

Article

Evaluation of Sheep Wool as a Substrate for Hydroponic Cucumber Cultivation

Monika Komorowska ^{1,*}, Marcin Niemiec ¹, Jakub Sikora ^{2,3}, Zofia Gródek-Szostak ⁴ , Hatice Gurgulu ⁵, Maciej Chowaniak ⁶ , Atilgan Atilgan ⁷ and Pavel Neuberger ⁸ 

¹ Department of Agricultural and Environmental Chemistry, University of Agriculture in Krakow, 21 Mickiewicza Av., 31-120 Krakow, Poland

² Faculty of Production and Power Engineering, University of Agriculture in Krakow, 30-149 Krakow, Poland

³ Institute of Management and Production Engineering, Cavalry Captain Witold Pilecki State University of Małopolska in Oświęcim, Maksymiliana Kolbego 8, 32-600 Oświęcim, Poland

⁴ Department of Economics and Enterprise Organization, Cracow University of Economics, 31-510 Krakow, Poland

⁵ Faculty of Agriculture, Ege University, Izmir 35100, Turkey

⁶ Department of Agroecology and Crop Production, Faculty of Agriculture and Economics, University of Agriculture in Krakow, Al. Mickiewicza 21, 31-120 Krakow, Poland

⁷ Department of Biosystem Engineering, Alaaddin Keykubat University, Kestel Mahallesi, Alanya 07425, Turkey

⁸ Faculty of Engineering, Czech University of Life Sciences Prague, Kamycká 129, 165 21 Praha, Czech Republic

* Correspondence: monika.komorowska@urk.edu.pl

Abstract: The problem of the use and disposal of horticultural substrates is an important element of the optimization of plastic greenhouse production in terms of economic and environmental efficiency. The production of mineral substrates is associated with a high energy expenditure, which generates costs and greenhouse gas (GHG) emissions. An important factor is also the transport of professional substrates over long distances. The research objective was to evaluate the possibility of using sheep wool to create horticultural substrates in the hydroponic production of cucumber. The modifier of production technology was the use of substrates of various origins. The experiment was based on the use of two substrates: one was a conventional substrate, made of mineral wool, and the other was made of greasy Gissar sheep wool, which is considered waste or a nuisance byproduct of sheep farming today. The adopted functional unit was 1 ton of commercial cucumber yield. The boundaries of the system were soil formation, fertilization, irrigation, and harvesting. The amount of GHG emissions was calculated in accordance with the ISO 14040 and ISO 14044 standards. The results of the experiment show that the use of sheep wool as a substrate in the hydroponic cultivation of cucumbers reduced yield by approximately 8%, but it allowed for a higher efficiency of water and mineral fertilizer use per crop mass unit. Within the adopted system boundary, the value of the carbon footprint in the object with the conventional substrate was 276.9 kg CO₂ eq · Mg⁻¹. The value of this parameter for the object with the sheep wool was 193.9 kg CO₂ eq · Mg⁻¹. The use of sheep wool did not increase the phytosanitary risk of the cultivated plants. An important goal for achieving sustainability, especially in food production, is to use materials that are easily recyclable and renewable, locally available, and environmentally friendly. The use of sheep wool as a substrate for soilless plastic greenhouse cultivation is a rational solution, as this material consists of 60% animal protein fibers, 10% fat, 15% moisture, 10% sheep sweat, and an average of 5% impurities. This makes it an easily recyclable, easily renewable, and environmentally friendly source of raw material for hydroponic substrates in food production, contrary to rockwool, which produces waste that is difficult to manage and a nuisance to the natural environment. In the countries of Central Asia, the sheep population is over 20 million; therefore, the potential for using sheep wool material for agricultural production is significant.

