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Evaluation of substitutes for rock wool as growing substrate for hydroponic tomato production

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Summary

To reduce the rock wool waste, the present study is focused on the evaluation of sheep wool, cultivated *Sphagnum* biomass and hemp, which may be used as replacement for rock wool as growing substrate for hydroponic tomato production. As such, physical and chemical properties of substrates, the plant growth, yield, fruit characteristics, as well as primary and secondary metabolites of tomatoes were considered.

The marketable fruit yield of plants grown in *Sphagnum* slabs (12.8 kg plant^{-1}) was reduced to only a small extent compared to the yield produced by rock wool slabs (13.8 kg plant^{-1}). Sheep wool (12.3 kg plant^{-1}) and hemp (10.4 kg plant^{-1}), however, showed higher deviations. The lowest yield of blossom end rot (BER) fruit was produced by *Sphagnum*. Compared to this result, the BER-yield was nearly 2-fold higher caused by sheep wool. The soluble solid content in fruit ripened by the hemp material was decreased compared to those caused by the remaining substrates. Furthermore, it was found that the volume of easy available water (EAW) was mainly responsible for changes in plant development. As such, a high correlation was found between EAW and: leaf area (r = 0.851); flowers (r = 0.785); lycopene (r = -0.918); ß-carotene (r = -0.997); penolics (r = -0.918); L-ascorbic acid (r = -0.848).

The findings suggested that cultivated *Sphagnum* biomass dried and pressed as slabs can be used as replacement for rock wool slabs, whereas the usage of slabs consisting of hemp and sheep wool is not suitable as growing substrate for hydroponic tomato production.

Introduction

Nowadays, not only the product quality but also the sustainable production plays a major role when foods are purchased by the consumer, where economic, social and ecological aspects are considered in the purchase decision (Vermeir and Verbeke, 2008). Since the ecological part also includes the waste management during the production cycle, a multitude of scientists are concerned with the further development of hydroponic systems in greenhouses in order to realize a more environmentally friendly production of vegetables.

The transition to closed hydroponic systems was a first step to relieve the environment, whereas substrates as growing material can contribute to the main waste flow in greenhouse production (Papadopoulos and Gosselin, 2007). This applies in particular to the rock wool substrate, which is the most common substrate used for the cultivation of tomato, cucumber and red pepper in hydroponic systems in a wide range of countries (Benoit and Ceustermans, 1995; Shinohara et al., 1999; Jeong and Hwang, 2000; Bussell and Mckennie, 2004). This growing medium is often disposed after one culture period and cannot always be recycled, whereby up to 150 m^3 of rock wool waste per ha are produced per year resulting in this fact that landfills threaten to become scarce (Pieters et al., 1998; Göhler and Molitor, 2002). In the Netherlands, for instance, 90 % of the used rock wool slabs are recycled and returned to the material cycle in form of new rock wool products, whereas the entire rock wool waste of the Canadian greenhouse production is stored exclusively on landfills (van den Bosch, 2004; Papadopoulos and Gosselin, 2007). Furthermore, an average primary energy demand of 275 kWh is required to produce one cubic metre of rock wool, where 167 kg CO_2 are released into the environment (Brandhorst et al., 2012). In these calculations, however, the energy expenditure for recycling processes is not considered.

Despite these circumstances, rock wool slabs are preferably used as a horticultural substrate in soilless systems due to numerous advantages, such as a high total pore space, as well as inert, sterile and homogeneous conditions caused by the production process of this material and the achievement of constant yields during the cultivation period (Olympios, 1992; Bussell and Mckennie, 2004). However, the use of environmentally friendly growing substrates, which are, for example, biodegradable or can be used over several years, may reduce the waste flow under protected growing conditions (van Os, 1994; Pieters et al., 1998). In this context, rock wool surrogates should be used, which provide equally good results in terms of fruit quantity and quality as achieved using rock wool substrates. Therefore, in recent years, various growth media were tested for their suitability as substrate for the hydroponic cultivation of vegetables. Shinohara et al. (1999), for instance, found no differences in growth, yield and soluble solid content (SSC) of tomato plants, regardless of whether they were grown in rock wool, coconut fibre, bark or rice husk. The same applies if exactly the same substrates were used for further experiments. Similar results were found when rock wool was compared with almond shell as growing media, whereas the SSC of tomato plants grown in the organic media was higher than that synthesized on rock wool (Urrestarazu et al., 2005). Furthermore, Manios et al. (1995), Martinez and Abad (1992), and Allaire et al. (2005) demonstrated that hydroponically cultivated tomato plants showed comparable yields of tomatoes when they were produced in substrates consisting of sieved pumice and peat-lite (85% : 15%, v/v), perlite and peat (85% : 15%, v/v), sepiolite and perlite (80% : 20%, v/v), sepiolite and leonardite (97% : 3%, v/v), peat and composted bark (66.6% : 33.4%, v/v) or rock wool. However, tomato yields in substrates mixed from fresh white spruce and fir sawdust (40% : 60%, v/v), as well as from white spruce and fir shavings (40% : 60%, v/v) were lower than those obtained with rock wool (Allaire et al., 2005).

Based on these results, the present study is focused on the evaluation of cultivated *Sphagnum* biomass, sheep wool and hemp pressed as substrate slabs, which may be used as replacement for rock wool slabs as growing substrate for hydroponic tomato production. The main objectives of this research were to analyse the physical properties of the used renewable organic substrates compared to rock wool and to find out interactions between the physical properties of these substrates and the plant development, as well as the tomato yield. Furthermore, information about the influence of the physical properties of different substrates used for hydroponic systems on the accumulation of primary and secondary metabolites are scarce, although it is well known that the latter possess health-promoting properties

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for humans (DILLARD and GERMAN, 2000). In order to exclude negative quality effects of possible substitutes for rock wool as growing substrate for hydroponic tomato production, the present study was also conducted to investigate the effects of different growing media on the contents of valuable plant compounds, such as lycopene, ß-carotene, phenolics, L-ascorbic acid (LAA), soluble solids (SSC), titratable acids (TA), as well as micro- and macronutrients in tomatoes. Additionally, the experiments were also used to identify the impact of different substrates on fruit characteristics, such as dry matter content, fruit firmness and the occurrence of blossom end rot fruit.

Materials and methods

Experimental set-up

Greenhouse facility

The experiments were carried out in two compartments (each 40 m^2), which were integrated in a N-S oriented Venlo-type glasshouse (307 m^2) at the Humboldt-Universität zu Berlin. This greenhouse consists of double glazing (16 mm) in the standing wall region and single glazing (4 mm), as well as one energy screen in the roof region and was operated by a conventional microclimatic control strategy. This means that the energy screen was closed at a global radiation of less than 3 W m^{-2}, the floor level heating was set at a target temperature of 17 °C for day and night, the ventilation was opened above 23 °C and the CO_2 concentration was kept at 800 ppm during daylight hours. The CO_2 supply was stopped when the ventilation exceeded an opening of 10%. These processes were controlled using the application of proportional integral differences, including data obtained from different sensors to maintain the sought microclimatic conditions in the compartments of the greenhouse. The sensors were evenly distributed in the canopy and the measurements were forwarded to a central computer and recorded every 30 seconds. The microclimate conditions for each compartment are shown in Tab. 1, which represent mean values from planting until the end of experiments.

