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ORIGINAL PAPER

YIELD AND NUTRIENT STATUS OF GREENHOUSE TOMATO (*LYCOPERSICON ESCULENTUM* MILL.) GROWN IN NEW AND RE-USED ROCKWOOL, POLYURETHANE, NFT AND AEROPONICS*

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Abstract

There is a need to introduce to horticultural practice new methods of plant cultivation which will allow us to obtain optimal yields while reducing water and fertilizer consumption and avoiding environmental pollution. Four methods of growing greenhouse tomato cv. Tomimaru Muchoo F_1 in a system with nutrient solution recirculation were compared, i.e. cultivation in new and re-used 1- or 2-year-old rockwool and polyurethane foam slabs, NFT and aeroponic culture. The highest marketable and total fruit yields were in the aeroponic culture. They were by 29.8 - 30.8% higher than in new rockwool slabs. Positive effects on tomato yield were obtained in the NFT (28.2% higher than in new rockwool slabs) and re-used 1-year-old (26.7 - 29.4% higher) or 2-year-old polyurethane foam slabs (23.5 - 25.4% higher). Tomato growing in re-used 1-year old rockwool slabs was demonstrated as a feasible solution. The marketable and total yields were by 10.0 - 7.5% higher (respectively) than from tomatoes grown in new rockwool. The marketable and total greenhouse tomato yields obtained in re-used 1- or 2-year-old polyurethane foam slabs were significant higher than in new polyurethane slabs. The increase was 14.7 - 15.9% for marketable and 14.2 - 19.7% for total yield. Greenhouse tomato yield in re-used 1- or 2-year-old polyurethane foam slabs was significantly higher than in new and re-used rockwool slabs. In re-used 1- or 2-year-old polyurethane foam slabs, the $N\text{-}NO_3$, Ca, and Na content was significantly higher, which meant a higher EC of the nutrient solution. There was a significant decrease in the P content in re-used 1- or 2-year-old polyurethane slabs. A significant increase in the Ca content in re-used rockwool slabs was determined alongside a tendency towards higher Na, $S\text{-}SO_4$ and EC in this substrate. The content of P, Zn and Cu in leaves of tomato plants grown in aeroponic culture was significantly lower, but Mg was higher than in leaves of tomatoes grown in rockwool, polyurethane and the NFT. A significantly lower content of K and Fe was determined in leaves of tomatoes grown in aeroponics than in rockwool and polyurethane substrates.

Keywords: closed system, recirculation of nutrient solution, fertigation, plant nutrition.

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INTRODUCTION

Tomato cultivation is one of the most common and profitable types of greenhouse vegetable production. There is insufficient research presenting a comprehensive assessment of different tomato cultivation methods in modern technologies. The prevalent greenhouse method in Poland is to grow tomato plants in rockwool without the recirculation of nutrient solution (Komosa et al. 2011). More and more producers are growing tomatoes in organic substrate, mainly in coconut coir (Kowalczyk, Gajc-Wolska 2011, Xiong et al. 2017). 12 million tones of this substrate are produced annually in the world (Nichols 2013). Coconut coir could be an alternative to growing horticultural plants in rockwool (Barret et al. 2016).

In the 1980s, research into using synthetic organic media in soilless culture of horticultural plants initiated. Benoit and Ceustermans (1995), in a 10-year long study, showed that polyurethane foam (PUR) was highly suitable as a substrate for tomato growing in greenhouses. In contrast to rockwool, which could be re-used in horticultural plant cultivation for 1 to 2 years, this substrate remains useful for 10 to 15 years. In the study of Benoit and Ceustermans (1994) on greenhouse tomato, early and total fruit yields were unaffected by the re-use of polyurethane foam (PUR) substrate over 10 years. Chohura and Komosa (2002) compared the yield of greenhouse tomato cv. Recento F_1 grown in rockwool, expanded clay and polyurethane foam, and identified the highest yield in the rockwool cultivation, while the lowest yield was harvested from tomatoes kept in polyurethane foam.