Keywords: greenhouse gas emissions; cucumber; horticulture substrates; sheep wool; energy resources; sustainability; environmental impact



Citation: Komorowska, M.; Niemiec, M.; Sikora, J.; Gródek-Szostak, Z.; Gurgulu, H.; Chowaniak, M.; Atilgan, A.; Neuberger, P. Evaluation of Sheep Wool as a Substrate for Hydroponic Cucumber Cultivation. *Agriculture* **2023**, *13*, 554. <https://doi.org/10.3390/agriculture13030554>

Academic Editors: Athanasios Koukounaras and Michael Blanke

Received: 7 December 2022

Revised: 25 January 2023

Accepted: 22 February 2023

Published: 24 February 2023



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1. Introduction

Sheep breeding is a very important branch of the economy of the Kyrgyz Republic. When Kyrgyzstan was part of the Soviet Union, breeds with thin wool fibers were improved for the benefit of the textile industry. However, after Kyrgyzstan became independent, the existing international channels of wool distribution collapsed, and local breeders returned to traditional breeds with coarse fibers, but with a taste that is more favored by the Kyrgyz. Another reason for the return to local breeds was the collapse of the feed market, which also limited the possibilities of developing the production of more demanding woolly breeds [1,2]. Thick-wool breeds are independent of forage crops. The problem of Kyrgyz agriculture is the difficulty of gathering feed for winter. The lack of infrastructure for the production, transport, and storage of feed in farms prevents the improvement of wool breeds. Traditional breeds make better use of natural forage and are more resistant to adverse conditions in winter. Another factor limiting wool production in Kyrgyzstan was the collapse of the global wool market in the early 1990s. In recent years, world markets have seen an increased demand for high-quality wool. Some producers in the area of Kyrgyzstan started producing wool, but the production of a high-quality product requires establishing a logistics system to acquire, store, and process wool. Most of the farms in Kyrgyzstan are small, family-run farms, and they use their products for their own use. These days, meat is sold in local markets, while wool is left in the fields or stored on the farm. In the Republic of Kyrgyzstan, there are over 9 million hectares of meadows and pastures, most of which are not suitable for cattle grazing. The improvement of sheep production in these areas is environmentally sound. From an economic point of view, it is important to search for methods of processing and using wool, as selling this raw material would improve the economic condition of many farms in central Asia [3].

Changes in the food and wool markets have led to a significant decrease in the profitability of wool production not only in Kyrgyzstan but also in neighboring countries, such as Uzbekistan, Tajikistan, and Kazakhstan. Therefore, large surpluses of this raw material are observed in these countries. Maintaining the profitability of sheep production in these countries is possible, inter alia, by searching for alternative methods of its use. It is a material with a high potential for use in the construction and agricultural industries [3,4]. Wool is a material that, when introduced into soil, improves its properties, especially in terms of the formation of soil aggregates. In addition, it increases the water capacity in the soil and improves the efficiency of its use by plants [5–7].

One of the most important elements in modern agriculture development is the rationalization of the use of the means of production in the context of sustainable development. Activities that reduce soil degradation and optimize nutrient use are in line with the principles of the most important quality management systems in primary production [8–10]. What is significant from the point of view of reducing the environmental impact of agriculture is the possibility of using ecological waste materials from other industries, as they contain chemical elements that are plant nutrients [11]. Sikora et al. [12,13] point to the possibilities of using waste from various production branches to produce energy and fertilizers or soil enrichment agents. In modern horticultural production, disposable substrates are used since plant health is easier to manage [14,15]. Plant cultivation in soil is associated with the accumulation of diseases and pests. Therefore, when plants grow in soil, it is necessary to use more plant protection products, which increases the environmental impact and decreases the quality of the product. Plant production in soil generally achieves lower fertilization efficiencies. Sikora et al. [16] found that, in vegetable cultivation, it is possible to increase the efficiency of fertilization with slow-release fertilizers. These authors found a dozen-fold improvement in fertilization efficiency using this method, but achieving fertilization efficiency at the level observed in hydroponic crop systems is impossible. From the point of view of the organization of fertilization and plant protection, the use of mineral substrates is easier than in the case of cultivation in soil [17]. The substrates dedicated to horticultural production are characterized by reproducible quality parameters, such as pore size, volumetric weight, and water retention potential [18]. This allows precise

cultivation technologies to obtain high yields with the desired quality values. In such crops, the substrate is a stabilizer for roots and creates conditions for water and nutrient uptake. Mineral substrates are also characterized by a low bulk density and a high share of pores in their volume [19]. In addition, they are characterized by a low buffer capacity, which makes it easier to regulate the pH and precisely deliver nutrients to plants.

