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EFFECT OF DIFFERENT GROWING SUBSTRATES ON THE PHOTOSYNTHESIS PARAMETERS AND FRUIT YIELD OF GREENHOUSE-GROWN TOMATO

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Abstract. In the period 2009–2011, a study was conducted in a greenhouse, using fertigation, to determine the photosynthetic activity of leaves and tomato fruit yield of plants grown on different substrates. The plants were grown on rockwool slabs, 15 dm^3 in volume, and slabs of the same volume made of the following straw chaff: rape straw; rape straw + peat (3:1); rape straw + pine bark (3:1); triticale straw; triticale straw + peat (3:1), triticale straw + pine bark (3:1). Two tomato plants were grown on each slab, leaving 22 fruit clusters on each plant during the period from February to October. The obtained results showed that photosynthetic pigment content, chlorophyll fluorescence, rate of photosynthesis and substomatal CO_2 concentration in the leaves of tomato grown on rockwool and on rape or triticale straw chaff substrates did not differ statistically significantly. No significant differences were found in total yield of tomato fruits. Peat or pine bark addition to the rape or triticale straw substrates had no significant effect on the change in their usefulness. The substrates used differed only in the content of total phenolic compounds after tomato harvest. The substrates prepared from triticale straw and its mixture with peat and bark as well as from rape straw with bark were characterized by a higher level of phenolic compounds than the other substrates. In the opinion of the present authors, substrates of rape or triticale straw alone, and even more so with the addition of peat or pine bark are not inferior in any way to commonly used rockwool.

Key words: fertigation, organic substrates, chlorophyll, carotenoids, fluorescence, photosynthesis, tomato yield, phenolics

INTRODUCTION

Economic activity in the countries being members of the European Union presents special challenges to producers of vegetables, flowers and fruits grown in shade houses,

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since the production process may not pose a threat to the environment, and the produced product must meet high quality standards and satisfy consumer demands. One of the factors that largely determines the success of polyhouse cultivation is the growing medium. Throughout the entire growing period, the growing medium should well supply the roots of the crop plant with water, necessary macro- and micronutrients as well as air. Plants respond with stress to an insufficient level of any of the above mentioned factors and stress, in turn, causes among other things, changes first in chlorophyll fluorescence, and then in leaf chlorophyll content [Björkman and Demming 1987, Schreiber et al. 1994, Lichtenthaler and Mieché 1997, Cechin 1998, Congming Lu and Iianhua Zhang 1998], an increased level of substomatal CO_2 concentration [Sánchez-Rodriguez at al. 1999, Blamowski et al. 2001], and a decreased rate of gas exchange [Cechin 1998, Borowski et al. 2000, Borowski and Nurzyński 2007].

In Poland rockwool has been used most commonly for a number of years, in particular in greenhouse vegetable production. This is associated with a number of physico-chemical properties possessed by this substrate which are beneficial to plants [Chochura and Komosa 1998]. But prolonged cultivation of plants in the same substrates leads to phytotoxicity of the medium and causes, among others, accumulation of phenolic compounds [Politycka and Wójcik-Wojtkowiak 1988, 1991, Politycka and Adamska 2003]. On the other hand, the studies of Largué-Saaverda [1979] and Wajahatullach et al. [2003] show that these substances affect photosynthesis primarily through increased stomatal diffusion resistance. Zeng et al. [2001] also report that phenolic substances have a negative effect on the photosynthetic apparatus of plants, since they reduce the chlorophyll content and cause disturbances in electron transport. However, because rockwool is difficult to recycle [Benoit and Ceustermans 1989], research has been conducted on the possibility of replacing it with other mineral and organic substrates.

A solution for this problem could be the use of cereal or rape straw and its mixtures with other organic materials for the preparation of horticultural growing media. In Poland 8 582 600 ha of cereals as well as 810 000 ha of rape and agrimony are grown [Statistical Yearbook of Poland, GUS (Polish Central Statistical Office), 2009], therefore straw from these plants is easily available and, particularly in the case of rape, there are even problems how to use it productively. The wider lack of a concept of the use of cereal straw for the preparation of growing media results from low durability of straw, which, when used as a substrate in tomato growing, decomposes completely in about 70% within the growing period [Nurzyński 2006]. It also has a low water-holding capacity (1 dm^3 retains 0.2–0.3 dm^3 of water) and a low sorptive capacity, which is only 50 milliequivalents in 1 dm^3 [Turski et al. 1980]. But these adverse physico-chemical properties of straw as a substrate are not very important in polyhouse cultivation using fertigation. They can also be partially enhanced by cutting straw into chaff and the preparation of chaff slabs of appropriate dimensions using pressure moulding as well as by using straw chaff in mixtures with other components. So far, the usefulness of rye and wheat straw as well as of their mixtures with other organic materials has been investigated in strictly controlled greenhouse experiments relating to greenhouse cultivation of cucumber, tomato, and lettuce [Babik 2006, Kowalczyk and Dyśko 2006, Stępowski and Nowak 2006, Borowski and Nurzyński 2007].