After 1979, a rapid progress was made in the commercial development of a new horticultural method called the Nutrient Film Technique (NFT), following the publication by Cooper titled “ABC of NFT”. The Nutrient Film Technique (NFT) is a hydroponic method of plants grown in a thin film of an aerated nutrient solution continuously recirculated. In this method, plant roots are exposed to adequate supplies of water, oxygen and nutrients (Cooper 1979). The main advantages of NFT include: reduced consumption of water and fertilizers, avoidance of pollution to the natural environment, and improved control of soil-borne diseases. Papapadopoulos et al. (1999) compared the growing of tomato cv. Trust in an open rockwool system with standard rockwool nutrient feeding (conventional method), and in two closed rockwool systems with the standard rockwool nutrient feeding or NFT nutrient feeding. There were no significant differences in plant growth, development, marketable yield and fruit quality among the three culture systems. Savings in water and fertilizer in the closed rockwool culture system with the NFT nutrient feeding can promote this method of tomato culture. The above authors stated that the closed rockwool culture system with appropriate nutrient feeding can reach similar or better yield and quality than the conventional open rockwool system. In later studies of Valenzano et al. (2008), it was shown that the NFT method included in a closed system generated a higher yield with lower water and fertiliser consumption than the growing of greenhouse tomato in an open rockwool system.

An important role in the improvement of cultivation methods applied to horticultural plants grown in greenhouses it played by one of the most recent solutions, i.e. the aeroponic culture. Aeroponics was defined by the 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.’ There are no any solid substrates. This creates favourable relations between air and water in the root environment. Continuous contact with oxygen stimulates metabolic processes, which has a positive effect on the development of roots and nutrient uptake (Stoner, Clawson 1997). Komosa et al. (2014) compared the yields of greenhouse tomato cv. Alboney F_1 grown in rockwool with an open and a closed system, and in an aeroponic culture, finding out that that highest total and marketable yield was in rockwool with the closed system, and lower in rockwool with the open system and in the aeroponic culture. Noteworthy, the consumption of nutrient solution in the aeroponic culture was by 58.1% than in the rockwool open system and by 18.8% lower than in the rockwool closed system.

The main purpose of this research was to compare the yield and nutritional status of greenhouse tomato (*Lycopersicon esculentum* Mill.) cv. Tomimaru Muchoo F_1 grown in new and 1- or 2-year-old rockwool and polyurethane foam slabs with the recirculation of a nutrient solution, the Nutrient Film Technique and in an aeroponic culture.

MATERIAL AND METHODS

The experiment involved greenhouse tomato (*Lycopersicon esculentum* Mill.) cv. Tomimaru Muchoo F_1, which belongs to the raspberry coloured cultivars. The plants were grown in new and re-used 1- or 2-year-old rockwool and polyurethane foam slabs with the recirculatation of a nutrient solution, the Nutrient Film Technique (NFT) and in an aeroponic culture. The study was carried out in 2016-2017. The following nutrient solution was applied in the variants with rockwool, polyurethane and NFT (mg dm^{-3}): N-NH_4 <14, N-NO_3 150, P-PO_4 40, K 250, Ca 160, Mg 70, S-SO_4 90, Cl 42, Fe 0.90, Mn 0.40, Zn 0.60, B 0.38, Cu 0.025, Mo 0.025, pH 5.50, EC 2.30 mS cm^{-1} (EC of water 0.72 mS cm^{-1}). In the aeroponic culture, the nutrient solution consisted of (mg dm^{-3}): N-NH_4 <14, N-NO_3 147, P-PO_4 49, K 246, Ca 119, Mg 59, S-SO_4 92, Cl 42, Fe 1.17, Mn 0.60, Zn 1.45, B 0.26, Cu 0.055, Mo 0.044, pH 5.50, EC 2.30 mS cm^{-1} – EC of water 0.72 mS cm^{-1} (Komosa et al. 2014). The tap water from the Poznań municipal waterworks was used, containing an average from 2016-2017 (mg dm^{-3}): N-NH_4 traces, N-NO_3 0.3, P-PO_4 0.2, K 2.1, Ca 61.1, Mg 14.3, S-SO_4 56.1, Cl 42.0, Fe 0.82, Mn 0.06, Zn 0.60, B 0.01, Cu traces, Mo traces, pH 7.11, EC 0.72 mS cm^{-1}.

In the experimental trial with tomato cultivation in rockwool, seeds of tomato were sown to rockwool cubes 10 × 10 × 7.5 cm in size, and after 6 weeks seedlings were transferred onto new and 1- or 2-year-old rockwool slabs 100 × 15 × 7.5 cm in size. In the experiment where tomato plants were grown in polyurethane, tomato seedlings produced in rockwool cubs were transferred onto new and 1- or 2-year-old slabs 100 × 15 × 7.5 cm in size.