An important problem, which many authors point to, is the disposal of postproduction waste. In some countries, such as the Netherlands, most of the mineral wool substrates used are recycled, but in most countries, landfilling is still the primary method of disposal of horticultural substrates [20]. The alternative to mineral substrates is usually organic substrates; the most common substrates are peat, manure, sawdust, straw, and wood shavings. The consequence of the use of peat is the excessive exploitation of peatlands, which are critical for the functioning of many ecosystems, especially wetland ecosystems [21]. An alternative to the substrates produced with peat is the use of organic waste compost, both agricultural and urban, as pointed out by Gavilanes-Terán et al. [22]. The use of organic-waste-compost-based substrates can be problematic due to the high variability in the properties of both the raw materials and the products of the composting process. Composts contain significant amounts of biogenic elements, making it difficult to precisely feed plants in individual growth stages. One of the most important elements of modern horticultural production is the precise dosing of fertilizing elements, as required by the plants. During the vegetation period, compost-based substrates undergo mineralization, which changes the supply of elements for plants and the salinity of the substrate. Many composts have an inappropriate pH, which must be regulated at the stage of substrate preparation or during plant growth. During the vegetation of plants, the substrate is compacted, and its water capacity and pore capacity decrease. Changes in substrate parameters hinder maintaining optimal substrate parameters for plants. Increasing the availability of certain elements, such as nitrogen, could have the consequence of the excessive accumulation of nitrates in the crop [23–25]. Organic substrates increase the risk of the excessive accumulation of heavy metals and increase the microbiological risk to consumers [26]. Organic waste can contain parasite eggs or pathogens. Sheep wool is a material that generates no risks to plant health. The greasy wool microbiome does not affect the phytosanitary status of agrocenosis [27]. In agricultural production that follows quality management systems, such as Global GAP or SAI Platform, the microbiological risk should be taken into account when using substrates. From the point of view of rationalizing the management of environmental resources and the development of waste-free production technologies, it is appropriate to support the search for the opportunity to use alternative horticultural waste substrates, which are safe for plants and consumers. The use of waste-based substrates is always environmentally justifiable; however, the economic and quality aspects should be always assessed before the production of such substrates.

The research objective of this study was to evaluate the possibility of using sheep wool to create horticultural substrates in the hydroponic production of cucumber.

2. Materials and Methods

The adopted goal was achieved based on growing experience, which allowed for GHG emissions to be calculated in two technological variants. The experiment was carried out on a commercial farm located in the village of Sierzchów (33.664 N, 150.730 E) in Wielkopolskie Province, Poland. The farm produces cucumbers in a hydroponic system on mineral substrates. Nutrients are supplied to plants in a liquid that circulates in a closed system. Wastewater is disinfected, and its conductivity and pH are regulated. The EC of the medium is maintained in the range of 2.2 to 2.5 mS · cm^{−1}. The nutrient solution is delivered directly to the plant roots using drippers. The experiment was based on the use of two substrates: one was a conventional substrate, made of mineral wool, and the other was made from grease wool obtained from Hissar sheep from the town of Kalba in the northwest part of the Kyrgyz Republic. The wool substrate was made by cutting and pressing the raw greasy wool. The mechanical properties of both substrates are given in

Table 1. The mechanical properties of the substrates were determined in accordance with the standard [28]. The size of the mats used in the process was 1 m × 0.2 m × 0.07 m. The number of wool mats per 1 ha was 4900 pcs. Each mat held 3 cucumber seedlings, and each object included 48 plants.

Table 1. Basic mechanical and physical properties of the substrates used in the experiment.

