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Effect of Re-Used Lignite and Mineral Wool Growing Mats on Plant Growth, Yield and Fruit Quality of Cucumber and Physical Parameters of Substrates in Hydroponic Cultivation

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Abstract: In hydroponic cultivation of vegetables with a solid substrate, mineral wool predominates. The pro-ecological policy and consumers' expectations cause an increase in interest in organic substrates, which, when properly used, are less harmful to the environment. The aim of this study was to determine the effect of reusing lignite substrate in hydroponic cultivation on the growth, yield and quality of cucumber fruit and on the physical parameters of the substrate. The greenhouse cucumber cultivar 'Mewa F1' with semi-long fruits and smooth skin was used for the study. The plants were grown in the 'Carbomat' lignite substrate and 'Grotop Master' rockwool in two cycles. In cycle 1, new growing mats were used, while in cycle 2 the same growing mats as in cycle 1 were used again. In the hydroponic cultivation carried out on mineral wool and in the lignite substrate, both in the new and the reused substrate, the cucumber obtained mostly similar plant growth parameters and fruit color. Cucumber grown on the new mineral wool had a higher number and weight of fruits, which were characterized by a higher content of β-carotene and lutein compared to fruits from plants grown in the new lignite substrate. On the other hand, the reused lignite substrate resulted in higher cucumber yields and fruits with higher firmness and higher carotenoid content compared to cucumber grown on reused mineral wool. At the same time, the content of dry matter and sugar extract in fruits obtained from plants growing in the new and reused lignite substrate was higher compared to fruits grown in mineral wool. Both new and reused lignite substrate were characterized by very low plant-available water content. In contrast; the air and water holding capacity of lignite after cultivation did not change as much as that of mineral wool.

Keywords: substrate parameters; water retention; air-water properties of the organic substrate; SPAD-index; total soluble salts; CIE Lab

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1. Introduction

Increasing problems with environmental pollution, excessive CO_2 emissions and difficulties in the efficient production of food of a high, standardized quality are the reasons for looking for new solutions in the technology of vegetable production under cover. Many researchers are intensively searching for new cultivation technologies, including energy-saving and pro-environmental solutions, which will ensure optimum plant yields throughout the year.

Cucumber *Cucumus sativus* L. is, after tomato, the second most important vegetable species in production under covers in Poland and worldwide [1]. Throughout the year, the demand for high quality cucumber fruit is very high and does not decrease during winter [2]. The amount and quality of the yield are affected by many factors, including temperature, humidity, light intensity, the degree of plant nutrition and the type of substrate [1,3]. The most commonly used substrate for growing vegetables in hydroponic systems is mineral wool [4,5], which is usually not recycled but disposed of after one growing cycle, leading to an accumulation of post-production waste. Annually, a production greenhouse with 1 ha of growing area leaves 150 m^3 of used mineral wool [5]. The properties of the mineral wool substrate make it possible to increase yields and production efficiency compared to conventional cultivation. Mineral wool is an inert, universal substrate and is most applicable in commodity vegetable cultivation. This does not change the fact that the amount of mineral wool waste and the problem with its utilization force the search for alternative substrates for hydroponic cultivation [5–7]. Increasingly, producers under covers are starting to use coconut fiber growing mats [8]. It is an organic substrate produced in tropical countries. It has stable physical and biological properties, but tends to accumulate minerals, leading to an increase in EC (electric conductivity) over time [9,10]. Currently tested organic substrates used for hydroponic production are, for example, post-production waste from the wood industry (bark, sawdust) or plant residues from other production departments or industries. Compost and biochar obtained from plant waste can be used as substrates for hydroponic production [11–13]. Composts often have a high variability of physical characteristics depending on the composition of the waste from which they are made [11], and the production and use of biochar in agriculture is considered too capital intensive [14,15]. Plant residues used as substrates are rye or rapeseed straw [16], *Miscanthus* [6], rice husks [17], almond and hazelnut shells [18–20], grape marc [21], oil palm waste [22] or sheep wool and hemp fibers [5]. All these products have beneficial properties for plants, but are often unstable [7], leading to a reduction in easily available water and oxygen in the root zone. Such examples are hemp and sheep wool slabs, which, as research has confirmed, are not a good substitute for mineral wool in hydroponic cultivation [5]. Often mineral substrates such as perlite, mineral wool or vermiculite are mixed with organic substrates to maintain structure and improve physical properties [23]. Studies on the reuse of almond shells have shown that this substrate can be used in tomato and melon cultivation for two years without affecting yield or fruit quality [19]. An additional benefit of using organic substrates is that they can be used after cultivation as a fertilizer in conventional crops, compost or solid fuel. Studies on the *Miscanthus* substrate have shown that the plant can be grown conventionally, then used as a substrate in hydroponic cucumber and tomato crops, and burned after use [6]. A biodegradable substrate based on lignite appears to be a similar solution. After cultivation, lignite can provide a source of organic matter for conventional crops without a detrimental effect on the environment [24]. For instance, currently, waste lignite is used for the reclamation of anthropogenically altered soils, and in agriculture, coal dust and lignite are sometimes used for soil improvement or decontamination [25–28]. World lignite resources are estimated at 512 billion tonnes, while in Poland about 23 billion tonnes. The world leader in lignite production is Germany. Poland is on the fifth place just behind Russia, Australia and the United States [25,26]. Lignite is formed from peat in the presence of high temperature and pressure. It contains many organic substances, among others, and it is a very rich source of humic and fulvic acids [27]. Lignite has good physical properties due to highly condensed organic matter, it is sufficiently porous, absorbs water well and maintains a stable homogeneous structure [28–30], and moreover it is a good absorber of mineral components necessary for plant functioning [27,30,31]. According to Kwiatkowska [28], lignite is a sustainable organic material, which can be used in agriculture and greenhouse crops. Currently, the interest in generating energy from coal is decreasing in favor of renewable energy sources, while at the same time there is an increasing interest in a diverse use of lignite in agricultural and horticultural crops [28–30].

