August, the 8^{th} or 9^{th} leaf from the top of one plant was sampled for chemical analyses. One average sample included 8 leaves collected from 8 plants. The mineralization of leaves was done by the following methods: N in sulphuric and sulphosalicilic acid and reduction of $N\text{-}NO_3$ to $N\text{-}NH_4$ with sodium trisulphate and an addition of selenium, P, K, Ca and Mg in sulphuric acid, sulphur – dry mineralization in muffle furnace with HNO_3 and $Mg(NO_3)_2$. After mineralization, the following methods were used: N-total – by Kjeldahl, P – colorimetrically with ammonium molibdate, K, Ca – photometrically on flame photometer, Mg, AAS, S – Butters-Chenery method [IUNG 1972].

Results on the yield and nutrient contents in leaves were statistically analyzed using Duncan's test (α 0.05).

RESULTS AND DISCUSSION

Comparison of total and marketable fruit yields of tomato cv. 'Admiro F_1' grown in aeroponic culture with application of A-1, A-2 and A-3 nutrient solutions in relation to cultivation in rockwool with or no recirculation of nutrient solution systems is given in table 2 and 3. It was shown that significant highest total fruit yield was in cultivation of tomato in rockwool with recirculating nutrient solution (tab. 2). The lower total yield, was in rockwool without recirculation and aeroponic culture with application of A-1 and A-2 nutrient solutions but the lowest in aeroponics with A-3 nutrient solution.

The effect of cultivation methods and nutrient solutions on marketable yield was similar to the results obtained for the total yield (tab. 3). The highest marketable yield was in cultivation of tomato in rockwool with recirculting nutrient solution. The lower, however being in the same significance range, was in cultivation in rockwool without recirculation and aeroponic system with application of A-1 and A-2 nutrient solutions. The A-3 nutrient solution caused significant reduction of yield.

Summing up, it could be stated, that total and marketable yields of fruits obtained in aeroponic culture of tomato with application of A-1 and A-2 nutrient solutions were the same as in the cultivation in rockwool without recirculation of nutrient solution, however the highest yields were in recirculating nutrient solution. The average decreasing of the total yield, in relation to recirculating system, was: 5.3% for non-recirculating system, 12.7% for aeroponic A-1, 12.2% for A-2% and 28.6% for A-3. In the case of marketable yield this reduction was (respectively): 9.5%, 15.4%, 16.5% and 38.4%.

Table 2. Total fruit yield of tomato cv. 'Alboney F_1' in aeroponic and rockwool culture with recirculating and non-recirculating nutrient solution (2009–2011)

Cultivation method	2009	2010	2011	$\bar{x}$
	g·plant^{-1}			
Recirculation	9223 m	7508 h–j	8911 łm	8547 d
No recirculation	8854 l–m	6904 c–h	8503 k–m	8087 cd
Aeroponic (A-1)	8278 j–ł	6698 b–h	7395 f–j	7457 bc
Aeroponic (A-2)	8023 i–ł	7020 e–h	7463 g–j	7502 bc
Aeroponic (A-3)	6906 d–h	5527 a	5865 ab	6099 a
$\bar{x}$	8257 c	6731 a	7627 b	-

Values marked with the same letter did not differ significantly

It should be noted, that average saving of nutrient solutions in aeroponic culture, independently on the nutrient solutions, in relation to the non-recircultaing system, was 58.1%, but for recirculating system – 18.8%. It is also important statement, that the total and marketable fruit yields produced by the plants in aeroponic system A-1 were obtained with reducing by 30% concentration of nutrients in the nutrient solution comparing with A-2 nutrient solution applied in rockwool cultivation without recirculation.

Table 3. Marketable fruit yield of tomato cv. 'Alboney F_1' in aeroponic and rockwool culture with recirculating and non-recirculating nutrient solution (2009–2011)

Cultivation method	2009	2010	2011	$\bar{x}$
	g·plant^{-1}			
Recirculation	8937 ł	7106 f–i	7340 h–j	7794 d
No recirculation	8446 lł	6025 b–e	6681 e–h	7051 c
Aeroponic (A-1)	7862 j–l	6358 d–f	5541 b	6587 bc
Aeroponic (A-2)	7479 h–k	6480 d–g	5548 bc	6502 bc
Aeroponic (A-3)	5786 b–d	4221 a	4386 a	4798 a
$\bar{x}$	7702 b	6038 a	5899 a	

Note: see Table 2

There is a lack of modern study on the efficiency of tomato cultivation in aeroponic culture. Leoni et al. [1994] showed a high yield of tomato grown aeroponically, as the effect of multiplication of cycles of cultivation. This system was called High Density Aeroponic System (HDAS). Nichols and Christie [2002] indicated the acceptable yield of tomato grown in aeroponic system in comparison with the modern greenhouse technologies. They considered that in aeroponic cultivation of tomato and cucumber is possible to increase yield up to 25% by eliminating the period from transplanting to harvest.