Substrate Type	Bulk Density (BDh)	Total Pore Space (TPS)	Air Capacity (AIRC)	Total Water-Holding Capacity (TWHC)	Shrinkage
Unit	kg · dm ⁻³	%	%	kg · m ⁻³	%
Quality requirements for the substrate	<0.4	>85	20–30	600–1000	<30
Mineral wool	0.0722	96.3	28	698	0.9
Sheep wool	0.0800	93.1	25	572	0.8

During cultivation, a careful monitoring of the climate parameters and the properties of the nutrient solution was carried out. The variety used in the experiment was greenhouse cucumber Meleas RZ F1. The cucumbers were planted on 2 July 2019, and the experiment was completed on 17 October 2019. The hydroponic system was semi-closed to optimize the use of the water and nutrients. Each object was irrigated separately, but not each repetition. The composition of the fertigation mixture used in the plastic greenhouse cultivation of the cucumbers was standard. The EC value of the medium ranged and was maintained between 1.6 and 2.2 mS cm⁻¹. Plant protection treatments were carried out with continuous cultivation monitoring and the use of biological protection. During the experiment, there was no need for chemical crop protection, as nonchemical protection methods proved to be sufficient. The experiment was carried out in 4 replicates. Due to the controlled climate conditions and the repeatability of the substrate, the repetitions were not performed in the random block system. In both variants, the plants were grown on mats of 1 m × 0.2 m × 0.075 m, in which 3 plants were inserted. The plant stock was 14,700 pcs · ha⁻¹, and the amount of wool used was 75 m³ · ha⁻¹. During the experiment, the cucumbers were harvested, and the size and components of the yield were determined. The total yield, the number of cucumbers obtained from one plant, and the weight of one cucumber were determined. At the same time, the consumption of water and nutrients was monitored. The climatic conditions in the greenhouse were controlled during the growing season. The plants were not illuminated.

Before starting the research, a chemical analysis of the sheep wool used in the experiment was performed (Table 2). The content of carbon, nitrogen, and sulfur was determined using the elemental analysis method with a Vario Max Cube device by Elementar. The content of the remaining elements was determined using atomic emission spectrometry with an Optima 6700 device from Parkin Elmer. The wool samples were dry-mineralized in an open system and then digested in nitric acid (approx. 20% v/v).

Table 2. Chemical composition of sheep wool.

C	N	Ca	S	Mg	P	K	Na	Fe	B	Al
	%				g · kg ⁻¹				mg · kg ⁻¹	
41.8	7.8	5.822	5	1.42	0.905	30.35	1.128	249	9.8	162

Statistical Analysis

The obtained results were subjected to a variance analysis. The significance of the differentiation of the mean values was determined using Tukey's test ($\alpha \leq 0.05$). Statistica 13 software (TIBCO Software Inc. Palo Alto, California) was used to statistically analyze the results.

System boundaries

The boundaries of the established system included:

1. The production of fertilizers and agrochemicals used to grow plants.
2. The production of substrates used in cultivation.
3. Energy consumption for irrigation.

To determine the environmental impact of the production of plastic greenhouse cucumbers, the following standards were used in two technological variants: ISO 14040 "Environmental Management—Life Cycle Assessment—Principles and Framework" and ISO 14044 "Environmental Management—Life Cycle Assessment—Requirements". The analysis was carried out according to recommendations outlined previously [29]. The research excludes the transport of substrates and products, packaging, the use of agricultural tools, and the marketing and disposal of substrates. To fully achieve the adopted goal, the boundaries of the system were narrowed down to the area related only to production. The research did not take into account the greenhouse gas (GHG) emissions related to the dispersion of biogenic elements in the environment or the emissions related to the transport of substrates and the finished product. Depending on the boundary of the adopted system, different results of the environmental impact level in terms of GHG emissions are obtained. Therefore, it is very important to adopt such a system boundary that would best achieve the goal [30]. In this study, the limits of the GHG emission assessment system were determined based on a parameter suitability study based on a risk analysis in accordance with the ISO 31000:2018 standard. The potential to generate the greenhouse effect was estimated based on GHG emissions expressed as carbon dioxide (CO₂) equivalents.