Awareness of problems with water availability, environmental pollution and the need to produce high and monitored quality of vegetables is largely contributing to the growing interest in hydroponic crops. In these crops, mineral wool is the most popular substrate.

This also applies to the year-round cultivation of cucumbers under cover in two or three cycles in a mineral wool substrate. Increasingly, research is being undertaken to develop an effective cultivation technology with a biodegradable substrate, which would significantly reduce the use of mineral wool, which is problematic in terms of utilization.

The study investigated the suitability of reused organic lignite-based substrate for hydroponic cucumber cultivation. Changes in the properties of reused organic lignite substrate in cucumber cultivation compared to mineral wool and their effects on growth, yield and fruit quality of cucumber were investigated.

2. Materials and Methods

The research was conducted in the Department of Vegetable and Medicinal Plants at the Greenhouse Experimental Centre of the Warsaw University of Life Sciences. In the greenhouse chamber, the conditions of microclimate and fertigation of plants were computer-controlled. The cultivation substrate consisted of lignite mats (CM) Carbomat by CarboHort, measuring 100 cm × 20 cm × 8 cm, and the control consisted of mineral wool mats (MW) Grotop Master by Grodan, measuring 100 cm × 20 cm × 7.5 cm. The greenhouse cucumber cultivar 'Mewa F1' by Rijk Zwaan was used for the study. It is an early variety, tolerant to low irradiance, with uniform yielding. It produces fruits 20–24 cm long, weighing 200–240 g, with dark green, smooth skin and slight ribbing. The plants were grown in two cycles. In the first one, cucumber seedlings were planted into a new medium of mineral wool (MW new) and lignite (CM new), and in the second cycle, into mineral wool growing mats after the first cultivation cycle (MW reused) and similarly into lignite mats (CM reused). The plants, after the first cultivation cycle were removed from the cultivation mats together with the seedling cubes, and in the second cycle the seedlings were planted in places next to the removed plants. While preparing the cucumber seedlings, on both dates, seeds were sown directly into mineral wool cubes on 20 November 2019, in the first cultivation cycle, and on 26 June 2020, in the second cycle. The wool cubes were soaked in nutrient solution with pH 5.4 and EC 1.8 mS·cm^{-1}. The seedling was produced on the first date with lighting by HPS lamps (Gavita GAN 600 W) at light levels averaging 170 μmol m^{-2}·s^{-1} PPFD (Photosynthetic Photon Flux Density), 16 h per day, average temperature D/N 22/21 °C, humidity averaging 24 h RH 60–70% and CO_2 800 ppm per day. Seedling for the second cycle of cultivation was produced under natural light, where temperature averaged D/N 25/21 °C, humidity RH 65–70% and CO_2 800 ppm.

In order to prepare new growing mats for planting plants in the first cycle, both lignite and mineral wool mats were flooded with nutrient solution with pH 5.5 and EC 2.8 mS·cm^{-1} in an amount of about 8 dm^3 per mat. After 48 h in the lignite mats, 2 vertical drainage holes, each 5 cm long, were made in the foil on the longer side of each mat and about 1 cm high from the bottom. In mineral wool mats, on the other hand, drainage holes were made as standard for this type of substrate. Preparing the substrate for the second cultivation cycle, the mats were poured with water of pH 5.5 at a rate of about 4 dm^3 per mat, obtaining an EC of 1.5 mS·cm^{-1} in the mats. Before planting the seedlings in the second cycle of cultivation, 24 h earlier the mats were soaked in the medium with pH 5.5 and EC 2.8 mS·cm^{-1}.

The first cycle of cultivation was conducted for 12 weeks and the second cycle for 9 weeks. In the first cycle, the daily sum of solar radiation averaged 134.0 J/cm^2 and the cucumber plants were illuminated with sodium lamps for 16 h per day, obtaining a light level of 220 μmol m^{-2}·s^{-1} PPFD on average over the tops of the plants, the lamps switched off automatically at a solar radiation level of 250 W m^{-2}. During the second cropping cycle, the daily solar radiation averaged 1474.9 J/cm^2. The temperature during the growing period averaged D/N 24/21 °C and D/N 25/22 °C in the first and second cycles, respectively, and the humidity and CO_2 concentration averaged RH 60–70% and CO_2 800 ppm in both cultivation cycles.