Tab. 1: Mean values of microclimatic conditions in the greenhouse during the experiments

Experimental facility	Temperature (°C)	Relative humidity (%)	CO_2-concentration (ppm)
Compartment 1	21.85	80.73	526.21
Compartment 2	21.96	79.92	530.49

Substrate slabs and crop cultivation

Four different kinds of growing substrates were used to produce tomato plants (*Solanum lycopersicum* L., cv. Pannovy) in an open hydroponic system in which the nutrient solution was drained after one use. In this context, tubular film-wrapped rock wool slabs (Cutilene®Exact; Tilburg, The Netherlands) with the dimensions of 100 cm × 20 cm × 7.5 cm (length × width × height) were compared to slabs consisting of three different organic materials. These materials include unpurified sheep wool of different breeds of sheep (exact breeds are unknown), hemp fibre processed into insulating mats with a thickness of 18 cm (Thermo-Hanf® PLUS, Hock GmbH & Co. KG; Nördlingen, Germany) and dried *Sphagnum palustre* biomass referred to as peat moss, which was cultivated and collected as fresh material in the Netherlands. To obtain substrate slabs with the same square shape and dimensions as described for the rock wool slabs, a defined amount of each growing media was moistened and then pressed into separate plastic bags by means of a self-constructed device. Subsequently, the open end of the plastic bags was welded, whereby an identical appearance of all substrate slabs was achieved. The only difference between the substrate slabs was the dry weight of them, where the highest level was caused by sheep wool (2000 g) followed by peat moss (1250 g), hemp (1200 g) and rock wool (750 g).

Each greenhouse compartment contained ten substrate slabs per growing media, resulting in a planting density of 2 plants m^{-2} and 2 tomato plants per substrate slab. Before the plants were grown on high gullies, seeds were germinated in perlite, transferred to rock wool cubes (7.5 cm × 7.5 cm; Cutilene®; Tilburg, The Netherlands) and transplanted in the prepared substrate slabs on 12th February 2013, when the first inflorescence became visible. Fertigation was realized by means of a localized drip irrigation system, providing nutrient solution for 150 seconds mainly after a light summation of 560 W m^{-2} and a minimal overwatering of 20% after each application. To obtain the water overflow and to meet the nutrient needs of the plants, the light summation for controlling the irrigation was regularly adjusted and the nutrient solution was prepared by mixing fresh water and stock solution according to the mixture recipe of GÖHLER and MOLITOR (2002).

Physical properties of the growing media

To evaluate the physical properties of the substrate slabs, 100 cm^3 metal rings were slowly pushed into the prepared substrate slabs before the plants were transplanted. Five samples were randomly taken from each substrate and greenhouse compartment (n = 10). Subsequently, the samples were saturated with water for 24 hours as described by VERDONCK and GABRIELS (1992) and then weighed to record the initial value at a suction point of pF = 0, which is necessary to calculate the total pore space (TPS) according to DE BOODT and VERDONCK (1972) as shown below. After this intermediate step, the volumetric water content of the samples was detected at different water tensions using the negative pressure method according to HARTGE and HORN (2009), where a sandbox (Sandbox, Eijelkamp; Giesbeek, The Netherlands) were used to obtain the measurements. In this context, the water-saturated samples were placed on a layer of synthetic sand and a suction point of pF = 1.0, pF = 1.7, as well as pF = 2.0 was successively applied, in order to calculate the air volume (AV), the easily available water (EAW) and the water buffer capacity (WBC) as defined by DE BOODT and VERDONCK (1972). After this procedure, the samples were dried at 105 °C until constant weight to determine the bulk density, which is the ratio of the dry weight of the substrate to the substrate volume (g cm^{-3}). All other variables, such as TPS, AV, EAW and WBC, are expressed as volume percent (vol%). The TPS is calculated under consideration of the weight of the water-saturated sample at the suction point pF = 0, the weight of the dried sample, the bulk density and a water density of 1 g cm^{-3}. The AV is calculated as the difference in vol% between the TPS and the volumetric water content at a suction point of pF = 1.0. The EAW and the WBC are the amounts of volumetric water content released from the samples when the suction point is increased from pF = 1.0 to pF = 1.7 and from pF = 1.7 to pF = 2.0, respectively.

To calculate the volume change of the substrate slabs at the end of the investigations, the slabs were weight in a dried state without plants at the beginning and the end of the experiments, where the root biomass in the slabs was not removed. The weight reduction was expressed as percent (%).

Assessment of crop growth and yield

To determine the number of leaves and the leaf area (LA) per plant six weeks after planting, a total of eight plants per growing media and greenhouse compartment (n = 16) was selected randomly. The number of leaves was noted and the leaf length and width of each leaf was measured with a folding ruler. The measurements were inserted in an exponential function developed by Dannehl et al. (2014) to estimate the LA of each individual leaf non-destructively. Subsequently, the calculated values were added up to obtain the LA per plant, which was expressed as m^2 $plant^{-1}$.

Before the first leaves were removed from the tomato plants as is common in the conventional crop management, the number of flowers and formed fruit per plant of the same tomato plants as described earlier was recorded, in order to investigate the effects of different growing media on the development of fruit set. The average fruit set per plant were calculated according to the ratio of the number of formed fruit to the number of flowers and expressed as %.

At the end of the experiments on 16^{th} august 2013, the number of panicles and the plant height of the randomly selected plants were measured after the stem was cut directly above the substrate slabs. Furthermore, the tomatoes were harvested, counted and weighed weekly, distinguishing between marketable fruit (> 50 g) and fruit categories (A-class ≥ 70 g; 50 g ≤ B-class < 70 g; C- class < 50 g; blossom end rot (BER) class > 20 g). After the trials were finished, the recorded data in terms of all quality classes were summed up to compare the fruit yield, fruit weight and the number of fruit per plant depending on different growing substrates. The fruit yield, fruit weight and the number of fruit were expressed as kg $plant^{-1}$, g $fruit^{-1}$ and number $plant^{-1}$, respectively.

Chemical and physical analyses

Sampling, sample preparation and sample properties

To determine the chemical composition of the unused organic substrates, ten composite samples, each containing 200 gram, were taken from five different slabs per growing media. These were dried at 75 °C until a constant weight, ground (MM 30, Retsch GmbH; Haan, Germany) and stored until the macronutrients were analysed *via* inductively coupled plasma-optical emission spectrometry (ICP-OES) as described below.