3. Results and Discussion

The wool used in the experiment is a biological material subject to decomposition. To assess the potential of enriching the substrate with nutrients and trace elements, the chemical composition of the substrate was analyzed. The wool used in the experiment had a high content of nitrogen and potassium (Table 2). A total of 388 kg of nitrogen and more than 150 kg of potassium, according to the pure element, were introduced together with the sheep wool substrate.

The content of phosphorus in the material used was in amounts irrelevant to the production process. Wool decomposition can lead to an uncontrolled release of these elements. This can be problematic when planning a fertilization process where wool is used as a soilless substrate. When sheep wool is used for substrate production, the variability in the chemical composition of the raw material can prove problematic. The chemical composition of wool can vary significantly depending on the breed of the sheep and their diet. Dannehl et al. [20] found approximately 50% more nitrogen and potassium in the wool used in tomato cultivation. In hydroponic technologies, fertilization requires a very precise regulation of the EC level due to the very low buffering of the nutrient medium used. The release of elements from decomposing wool can lead to sudden changes in salinity, which can negatively affect the growth and development of plants [30,31]. Böhme et al. [32] emphasize that, under favorable conditions, the decomposition of wool in soil could take place within a few weeks. A good-quality substrate should not change the quality parameters for at least two production cycles so that the use of the substrate is economically justified [33].

The results of the analysis of the salinity level of the nutrient solution did not indicate an intensified wool decomposition process during the course of the experiment; no visible changes were observed.

The results of the experiment show a slight impact of the substrate used on the yield parameters of the cucumber. There was no statistically significant difference in the number of cucumbers obtained from one plant. In the case of the mineral wool substrate, the average number of cucumbers obtained from one plant was 24.58, while in the case of the sheep wool, this value was 23.77 pcs · plant^{−1} (Table 3).

Table 3. Cucumber yield.

Yield Structure	Unit	Mineral Wool Substrate		Sheep Wool Substrate	
		Average Value	Range	Average Value	Range
No. of pcs. per plant	pcs · plant ^{−1}	24.58 a	22–27	23.77 a	22–26
No. of kg per 1 plant	kg · plant ^{−1}	10.81 a	8.86–12.31	9.98 a	8.72–13.24
Cucumber yield	t · ha ^{−1}	159.5 b	153.7–162.6	146.8 a	144.2–153.9
Average weight of 1 cucumber	kg	0.447 a	0.383–0.495	0.422 a	0.372–0.498

Different letters mean statistically significant differences at the significance level of $p = 0.05$.

Figure 1 is a graphical presentation of the results of the univariate analysis of the variance of cucumber yields depending on the wool substrate used. It can be seen that the type of substrate used impacts the yield of cucumber in hydroponic cultivation. For the substrate made of sheep wool, the yield was 7.96% lower and significantly different from the yield obtained on rockwool substrate. Although the use of sheep wool as a substrate in the hydroponic cultivation of cucumber reduces the yield, it allows for a material that can be managed by means of biological processes after the cultivation cycle is complete.