In both cycles, 3 plants per mat were planted. The experiment was set up using the randomized block method, in 4 replications, with 6 plants in each. Fertilization was carried out using a fertilization computer. Concentrated medium was prepared from single or two-component mineral fertilizers designed for hydroponic cultivation. Dosatron dispensers (D25RE2 0.2–2%) were used for diluting the nutrient solution and dosing acid for pH regulation of fertigation medium. The fertigation medium contained in $mg \cdot dm^{-3}$: $N\text{-}NO_3$ 230, $N\text{-}NH_4$ 10, $P\text{-}PO_4$ 50, K 330, Ca 180, Mg 55, $S\text{-}SO_4$ 80, Fe 2.5, Mn 0.80, Zn 0.33, Cu 0.15 and B 0.33. In both cycles, plants were run by strings on a single shoot, removing all side shoots and tendrils from leaf corners. The first 4 fruit buds on the main shoot, in each cropping cycle, were removed and then, in order to prevent the shedding of excess fruit buds, every other fruit bud on the main shoot was removed preventively.

2.1. Morphological Examination and Chlorophyll Content of Leaves

For morphological tests performed weekly, 6 test plants from each combination were selected. The weekly growth of the cucumber shoot in length was studied by measuring the shoot growth from the height of the shoot apex of the plant, marked on a string (marker) a week before. The results allowed the total length of the cucumber shoot to be determined. The shoot diameter was measured with an electronic caliper in the middle of the internode, between the 3rd and 4th fully developed leaf, counting from the shoot apex of the plant. The length and width and the length of the petiole of the 4th fully developed leaf from the apex of growth were examined. The approximate area of the 4th leaf was determined as the product of leaf length and width. Leaf increment per shoot per week was also determined.

The relative chlorophyll content of leaves was measured using the SPAD (Soul Plant Analysis Systems) test with a Minolta SPAD-502 Plus portable meter. The measurement was carried out on the 4th fully expanded leaf counting from the growth apex. Peel color and fruit hardness were measured. The firmness was measured with the HPE firmness tester at an angle of 90° to the cucumber fruit in the middle of its length. The results are given on the HPE scale (0–100 units).

2.2. Yield, Bioactive Compounds and Colour of Fruit

Cucumber fruits were harvested every two days; the number and weight of harvested fruits were determined. Selected physicochemical parameters determining fruit quality were analyzed in cucumber fruits. For the analyses, 3 fruits were taken randomly from each repetition for each combination. All measurements were performed in three replications.

The dry matter content of the fruit was determined by the weight method at 105 °C. Total soluble solids (TSSs) were determined by refractometric method using a digital refractometer, giving the result in °Brix. The contents of β-carotene, lutein and chlorophyll a and b were determined using high-performance liquid chromatography HPLC (Shimadzu Scientific Instruments company), where cucumber fruits were homogenized with 2 g Na_2SO_4 per 100 g^{-1} fresh weight of sample. The prepared homogenate was weighed out on a laboratory balance at 5 g and then grinded in a mortar with cold acetone (−20 °C) and quartz sand. The samples were then extracted by transferring the extracts to 50 mL volumetric flasks five times and refilled with cold acetone. The samples were centrifuged in test tubes (15,000 revolutions). The resulting supernatant was filtered again through a 0.22 μm syringe filter (Supelco IsoDisc™ PTFE 25 mm × 0.22 μm), then the extract was placed in 1 mL containers into an automatic sample feeder. Using a SIL-20AC HT automatic sample feeder (tray temperature 4 °C), 5 μL of extract was applied to the chromatograph column. Compound separation was obtained using isocratic elution with methanol at 40 °C on a Kinetex 2.6 μm C18 100 Å 100 mm × 4.6 mm column from Phenomenex, flow rate 2 mL min^{-1}. Analysis time was 5 min. The wavelength range was for β-carotene, chlorophyll a and b respectively: 450 nm, 430 nm and 470 nm. From the results of chlorophyll a and chlorophyll b, the sum of chlorophyll a + b was calculated.

Fruit color was measured using the CIE Lab scale (MiniScan XE PLUS D/8-S)—red share—a *, yellow share—b * and brightness—L. Fruit color and hardness were measured on fruit in 3 replicates at 3 locations.

2.3. Physical Properties of Substrates

The use of two different types of substrates (mineral wool mat and loose lignite) requires the use of appropriate analytical methods, differing in the method of sample preparation for analysis of physical properties.

The physical properties of the lignite substrate before and after two cycles of cucumber cultivation were determined according to the PN-EN 13041 standard [32]. The determinations were made in cylinders of 10 cm diameter and 5 cm height. The specific and most important element of this method is sample preparation based on natural settlement of 10 cm layer (double ring) of loose substrate brought previously to water potential −57 cm H_2O. The water–air properties were tested on an 'Eijkelkamp' sand apparatus in the vacuum range of 0–100 cm H_2O, using a 24-h water equilibrium establishment time at each of 5 vacuum levels (−3.2, −10, −32, −50 and −100 cm H_2O). After completion of the sand apparatus determinations, the samples were dried at 105 °C and the shrinkage of the substrates was determined by determining the volume loss. The organic matter content was determined after sample incinerating in accordance with PN-EN 13039 [33]. Porosity, substrate density and water and air content were calculated in accordance with PN-EN 13041.