Tomato seedlings grown in rockwool cubs (10 × 10 × 7.5 cm) with the NFT were placed on the bottom of U-shaped metal gutters, which were 11 cm wide, 15 cm high and 14 m long. These gutters were lined with black and white (outside) plastic foil to prevent the access of light to tomato roots. The slope angle of the gutters was 0.2%. This allowed free flow of recirculating nutrient solution. The nutrient solution was applied to rockwool cubs through drippers.

In the aeroponic culture tomato seedlings grown in rockwool cubs (10 × 10 × 7.5 cm), were hung in U-shape gutters and did not touch the bottom. This allowed growing roots to hang freely in the gutters. The gutters were lined with black and white (outside) plastic foil and were positioned at a sloping angle of 0.2%. On the bottom of the gutters, pipes (ϕ 12 mm) were placed with foggers in a distance at 50 cm. This resulted in good saturation of the root environment with a mist of the nutrient solution. During daytime, the nutrient solution was injected every 15 min for 15 s for young plants and every 30 min for 30 s for mature plants. At nights, the nutrient solutions was applied every 60 min for 60 s to prevent drying of the roots. The excess of the nutrient solution not taken up by the plants, after filtration, was collected in a tank, mixed with the rest of the nutrient solution and re-used. The nutrient solution for aeroponic cultivation was prepared in 1000-liter tanks from 100-fold concentrated stock solutions A and B, containing all macro- and micronutrients as well as nitric acid to lower pH to 5.50.

The cultivation of tomato in rockwool, polyurethane foam and NFT included recirculation of the nutrient solution. The nutrient solution was prepared with the use of a fertilizer mixer (ScanGrow 10). Drain water flowing out from the rockwool, polyurethane slabs and rockwool cubs in the NFT method was collected in a tank, diluted with tap water and enriched with inadequate levels of macro- and micronutrients, from 100-fold concentrated stock solutions A and B. The nutrient solution reaction was adjusted to pH 5.50 using nitric acid (38%) from tank C. The nutrient solution was applied 10 - 15 times per day in doses of 135 to 210 cm^3 $plant^{-1}$, depending on the growing season and plant development. The density of cultivated plants was 2.7 plants per m^2. The experiment was set up in 4 replications, with 6 plants in one replication.

Seeds of tomato cv. Tomimaru Muchoo F_1 were sown to the cubes of rockwool (10 × 10 × 7.5 cm) on around 1^{st} of March and 6 weeks later, around 15th of April, the plants were transferred to the main experiment treatments, which were continued to the end of August.

Biological protection consisted of the application 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 discarded fruits. The marketable yield included classes I – V.

Every month from April to August, at monthly intervals, samples of the nutrient solution from the drippers, rockwool and polyurethane foam slabs were collected for chemical analyses. One sample from one replication consisted of 400 cm^3 of the nutrient solution. The nutrient solution samples from the rockwool and polyurethane new and 1- or 2-year old slabs were taken with a medical syringe. In these samples, the available forms of macro- and micronutrients, sodium, pH and EC were determined. In the middle of June, July and August, the 8th and 9th leaf from the top of one plant were sampled for chemical analyses – 12 leaves represented one replication. The total forms of macro- and micronutrients in leaves were analyzed.

Results of chemical analyses of the nutrient solution, leaf analyses and marketable and total fruit tomato yield were statistically analyzed using the Duncan's test (α 0.05).

RESULTS AND DISSCUSSION

Yield of greenhouse tomato grown in new and re-used 1- or 2 year old rockwool and polyurethane foam slabs with recirculation nutrient solution, Nutrient Film Technique and aeroponic cultures

The highest marketable tomato yield was in the aeroponic culture and the Nutrient Film Technique variants, slightly lower yield was obtained from re-used polyurethane foam 1- and 2-year-old slabs, significantly less was harvested from new polyurethane foam and re-used 1-year-old rockwool slabs, and the lowest yield was collected from new and re-used 2-year-old rockwool slabs (Table 1). The marketable yield in the aeroponic culture was by 29.8% higher than from tomato plants grown in new rockwool slabs, treated as the control object. A similar increase in marketable yield (28.2%) was found in the NFT variant. Re-used 1- and 2-year-old polyurethane foam slabs turned out to be good substrates, ensuring a 25.4 - 26.7% increase in marketable yield. A significantly lower increase in this yield, higher by 9.3 - 10.0% than the control, was produced on new polyurethane foam and 1-year-old rockwool slabs, but the lowest marketable yield was obtained from new and re-used 2-year-old rockwool slabs (Table 1).