The aim of the present study was to determine the content and fluorescence activity of photosynthetic pigments, rate of photosynthesis, content of phenolic compounds in substrate, and fruit yield in greenhouse-grown tomato, using fertigation, cultivated on rape and triticale straw substrates as well its mixtures with peat and bark. Plants grown on rockwool were the control in the experiment.

MATERIALS AND METHODS

The experiments were carried out in a greenhouse of the Department of Cultivation and Fertilization of Horticultural Plants in Felin in the period 2009–2011. The experimental plant was tomato cv 'Admiro F_1', cultivated in the period from the beginning of February to about 25 October, leaving 22 fruit clusters on each plants, at a density of 2.4 plants per 1 m^2.

The plants were grown on the following substrates: rockwool, rape straw, rape straw + peat (3:1 vol.), rape straw + pine bark (3:1 vol.), triticale straw, triticale straw + peat (3:1 vol.), triticale straw + pine bark (3:1 vol.). The substrates were prepared each year and used only once.

Straw cut into chaff (pieces with a length of ca. 2 cm) and a mixture of chopped straw with highmoor peat or pine bark were placed in 15 dm^3 boxes, tightly lined with white plastic film with holes to drain away the excess nutrient solution. Two tomato plants were planted both in a box with 15 dm^3 of straw, or a mixture of straw with peat or bark, and in a rockwool slab with the same volume (15 dm^3); hence, one plant had a substrate of 7.5 dm^3 in volume. The box or slab with two tomatoes plants was one plot. The experiment was conducted in 8 replicates during the three years of the study.

Nutrients were supplied with water to the root system of each plant using a drip-irrigation system without recirculation. The frequency of fertigation was controlled by a solar timer that activated the pumps feeding the nutrient solution depending on light intensity. All experimental plants received the same nutrient solution, in the same quantity, and at the same time. The composition of the applied nutrient solution was the following ($mg \cdot dm^{-3}$): total N– 210; P – 54; K – 340; Ca – 250; Mg – 80; S/SO_4 – 150; Cl – 20; Fe – 2; Mn – 0.95; Zn – 0.50; B – 0.54; Cu – 0.09; Mo – 0.09. EC of the nutrient solution was 2.4 $mS \cdot cm^{-1}$ and its pH 5.8, while water EC was 0.7 $mS \cdot cm^{-1}$ and its pH 7.3. During periods of high air temperature, each plant received about 4.2 dm^3 of the nutrient solution in 11–13 doses with 20% excess (overflow).

Measurements of chlorophyll activity and rate of photosynthesis were performed at the flowering stage of the 8th – 9th fruit cluster (21 April 2009), or the 14th – 15th fruit cluster (8 June 2010 and 2011), in the terminal leaflet or the first lateral leaflet of the leaf subtending, respectively, the seventh or ninth fruit cluster. Chlorophyll fluorescence measurements were designed to determine minimum fluorescence (Fo) and maximum fluorescence (Fm) as well as the maximum efficiency of photosystem II (PS II), that is, the parameter Fv/Fm. The determinations were made in quintuplicate in the afternoon hours during a cloudless day, using a Handy PEA fluorometer (Hansatech Instruments) on leaf blade sections that had been prior darkened for 15 minutes by means of special clips.

Measurements of rate of photosynthesis and substomatal CO_2 concentration in leaves were performed in 10 replicates using a portable leaf microclimate control system LCA-4, with a PAR irradiance of 1400–1600 $\mu mol \cdot m^{-1} \cdot s^{-1}$, and temperature in the recording chamber of 30–32°C.

The determinations of chlorophyll and carotenoid content in the 2010 and 2011 experiments were performed on fresh leaf material that had been earlier used to measure chlorophyll fluorescence and rate of photosynthesis. Chlorophyll content was determined following the method of Arnon [1949] and carotenoid content according to Britton [1985].