The physical properties of mineral wool mats were determined using a method developed at the experimental station in Naaldwijk, the Netherlands [32–36]. From the mats, samples of 15 cm × 15 cm were cut with a sharp knife. The prepared samples were placed in a box on a grate (3 cm from the bottom), then the box was filled with distilled water above 1 cm above the sample. The samples were soaked for 24 h ± 2 h, then the water was drained and the samples were left like this for 3 h. After this time, the samples were again flooded with distilled water in the same box for 30 min, then immediately after draining the water they were transferred to a sand block (Eijkelkamp) and a vacuum of −100 cm H_2O was set for 30 min. The samples were then flooded again at 3 cm above the sample, soaked for 24 h ± 2 h and proceeded to the determination of air–water properties, in the vacuum range 0–100 cm H_2O, using a 24 h time to establish water equilibrium at each of the 5 vacuum levels (−4.5, −10, −32, −50 and −100 cm H_2O). After completion of the sand apparatus determinations, the samples were dried at 103 °C ± 2 °C and the shrinkage of the substrates was determined by determining the volume loss. The content of organic matter and ash was also determined in PN-EN 13039 [33], which is necessary for calculating the total porosity in PN-EN 13041 [32].

2.4. Statistical Analysis

The results were statistically processed using Statgraphics Centurion XVII 2016. The one-way analysis of variance (ANOVA) was performed and mean values were compared using the Tukey's HSD test (HSD) at a significance level of $\alpha = 0.05$.

3. Results and Discussion

Current research directions include the search for an organic substrate that could provide efficient plant yields comparable to the standard substrate, which in hydroponic cultivation is mineral wool [6,16,24]. The results obtained indicate that the lignite substrate used for the hydroponic cultivation of cucumber can be used as a new substrate and reused in the next cultivation cycle just as the mineral wool growing mats (Figure 1).

On the basis of morphological measurements, it was found that cucumber plants grown hydroponically on both the lignite and mineral wool substrates were characterized by similar growth parameters such as the weekly shoot length increment, leaf length and width, leaf area and petiole length (Table 1). Both in cultivation carried out in cycle 1, when plants were grown on a new substrate, and in cycle 2, when plants were grown on a used substrate, leaf blade area and cucumber shoot diameter did not depend on the type of substrate. There were also no significant differences in shoot length in the lignite combination compared to mineral wool cycle 1 and 2. A study on tomato growing in organic media showed no significant differences in the case of number of leaves per plant or stem length, while a significantly higher stem diameter was recorded in plants growing on mineral wool [37]. For cucumber plants growing on date palm waste substrate and perlite, stem diameter and stem length were significantly higher in date palm substrate compared to perlite [38]. Alifar et al. [39] investigating the effect of five substrates (coconut fiber, coconut fiber-perlite, coconut fiber-perlite-peat and perlite-peat) on morphological parameters and yield of cucumber obtained the highest stem diameter and the highest number of fruits in plants grown in coconut fiber.

(**a**) (**b**)

Figure 1. Cucumber plants of 'Mewa F1' growing in cycle 1: (**a**) in mineral wool substrate. Photo by R. Łaźny; (**b**) growing in lignite substrate. Photo by R. Łaźny.

Table 1. Selected morphological parameters of cucumber in cycle 1 and cycle 2 of cultivation depending on the type of substrate.

Parameter	Unit	Cultivation Cycle 1 New Substrate		Cultivation Cycle 2 Second-Hand Substrate	
		Mineral Wool	Lignite	Mineral Wool	Lignite
Weekly increment shoot to length	(cm)	51.8 ± 1.58 a *	51.4 ± 1.60 a	52.6 ± 1.22 a	52.9 ± 1.10 a
Shoot length	(cm)	213.6 ± 3.22 a	212.1± 3.07 a	423.1 ± 2.22 a	451.1 ± 3.00 b
Shoot diameter	(mm)	5.8 ± 0.07 a	5.8 ± 0.02 a	6.6 ± 0.97 a	6.5 ± 1.10 a
Number of leaves per week	(pcs·plant^{-1})	4.0 ± 0.70 a	4.2 ± 0.37 a	3.5 ± 0.53 a	4.0 ± 0.69 a
Leaf length	(cm)	22.2 ± 1.68 a	22.8 ± 1.90 a	18.7 ± 1.95 a	18.2 ± 1.41 a
Leaf width	(cm)	25.5 ± 1.71 a	26.0 ± 1.31 a	24.3 ± 1.47 a	22.6 ± 1.57 a
Leaf area	(cm^2)	600.0 ± 13.5 a	629.0 ± 12.1 a	455.2 ± 10.03 a	438.3 ±11.18 a
Petiole length	(cm)	11.4 ± 1.56 a	10.7 ± 1.39 a	12.5 ± 1.78 a	12.9 ± 1.34 a
SPAD leaf 4.	SPAD	37.1 ± 1.24 a	37.7 ± 1.12 a	40.1 ± 1.10 a	40.6 ± 1.06 a

* Average values marked with the same letters are not significantly different within the analyzed parameter at $p < 0.05$. Values with the prefix ± represent standard deviation.

In the study, higher total number of fruits per plant and higher total fruit weight were recorded in plants grown on mineral wool in the 1st cropping cycle (Table 2). For the second cropping cycle, the highest total fruit weight was obtained from plants growing on reused lignite substrate compared to reused mineral wool. This is probably due to more favorable conditions for the activity of the cucumber root system (uptake of water and mineral nutrients) as fertigation was similarly carried out for both substrates. Fruits in the second cropping cycle grew faster, which may have been influenced by the date of cultivation and more favorable microclimatic conditions (Table 2).

Table 2. Total yield and average weight of cucumber fruit in cycle 1 and cycle 2 of cultivation depending on the type of substrate.