Table 1

Total and marketable fruit yields of greenhouse tomato cv. Tomimaru Muchoo F_1 grown according to different cultivation methods with recirculation of the nutrient solution (means from 2016-2017)

Cultivation	Yield (g plant^{-1})		Yield increase or decrease to rockwool-new (%)		Share of marketable in total yield (%)
	marketable	total	marketable	total	
Rockwool new	3566.0*a**	3913.1*a*	-	-	91.1
Rockwool 1-year-old	3924.5*abc*	4208.4*ab*	10.0	7.5	93,2
Rockwool 2-year-old	3418.3*a*	3806.5*a*	-4.1	-2.7	89.8
Polyurethane foam new	3897.9*ab*	4232.0*ab*	9.3	8.1	92.1
Polyurethane foam 1-year-old	4520.4*cd*	5067.0*c*	26.7	29.4	89.2
Polyurethane foam 2-year-old	4473.7*bcd*	4836.0*bc*	25.4	23.5	92.5
NFT	4571.8*d*	5020.2*c*	28.2	28.2	91.0
Aeroponics	4631.6*d*	5121.4*c*	29.8	30.8	90.4

* Means marked with the same letter within the column did not differ significantly.

The suitability of the tested methods for the cultivation of greenhouse tomato determined on the basis of marketable yield was confirmed by the results of total yield (Table 1). The best tomato growing methods were: aeroponics, NFT and re-used 1- or 2-year-old polyurethane foam slabs, where the increase in total yield was 23.5 - 30.8% in the relation to new rockwool slabs. The second best group was composed of: re-used 1-year-old rockwool slabs and new polyurethane foam slabs, with the increase by 7.5 - 8.1%. The third group, with the lowest total yield, included new and re-used 2-year-old rockwool slabs.

The highest share of the marketable yield in the total yield was found for tomato cultivation on re-used 1-year-old rockwool and new or re-used 2-year-old polyurethane foam slabs, where it ranged around 92.1 - 93.2% (Table 1). A slightly lower percentage of marketable yield in total yield, 90.4 - 91.1%, was identified for aeroponics, NFT and rockwool new slabs. The lowest share (89.2 - 89.8%) was obtained from re-used 1-year-old polyurethane and 2-year-old rockwool slabs.

In an earlier study by Komosa et. al (2014), with greenhouse tomato cv. Alboney F_1, aeroponics was not determined to produce a higher marketable and total yield in relation to open and closed rockwool culture. This may be related to different responses of cultivars to the growing methods. Cultivar Alboney F_1 belongs to the red coloured tomatoes, but Tomimaru Muchoo F_1 represents the raspberry coloured cultivars. Other reasons can be longer duration of the experiment with Alboney F_1 cultivar in a given year resulting in higher yields and another origin of rockwool slabs.

High yield of tomato cv. Tomimaru Muchoo F_1 was noticeable in the NFT method. Yield results were close to ones obtained in the aeroponic culture. In an experiment with tomato cv. Trust, PAPAPADOPOULOS et al. (1999) did not find any differences in plant growth, development, marketable yield and fruit quality among open and closed rockwool systems and the NFT. According to these authors, savings in water and fertilizer in the closed rockwool culture and the NFT could promote these methods for tomato growing in the future. VALENZANO et al. (2008) showed that NFT gave a higher yield with lower water and fertilizer use than growing greenhouse tomato in an open rockwool system.