To analyse the sample properties, the primary and secondary metabolites, as well as the nutrients of tomatoes, three replicates containing 30 tomatoes (> 70 g) were randomly harvested from different plants per growing media and greenhouse compartment at a ripening stage 10, where the freshly picked tomatoes were matured at the same height in the canopy. This sampling was repeated five times during five weeks from June to July, in order to compare five dates of three biological replicates. Immediately after harvesting, the fruit firmness of each tomato was measured using a Shore A instrument (HHP-2001, Bareiss Prüfgerätebau GmbH; Oberdischingen, Germany) equipped with a stamp of 0.25 cm^2. The firmness was measured in the range of 0 to 100, where the latter value is the measured data caused by a standardised metal disc. The investigation for each fruit was carried out non-destructively on three equidistant measuring points of the equatorial region. This means that the result caused by each growing substrate represents the average value of fruit firmness recorded over five weeks on 150 tomatoes. The fruit firmness was expressed as Shore A. After this procedure, each tomato was quartered and two quarter of these tomatoes were mixed (KenwoodHB856, De'Longhi Deutschland GmbH; Neu-Isenburg, Germany) to obtain a homogenous starting material of fresh tomatoes with respect to the relevant sample material. The homogenized fresh material of each replication was used to detect the contents of fruit dry matter, carotenoids, phenolics, L-ascorbic acid (LAA), titratable acids (TA) and soluble solids (SSC) performed in duplicate. In this context, fresh mass and dry mass from all homogenised fruit samples were measured before and after drying in a ventilated oven for 24 hours at 105 °C, respectively. The fruit dry matter content was calculated by the ratio of the dry mass to the fresh mass and is expressed as g $100g^{-1}$ fresh weight (FW). Other parts of the quartered tomatoes from the same samples were freeze-dried (Christ Alpha 1-4, Christ; Osterrode, Germany) and ground (Prep'line TEF8100, Groupe SEB – Tefal; Offenbach, Germany) to a fine powder, in order to determine the contents of specific macro- and micronutrients in tomatoes.

Primary and secondary plant compounds

The contents of primary and secondary plant compounds in the homogenized material were analysed promptly. The TA was determined using potentiometric titration with 0.05 mol L^{-1} NaOH by pH endpoint at 8.1 according to ASU-L-26.11.03-4 (1983). These analyses were carried out using a pH meter (pH526, WTW; Weilheim, Germany) consisting of a glass electrode (SenTix 41, WTW; Weilheim, Germany). Furthermore, the SSC was analysed using a digital refractometer (PR101, ATAGO; Karlsruhe, Germany), which detects reducing sugars and other soluble solids. The results obtained for TA and SSC were converted to a 100 g FW basis and were expressed as gram citric acid and gram SSC per 100 g FW, respectively. From these data, the sugar : acid ratio was calculated.

The content of LAA was assayed using the enzymatic test kit (L-Ascorbate, Megazyme International Ireland; Bray, Ireland). Briefly, the tetrazolium salt MTT [3-(4,5-dimethylthiazolyl-2)-2,5-diphenyltetrazolium bromide] was reduced by LAA to a formazan compound (MTT-formazan) under the presence of phenazinium methylsulfate. MTT-formazan was determined spectrophotometrically at a wavelength of 578 nm. Other reducing substances were measured in the same way after removing LAA using ascorbic acid oxidase. To calculate the LAA content given as mg 100 g^{-1} FW, the differences between both absorbance values were used.

Lycopene, ß-carotene and total phenolic contents were determined by spectrophotometry (Model 690, Gamma Analysen Technik GmbH; Bremerhafen-Lehe, Germany), where the extracts of these secondary metabolites were measured at wavelengths of 505 nm, 453 nm and 765 nm, respectively. Briefly, lycopene and ß-carotene contents in tomato samples were extracted using the method described by Fish et al. (2002), including modifications defined by Dannehl et al. (2012). Afterwards, the contents of carotenoids were calculated according to Nagata and Yamashita (1992) and expressed as mg 100 g^{-1} FW. However, The phenolics were extracted as described by Connor et al. (2002). To analyse the amount of phenolic compounds in the extracts, the Folin-Ciocâlteu method according to Slinkard and Singleton (1977) was applied. Modifications regarding this analysis were described exactly by Dannehl et al. (2011). The contents of phenolics were expressed as mg gallic acid per 100 g FW (mg GAE 100 g^{-1} FW).

Detection of minerals in growing media and tomatoes

To determine the easy available minerals in growing media and in tomatoes, an aliquot of 0.5 g of each dried sample was weighed into deionized containers. The microwave digestion, which was carried out as a preparation for determining the amount of minerals in the samples, was described in detail by Dannehl et al. (2012). After this procedure, the analysis of the elements in the digestion solution was conducted *via* inductively coupled plasma-optical emission spectrometry (ICP-OES) using an ICP Emission Spectrometer (iCAP 6300 Duo MFC, Thermo; Waltham, USA). The operating conditions employed for ICP-OES were 1150 W RF power and 0.55 L min^{-1} nebulizer gas flow, where argon was used as a plasmogen and carrier gas. The analyses were performed with a cross-flow nebulizer (MIRA Mist, Thermo Scientific; Cambridge, England) and from a radial (Ca, K, Mg, P, S) and axial (Fe) view. Regarding each element, a single-standard solution (Carl Roth GmbH; Karlsruhe, Germany) of 1000 mg L^{-1} was used to prepare the reference solutions in 1.4 mol L^{-1} HNO_3. The calibration curves were generated with the

following reference solutions: blank 1.4 mol L^{-1} HNO_3; 0.5-300 mg L^{-1} of K; 0-100 mg L^{-1} of Ca; 0-50 mg L^{-1} of Mg and P; 0-20 mg L^{-1} of S and Fe. The respective element in the digestion solutions was measured in duplicate at the following wavelength: K = 766.5 nm; Ca = 317.9 nm; Mg = 279.1 nm; P = 213.6 nm; S = 182.2 nm; Fe = 259.9 nm. The contents of minerals in the growing media were expressed as g kg^{-1} dry weight (DW) and those contained in tomatoes as mg 100 g^{-1} FW, as well as mg g^{-1} DW.
An aliquot of 0.3 g of the freeze-dried samples were used to quantify the contents of carbon and nitrogen in growing substrates and tomatoes using an elemental analyser (vario MAX, Elementar Analysensysteme GmbH; Hanau, Germany) and according to DIN-ISO-10694 (1995) and DIN-ISO-13878 (1998). The modified method was described in detail by DANNEHL et al. (2012). The C- and N-contents in the growing media and tomatoes were expressed just as described above.