Parameter	Unit	Cultivation Cycle 1 New Substrate		Cultivation Cycle 2 Second-Hand Substrate	
		Mineral wool	Lignite	Mineral wool	Lignite
Number of fruits of the total crop	(pcs·plant^{-1})	14.8 ± 0.84 b *	13.8 ± 0.91 a	15.2 ± 1.10 a	15.6 ± 1.17 a
Total weight of yield	(g·plant^{-1})	2923.0 ± 24.20 b	2617.9 ± 14.40 a	3599.8 ± 15.00 a	3783.0± 15.10 b
Average weight of fruit	(g·fruit^{-1})	197.5 ± 20.51 a	189.7 ± 18.00 a	236.8 ± 11.4 a	242.5 ± 10.00 a

* Average values marked with the same letters are not significantly different within the analyzed parameter at $p < 0.05$. Values with the prefix ± represent standard deviation.

No differences were found for relative chlorophyll content in cucumber leaves SPAD index, both on new and reused substrates (Table 1). The numerical value of SPAD is proportional to the chlorophyll content. The higher the numerical value of SPAD, the better the plant nutrition, because the chlorophyll content increases with increasing nitrogen [40].

Dyśko et al. [29] investigating the effect of lignite substrate on the yield of tomato cv. 'Growdena F1', did not obtain differences in yield compared to mineral wool. Other researchers, comparing organic substrates to mineral substrates also reported no significant differences in vegetable yield at optimal plant nutrition [6,29,38]. Different results were obtained comparing the yield of cucumber grown on mineral wool substrate and perlite to coconut fiber, where the yield in the combination with coconut fiber was found to be lower [41]. The number of buds and hence fruits per plant can be influenced by the cultivation date, number of leaves and solar radiation efficiency [42].

Many authors report that fruit dry matter content depends on climate, excessive temperature rise and regulation of the number of buds per plant [42–44]. The dry matter content of fruit can also be affected by the substrate, which is confirmed by the results of the study in cycle 1, where higher fruit dry matter content was found in plants grown on new lignite compared to mineral wool (Table 3). Nurzyński [16] also obtained a significantly higher dry matter content in tomato fruits grown on rape straw substrate compared to mineral wool. Analyzing the obtained results, organic substrate such as lignite also influenced the concentration of TSS in cucumber fruits. In the present study, a significantly higher TSS content in cucumber fruits was recorded in the combination with lignite in cycle 1. In cycle 2 of cultivation, on the substrates used again, the TSS content in fruits was also higher in the combination with lignite than with mineral wool (Table 3). As reported by Peet et al. [44], yield and especially fruit quality (e.g., Brix value) depend on cultivar and cultivation method, but the effect of substrate on these parameters is difficult to determine unequivocally.

Biologically active components are particularly valuable for humans and are needed to maintain proper functioning of the body [45]. In case of the first cultivation cycle, significantly higher contents of β-carotene, lutein, chlorophyll a and the sum of chlorophyll a and b were recorded in fruits of plants grown on a new mineral wool substrate as compared to lignite. This tendency is not confirmed by the results obtained in cycle 2, where the contents of β-carotene, lutein and chlorophyll a, b and the sum of chlorophyll a and b were higher in the fruits obtained from plants grown on the reused lignite substrate compared to mineral wool (Table 3).

Table 3. Contents of dry matter and selected chemical components in cucumber fruit in cycle 1 and cycle 2 of cultivation depending on the type of substrate.

Parameter	Unit	Cultivation Cycle 1 New Substrate		Cultivation Cycle 2 Second-Hand Substrate	
		Mineral Wool	Lignite	Mineral Wool	Lignite
Dry matter	(%)	3.2 ± 0.01 a *	3.4 ±0.05 b	3.7 ± 0.06 a	3.8 ± 0.09a
β-carotene	(mg 100 g^{-1} FW)	6.3 ± 0.11 b	6.1 ± 0.13 a	5.5 ± 0.16 a	6.2 ± 0.42 b
Lutein	(mg 100 g^{-1} FW)	9.5 ± 0.10 b	9.2 ± 0.13 a	10.7 ± 0.25 a	13.2 ± 1.14 b
Chlorophyll a	(mg 100 g^{-1} FW)	86.2 ± 0.70 a	82.7 ± 0.66 a	73.2 ± 1.72 a	98.6 ± 1.81 b
Chlorophyll b	(mg 100 g^{-1} FW)	35.2 ± 1.90 a	35.4 ± 0.33 a	33.1 ± 1.59 a	49.3 ± 2.84 b
Total chlorophylla + b	(mg 100 g^{-1} FW)	121.4 ± 1.61 b	118.1 ± 0.99 a	106.3 ± 1.40 a	147.9 ± 1.62 b
TSS	(°Brix)	3.1 ± 0.05 a	3.4 ± 0.10 b	3.6 ± 0.05 a	3.9 ± 0.10 b

* Average values marked with the same letters are not significantly different within the analyzed parameter at $p < 0.05$. Values with the prefix ± represent standard deviation.