Following the promising outome of aeroponics and NFT, the cultivation of greenhouse tomato cv. Tomimaru Muchoo F_1 in polyurethane re-used 1- or 2-year-old slabs proved to be an effective method, too. As shown in this experiment, the yields of tomato plants grown in these root media were significantly higher than in the variants with new polyurethane foam and new rockwool slabs. This may be attributed to a beneficial change in water retention over time in this substrate. BENOIT and CEUSTERMANS (1995) found that roots remaining in this substrate after 4 years of cultivation increased water retention. This effect could emerge after 2 or 3 years of tomato cultivation in our experiment. In addition, our research has shown that good yield of tomato growing in polyurethane re-used 1- or 2-year-old slabs could be an effect of the increasing content of available nitrogen ($N-NO_3$) in the slabs with the time of their use (Table 2). This could be connected with the root residue left over from previous tomato cultivation. CHOHURA and KOMOSA (2002) reported that yield of greenhouse tomato cv. Recento F_1 grown in new rockwool slabs, expanded clay and new polyurethane foam slabs was the highest in rockwool, decreased by 11.8% in polyurethane foam. In our experiment, the total and marketable yield of greenhouse tomato cv. Tomimaru Muchoo F_1 was by 8.1 - 9.3% higher in new polyurethane foam than in new rockwool slabs (Table 1).

Desirable yield of greenhouse tomato obtained on re-used 1-year-old rockwool slabs compared to new rockwool ones should be emphasized. Total and marketable yields were 7.5 - 10.0% higher on re-used 1-year-old rockwool slabs. The use of 2-year-old rockwool slabs resulted in a decrease in total and marketable yield by 2.7 – 4.1% compared to new rockwool (Table 1). BOROSIĆ et al. (2009) showed that marketable yield of greenhouse tomato grown on new and re-used 1-year-old rockwool slabs was similar, decreasing significantly in re-used 2-year-old slabs, same as in our research.

Differences of chemical nutrient composition between the nutrient solution collected from the drippers and from rockwool or polyurethane foam slabs, regardless of their age, in tomato cultivation with recirculation of the nutrient solution

During tomato cultivation, there were significant changes of nutrient contents, sodium, pH and and EC in rockwool and polyurethane foam slabs. It was shown that content of Ca, S-SO_4, Na and Cl in the nutrient solutions collected from the rockwool and polyurethane foam slabs, regardless of their age, was significantly higher than in the nutrient solution flowing out from the drippers (Tables 2 and 3). Similar results were reported by Komosa et al. (2011). Additionally, an increase in the N-NO_3 and Mg content in the polyurethane foam slabs was determined, which confirms the earlier results

Table 2

Content of N-NH_4, N-NO_3, P, K, Ca in nutrient solutions collected from drippers, new and re-used rockwool or polyurethane foam slabs in cultivation of greenhouse tomato cv. Tomimaru Muchoo with recirculation of nutrient solution (means from 2016-2017)

Root medium	N-NH_4	N-NO_3	P	K	Ca
	nutrient solution (mg dm^{-3})				
Drippers	5.1 ns	115.6*a**	34.1*cd*	250.4*b*	170.9*a*
Rockwool new	3.6 ns	113.2*a*	27.9*ab*	238.2*ab*	266.5*b*
Rockwool 1-year-old	3.9 ns	117.6*a*	27.7*ab*	217.3*ab*	299.3*bc*
Rockwool 2-year-old	3.7 ns	135.1*b*	25.1*a*	211.1*a*	314.6*c*
Polyurethane foam new	3.9 ns	143.3*bc*	34.8*d*	225.6*ab*	285.7*bc*
Polyurethane foam 1-year-old	3.8 ns	133.5*b*	30.7*bcd*	221.0*ab*	297.9*bc*
Polyurethane foam 2-year-old	4.2 ns	151.7*c*	29.6*abc*	235.4*ab*	368.5*d*

* Means marked with the same letter within the column did not differ significantly; ns – not a significant difference.

Table 3

Content of Mg, S-SO_4, Na and pH and EC of nutrient solutions collected from drippers and new or re-used rockwool and polyurethane foam slabs in growing of greenhouse tomato cv. Tomimaru Muchoo with recirculation of nutrient solution (means from 2016-2017)

Root medium	Mg	S-SO_4	Na	pH	EC (mS cm^{-1})
	nutrient solution (mg dm^{-3})				
Drippers	62.8*a**	97.0*a*	55.7*a*	5.84*a*	2.20*a*
Rockwool new	70.6*ab*	119.0*b*	108.8*b*	6.88*b*	2.94*bc*
Rockwool 1-year-old	71.4*ab*	123.2*b*	117.2*bc*	6.95*b*	2.98*bc*
Rockwool 2-year-old	71.7*ab*	132.6*b*	119.0*bc*	6.89*b*	3.04*bc*
Polyurethane foam new	69.9*ab*	116.5*b*	102.6*b*	6.76*b*	2.91*b*
Polyurethane foam 1-year-old	71.8*ab*	129.0*b*	112.5*b*	6.77*b*	3.08*bc*
Polyurethane foam 2-year-old	73.1*b*	128.4*b*	134.9*c*	6.83*b*	3.36*c*