Statistical analysis

Differences in physical properties of substrates and the effects of these on the vegetative and generative plant growth, fruit yield, quality characteristics, minerals, as well as on primary and secondary plant compounds of tomatoes were evaluated using analysis of variance (ANOVA) with SPSS, package version 19.0. Significant differences were calculated using Tukey-tests at a significance level of $p < 0.05$, where different small letters describe significant differences. The mean variability was indicated using standard deviation, which was illustrated by ± or bars that have both positive and negative values. In order to detect interactions between the volume of easily available water caused by different substrates and the leaf area, as well as the number of flowers and between the leaf area and the yield of marketable fruit, as well as BER-fruit, linear correlations between two variables were calculated using Pearson correlation (r) at a significant level of $p < 0.05$. The same statistical procedure was applied for correlations between chemical elements and primary, as well as secondary plant compounds in tomatoes.

Results and Discussion

Chemical composition of organic materials

The analyses showed differences in chemical composition of the unused organic materials (Tab. 2). In this context, the lowest levels of minerals were detected in the hemp substrate. The highest content of nitrogen (N) was found in sheep wool slabs, which was 8-fold and 26-fold higher than that found in peat moss and hemp, respectively. This was mainly caused by faeces and urine, which was contained in unpurified sheep wool. These residues were washed out by fertilization during the experiments resulting in turbid nutrient solution. Thereby, it may be possible that the nutrient composition needs to be adjusted more frequently than normally required in recirculating hydroponic systems. Additionally, filters should be used to avoid contaminations of the drip irrigation system, which can be transferred into the nutrient solution by the sheep wool residues.

Tab. 2: Chemical composition of the unused organic substrates

	Content (g kg^{-1} DW)[a]					
Substrate	Ca	K	Mg	P	N	C
Sheep wool	5.77	54.09	1.37	1.76	127.4	452.2
Peat moss	13.97	13.75	7.22	4.00	15.5	328.9
Hemp	4.28	6.17	0.55	1.03	4.9	441.3

[a] The content of each element represents the mean value of five slabs per growing substrate.

Compared to peat moss and hemp, the content of potassium (K) in sheep wool was increased more than 4-fold and 9-fold, respectively. However, the highest amounts of calcium (Ca), magnesium (Mg) and phosphor (P) were analysed in peat moss (Tab. 2). In this context, the contents of Ca and P in peat moss were almost 2.5-fold higher compared to those measured in sheep wool, whereas a nearly 4-fold difference in contents of the mentioned elements were calculated in terms of hemp. Even greater differences were observed with respect to the Mg content, where peat moss contained a 5-fold or 13-fold higher content of this mineral then that found in sheep wool and hemp, respectively. Comparable results, however, were analysed regarding the carbon (C) content in sheep wool and hemp, which ranged between 452.2 and 441.3 g kg^{-1} DW. The same parameter was reduced to 328.9 g kg^{-1} DW in peat moss (Tab. 2). Whether these differences in chemical composition of the unused organic materials can affect plant responses will be discussed in sections below.

Physical properties of substrate slabs

Physical properties of an ideal substrate are mainly based on results found by ABAD and NOGUERA (2000), ABAD et al. (1993), BOERTJE (1983), DE BOODT and VERDONCK (1972) and JENKINS and JARRELL (1998), who primarily considered substrates for ornamental plant production. However, only minor information about ideal physical parameters of substrates used in hydroponic systems exist (ALLAIRE et al., 2005), which is why the optimum values regarding physical properties of substrates were extracted from results of the listed studies above (Tab. 3).

Tab. 3: Physical properties of the substrate slabs

Substrate	Total pore space[a] (vol%)	Air volume[a] (vol%)	Bulk density[a] (g cm^{-3})	Easily available water[a] (vol%)	Water buffer capacity[a] (vol%)	Weight reduction[b] (%)
Rock wool	97.6 ± 1.8 c	58.5 ± 5.2 b	0.06 ± 0.005 a	37.4 ± 4.5 d	0.13 ± 0.05 a	+ 17.0 ± 5.0 c
Sheep wool	92.2 ± 3.3 b	75.5 ± 3.9 c	0.09 ± 0.008 b	4.2 ± 0.9 a	0.41 ± 0.09 b	- 42.5 ± 1.5 a
Peat moss	86.0 ± 2.4 a	9.9 ± 0.8 a	0.08 ± 0.003 a	32.0 ± 2.2 c	0.21 ± 0.05 a	- 12.8 ± 4.1 b
Hemp	87.2 ± 4.4 ab	60.7 ± 6.0 b	0.12 ± 0.004 c	9.8 ± 2.2 b	0.59 ± 0.11 c	- 49.3 ± 5.5 a
Optimum value[c]	75 to > 85	10 to 30	< 0.4	20 to 30	4 to 10	≯ 30

[a] The data represent mean values of ten samples per substrate and greenhouse compartment (n = 20) collected at the beginning of the experiments, whereas [b] describes the mean values of the volume change of eight slabs including root biomass per growing substrate and compartment (n = 16) at the end of the experiments. All values were tested using Tukey-test, where different small letters without square brackets indicate significant differences ($p < 0.05$). The symbol ± is given as standard deviation. [c] According to ABAD and NOGUERA (2000), ABAD et al. (1993), DE BOODT and VERDONCK (1972), BOERTJE (1983) and JENKINS and JARRELL (1998).

The total pore space of the investigated substrates differed significantly from each other. As such, the highest total pore space was caused by rock wool slabs (97.6 vol%), followed by substrate slabs filled with sheep wool (92.2 vol%), hemp (87.2 vol%) and peat moss (86 vol%) (Tab. 3). Böhme et al. (2008) reported similar results in terms of rock wool and sheep wool slabs, where these results differed by 6.9 vol% and -4.6 vol%, respectively, compared to those calculated in the present study. However, Blievernicht et al. (2012) detected that the total pore space of the peat moss substrate used for potted plants is 13.3 vol% higher than that measured in the current study, which can be explained by an increased bulk density induced by the stuffed peat moss slabs. In this context, the bulk density of the investigated substrates ranged from 0.06 g cm^{-3} to 0.12 g cm^{-3}, where significantly differences between the highest value reached by hemp and those caused by the remaining substrates were observed (Tab. 3). The lowest bulk density was found for rock wool and peat moss slabs, which did not differ significantly from each other. Nevertheless, all growing media were in the range of the recommended optimum values regarding the total pore space (> 85 vol%) and the bulk density (< 0.4 g cm^{-3}) as demonstrated by De Boodt and Verdonck (1972) and Abad et al. (1993), respectively.

The air volume and the easy available water are the most important physical parameters of substrates (Bunt, 1976; Abad et al., 1993). In the present study, the significantly highest air volume was measured in the sheep wool substrate (75.5 vol%), followed by hemp (60.7 vol%), which contained nearly the same air volume level as detected in rock wool slabs (Tab. 3). The lowest value was calculated for peat moss (9.9 vol%). In this context, there is a controversial discussion on the minimum and maximum air volume in substrates used for tomato production. While Bunt (1976) defined an optimum value of 10 vol%, Scharpf (1997) observed only a moderate sensitivity of tomatoes when they were exposed to an air volume between 6 and 32 vol%. If all investigated substrates in terms of the air volume are suitable for tomato production will be discussed in the following sections, where optimum values will be defined depending on the plant development.