More experiments were done on the comparison of yield of tomato grown in rockwool with and no recirculation of nutrient solution. No significant differences were found by Hardgreve [1993], Zekki et al. [1966] and De Kreij et al. [2004]. In study by Komosa et al. [2011] although there was no significant differences, then total and marketable yield was higher by 5.4–5.6% in the non-recirculating nutrient solution system. It was not confirmed by the date presented in this research. As describe earlier, the total and marketable yields were highest in the recirculation system. Wide evaluation of plant yield obtained in soilless culture systems with an emphasis on its quality and the need to use closed fertigation systems in horticultural practice was presented in the review by Gruda [2009].

In our study the saving of nutrient solution in the recirculating system reached 48.3%, in relation to the non-recirculationg one. Komosa et al. [2011] revealed that in growing of tomato in rockwool with recirculation system was saved 42.5% nutrient solution whereas Dhakal et al. [2005] pointed on 31.5%. These results are in agreement with our results.

Table 4. Nitrogen and phosphorus contents in leaves of tomato cv. 'Alboney F_1' in aeroponic and rockwool culture with recirculating and non-recirculating nutrient solution (the 8th or 9th leaf from the top; means from 2009–2011)

	Cultivation method	I*	II	III	$\bar{x}$
% N in leaves d.m.	recirculation	4.02 b-g	3.93 a-e	3.88 a-c	3.94 a
	no recirculation	4.05 b-g	3.78 a	3.82 ab	3.88 a
	aeroponic (A-1)	3.91 a-d	3.95 a-f	3.94 a-f	3.93 a
	aeroponic (A-2)	4.20 g	4.11 c-g	4.04 b-g	4.12 b
	aeroponic (A-3)	4.13 d-g	4.18 fg	4.17 e-g	4.16 b
	$\bar{x}$	4.06 a	3.99 a	3.97 a	
% P in leaves d.m.	recirculation	0.84 ef	0.73 cd	0.51 a	0.69 a
	no recirculation	0.86 f	0.76 de	0.72 cd	0.78 b
	aeroponic (A-1)	0.95 g	0.88 fg	0.62 b	0.82 b
	aeroponic (A-2)	1.15 i	1.04 h	0.66 bc	0.95 d
	aeroponic (A-3)	1.07 h	0.91 fg	0.67 b-d	0.88 c
	$\bar{x}$	0.97 c	0.86 b	0.64 a	

*I, II, III – mid of June, July and August; values marked with the same letter did not differ significantly

Average content of nitrogen in leaves did not differ significantly in plants grown in rockwool with recirculating and non-recirculating nutrient solution and in aeroponic culture with application of A-1 nutrient solution (tab. 4). The increase of nitrogen content was appeared after application of A-2 and A-3 nutrient solutions. It could be emphasized that application of A-1 nutrient solution in aeroponic culture with reduced by

30% of nitrogen contents caused the same status of nitrogen in leaves as in growing in rockwool with and without recirculation in which the standard solution (A-2) was applied.

There was a tendency to lowering of nitrogen contents in leaves of tomato grown in rockwool with and without recirculation from the mid of July to the mid of August. It was not visible in aeroponic culture with the exception of A-2 nutrient solution. Komosa at al.[2011] found significant decreasing of nitrogen content in leaves at this period in growing of tomato in rockwool with and no recirculation. Chohura et al. [2004] in cultivation of tomato in rockwool without recirculation revealed that content of nitrogen in leaves increased from the mid of June to the mid of July and then decreased by the mid of August.

Nitrogen status in leaves of tomato grown in rockwool with or no recirculation was 3.78–4.05% N in dry matter (d. m.) and in aeroponics (A-1 to A-3) 3.91–4.20% N d. m.

These contents correspond with the standard range for tomato (tab. 5). De Kreij et al. [1990] as the standard value indicated on 2.80–4.20% N, Haifa 3.5–4.0% N, Campbell [2000] 3.5–5.0% N and Hill Laboratories 4.5–5.5% N in d. m. of leaves.