Studies on tomatoes grown in organic substrates (pine bark, rapeseed straw, high peat and their mixtures) proved a higher content of vitamin C and nitrogen in fruits compared to fruits obtained from plants grown on mineral wool [16]. This is also confirmed by the study of Kowalczyk et al. [46]. A higher content of dry matter and chlorophyll in SPAD units was obtained by Nerlich and Dannehl [40] in lettuce growing in hemp substrate in comparison to mineral wool, wood shavings and peat. In contrast, the highest concentrations of secondary metabolites were obtained in lettuce grown on hemp and wood sawdust substrates. Tzortzakis and Economakis, [47] adding shredded corn stalks to perlite, showed an increase in total TSS and carotenoid content in cucumber fruits compared to fruits obtained from plants grown in perlite and pumice.

Salad cucumber fruits are eaten raw. For this vegetable, hardness is the first important parameter indicating their quality [48]. The conducted statistical analysis proved the absence of differences in the case of hardness of cucumber fruits obtained from plants grown in new substrates in one cultivation cycle. Fruits of plants grown in the combination with reused lignite were characterized by higher hardness in comparison to reused mineral wool (Table 4). Parks et al. [49] reported no differences in the hardness of cucumber fruits harvested from plants grown in coconut fiber and sawdust. According to many authors, skin color is the second important indicator of cucumber fruit quality [50,51]. In the present study, there was no effect of substrate on fruit color on the CIE Lab scale in the 1st and 2nd cycle (Table 4). The CIE Lab scale is a mathematical transformation of the CIE XYZ space. Perpendicular to the ab plane at the achromatic color point is the color brightness axis L with a scale from 0 (black) to 100 (white). The coordinates a and b can take either positive or negative values. Positive values for a indicate red, negative values indicate green. Positive values of the b coordinate refer to the proportion of yellow color and negative values to blue color [52]. Schoutena et al. [53] in their study confirmed the effect of maximum plant nutrition or adequate crop density on maximum/proper cucumber fruit color. However, skin color also depends on varietal characteristics [51,53]. The obtained results of the study do not allow to unequivocally state the influence of substrate type on fruit color and hardness. No effect of applied substrates on cucumber fruit color parameters was found in the study (Table 4).

Mineral (mineral wool), organic (based on peat, coconut fiber, lignite, straw, composted bark and wood fiber) and organic–mineral (mixtures of organic with perlite, expanded clay, vermiculite and sand) substrates can be used for cucumber cultivation [54–56]. The physical properties, especially air–water properties of these substrates differ significantly [5]. The recommended basic physical parameters for substrates intended for cucumber cultivation such as volumetric density, porosity or water and air capacity at −10 cm H_2O are within a very wide range, i.e., volumetric density 30–1400 kg·m^{-3}, total porosity 45–99 (% vol), water holding capacity at −10 cm H_2O 15–85 (% vol) and air holding capacity at −10 cm H_2O 20–80 (% vol). Such discrepancies give great scope for using many substrates for cucumber cultivation, which does not necessarily translate into yield quality and quantity. With such varied parameters, it is important to maintain optimal air and water properties in the substrate by controlling irrigation and fertilization [56,57].

Table 4. Cucumber fruit hardness and color in the CIE Lab system.

Parameter	Unit	Cultivation Cycle 1 New Substrate		Cultivation Cycle 2 Second-Hand Substrate	
		Mineral Wool	Lignite	Mineral Wool	Lignite
Hardness	(HPE)	60.9 ± 1.70 a *	61.1 ± 1.68 a	56.8 ± 1.51 a	63.6 ± 1.50 b
Color (CIE Lab)	a *	−6.6 ± 0.95 a	−6.4 ± 0.51 a	−6.6 ± 1.00 a	−6.8 ± 0.73 a
	b *	11.7 ± 2.29 a	10.9 ± 1.33 a	11.1 ± 1.41 a	12.2 ± 2.02 a
	L	32.8 ± 1.54 a	31.6 ± 1.55 a	29.8 ± 1.50 a	30.1 ± 1.51 a

* Average values marked with the same letters are not significantly different within the analyzed parameter at $p < 0.05$. Values with the prefix ± represent standard deviation.

The parameters characterizing the mineral wool cultivation mats used in the experiment, i.e., bulk density, total porosity, water and air capacity (after gravity water drainage and at a potential of −10 cm H_2O) were within the optimum range for this substrate. The new mineral wool before cultivation had low bulk density, high total porosity, high water and air capacity at a potential of −10 cm H_2O (Table 5). However, it lost its good properties during cultivation and a significant deterioration in physical properties was observed after cultivation compared to the new mineral wool. An increase in the bulk density of the mineral wool mat was observed after 2 cycles of cultivation compared to the new one. However, this did not affect the overall porosity of the wool, but contributed to a significant decrease in air content (Figure 2) and an increase in water content at a potential of −10 cm H_2O (Table 5). The deterioration of the air–water properties in the mat after two cultivation cycles could also have been caused by substrate settlement [34] or an expanding root system [58]. A decrease in total porosity and an increase in bulk density are observed with longer cultivation on mineral wool [34]. This has important implications for changes in air–water properties [34,59], which have a negative effect on plant growth over longer cropping periods [59–62].