Furthermore, the rock wool slabs showed with 37.4 vol% the significantly highest easily available water (EAW) among all examined substrates (Tab. 3). Although the EAW of the stuffed peat moss slabs was significantly decreased to 32.0 vol% compared to rock wool, the EAW of both substrates were close to an ideal growing media as described by De Boodt and Verdonck (1972) and Abad et al. (1993). Sheep wool and hemp, however, did not provide sufficient amounts of EAW, which remained far below the optimum values as shown in Tab. 3. The lower EAW in sheep wool slabs (4.2 vol%) was probably based on the hydrophobic character of sheep wool, which can be caused by the wool fat. Under this circumstance, Gruda and Schnitzler (2004a) recommend to increase the irrigation frequency. An overflow between 20% and 50% should be considered after each irrigation cycle (Peet and Welles, 2005), which was guaranteed in the present study (data not shown).

The water buffer capacity (WBC) is the amount of volumetric water content released from the substrates when the suction point is increased from pF = 1.7 to pF = 2.0, where this water content can be seen as a reserve for plants during intense plant transpiration. It was found that the WBC of organic substrates is much better than that of the inert material (Tab. 3). The significantly highest WBC was calculated for hemp (0.59 vol%), followed by sheep wool (0.41 vol%), peat moss (0.21 vol%) and rock wool (0.13 vol%), where the last two values did not differ significantly. The results obtained do not correspond to the optimal values, which should be in the range between 4% and 10% (De Boodt and Verdonck, 1972). However, these values were recommended for growing media used for the production of ornamental plants. Generally, rock wool or organic materials used as substrate slabs in hydroponic systems have a small water buffer capacity (Da Silva et al., 1995; Urrestarazu et al., 2008). Regarding rock wool slabs, Benoit and Ceustermans (1990) and Urrestarazu et al. (2008) found a WBC of 3.5 vol% and 1.1 vol%, respectively. Slabs consistent of almond shell reached a WBC of 2.6 vol%, whereas a WBC of 0.5 vol% was calculated for coir waste slabs (Urrestarazu et al., 2005; Urrestarazu et al., 2008). It is assumed that a small WBC of substrates does not influence the nutrient uptake of plants grown in hydroponic systems, provided that the supply of nutrient solution to the roots is continuously maintained, e.g., by sufficient irrigation frequency and under consideration of the recommended overflow as described above.

The shrinkage of the substrate slabs should not be higher than 30% (Abad and Noguera, 2000). In the present study, however, the decomposition of the hemp and sheep wool materials was the fastest when all substrates were compared, resulting in a significantly weight reduction of 49.3% and 42.5%, respectively (Tab. 3). It has to be taken into account that these results do not include the root biomass removal, whereby it is likely that the real level of weight reduction is even higher than that represented in Tab. 3. In this context, it was observed that the hemp slabs were slightly lifted after two month, whereby the stability of the plants was negatively affected. This effect was more pronounced, the longer the plants were growing in this substrate. In contrast, the peat moss slabs showed a very good position stability of tomato plants during the culture period, which was based on the lower level of decomposition of this organic material. The weight of this substrate was significantly reduced by 12.8 %. Nevertheless, it is obvious that the recommended optimum value is not exceed, even if the biomass would be removed. Therefore, the quality of peat moss as substrate is as high as the quality of rock wool in terms of this physical parameter.

Crop growth and yield

The leaf area development within the first six weeks showed that the highest LA with 1.29 m^2 $plant^{-1}$ was achieved by the influence of the peat moss substrate, although the air volume was the smallest of all tested growing media (Tab. 3, 4). Since the impact of rock wool slabs differed only to a lesser extent compared to this result and the plant development can be negatively affected by oxygen deficiency in the root zone as reported by Chérif et al. (1997), it was concluded that an air volume in a wide range from 9.9 vol% to 58.5 vol% is suitable for tomato production in hydroponic systems. However, it was found that an air volume > 60 vol% contained in hemp and sheep wool could be one reason to significantly decrease the LA of tomato plants by 31% and 21%, respectively, compared to that induced by peat moss slabs (Tab. 4). Due to the insignificant differences in terms of the number of leaves, these reduced leaf areas were caused by a smaller LA per leaf. However, an effect of the chemical composition of the different organic materials on the LA development was excluded, because the nutrient solution supply was ensured regularly and the results obtained were opposite to the results demonstrated in other studies. In the present study, it was found that plants grown in peat moss slabs, which contained a much lower level of N and K than sheep wool slabs, produced the highest LA. Evans (1989) and Tei et al. (2000), however, showed that an increase in N availability led to higher rates of photosynthesis, followed by an enhanced plant growth. The same applies to the K availability, where the tomato plant growth increased with increasing concentrations of K as shown by Besford and Maw (1975). Rather, the mentioned results can be further explained by the volume of EAW, because a significant correlation was found between this physical property and the LA (r = 0.851, p = 0.048). This result is confirmed by Kirda et al. (2004), who demonstrated that a water deficit irrigation between 30% and 50% led to a slightly reduced LA of tomato plants compared to a full watering situation. These

Tab. 4: Effects of different substrates on the vegetative and generative plant growth

Substrate	Leaf area[a] (m^2 $plant^{-1}$)	Leaves[a] (number $plant^{-1}$)	Flowers[a] (number $plant^{-1}$)	Fruit sets per plant[a] (%)	Panicles[b] (number $plant^{-1}$)	Plant length[b] (m)
Rock wool	1.23 ± 0.12 b	18.8 ± 1.4 a	81.6 ± 9.6 b	94.9 ± 7.9 a	27.5 ± 0.96 a	6.28 ± 0.10 a
Sheep wool	1.02 ± 0.13 a	19.0 ± 2.3 a	71.4 ± 9.2 ab	95.2 ± 7.3 a	26.3 ± 0.96 a	6.10 ± 0.08 a
Peat moss	1.29 ± 0.10 b	18.8 ± 0.9 a	75.5 ± 8.9 ab	95.1 ± 7.4 a	26.3 ± 0.99 a	6.05 ± 0.25 a
Hemp	0.89 ± 0.09 a	18.1 ± 1.8 a	68.4 ± 5.6 a	96.2 ± 6.6 a	26.0 ± 0.82 a	6.05 ± 0.13 a

The data represent mean values of eight plants per substrate and greenhouse compartment (n = 16) [a] calculated six weeks after planting or [b] at the end of the experiments. Values followed by the same letter without square brackets do not differ significantly according to Tukey-test ($p < 0.05$). Values with the prefix ± indicate the standard deviation.

findings are also in agreement with the observations by GRUDA and SCHNITZLER (2004b), who reported from an increase in LA and fresh matter of leaves, stem, as well as roots of tomato plants grown in substrates with a higher volume of EAW. From these results it can be derived that the shrinkage of the hemp and sheep wool slabs due to the decomposition of these organic substrates should not be ignored, because it might be possible that this alteration was accompanied by a decreased volume of air and EAW inside these materials resulting in a reduced LA development.