Table 5. Standard contents of macronutrients in leaves of greenhouse tomato according to various authors

Nutrient	De Kreij et al. [1990][a] whole period	Haifa[b]		Campbell [2000][c] whole period	Hill laboratories[d] first fruit mature
		before fruiting	during fruiting		
	% in leaves d. m.				
N	2.80–4.20	4.0–5.0	3.5–4.0	3.5–5.0	4.5–5.5
P	0.31–0.47	0.5–0.8	0.4–0.6	0.30–0.65	0.4–0.7
K	3.50–5.08	3.5–4.0	2.8–4.0	3.5–4.5	4.0–6.0
Ca	1.60–3.20	0.9–1.8	1.0–2.0	1.0–3.0	1.2–2.0
Mg	0.36–0.49	0.5–0.8	0.4–1.0	0.35–1.0	0.4–0.7
S	1.28	0.4–0.8	0.4–0.8	0.2–1.0	0.6–2.0

[a] – the young fully developed leaves, [b] – the newest fully expanded leaf below the last open flower cluster, [c] – the most recent mature and fully expanded leaf, without petiole and midrib, usually the 3rd or 4th leaf from the top, [d] – youngest mature leaf

It was found significant effect of cultivation methods and nutrient solution on phosphorus content in leaves (tab. 4). The lowest content was in growing of tomato in rockwool with recirculation of nutrient solution. The increase of phosphorus content was found in cultivation in rockwool without recirculation and was similar as in aeroponic culture with application of A-1 nutrient solution. Increasing concentration of phosphorus in nutrient solution A-2 and A-3 applied in aeroponics enhanced the phosphorus contents in leaves. Similarly as for nitrogen, the reduced content of phosphorus by 30% in A-1 nutrient solution applied in aeroponics caused the same result in phosphorus nutrient status as A-2 applied in rockwool culture without recirculation. Biddinger et al.

[1998] found that decrease of phosphorus concentration in the nutrient solution resulted in reducing of biomass production. Insufficient status of phosphorus decreased net CO_2 assimilation and stomatal conductance. Phosphorus concentrations in roots and shoots decreased with lowering of phosphorus concentration in the nutrient solution.

The content of phosphorus in leaves, in cultivation of tomato in rockwool and aeroponics, was declined from the mid of June to the mid of August. It was particularly evident between the mid of July and mid of August (tab. 4). This tendency was not indicated in previous study by Komosa et al. [2011]. They did not find significant changes in phosphorus content in leaves of tomato cultivated in rockwool.

The phosphorus content in leaves of tomato grown in rockwool with or no recirculation was 0.51–0.86% P but in aeroponics (A-1 to A-3) 0.61–1.15% P in d. m. Generally, in aeroponic culture the phosphorus content was higher than in rockwool. According the data presented in table 5, the contents of phosphorus in leaves in the I and II terms (mid of June and mid of July) was higher than recommended for tomato. The standard range, according to De Kreij et al. [1990] was 0.31–0,47% P, Haifa 0.4–0.6% P, Campbell [2000] 0.30–0.65% P and Hill Laboratories 0.4–0.7% P in d. m. of leaves. Only in the III term (mid of August) nutritional status of tomato with phosphorus cold be considered as the standard. It seems that phosphorus content in the nutrient solutions amounting: 49.0 mg P (A-1), 70.0 mg P (A-2) and 91.0 mg P·dm^{-3} (A-3), could be much reduced.

Table 6. Potassium and calcium contents in leaves of tomato cv. 'Alboney F_1' in aeroponic and rockwool culture with recirculating and non-recirculating nutrient solution (the 8th or 9th leaf from the top; means from 2009–2011)

	Cultivation method	I*	II	III	$\bar{x}$
% K in leaves d.m.	recirculation	4.85 b–e	4.56 a–c	4.47 ab	4.63 a
	no recirculation	5.28 e–g	4.94 c–f	5.46 g	5.23 c
	aeroponic (A-1)	4.56 a–c	4.69 a–c	4.33 a	4.53 a
	aeroponic (A-2)	4.57 a–c	4.90 b–f	5.21 d–g	4.89 b
	aeroponic (A-3)	4.78 a–d	5.32 fg	5.59 g	5.23 c
	$\bar{x}$	4.81 a	4.88 ab	5.01 b	
% Ca in leaves d.m.	recirculation	3.31 a–c	4.25 e–g	4.75 fg	4.10 c
	no recirculation	2.87 a	3.96 c–f	3.79 b–e	3.54 a
	aeroponic (A-1)	3.39 a–d	3.13 ab	4.45 e–g	3.66 ab
	aeroponic (A-2)	4.21 d–f	2.81 a	5.04 g	4.02 bc
	aeroponic (A-3)	4.15 d–f	4.14 d–f	4.18 d–f	4.16 c
	$\bar{x}$	3.59 a	3.66 a	4.44 b	