* Means marked with the same letter within the column did not differ significantly.

by Komosa and Olech (1996*a*,*b*). Higher concentrations of $N-NO_3$, Mg, Ca, $S-SO_4$, Na and Cl in the root environment of soilless culture is a consequence of the domination of water transpiration over the nutrient uptake as well as the selective uptake of nutrients by plants. The increase of nutrient and sodium contents in the root environment leads to a rise in the EC of nutrient solution (Table 3). This dependence has also been demonstrated by Snapp et al. (1991) and Alarcon et al. (1994). It should be noted that an increase of $N-NO_3$, which is the nutrient having the strongest positive effect on yield, in re-used polyurethane slabs could have had a significant impact on the yield of tomato.

In contrast to $N-NO_3$, Mg, Ca, $S-SO_4$, Na and Cl, a significant decline in the Fe and Mn content was indicated in the nutrient solution collected from rockwool and polyurethane foam slabs in comparison with the nutrient solution dripping from the emitters. The content of P decreased significantly in the rockwool slabs, but there was only a decreasing tendency in polyurethane slab (Table 4). The decreasing content of P, Fe and Mn in rockwool

Table 4

Content of Cl, Fe, Mn, Zn and Cu in nutrient solution collected from drippers and new or re-used rockwool and polyurethane foam slabs in cultivation of greenhouse tomato cv. Tomimaru Muchoo with recirculation of nutrient solution (means from 2016-2017)

Root medium	Cl	Fe	Mn	Zn	Cu
	nutrient solution (mg dm^{-3})				
Drippers	46.4*a**	0.462*b*	0.132*b*	0.516*ab*	0.018 ns
Rockwool – new	61.7*b*	0.205*a*	0.082*ab*	0.598*b*	0.017 ns
Rockwool – 1-year-old	68.5*b*	0.170*a*	0.044*a*	0.507*ab*	0.016 ns
Rockwool – 2-year-old	65.6*b*	0.171*a*	0.034*a*	0.461*a*	0.017 ns
Polyurethane foam – new	60.7*b*	0.202*a*	0.075*ab*	0.607*b*	0.015 ns
Polyurethane foam – 1-year-old	67.4*b*	0.198*a*	0.057*a*	0.585*b*	0.016 ns
Polyurethane foam – 2-year-old	60.2*b*	0.202*a*	0.065*a*	0.550*ab*	0.014 ns

* Means marked with the same letter within the column did not differ significantly; ns – not a significant difference.

and polyurethane slabs is the result of soluble compounds of these elements (available for plants) converting into insoluble forms (unavailable for plants) as pH of nutrient solution rises to very slightly acid or neutral reaction, pH in H_2O 6.50-7.00 (Urrutia et al. 2013, Rengel 2015). In our study, the nutrient solution flowing out from the drippers had a pH of 5.84, but in rokwool it was 6.88 – 6.95 and in polyurethane slabs it equalled 6.76 - 6.83 (Table 3). A rise in pH is the result of increasing Ca, Mg and Na content in rockwool and polyurethane slabs during the growing season of tomato.

Differences in chemical composition of nutrient solution in re-used rockwool and polyurethane foam slabs, depending on their age, in tomato cultivation with recirculation of nutrient solution

With consecutive years of using rockwool and polyurethane foam slabs in tomato cultivation there appeared a significant increase in the Ca content (Table 2). The highest Ca content in these root media was determined in re-used 2-year-old slabs, both rockwool and polyurethane. This could be connected with the rise in sulphates in older slabs and the formation of slightly soluble calcium sulphate ($CaSO_4$ – gypsum). In the case of polyurethane slabs, a significant increase in the $N\text{-}NO_3$ and Na content occurred with the extended time of cultivation, but in rockwool there was only a tendency towards a higher content of these compounds (Table 2). Accumulation of Na in root media is unfavourable because it decreases tomato fruit yield in a closed system of fertigation (Nakano et. al. 2010). According to Baas and Berg (1999), the content of Na in nutrient solution collected from rockwool slabs in a closed system of plant cultivation was 184 mg Na dm^{-3}. In our study, it was much lower, for example 108.8 - 119.0 mg Na dm^{-3} in rockwool, and 102.6 - 134.9 mg Na dm^{-3} in polyurethane foam slabs (Table 3).