Tomato fruits were picked up 2 times a week during the period May – October; after harvest, the content of total phenolic compounds in the substrates was determined. To this end, after the substrate was "knocked out of" the boxes, 2 transverse cuts were made with a plastic knife throughout the whole thickness of the substrate in the immediate vicinity of the root mass to collect a ca. 0.5 kg sample. In two collected and combined substrate samples from each box, the content of phenolic compounds was determined following the method of Swain and Hillis [1959] and using chlorogenic acid as a standard.

The obtained results were statistically analysed using single classification analysis of variance at the significance level $\alpha = 0.05$.

RESULTS AND DISCUSSION

The results in Table 1 show that the leaves of tomato growing on rockwool were characterized by the highest chlorophyll content (ca. 2.25 $mg \cdot g^{-1}$ FW), while the leaves of tomato growing on the mixtures of triticale straw with peat had almost the same chlorophyll content (ca. 2.16 $mg \cdot g^{-1}$ FW). The content of chlorophyll was slightly lower, by only about 11% and 14%, respectively, in the plants cultivated on the mixtures of rape straw with peat and triticale straw with bark. The leaves of the plants growing on rape straw alone, rape straw with bark, and triticale straw had the lowest amount of pigment; the content was lower by 16.5% compared to the leaves of the plants growing on rockwool. The results for carotenoid content in the tomato leaves were also similar to those for chlorophyll pigment content. The leaves of the plants growing on the triticale straw substrate with the addition of peat and on rockwool had the highest amount of yellow and orange pigment (0.38 $mg \cdot g^{-1}$ FW). The plants that had grown on rape straw alone and on straw with peat addition as well as on the triticale straw and triticale straw with bark had an average level of carotenoids (0.31 $mg \cdot g^{-1}$ FW). Tomato growing on rape straw with the addition of bark had the least amount of these pigments (0.28 $mg \cdot g^{-1}$ FW), similarly as in the case of chlorophyll pigments. It seems that the lowest chlorophyll and carotenoid content in tomato plants grown on rape straw with bark addition could have been associated with a relatively high phenolic content in this substrate (fig. 1) [Zeng et al. 2001]. However, it can be generally stated that the differences in the contents of all the pigments in question between the plants from the individual experimental series were small and statistically insignificant (tab. 1).

Table 1. Effect of substrate type on chlorophyll and carotenoid content in tomato leaves
Tabela 1. Wpływ rodzaju podłoża na zawartość chlorofilu i karotenoidów w liściach pomidora

Substrate Podłoże	Chlorophyll, mg·g^{-1} FW Chlorofil, mg·g^{-1} sw.m.		Carotenoids, mg·g^{-1} FW Karotenoidy, mg·g^{-1} sw.m.	
	2010	2011	2010	2011
Rockwool Wełna mineralna	2.18	2.33	0.36	0.38
Rape straw Słoma rzepakowa	1.86	1.89	0.29	0.31
Rape straw + peat Słoma rzepakowa + torf	1.75	2.25	0.30	0.36
Rape straw + bark Słoma rzepakowa + kora	1.61	2.06	0.26	0.31
Triticale straw Słoma pszenżyta	1.90	1.81	0.34	0.28
Triticale straw + peat Słoma pszenżyta + torf	2.16	2.16	0.39	0.37
Triticale straw + bark Słoma pszenżyta + kora	1.88	2.00	0.30	0.34
LSD 0.05 NIR 0,05	n.s. r.n.	n.s. r.n.	n.s. r.n.	n.s. r.n.

n.s. – not significant; r.n. – różnice nieistotne

Chlorophyll fluorescence measurements performed during the three years of the study also showed that there were no significant differences resulting from the type of substrate used (tab. 2). Minimum fluorescence, which is emitted primarily from the antennae of light-harvesting pigments in photosystem II, was the lowest in the plants on rockwool, and the highest on the rape straw or triticale straw substrates. The addition of peat or bark to both types of straw caused a slight decrease in the value of Fo in all the three years of the study. A similar relationship between rye grown on straw alone and on straw with the addition of peat or bark was observed in our earlier study [Borowski and Nurzyński 2007].