Note: see Table 4

The lowest average potassium content in leaves was in rockwool cultivation with recirculating nutrient solution similarly as in aeroponic culture with A-1 nutrient solution (tab. 6). Plants grown in rockwool without recirculation and in aeroponics with application of A-2 and A-3 nutrient solutions had higher potassium contents than in recirculating system. It could be stated that increasing potassium concentration in the nutrient solutions applied in aeroponic culture resulted in the upraising of this nutrient in leaves. Plants grown with the decreased by 30% concentration of potassium in A-1 nutrient solution applied in aeroponics shown the same potassium status as in cultivation in rockwool with recirculating system. Plants in non-recirculating system and in aeroponics with A-3 nutrient solution had the highest potassium content in leaves.

During vegetation period content of potassium in leaves did not change significantly in rockwool cultivation and in aeroponic culture with A-1 nutrient solution but the increase was found in aeroponic system with A-2 and A-3 nutrient solutions. Komosa et al. [2011] stated that in growing of tomato in rockwool with and without recirculation the content of potassium in leaves significantly decreased from the mid of June to the mid of August.

There is shortage of study on the efficiency of potassium nutrition in aeroponics. More information is on growing tomato in rockwool with recirculating and non-recirculating system. In our study, the higher potassium content was in plant grown in non-recirculating system. The same result was obtained by Komosa et al. [2011].

It could be stated that plants grown in recirculating nutrient solution contained 4.47–4.85% K, without recirculation 4.94–5.46% K, in aeroponic culture with A-1 4.33–4.69% K, A-2 4.57–5.21% K and A-3 4.78–5.59% K in d. m. of leaves shown sufficient or high nutritional potassium status (tab. 5). The standard range, according to De Kreij et al. [1990] was 3.50–5.08% K, Haifa 2.8–4.0% K, Campbell [2000] 3.5–4.5% and Hill Laboratories 4.0–6.0% K in d. m. of leaves.

The content of calcium was differentiated (tab. 6). The lowest calcium leaves contents was in non-recirculating nutrient system and in aeroponic culture with A-1 nutrient solution, however there were no symptoms of blossom end rot (BER) on the fruits. Plants grown in recircultaing system and aeroponic culture with A-2 and A-3 nutrient solutions showed the higher content of calcium in leaves. The increasing of calcium concentration in the nutrient solutions used in aeroponics resulted in the enhancing of calcium contents in leaves. Similarly as in the study by Komosa et al. [2011] calcium leaves content was higher in tomato grown in recirculating than in non-recirculationg system. The calcium contents in leaves significantly increased between the mid of July and mid of August.

Plants grown in recirculating nutrient solution contained 3.31–4.75% Ca, without recirculation 2.87–3.96% Ca, in aeroponic culture with A-1 3.13–4.45% Ca, A-2 2.81–5.04% Ca and A-3 4.14–4.18% Ca in d. m. of leaves shown standard or high nutritional potassium status (tab. 6). The standard range, according to De Kreij et al. [1990] was 1.60–3.20% Ca, Haifa 1.0–2.0% Ca, Campbell [2000] 1.0–3.0% Ca and Hill Laboratories 1.2–2.0% Ca in d. m. of leaves (tab. 5). It could be stated that nutrition status of plants in calcium was sufficient or high. It appears that concentration of calcium in the nutrient solutions A-2 (170.0 mg $Ca \cdot dm^{-3}$) used for growing tomato in rockwool with and without recirculation as well as in aeroponic system with A-2 (170.0 mg $Ca \cdot dm^{-3}$) and A-3 (210.0 mg $Ca \cdot dm^{-3}$) nutrient solutions could be reduced.

Magnesium content in leaves of plants cultivated in aeroponic culture was higher than in rockwool (tab. 7). The increase of magnesium content in the nutrient solutions did not influence on the level of magnesium in leaves. It was not found differences in leaves magnesium content between recirculating and non-recirculating nutrient solution systems as well as in growing period. In the study by Komosa et al [2011] significant higher content of magnesium in leaves was in tomato grown in recirculating system. Similarly as shown by Chohura et al [2004] there was not distinct changes in magnesium contents between the mid of July and mid of August in rockwool cultivation without recirculation.