Furthermore, it was demonstrated that the different organic and inorganic substrates did not significantly affect the plant length, fruit sets and the number of panicles per plant (Tab. 4). In this context, it was concluded that no differences regarding the number of leaves of the cv. Pannovy existed neither six weeks after planting nor at the end of the investigations, because HEUVELINK (2005) found that each panicle of other tomato cultivars is formed after the formation of three leaves. Nevertheless, the number of panicles formed by plants grown in the rock wool slabs showed at least a tendency to increase by one panicle per plant compared to plants cultivated in the remaining growing substrates (Tab. 4). This behaviour of panicle development could be one explanation for the highest formation of flowers on plants produced in rock wool slabs (81.6), followed by an insignificant impact by peat moss (75.5) and sheep wool (71.4), as well as an significant effect by hemp (68.4) (Tab. 4). In this context, it was calculated that the number of flowers increased with an increasing volume of EAW ($r = 0.785$, $p = 0.043$), which supported the statement that the EAW contained in substrates is one of the most important physical parameter as mentioned above. Furthermore, GUO-JING et al. (2001) found a relation between physical parameters and the temperature behaviour inside the substrates, where growing media with a high air volume and a low volume of EAW tend to a faster warming. These physical properties were associated with the substrate slabs consisting of hemp and sheep wool. In comparison to these conclusions, it was logically assumed that the physical parameters found in rock wool and peat moss slabs led to slightly colder temperatures, which can result in a higher number of flowers as shown by PHATAK et al. (1966).

Since all growing media influenced the fruit weight regarding all weight categories to the same extent (Tab. 5), the higher number of flowers caused by rock wool slabs and the fact that the number of fruit sets per plants remained unaffected depending on the different substrates were the deciding factors for the highest number of marketable fruit (161.5) matured on rock wool slabs (Tab. 5). Taking this result into account, the number of fruit were reduced by 5%, 14% and 24% owing to the impact of peat moss, sheep wool and hemp, respectively, where the last to variants differed significantly. While the efficiency of the number of fruit in terms of the weight classes B and C was not influenced by the substrate usage, alterations in A-class fruit production were observed. This circumstance was mainly responsible for changes in the number of marketable

Tab. 5: Fruit responses on different growing substrates

Fruit characteristic	Substrate	Marketable fruit (> 50 g)	A-class (≥ 70 g)	B-class (< 70 g to 50 g)	C-class (< 50 g)	BER-class (> 20 g)
Fruit yield (kg $plant^{-1}$)	Rock wool	13.8 ± 1.4 b	12.2 ± 1.6 b	1.6 ± 0.8 a	0.3 ± 0.1 a	1.2 ± 0.5 ab
	Sheep wool	12.3 ± 1.2 b	11.2 ± 1.4 ab	1.1 ± 0.5 a	0.2 ± 0.1 a	1.9 ± 0.5 b
	Peat moss	12.8 ± 1.4 b	11.3 ± 1.7 b	1.5 ± 0.7 a	0.2 ± 0.1 a	1.0 ± 0.4 a
	Hemp	10.4 ± 1.4 a	9.1 ± 1.8 a	1.3 ± 0.6 a	0.4 ± 0.2 a	1.8 ± 0.5 ab
Fruit weight (g $fruit^{-1}$)	Rock wool	85.4 ± 5.6 a	89.4 ± 5.3 a	63.2 ± 3.3 a	31.0 ± 5.5 a	44.1 ± 6.8 a
	Sheep wool	89.1 ± 6.5 a	92.5 ± 6.0 a	63.0 ± 2.6 a	34.2 ± 17.0 a	38.7 ± 2.9 a
	Peat moss	83.4 ± 4.4 a	87.5 ± 4.2 a	61.3 ± 1.6 a	30.2 ± 10.8 a	42.8 ± 6.3 a
	Hemp	84.1 ± 4.5 a	88.8 ± 3.2 a	62.0 ± 1.6 a	35.7 ± 14.5 a	38.1 ± 9.0 a
Fruit (number $plant^{-1}$)	Rock wool	161.5 ± 15.8 c	136.0 ± 1.4 b	25.5 ± 12.5 a	8.8 ± 4.5 a	28.4 ± 12.7 ab
	Sheep wool	138.9 ± 13.5 ab	121.3 ± 2.3 ab	17.6 ± 10.5 a	6.4 ± 5.4 a	48.8 ± 14.8 ab
	Peat moss	153.4 ± 12.1 bc	129.1 ± 0.9 b	24.3 ± 10.6 a	7.8 ± 3.4 a	26.0 ± 13.8 a
	Hemp	123.4 ± 13.1 a	101.8 ± 1.8 a	21.6 ± 10.6 a	9.4 ± 5.1 a	50.8 ± 19.5 b

The data represent mean values of eight plants per substrate and greenhouse compartment (n = 16). Comparisons were calculated using Tukey-test, where values followed by different letters differ significantly from each other ($p < 0.05$). Values with the prefix ± represent the standard deviation fruit, where the number of A-class fruit were affected in a similar manner as presented for the number of marketable fruit (Tab. 5). In consequence thereof, the highest marketable fruit yield showed plants grown in rock wool slabs (13.8 kg plant^{-1}), followed by plants produced in peat moss slabs (12.8 kg plant^{-1}), sheep wool slabs (12.3 kg plant^{-1}) and hemp slabs (10.4 kg plant^{-1}). In this context, the hemp material reflected the weakest form of the used substrates, which caused a significant reduction in fruit yield compared to those obtained by the remaining growing materials. The surplus yield achieved by the other substrates was based more on changes in yield of A-class fruit than on B-class and C-class fruit, because significant differences were only calculated for the first mentioned fruit category (Tab. 5). It might be possible that the higher amount of EAW and the lower air volume in rock wool and peat moss slabs were partly responsible for the higher yields in terms of these substrates, because ALLAIRE et al. (2005) found that the marketable fruit yield of tomatoes was positive related to EAW and negatively related to the air volume. These results are supported by KIRDA et al. (2004), who demonstrated a yield reduction based on a low water retention capacity in substrates. Beside these possibilities, it was found that the leaf area correlated positively with the marketable fruit yield ($r = 0.865$, $p = 0.044$). Generally, the photosynthesis can be improved by a higher photosynthetically active leaf area (ENGELS et al., 2012). In this context, it was assumed that the lower leaf area from plants grown in sheep wool and hemp slabs led to a reduced assimilate supply, resulting in a yield decline. This hypothesis is supported by MARCELIS and HEUVELINK (1999) and HEUVELINK and DORAIS (2005), who demonstrated that higher assimilation rates promoted the formation of cucumber fruit and flowers of tomatoes. It is more likely, however, that both a higher volume of EAW and a higher leaf area can be used as explanatory approaches for changes in marketable fruit yield.