Maximum fluorescence (Fm) was on average 5.7 times higher than minimum fluorescence; this is a proper value for the Fm/Fo ratio in plants adapted to darkness prior to measurement [Björkman and Demming 1987, Schreiber et al. 1994, Borowski and Nurzyński 2007]. The value of this parameter was, in turn, the highest in the plants grown on rockwool; thus, chlorophyll excitation (Fm-Fo) under the effect of a red light pulse was highest in the leaves of the tomato plants on this substrate [Lichtenthaler and Mieché 1997]. On the other hand, the pigment in the leaves of the plants on the solely rape or triticale straw substrate had the lowest value of Fm. The addition of peat or bark to both types of straw resulted in an insignificant increase in maximum fluorescence. The ratio of variable fluorescence (Fv) to maximum fluorescence Fv/Fm “tells” the most about the photosynthetic activity of chlorophyll, since it reflects the quantum yield of chlorophyll. According to some researchers [Schreiber et al. 1994, Cechin 1998, Congming Lu and Jianhua Zhang 1998], its value should be within a range of 0.80–0.83. In the present study, chlorophyll in the leaves of tomato grown on rockwool showed the highest quantum yield (0.834), whereas this value was the lowest in the plants on triticale straw (on average 0.807) and on rape straw (on average 0.808) hence it was within the recommended range (tab. 3). In the earlier studies of the present authors [Borowski, Nurzynski 2007], chlorophyll in the leaves of tomato grown on rye and wheat straw showed similar values of the Fv/Fm ratio.

Table 2. Effect of substrate type on minimum (Fo) and maximum (Fm) chlorophyll fluorescence in tomato leaves
Tabela 2. Wpływ rodzaju podłoża na minimalną (Fo) i maksymalną (Fm) fluorescencję chlorofilu w liściach

Substrate Podłoże	Fo			Fm		
	2009	2010	2011	2009	2010	2011
Rockwool Wełna mineralna	331	341	360	2188	2196	2205
Rape straw Słoma rzepakowa	389	392	398	2031	2049	2061
Rape straw + peat Słoma rzepakowa + torf	352	358	364	2105	2115	2195
Rape straw + bark Słoma rzepakowa + kora	365	369	376	2095	2087	2104
Triticale straw Słoma pszenżyta	382	391	402	2018	2055	2067
Triticale straw + peat Słoma pszenżyta + torf	375	372	369	2087	2098	2198
Triticale straw + bark Słoma pszenżyta + kora	364	384	382	2074	2082	2115
LSD 0.05 NIR 0,05	n.s. r.n.	n.s. r.n.	n.s. r.n.	n.s. r.n.	n.s. r.n.	n.s. r.n.

Undoubtedly, the sufficient content of photosynthetic pigments in the leaves of tomato grown on all the substrates (Tab. 1) and its high photosynthetic activity (tab. 2 and 3) demonstrate that the plants during the three years of the study had good conditions for CO_2 assimilation [Borowski et al. 2000]. The results in Table 4 show that, similarly as in the case of the content of photosynthetic pigments and chlorophyll fluorescence parameters, the photosynthesis rate was the highest in the plants on rockwool and the lowest on rape straw and triticale straw alone. The addition of peat or bark to both types of straw resulted in an insignificant increase in the rate of photosynthesis (tab. 4). The higher photosynthetic rate in the leaves of plants grown on rockwool, compared to the other growing media, could have resulted from a 2–5 times lower level of phenolic substances. After their uptake by plants, these compounds reduce the photosynthetic pigment content and electron transport, thereby the effectiveness of photosystem II, as well as they increase stomatal diffusion resistance [Largué-Saaverda 1979, Zeng et al. 2001, Wajahatullach et al. 2003]. In an earlier study with tomato grown on rye and wheat straw, the authors obtained similar results [Borowski and Nurzyński 2007].

Table 3. Effect of substrate type on maximum efficiency of photosystem II (Fv/Fm) and substomatal CO_2 concentration in tomato leaves

Tabela 3. Wpływ rodzaju podłoża na maksymalną efektywność fotosystemu drugiego (Fv/Fm) i podszparkowe stężenie CO_2 w liściach pomidora

Substrate Podłoże	Fv/Fm			Substomal CO_2 concentration Podszparkowe stężenie CO_2 $\mu mol \cdot mol^{-1}$		
	2009	2010	2011	2009	2010	2011
Rockwool Wełna mineralna	0.832	0.838	0.831	238.2	228.8	235.6
Rape straw Słoma rzepakowa	0.809	0.802	0.812	257.2	257.3	266.2
Rape straw + peat Słoma rzepakowa + torf	0.815	0.821	0.830	240.4	230.4	232.4
Rape straw + bark Słoma rzepakowa + kora	0.819	0.815	0.824	262.8	227.5	248.3
Triticale straw Słoma pszenżyta	0.810	0.810	0.802	264.3	255.9	267.8
Triticale straw + peat Słoma pszenżyta + torf	0.822	0.818	0.825	235.6	232.2	243.6
Triticale straw + bark Słoma pszenżyta + kora	0.819	0.803	0.818	268.8	254.2	251.1
LSD 0.05 NIR 0,05	n.s. r.n.	n.s. r.n.	n.s. r.n.	n.s. r.n.	n.s. r.n.	n.s. r.n.