Estimating the nutritional magnesium status it could be stated that plants grown in recirculating nutrient solution (containing 0.80–0.88% Mg in leaves d. m.) and without recirculation (0.74–0.85% Mg) shown standard magnesium status according values recommended by Haifa 0.4–1.0% Mg and Campbell [2000] 0.35–1.0% Mg or high nutrition status by De Kreij et al. [1990] 0.36–0.49% Mg and Hill Laboratories 0.4–0.7% Mg in d. m. of leaves (tab. 5). Magnesium nutrient status for aeroponic culture with application A-1 (1.15–1.20% Mg), A-2 (1.16–1.30% Mg) and A-3 (1.17–1.30% Mg in d. m. of leaves) was high according all authors and data presented in Table 5. This indicates on the possibility of reducing magnesium contents in the nutrient solutions used in aeroponic culture which were: A-1 59.0 mg, A-2 84.0 mg and A-3 110 mg $Mg \cdot dm^{-3}$ (tab. 1).

Table 7. Magnesium and sulfur contents in leaves of tomato cv. 'Alboney F_1' in aeroponic and rockwool culture with recirculating and non-recirculating nutrient solution (the 8th or 9th leaf from the top; means from 2009–2011)

	Cultivation method	I	II	III	$\bar{x}$
% Mg in leaves d.m.	recirculation	0.80 a	0.82 a	0.88 a	0.83 a
	no recirculation	0.85 a	0.74 a	0.76 a	0.78 a
	aeroponic (A-1)	1.19 b	1.15 b	1.20 b	1.18 b
	aeroponic (A-2)	1.30 b	1.16 b	1.24 b	1.23 b
	aeroponic (A-3)	1.30 b	1.17 b	1.20 b	1.22 b
	$\bar{x}$	1.09 b	1.01 a	1.06 ab	
% S in leaves d.m.	recirculation	1.02 a	1.07 a	0.96 a	1.02 a
	no recirculation	1.14 a	1.07 a	0.91 a	1.04 a
	aeroponic (A-1)	1.15 a	1.13 a	0.91 a	1.06 a
	aeroponic (A-2)	1.06 a	1.08 a	1.09 a	1.08 a
	aeroponic (A-3)	1.12 a	1.13 a	1.01 a	1.09 a
	$\bar{x}$	1.10 b	1.10 b	0.98 a	

Note: see Table 4

It was not found the diversity of sulfur content in leaves of tomato grown in rockwool and in aeroponics (tab. 7). It is worth emphasizing that widely increased concentration of sulfur in the nutrient solutions (A-1 92.0 mg $S\text{-}SO_4$, A-2 132.0 mg $S\text{-}SO_4$ and A-3 171.0 mg $S\text{-}SO_4 \cdot dm^{-3}$) did not change significantly the sulfur content in leaves. It was stable from the mid of June to the mid of July and then was a tendency to its lowering to the mid of August. Komosa et al. [2011] did not find significant differences in rockwool cultivation with and no recirculation. Chohura et al. [2004] indicated that dynamics of sulfur in tomato leaves was modified by the pH of nutrient solution.

Plants grown in rockwool with recirculating nutrient solution (leaves contained 0.96–1.07% S), without recirculation (0.91–1.14% S) and in aeroponic culture with A-1 (0.91–1.15% S), A-2 (1.06–1.09% S) and A-3 (1.01–1.13% S in d. m. of leaves) shown a standard sulfur nutrition according to Hill Laboratories (recommended 0.6–2.0% S) (tab. 5). According to Campbell [2000] (recommended 0.2–1.0% S in d. m.) the nutritional status could be defined as standard or high. Comparing with the range by Haifa (0.4–0.8% S) the nutrition level was high. De Kreij et al. [1990] as the satisfactory level pointed on 1.28% S in d. m. of leaves.

CONCLUSIONS

1. Comparison of total and marketable yields of tomato grown in rockwool with recirculationg and non-recirculating nutrient solution system and aeroponic culture with application of A-1, A-2 and A-3 nutrient solutions indicated that the higher yields were in cultivation in rockwool with recirculating nutrient solution. Lower total and marketable yields, being within the same significance range, were in growing of tomato in rockwool with non-recirculating nutrient solution and aeroponic culture with application A-1 and A-2 nutrient solutions. The lowest yields were in aeroponic culture with A-3 nutrient solution.