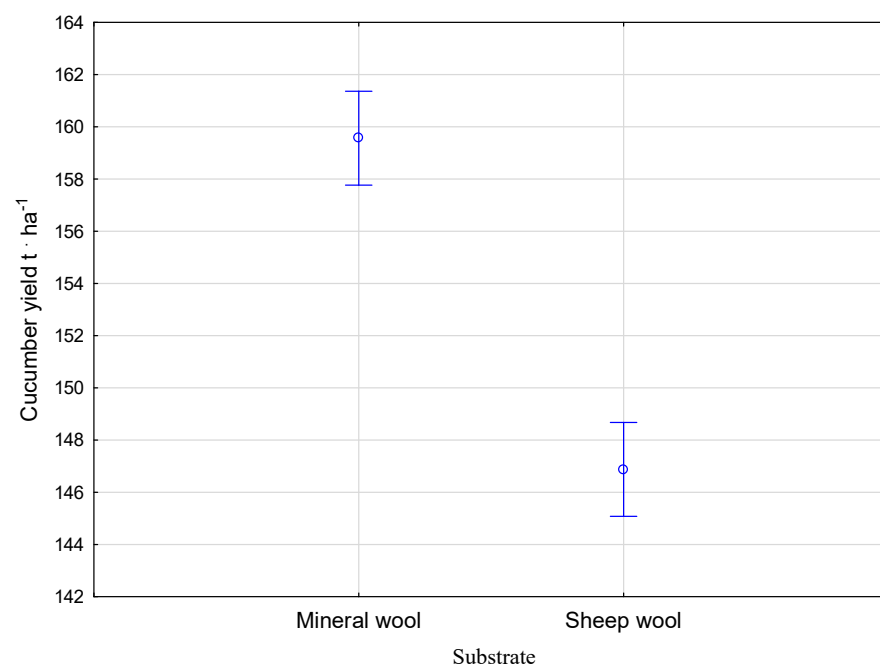


Figure 1. Average values of commercial cucumber yields depending on the wool substrate used.

Similarly, no difference in the amount of yield was found in terms of the weight of the marketable yield. In the case of the mineral wool, minor differences were observed between individual fruits. The unit weight of cucumber fruit is a very important factor in shaping its commercial quality. Minor differences in the morphometric parameters of the products are more favorable from the point of view of the efficiency of the product distribution process. Accordingly, from the point of view of the commercial quality of the crop, smaller differences between the size of the cucumbers were obtained with the conventional mineral-wool-based substrate. From the point of view of production efficiency, notwithstanding

the environmental aspects, the use of the mineral wool was a better technological solution. The yield obtained in the case of this substrate was approximately 8% higher than that obtained in the case of a sheep wool substrate. Dannehl et al. [20] found that tomato grown in sheep wool had slightly lower yields than that grown in mineral wool. The reason for the reduction in the yield in the authors' own research could be water stress related to an incorrect irrigation strategy. Sheep wool differs from mineral wool in terms of water and air capacity. Therefore, when sheep wool substrates are used on an industrial scale, irrigation and fertilization technology should be optimized. The same methods of assessing the water needs of the plants were used in both technological strategies [34].

In the case of an innovative sheep-wool-based potting mix, less water was used per production cycle. The amount of water used for the production of 1 ha of cucumbers in the conventional technology was 4511 m³, while for organic wool, it was 3941 m³ (Table 4).

Table 4. Water consumption for irrigation.

	Mineral Wool Substrate	Sheep Wool Substrate
Consumption of water for irrigation m ³ · ha ^{−1}	4500	3941
Use of water by plants m ³ · ha ^{−1}	1840	1932
Water losses (leaching) m ³ · ha ^{−1}	2660	2009
Consumption of water for irrigation dm ³ · kg ^{−1} of commercial yield	28.21	26.85
Use of water by plants dm ³ · kg ^{−1} of commercial yield	11.54	13.16
Water losses (leaching) dm ³ · kg ^{−1} of commercial yield	16.68	13.69

In the experiment, the water demand was calculated based on the climate parameters monitored in the greenhouse, the level of sunlight, and the monitoring of the moisture level in the substrate. In the experiment, the water consumption was 28.28 dm³ · kg^{−1} of commercial yield. A reduction in water consumption of approximately 12% was observed in the plants grown on the wool substrate compared to those grown on the rockwool substrate, per yield biomass. In the object with the sheep wool substrate, this value was 26.84 dm³ · kg^{−1}. Wu et al. [35] obtained efficient irrigation in a soilless, open system of tomatoes at 40 to 45 dm³ · kg^{−1}. In cultivations with no recirculation, water consumption is much higher. Khoshnevisan et al. [36] report water consumption in plastic greenhouse cucumber cultivation without recirculation at 157 dm³ per 1 kg of commercial yield. Sanz-Cobena et al. [37] found that irrigation is the most important parameter affecting production efficiency and the level of N₂O emissions in plastic greenhouse cultivation. This is related to the level of utilization of nitrogen by mineral fertilizers and the rearrangement of nitrogen compounds in the soil, which depends on the level of soil moisture. The results of the experiment show that the use of sheep wool can reduce water losses in soilless cultivations in plastic tunnels, despite a higher water consumption by plants, and that it can improve the efficiency of water use in plastic greenhouse cultivations. The inefficient use of water in soilless plastic greenhouse cultivations is one of the major environmental problems in the industry [38]. Incrocci et al. [39] report that approximately 80% of soilless cultivations are irrigated with no recirculation. This heavily burdens the environment due to the degradation of water resources and the leaching of nutrients into the environment. In EU countries, water recirculation in soilless cultivation is mainly used in the Netherlands, Belgium, and France. The share of soilless cultivation under cover in these countries ranges from 80 to 100%. In most EU countries, the share of water recirculation installations comprises no more than 10% of all soilless cultivations [39,40]. The introduction of soilless cultivations only makes sense when using highly efficient methods to calculate the water requirements of plants and nutrient recirculation. The mechanical and physical properties of the substrate used determine the effectiveness of the use of water and plant nutrients in hydroponic cultivation [41–43]. The substrates used in the authors' research are characterized by different