Substomatal CO_2 concentration inside the leaves is a simple consequence of the rate of photosynthesis [Sánchez-Rodriguez et al. 1999, Blamowski et al. 2001]; at a high level of CO_2 assimilation, its concentration decreases and inversely. Thus, the lowest concentration of this gas in the intercellular spaces of the assimilation parenchyma of the leaves was in the plants on rockwool (on average 234.2 $\mu mol \cdot mol^{-1}$) and the highest one in those growing on rape straw and triticale straw (on average 261.4 $\mu mol \cdot mol^{-1}$) (tab. 3). The study also found no significant differences in substomatal CO_2 concentration.

The mean values of tomato yield obtained on the substrates used during the 3 years of the study were similar and did not differ significantly. The difference between the

Table 4. Effect of substrate type on the rate of photosynthesis and total tomato fruit yield
Tabela 4. Wpływ rodzaju podłoża na intensywność fotosyntezy i plon ogólny owoców pomidora

Substrate Podłoże	Photosynthesis – Fotosynteza µmolCO$_2$·m^{-2}·s^{-1}			Fruit yield, kg·plant^{-1} Plon owoców, kg·roślina^{-1}		
	2009	2010	2011	2009	2010	2011
Rockwool Wełna mineralna	16.13	14.87	15.79	15.97	16.36	16.81
Rape straw Słoma rzepakowa	15.59	13.09	13.92	16.64	15.16	17.08
Rape straw + peat Słoma rzepakowa + torf	16.37	14.62	15.05	16.69	16.48	16.66
Rape straw + bark Słoma rzepakowa + kora	15.13	14.03	14.50	16.92	16.37	17.31
Triticale straw Słoma pszenżyta	15.10	13.25	14.02	16.19	14.63	16.48
Triticale straw + peat Słoma pszenżyta + torf	16.07	14.35	14.97	16.60	16.68	16.59
Triticale straw + bark Słoma pszenżyta + kora	15.74	13.79	14.34	15.63	17.20	17.04
LSD 0.05 NIR 0,05	n.s. r.n.	n.s. r.n.	n.s. r.n.	n.s. r.n.	n.s. r.n.	n.s. r.n.

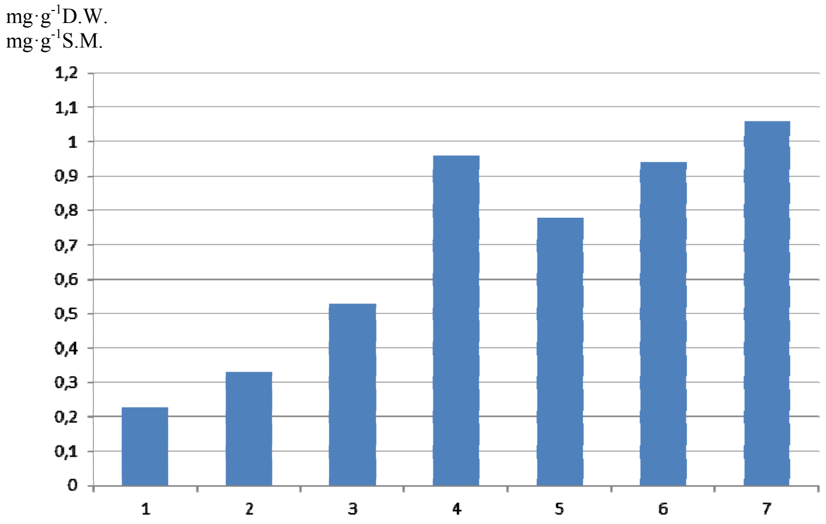

Fig. 1. Content of total phenolic compounds in substrates after harvest of tomato fruits: 1 – rockwool, 2 – rape straw, 3 – rape straw + peat, 4 – rape straw + bark, 5 – triticale straw, 6 – triticale straw + peat, 7 – triticale straw + bark