Regarding fruit quality, it was calculated that the significantly highest amount of BER-fruit were produced by sheep wool slabs (1.9 kg plant^{-1}), followed by hemp slabs (1.8 kg plant^{-1}), rock wool slabs (1.2 kg plant^{-1}) and peat moss slabs (1.0 kg plant^{-1}) (Tab. 5). In this context, it was demonstrated that the yield of BER-fruit decreased with increasing leaf area per plant ($r = -0.886$, $p = 0.041$). A reduced leaf area and a lower volume of EAW as caused by sheep wool and hemp can retard the transpiration stream, whereby the transport of calcium to the fruit can be inhibited. While the content of the most analysed macro- and micronutrients tended only to changes, the calcium content based on dry weight basis was significantly increased in fruit matured by peat moss slabs compared to those ripened by sheep wool slabs (Tab. 6). The results represented the evidence that the higher the calcium content in fruit the lower the yield of BER-fruit ($r = -0.951$, $p = 0.049$). Similar was found by GUICHARD et al. (2001), who explained the higher proportion of BER-fruit by a lower calcium uptake due to the lower water uptake in the root zone.

The firmness of tomatoes is one of the most important quality characteristic for consumers (BATU, 2004), where this attribute was not affected in the present study (Fig. 1). However, the dry matter in fruit produced by hemp (5.64 g 100 g^{-1} FW) was significantly decreased compared to rock wool (6.2 g 100 g^{-1} FW), sheep wool (6.3 g 100 g^{-1} FW) and peat moss (6.1 g 100 g^{-1} FW) (Fig. 1). Nearly the same relations apply to the SSC as well, where a high correlation between these quality characteristics was found ($r = 0.819$, $p = 0.032$). As such, the SSC differed by up to 0.3 g 100 g^{-1} FW between the lowest (hemp) and the highest (sheep wool) content in tomatoes, where no correlation between physical parameters of substrates and the dry matter content, as well as SSC was identified. Similar results were reported by DOBRICEVIC et al. (2008) regarding comparisons between rock wool slabs and organic materials. They found that the dry matter content and the SSC in tomatoes produced by rock wool slabs showed at least a tendency to decrease compared to fruit ripened by the influence of peat, whereas the results were vice versa in consideration of coconut fiber. The same applies to the tests carried out by KOWALCZYK et al. (2011), who found an increase in SSC by up to 0.4 g 100 g^{-1} FW caused by coconut fibre. Beside these results, TÜZEL et al. (2001) obtained different contents of TA from plants

Tab. 6: Effects of different growing substrates on minerals in tomatoes

Content	Element	Rock wool	Sheep wool	Peat moss	Hemp
(mg 100 g^{-1} FW)	C	2643.1 ± 349.3 a	2689.5 ± 151.5 a	2570.3 ± 228.9 a	2531.2 ± 154.5 a
	N	107.5 ± 16.8 a	113.9 ± 10.4 a	102.3 ± 7.0 a	101.9 ± 9.1 a
	P	30.0 ± 4.1 a	28.2 ± 1.4 a	28.8 ± 2.0 a	27.4 ± 2.5 a
	K	214.2 ± 36.6 a	216.6 ± 16.9 a	206.3 ± 22.2 a	200.3 ± 14.6 a
	Ca	7.7 ± 1.4 a	7.2 ± 0.9 a	7.8 ± 1.2 a	7.0 ± 0.7 a
	Mg	7.4 ± 1.4 a	7.5 ± 0.7 a	7.1 ± 0.9 a	7.0 ± 0.6 a
	S	9.6 ± 1.4 a	10.4 ± 0.4 a	9.5 ± 0.8 a	9.4 ± 0.9 a
	Fe	0.35 ± 0.03 a	0.40 ± 0.04 a	0.41 ± 0.09 a	0.42 ± 0.12 a
(mg g^{-1} DW)	C	441.2 ± 2.1 ab	442.8 ± 1.9 b	440.9 ± 2.6 ab	439.0 ± 2.1 a
	N	17.9 ± 0.7 a	18.7 ± 0.8 a	17.7 ± 0.4 a	17.7 ± 1.2 a
	P	5.0 ± 0.2 a	4.8 ± 0.1 a	4.9 ± 0.1 a	4.8 ± 0.2 a
	K	35.6 ± 1.7 a	35.6 ± 1.1 a	35.4 ± 1.0 a	34.2 ± 0.9 a
	Ca	1.3 ± 0.2 ab	1.0 ± 0.1 a	1.3 ± 0.1 b	1.1 ± 0.2 ab
	Mg	1.2 ± 0.1 a	1.2 ± 0.1 a	1.2 ± 0.1 a	1.2 ± 0.1 a
	S	1.6 ± 0.1 a	1.7 ± 0.1 a	1.6 ± 0.1 a	1.6 ± 0.1 a
	Fe	0.06 ± 0.01 a	0.07 ± 0.01 a	0.07 ± 0.02 a	0.07 ± 0.03 a

The contents of nutrients in tomatoes represent average values of five harvest dates, where three biological replicates per harvest date and two greenhouse compartments were considered (n = 30). Different small letters indicate significant differences according to the Tukey-test procedure at a significance level $p < 0.05$. Values with the prefix ± represent the standard deviation.

grown in different substrates, such as perlite, pumice or a mix of perlite and peat (80% : 20%, v/v), whereas no differences occurred in the present study in terms of TA and the sugar : acid ratio (Fig. 1). These calculated values are in agreement with the results provided by ABAK and CELIKEL (1994), who found no changes in TA neither in tomatoes grown in organic (spent mushroom compost and peat) nor in inorganic growing substrates (rock wool and volcanic tuff).
The knowledge about effects of different substrates used in soilless cultures on secondary plant compounds in tomatoes is scarce. ABAK and CELIKEL (1994), for instance, discovered no significant differences regarding contents of LAA when diverse growing materials were compared. However, KOWALCZYK et al. (2011) analysed a higher LAA content in tomatoes of the cultivar Admiro and DRW 7594, which were matured by coconut fibre instead by rock wool. Referring to the present study, it was found that secondary metabolites, such as lycopene, ß-carotene, phenolics and LAA, were not significantly affected by the application of different growing substrates (Fig. 2). Nevertheless, it was evidenced that the EAW contained in substrates has an impact on secondary plant compounds in tomatoes. As such, a high negative correlation was calculated between EAW and: lycopene ($r = -0.918$, $p = 0.040$); ß-carotene ($r = -0.997$, $p = 0.003$); penolics ($r = -0.918$, $p = 0.039$); LAA ($r = -0.848$, $p = 0.152$). Except for the LAA content, all correlations were significant. It might be possible that the lower Volume of EAW in hemp and sheep wool slabs was responsible for a slightly increase of carotenoids and phenolics in tomatoes, which was elicited by a minor water stress. This conclusion is supported by ZUSHI and MATSUZOE (1998), who demonstrated that a soil water deficit of 50% can lead to a lycopene accumulation in tomatoes by 25% compared to non-stressed plants. SANCHEZ-RODRIGUEZ et al. (2011)