properties: a higher specific gravity, a lower air capacity, and a much lower water capacity (Table 5).

Table 5. Consumption of mineral fertilizers and GHG emissions.

	Emission Factor CO ₂ eq · kg ⁻¹ *	Amount kg of Fertilizers · ha ⁻¹		Amount of Emission CO ₂ eq · ha ⁻¹	
		Mineral Wool	Sheep Wool	Mineral Wool	Sheep Wool
Ammonium molybdate	1.2	0.330	0.281	0.396	0.337
Magnesium sulfate	0.3	1033	878.1	309.9	263.4
Potassium nitrate	2.9	2785	2367	8077	6865
Calcium nitrate	3.3	2785	2367	9191	7812
Magnesium nitrate	2.8	333.2	283.2	933.0	793.0
Manganese sulfate	3.6	4.172	3.546	15.02	12.77
Zinc sulfate	3.8	4.152	3.529	15.78	13.41
Copper sulfate	4.0	0.582	0.495	2.328	1.979
Monoammonium phosphate	4.55	125.4	106.6	570.6	485.0
Borax	0.72	8.331	7.081	5.998	5.099
Iron chelate	1.55	3.75	3.188	5.813	4.941
Ammonium nitrate	7.99	20.83	17.71	166.4	141.5
Potassium sulfate	0.12	197.7	168.0	23.72	20.17
Total		7301	6206	1932	1641

* Kool et al. [34].