Ryc. 1. Zawartość związków fenolowych ogółem w podłożach po zbiorze owoców pomidora: 1 – wełna mineralna, 2 – słoma rzepakowa, 3 – słoma rzepakowa + torf, 4 – słoma rzepakowa + kora, 5 – słoma pszenżyta, 6 – słoma pszenżyta + torf, 7 – słoma pszenżyta + kora highest yield obtained from the plants on the mixture of rape straw with bark (16.87 kg·plant^{-1}), and the lowest one obtained on triticale straw (15.77 kg·plant^{-1}) was only 1.10 kg. However, the difference between fruit yield on rockwool as a standard substrate in greenhouse production and triticale straw was only 0.61 kg. The usefulness of other substrates prepared on the base of cereal straw for abundant fruiting of tomato has been confirmed by Kowalczyk and Dyśko [2006], Nurzyński [2006], Borowski and Nurzyński [2007], while for other vegetables by Babik [2006], Stępowska and Nowak [2006].

In the substrates used, the content of phenolic compounds was determined for the same purpose. These substances constitute one of the most important groups of phytotoxic compounds which are responsible for soil sickness [Politycka and Wójcik-Wojtkowiak 1988, 1991, Politycka and Adamska 2003]. Decomposing organic materials and plant residues are their source. The results in Figure 1 show that the lowest content of phenolic compounds was in rockwool; this is fully understandable, since rockwool is a mineral substrate. The phenolic substances in this substrate probably came from root exudates. The substrates prepared from rape straw and mainly triticale straw had a higher content of phenolics. The addition of peat or bark to both types of straw caused a distinct increase of these substances in the substrate. Our results show that after one year of growing tomatoes the content of phenolic compounds was very low in all the straw substrates used [Politycka and Wójcik-Wojtkowiak 1991, Politycka and Adamska 2003].

CONCLUSIONS

1. Photosynthetic activity (photosynthetic pigment content, chlorophyll fluorescence, CO_2 assimilation) of the tomato plants grown on rockwool and on rape or triticale straw substrates did not differ statistically significantly.
2. The addition of other organic substances (peat, pine bark) to the rape or triticale straw substrates had no significant effect on the change in their usefulness.
3. The rape and triticale straw substrates with the addition of pine bark showed the highest phenolic content, as determined after the end of the growing season, while the rockwool substrates exhibited the lowest phenolic content.
4. Tomato fruit yield from the plants grown on the substrates made of rockwool and rape or triticale straw alone and on their mixtures with peat or bark did not differ significantly.

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WPŁYW RÓŻNYCH PODŁOŻY NA WSKAŹNIKI FOTOSYNTEZY I PLON OWOCÓW POMIDORA UPRAWIANEGO W SZKLARNI

Streszczenie: W latach 2009–2011 przeprowadzono badania w szklarni z zastosowaniem fertygacji, dotyczące określenia aktywności fotosyntetycznej liści i plonu owoców pomidora uprawianego na różnych podłożach. Rośliny rosły na matach z wełny mineralnej o pojemności 15 dm^3 i matach o analogicznej pojemności przygotowanych z sieczki: słomy rzepakowej, słomy rzepakowej + torf (3:1), słomy rzepakowej + kora sosnowa (3:1), słomy pszenżyta, słomy pszenżyta + torf (3:1), słomy pszenżyta + kora sosnowa (3:1). W każdej macie rosły 2 rośliny, prowadzone na 22 grona w okresie od lutego do października. Uzyskane wyniki wykazały, że zawartość barwników asymilacyjnych, fluorescencja chlorofilu, tempo fotosyntezy i podszparkowe stężenie CO$_2$ w liściach pomidora uprawianego na wełnie mineralnej i podłożach przygotowanych z sieczki słomy rzepakowej lub pszenżyta nie różniły się w sposób istotny statystycznie. Nie stwierdzono także istotnych różnic w całkowitym plonie owoców pomidora. Dodatek torfu lub kory sosnowej do podłoży przygotowanych ze słomy rzepakowej lub pszenżyta nie wpłynął w istotny sposób na zmianę ich przydatności. Badane podłoża różniły się tylko zawartością związków fenolowych określoną po zakończeniu uprawy pomidora. Podłoża przygotowane ze słomy pszenżyta i jej mieszanek z torfem i korą, a także słomy rzepakowej z korą charakteryzowały się wyższym poziomem związków fenolowych niż pozostałe. W opinii autorów podłoże przygotowane z samej słomy rzepakowej lub słomy pszenżyta, a tym bardziej z dodatkiem torfu lub kory w niczym nie ustępują powszechnie stosowanej wełnie mineralnej.

Słowa kluczowe: fertygacja, podłoża organiczne, chlorofil, karotenoidy, fluorescencja, fotosynteza, plon owoców, fenole

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