Due to a significant increase in $N\text{-}NO_3$ and Na in polyurethane foam slabs in the consecutive years of their use, electrical conductivity (EC) of nutrient solution collected from these slabs rose significantly (Table 3). Also, a tendency for elevated EC in rockwool was noticed. This agrees with the research of Nakano et. al. (2010).

In contrast to $N\text{-}NO_3$, Ca and Na, the content of P in re-used 1- or 2-year-old polyurethane slabs significantly decreased and tended to lower in rockwool slabs (Table 2). As mentioned earlier, there was an ongoing fixation phosphorus process, which equated the transition of available phosphorus ($H_2PO_4^-$) to forms less available to plants (HPO_4^{2-} and PO_4^{3}) due to calcium accumulation in rockwool and polyurethane slabs (Sheraz Mahdi et al. 2012).

Nutrient status of greenhouse tomato grown in new and re-used rockwool and polyurethane foam slabs with recirculation of nutrient solution, NFT and aeroponic cultures

It was shown that the content of P, Zn and Cu in leaves of tomato grown in aeroponic culture was significantly lower, but the Mg content was higher than in rockwool, polyurethane and NFT cultures (Tables 5 and 6). The content of K and Fe was significantly lower in aeroponics than in rockwool and polyurethane tomato cultivation. It was found that the N leaf content in aeropnics was significantly lower than in rockwool. Changes in the content of Ca and Mn in the cultivation methods were multidirectional. No significant changes were noted in the leaf content of sulphur among the tested tomato cultivation methods.

By comparing the results of our work with the data on the sufficient tomato leaf ranges defined by other authors (Table 7), we can evaluate

Table 5

Content of macronutrients in greenhouse tomato leaves cv. Tomimaru Muchoo F_1 depending on different cultivation methods with recirculation of nutrient solution (the 8-9-th leaf from the top, means from 2016-2017)

Root medium	N	P	K	Ca	Mg	S
	g kg^{-1} d. m. of leaves					
Rockwool – new	37.1*d**	7.0*d*	58.2*bc*	28.1*a*	5.3*ab*	9.9 ns
Rockwool – 1-year-old	35.4*cd*	6.5*cd*	60.9*cd*	36.3*d*	4.8*a*	9.7 ns
Rockwool – 2-year-old	37.3*d*	6.8*cd*	55.5*b*	29.5*ab*	4.8*a*	9.9 ns
Polyurethane foam – new	34.3*bc*	6.6*cd*	62.3*d*	22.5*bc*	5.2*ab*	9.9 ns
Polyurethane foam – 1-year-old	34.4*bc*	6.5*cd*	56.9*b*	31.7*b*	5.1*ab*	9.3 ns
Polyurethane foam – 2-year-old	32.4*ab*	6.4*c*	55.7*b*	35.3*cd*	5.0*a*	9.5 ns
NFT	33.0*abc*	5.1*a*	46.5*a*	31.2*ab*	5.6*b*	9.2 ns
Aeroponics	30.9*a*	5.8*b*	50.0*a*	36.0*d*	10.3*c*	9.7 ns

* Means marked with the same letter within the column did not differ significantly; ns – no significant difference.

Table 6

Content of Fe, Mn, Zn and Cu in greenhouse tomato leaves cv. Tomimaru Muchoo F_1 depending on different cultivation methods with recirculation of nutrient solution (the 8th -9th leaf from the top, means from 2016-2017)

Root medium	Fe	Mn	Zn	Cu
	mg kg^{-1} d. m. of leaves			
Rockwool – new	134.1*bc**	164.4*bc*	73.3*b*	19.2*c*
Rockwool – 1-year-old	141.6*bcd*	173.4*c*	70.9*b*	15.6*ab*
Rockwool – 2-year-old	159.5*d*	191.3*d*	68.9*b*	17.4*bc*
Polyurethane foam – new	151.1*cd*	200.4*d*	73.3*b*	19.6*c*
Polyurethane foam – 1-year-old	138.7*bc*	150.8*ab*	65.5*b*	17.3*bc*
Polyurethane foam – 2-year-old	146.4*cd*	158.0*ab*	68.7*b*	15.5*ab*
NFT	124.6*ab*	146.9*a*	66.5*b*	33.4*d*
Aeroponics	110.3*a*	190.6*d*	47.9*a*	12.9*a*