Less air in the root zone can lead to abnormal uptake of nutrients, contributing to their accumulation, symptomatic of which is toxicity to plants manifested by chlorosis or necrosis of leaves [58,59]. In the case of lignite, physical properties determined after two cycles of cultivation underwent slight changes. These changes were not so unfavorable in the case of air and water capacity of the substrate as in the case of mineral wool also after two cycles of cultivation (Table 5). It was observed that the decrease in porosity in the lignite substrate after two cultivation cycles of cucumber was associated to a greater extent with a decrease in air content, to a lesser extent with water content at a potential of −10 cm H_2O. Thus, no such changes in air–water properties as in other organic substrates were observed [56,57]. The water retention curve (Figure 3) shows that at the end of cultivation the water content changed to a greater extent in mineral wool than in lignite. The largest fluctuations were observed at a potential of −10 cm H_2O in both substrates and for mineral wool at higher potentials (from −30 to −100 cm H_2O). No such significant differences in water retention were observed in the lignite substrate. However, the retention curves show that the substrates used in the experiment differed significantly in terms of plant-available water content.

Table 5. Physical and air–water properties of mineral wool and lignite mats, new and after second cucumber cultivation cycles.

Parameter	Units	Mineral Wool		Lignite	
		New Substrate	Substrate after 2nd Cultivation Cycle	New Substrate	Substrate after 2nd Cultivation Cycle
Organic matter content	(% of dry matter)	2.2 ± 0.10 a *	7.0 ± 0.69 b	85.0 ± 0.52 a	84.6 ± 0.98 a
Bulk density	(kg m^{-3})	58.5 ± 0.64 a	65.4 ± 2.00 b	394.3 ± 8.90 a	429.1 ± 11.50 b
Total porosity	(% vol)	97.8 ± 0.02 b	97.5 ± 0.17 a	76.1 ± 0.55 b	74.0 ± 0.76 a
Shrinkage	(% vol)	-	-	13.0 ± 1.25 a	10.1 ± 2.36 a
Water content after drainage of gravity water	(% vol)	94.0 ± 0.51 a	94.7 ± 1.49 a	56.9 ± 1.66 a	51.4 ± 2.87 a
Water content pressure at −10 cm H_2O	(% vol)	77.9 ± 0.51 a	87.7 ± 0.82 b	46.6 ± 1.35 a	41.9 ± 1.80 a
Air content after drainage of gravity water	(% vol)	3.8 ± 0.54 a	2.7 ± 0.61 a	19.1 ± 2.16 a	21.9 ± 4.49 a
Air content at −10 cm H_2O	(% vol)	19.9 ± 0.53 b	9.7 ± 1.02 a	41.9 ± 4.80 b	31.9 ± 4.70 a
Easily available water	(% vol)	51.4 ± 0.88 a	69.8 ± 0.97 b	8.1 ± 0.19 a	6.9± 0.11 a

* Average values marked with the same letters are not significantly different within the analyzed parameter at $p < 0.05$. Values with the prefix ± represent standard deviation.

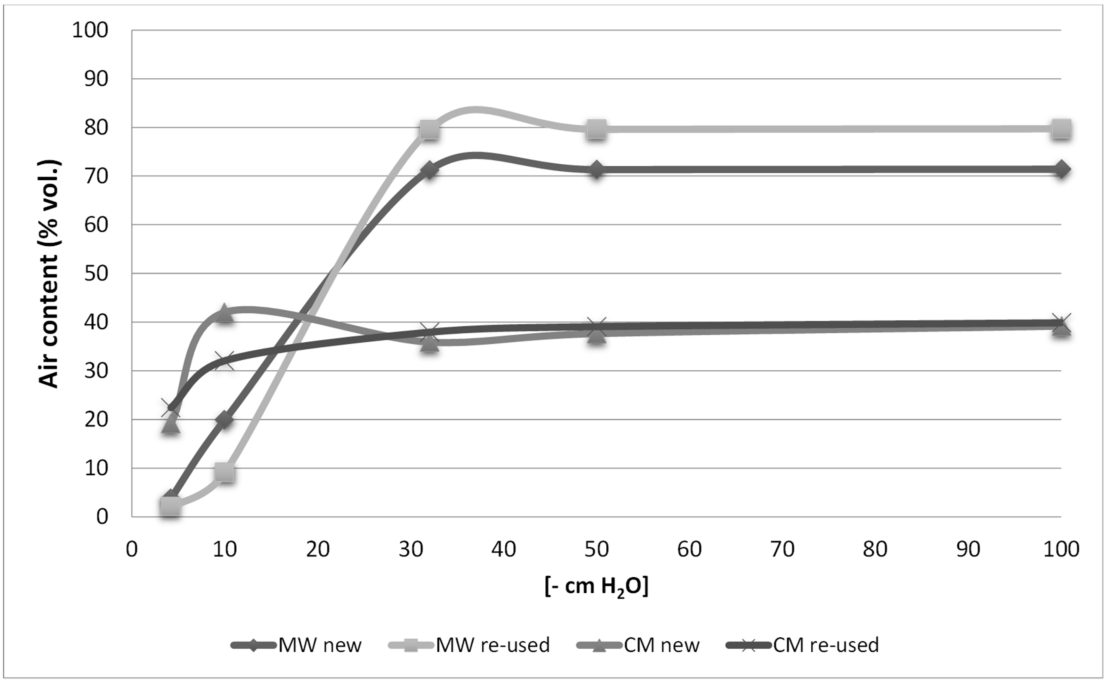

Figure 2. Air content for mineral wool and lignite substrate before and after two cycles of cucumber cultivation.