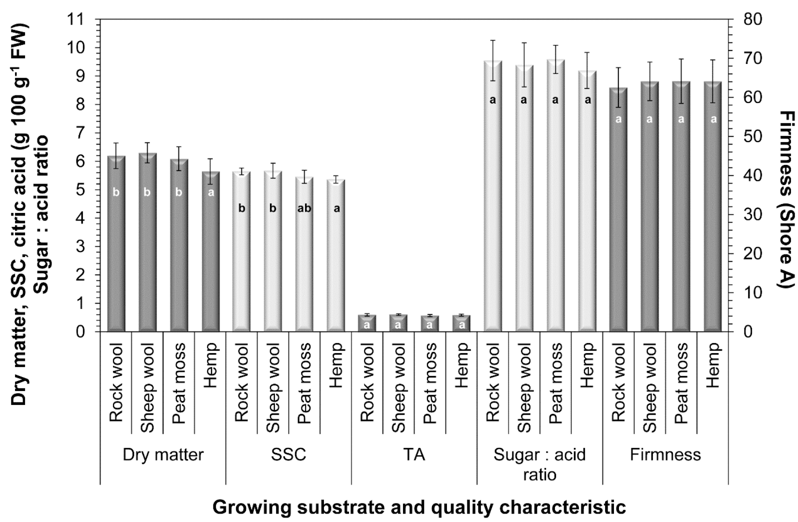

Fig. 1: Effects of different growing substrates on dry matter, soluble solid content (SSC), titratable acid (TA) and firmness of tomatoes. The results represent average values of five harvest dates, where three biological replicates per harvest date and two greenhouse compartments where considered ($n = 30$). Different small letters indicate significant differences according to the Tukey-test procedure at a significance level $p < 0.05$. Values with the prefix ± represent the standard deviation.

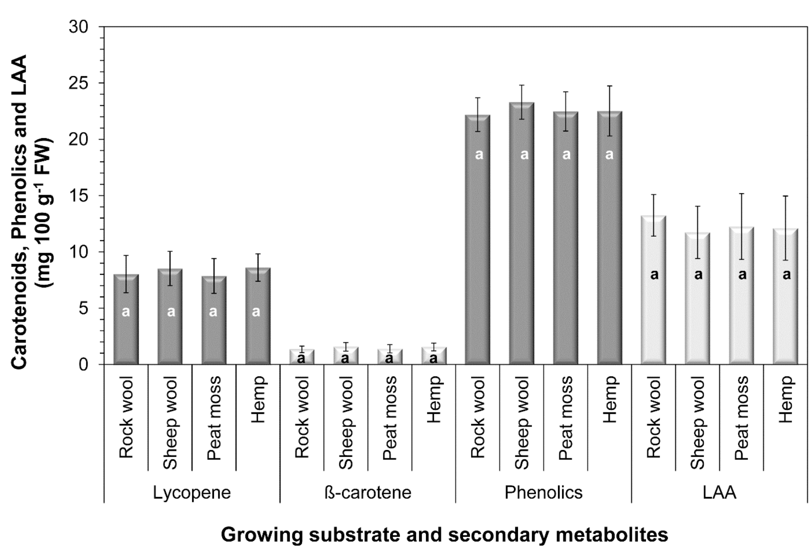

Fig. 2: Effects of different growing substrates on contents of carotenoids, phenolic compounds and L-ascorbic acid (LAA) in tomatoes. The results represent average values of five harvest dates, where three biological replicates per harvest date and two greenhouse compartments where considered ($n = 30$). Different small letters indicate significant differences according to the Tukey-test procedure at a significance level $p < 0.05$. Values with the prefix ± represent the standard deviation.

showed that a moderate water stress can increase phenylalanine ammonia-lyase activity and synthesized phenolics in more tolerant tomato cultivars, e.g., cv. Zarina. In the present study, it might also be possible that the higher lycopene content was a result of a lower calcium content in tomatoes as found for plants grown in hemp and sheep wool substrates, because a significant negative correlation was calculated between these variables (r = -0.990, p = 0.010). In contrast, the contents of ß-carotene, phenolics and LAA remained unaffected. Similar results were demonstrated by FANASCA et al. (2006) under a reduced concentration of calcium in the nutrient solution. Under consideration of all other macro- and micronutrients, no correlations were calculated in combination with the analysed secondary metabolites.

Conclusion

Sphagnum farming enables the production of a renewable organic substrate (WICHMANN et al., 2014). It can be recommended for practitioners that this dried peat moss material pressed as slabs (*Sphagnum palustre)* can be used as replacement for rock wool slabs as growing substrate for hydroponic tomato production. However, the usage of slabs consisting of hemp and sheep wool is not suitable as alternative for rock wool slabs. The findings suggested that comparable results in terms of plant growth, yield, as well as primary and secondary plant compounds were obtained when rock wool slabs and peat moss slabs were considered. The advantage of peat moss slabs is that they can be used to increase the fruit quality of tomatoes, where the yield of blossom end rot fruit was reduced by approximately 17% compared to that produced by rock wool slabs. Hemp and sheep wool slabs, however, promoted the formation of blossom end rot fruit to a much greater extent due to a decreased leaf area as a consequence of a lower volume of EAW, whereby the transpiration stream and therefore the accumulation of Ca in fruit can be retarded. These properties and the fast decomposition of these substrates resulted in plant instability and in an inhibited plant development followed by a yield reduction.

Furthermore, the newly-acquired knowledge about interactions between physical properties, especially EAW and air volume, and the leaf area, flowers, as well as secondary plant compounds can be used, in order to evaluate growing media for hydroponic systems. In this context, the lower air volume contained in peat moss slabs did not negatively affect the plant development. Considering peat moss and rock wool slabs, the optimum values regarding the air volume in substrates used for hydroponic systems have to be adjusted, where values in a range from 9.9 vol% to 58.5 vol% are acceptable for tomato production. The same applies for the adjustment of the optimum value in terms of EAW, which should be between 32.0 vol% and 37.4 vol% to optimize the plant development. Furthermore, a WBC between 0.13 vol% and 0.21 vol% did not affect the plant development negatively.

While production and recycling processes of rock wool slabs heavily pollute the environment as mentioned earlier, the peat moss slabs can be classified as an environmentally friendly growing substrate for hydroponic tomato production. This material can reduce the waste flow under protected growing conditions, because peat moss slabs belongs to organic materials and can therefore be composted environmentally friendly after using or can be used as soil additive or fertilizer under open field conditions. In this context, further investigations are necessary to proof the suitability of used peat moss as fertiliser and in what amounts fertiliser can be saved.

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