* Means marked with the same letter within the column did not differ significantly.

the nutrient tomato status. According to De Kreij et al., the N leaf content was sufficient and ranged between 28.0 and 42.0 g N kg^{-1} leaves d. m. Higher ranges (35.0 - 55.0 g N kg^{-1} leaves d. m.) are recommended by Campbell (2000), Haifa and Hill Laboratories (Table 7). According to these references, there was enough P, Mg, Fe, Mn and Cu in tomato leaves in all the cultivation methods tested in our experiment. Data published by Campbell (2000), Haifa and Hill Laboratories implicate the high content of K, Ca and sufficient or high content of S and Zn in leaves of tomato grown in rockwool, polyurethane, NFT and aeroponic cultures.

Table 7

Sufficient nutrient content in leaves of greenhouse tomato according to various references

Nut-rient	De Kreij et al. (1990)[a]	Haifa[b]		Campbell (2000)[c]	Hill Laboratories[d]
	whole period	before fruiting	during fruiting	whole period	first fruit mature
g kg^{-1} leaves d.m.					
N	28.0-42.0	40.0-50.0	35.0-40.0	35.0–50.0	45.0-55.0
P	3.1-4.7	5.0-8.0	4.0-6.0	3.0–6.5	4.0-7.0
K	35.0-50.8	35.0-40.0	28.0-40.0	35.0–45.0	40.0-60.0
Ca	16.0-32.0	9.0-18.0	10.0-20.0	10.0–30.0	12.0-20.0
Mg	3.6-4.9	5.0-8.0	4.0-10.0	3.5–10.0	4.0-7.0
S	12.8	4.0-8.0	4.0-8.0	2.0–10.0	6.0-20.0
mg kg leaves d.m.					
Fe	84-112	50-200	50-200	50-300	80-200
Mn	55-165	50-125	50-125	25-200	50-250
Zn	39	25-60	25-60	18-80	30-60
Cu	6.4	8-20	8-20	5-35	15-50
B	54,0-75.6	35-60	35-60	30-75	30-60
Mo	0.29-0.57	1-5	1-5	0.1-1.0	0.5-1.0

[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.

CONCLUSIONS

1. The highest marketable and total yields of greenhouse tomato cv. Tomimaru Muchoo F_1 were in the aeroponic culture. These yields were 29.8 - 30.8% higher than in the cultivation of tomato in new rockwool slabs. Highly positive yield-producing effects were obtained in the NFT (28.2% higher than in new rockwool slabs) and re-used 1-year-old (26.7 - 29.4%) or 2-year-old polyurethane foam slabs (23.5 - 25.4%).

2. It was proven that tomatoes can be successfully cultivated in re-used 1-year-old rockwool slabs. The marketable and total yields were 10.0 - 7.5% higher (respectively) than in new rockwool once.

3. The marketable and total greenhouse tomato yields obtained in re-used 1- or 2-year-old polyurethane foams were significantly higher than in new polyurethane slabs. The increase was 14.7 - 15.9% for marketable and 14.2 - 19. 7% for total yield. Greenhouse tomato yield in re-used 1- or 2-year-old polyurethane foam slabs was significantly higher than in new and re-used rockwool slabs.

4. Content of Ca, S-SO_4, Na and Cl in the nutrient solutions collected from rockwool and polyurethane foam slabs, regardless of their age, was significantly higher, but the Fe and Mn content was lower than in the nutrient solution flowing out from the drippers.

5. In re-used 1- or 2-year-old polyurethane foam slabs, there was a significant increase in the N-NO_3, Ca, and Na content and as a consequence the EC of the nutrient solution rose. There was a significant decrease in P in re-used 1- or 2-year-old polyurethane slabs.

6. A significant increase in Ca was shown in re-used rockwool slabs alongside a wards higher concentrations of Na, S-SO_4 and a higher EC in this substrate.

7. The content of P, Zn and Cu in leaves of tomato grown in the aeroponic culture was significant lower, but that of Mg was higher than in rockwool, polyurethane and NFT cultures. A significantly lower content of K and Fe was determined in leaves of tomato grown in aeroponics than in rockwool and polyurethane tomato cultivation.

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