2. The saving of nutrient solution in aeroponic culture, independently on the tested nutrient solutions A-1, A-2 and A-3, in relation to the growing of tomato in rockwool with non-recirculating system, was 58.1%. Comparing aeroponics to rockwool culture with recirculating system the saving was 18.8% of nutrient solution.

3. Plants grown in aeroponic culture with application of A-2 and A-3 nutrient solutions had higher contents of nitrogen, phosphorus and potassium in leaves than cultivated in rockwool with and no recirculation and aeroponic culture with A-1 nutrient solution. All tested nutrient solutions (A-1, A-2 and A-3) in aeroponic culture caused the higher contents of magnesium in leaves than in rockwool cultivation with or no recirculation. It was found not a significant effect of cultivation method and the nutrient solutions on sulfur contents in leaves of tomato.

4. Content of calcium in leaves was modified by the cultivation method and nutrient solutions. The highest calcium leaves content was in plants grown in rockwool with recirculationg nutrient solution and aeroponic culture with A-2 and A-3 nutrient solutions. Plants grown in rockwool with non-recirculating system shown the lowest calcium contents in leaves, however there was no symptoms of blossom end rot (BER) on the fruits.

5. Increasing concentration of nitrogen, phosphorus and potassium in the nutrient solutions A-1, A-2 and A-3 applied in aeroponic culture resulted in the increase of these nutrients in leaves of tomato. In the case of calcium significant increase was shown only in leaves of plant fed with A-3 nutrient solution. Contents of magnesium in leaves did

not change under the influence of increasing concentration of this nutrient in the nutrient solutions A-1, A-2 and A-3 applied in aeroponics.

6. The yield and macronutrient status of tomato in aeroponic culture with application of A-1 nutrient solution was similar to the plants grown in rockwool with non-recirculating standard nutrient solution A-2.

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WPŁYW POŻYWEK NA PLON I STAN ODŻYWIENIA POMIDORA (*Lycopersicon esculentum* Mill.) UPRAWIANEGO W SZKLARNI METODĄ AEROPONICZNĄ I W WEŁNIE MINERALNEJ BEZ RECYRKULACJI I Z RECYRKULACJĄ POŻYWKI

Streszczenie. Aeroponika umożliwia uprawę roślin bez gleby lub podłoża. Pozwala też na uzyskiwanie optymalnego plonu, zmniejszenie zużycia wody i pożywek oraz niezanieczyszczanie środowiska. W 3-letnim doświadczeniu wykazano, że największy plon ogólny i handlowy pomidora odmiany 'Alboney F_1' uzyskano w uprawie w wełnie mineralnej z recyrkulacją pożywki. Niższe plony, będące jednak w tym samym przedziale istotności, stwierdzono w uprawie w wełnie mineralnej bez recyrkulacji pożywki oraz w aeroponice z zastosowaniem pożywek A-1 i A-2, natomiast najniższe w uprawie aeroponicznej z pożywką A-3. Oszczędność pożywki w uprawie aeroponicznej w stosunku do uprawy w wełnie mineralnej bez recyrkulacji wynosiła 58,1%, a w stosunku do systemu recyrkulacyjnego 18,8%. Rośliny uprawiane aeroponicznie z zastosowaniem pożywek A-2 i A-3 wykazywały większą zawartość N, P i K w liściach niż w uprawie w wełnie mineralnej bez i z recyrkulacją pożywki oraz w aeroponice z pożywką A-1. Wszystkie pożywki testowane w aeroponicznej uprawie (A-1, A-2 i A-3) powodowały większy wzrost zawartości magnezu w liściach niż w wełnie mineralnej. Największą zawartość Ca w liściach miały rośliny uprawiane w wełnie mineralnej z recyrkulacją pożywki i aeroponice z zastosowaniem pożywek A-2 i A-3. Rośliny uprawiane w wełnie mineralnej bez recyrkulacji pożywki wykazywały najmniejszą zawartość Ca w liściach, jednak nie wywoływało to suchej zgnilizny wierzchołkowej (BER) na owocach. Plon i stan odżywienia pomidora w aeroponicznej uprawie z zastosowaniem pożywki A-1 był podobny jak plon i stan odżywienia roślin uprawianych w wełnie mineralnej bez recyrkulacji z zastosowaniem standardowej pożywki A-2.

Słowa kluczowe: uprawy bezglebowe, żywienie roślin, zawartość składników, fertygacja

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