Easily available water is the water content between the water potential of −10 and −50 cm H_2O [63]. The lignite substrate was characterized by a very low content of plant-available water, which before cultivation in the new substrate was 8.12% and after two cultivation cycles was 6.99%. In mineral wool, the easily available water content was much higher and in the mat before cultivation it was 51.39% and after two cycles it was 69.80%. The type of substrate and their sorption properties have a significant effect on large differences in the easily available water to plants. The structure of the mineral wool mat, i.e., the horizontal arrangement of the fibers and the different density depending on the height of the mat, favors water retention in low negative pressures (from 0 to −10 cm

H_2O), which has a significant impact on its content at the standard potential of −10 cm H_2O. At higher negative pressures (from −10 to −50 cm H_2O), water is less retained and more available for plants, thus significantly increasing the easily available water. Lignite, as an organic substrate, has different properties compared to mineral wool (Table 5). It is a heavier substrate and, depending on the fragmentation of carbon particles and their diameter, has different porosity, which significantly affects the water and air content in the substrate. Unfortunately, these properties are more unfavorable for water (Figure 3), which, at low porosity, is more strongly bound by carbon particles, reducing the content of easily available water. Verdonck et al. [64] report that 30–45 (% vol) of water defined as easily available is needed for optimum plant growth. The content of easily available water in lignite substrate is therefore much lower than that needed for proper plant growth. In fact, not all of this content is used by plants, as a large part of the water during plant growth is lost through evaporation and this amount reaches up to 30% of the total water supplied during irrigation [65,66]. Therefore, the content of easily available water in substrates is of great importance. In order to improve the availability of air and water in the substrate for hydroponically grown plants, an effective fertigation taking into account the properties of the substrates is very important.

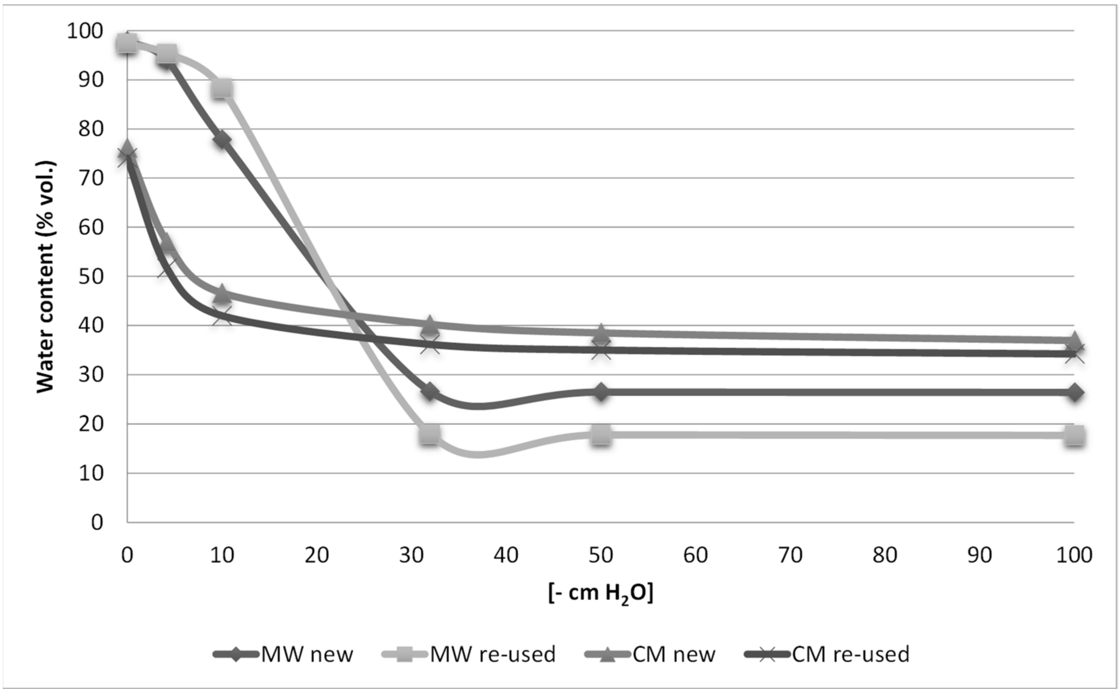

Figure 3. Water content for mineral wool and lignite substrate before and after two cycles of cucumber cultivation.

4. Conclusions

The reuse of lignite substrate in hydroponic cultivation did not reduce cucumber growth, yield and fruit quality compared to the reuse of mineral wool substrate. In addition, the reuse of lignite substrate resulted in higher cucumber yields and fruits with higher firmness and higher dry matter and sugar extract and carotenoid content compared to cucumber grown on reused mineral wool. In spite of the fact that the lignite substrate was characterized by a very low plant-available water content, after its reuse in cucumber cultivation the deterioration of air–water properties was not as high in relation to the parameters of the new substrate as in the case of mineral wool. It was observed that the reduction in porosity in the lignite substrate after two cycles of cucumber cultivation was related more to the reduction in air content and less to the difference in water retention. The results obtained indicate that the biodegradable lignite mat substrate can be reused in hydroponic cucumber cultivation. With the reuse of lignite in cucumber cultivation and appropriate fertigation management, good quality and high yield of cucumber can be obtained compared to the reused mineral wool substrate. The reuse of lignite substrate is pro-environmental and increases its effectiveness in comparison to substrates traditionally used in hydroponic cultivation of cucumber.

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