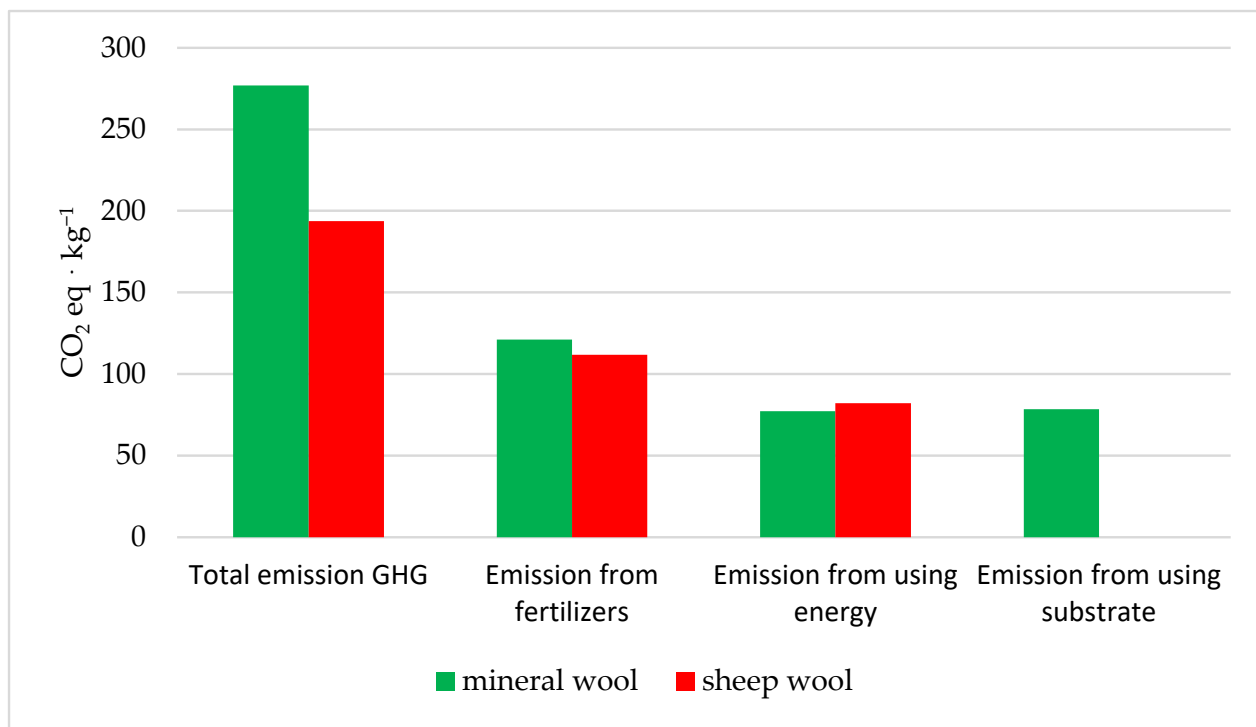
These properties could have influenced the better use of water by plants. In the object with the sheep wool substrate, water consumption was 8% lower than in the object with the conventional substrate. From the point of view of suitability for horticultural production, the water capacity of a good substrate should be 600 cm³ dm⁻³ of the substrate. In the case of a lower value of water capacity, it is necessary to create an irrigation technology to avoid the negative effects of periodic water deficits. The sheep wool substrate was below this value.

The method used to assess water demand in the experiment resulted in different levels of fertilization in the individual technological variants. In the case of the sheep wool substrates, the amount of fertilizers used was approximately 15% lower than that used in the object with the mineral wool. The lower consumption of fertilizers reduced the yield of the plants, while the yield obtained in the objects with the sheep wool was approximately 10% lower than that obtained in the objects with the conventional substrate made of mineral wool. In the proposed cultivation strategy, a slightly higher fertilization efficiency was found in the cultivation of the cucumber on a sheep wool substrate. The reduction in water demand resulted in a lower energy consumption in crop production. In the object with the mineral wool, the energy demand was 1333 kWh/ha⁻¹, while in the object with the sheep wool, the demand was 13,021 kWh/ha⁻¹ (Table 6). Reducing the amount of water used for irrigation directly reduced the amount of fertilizer. Reducing fertilization while keeping crop yields at a high level is one of the most effective methods of reducing GHG in primary production [44].

At the boundary of the adopted system, the value of the GHG emissions in the conducted vegetation experiment was 276.9 kg CO₂ Mg⁻¹ for the yield of cucumbers in the object with a mineral wool substrate and 193.8 kg CO₂ Mg⁻¹ for the yield of cucumbers with a sheep wool substrate. The significant differences in the level of the carbon footprint are related to the substrate used (Figure 2).

Table 6. GHG emissions related to electric power consumption and substrate production.

Unit		Mineral Wool Substrate			Sheep Wool Substrate		
		Quantity	Emission Factor CO ₂ eq · Unit ⁻¹	Total Emission CO ₂ eq · Unit ⁻¹	Quantity	Emission Factor CO ₂ eq · Unit ⁻¹	Total Emission in CO ₂ eq · ha ⁻¹ N
Substrate	m ³	75	167	12,525	75	0	0
Electric power	KWh	13,333	0.9245	12,326	13,021	0.9245	12,038

**Figure 2.** GHG emissions in cucumber cultivation.

The average energy demand to produce 1 m³ of mineral wool intended for plant cultivation substrate is 275 kWh, and when calculated as CO₂ emissions, this corresponds to 167 kg of CO₂ [45]. Zach et al. [46] report the emission factor CO₂ eq for the production of mineral wool to be approximately 90 kg · m⁻³, with a bulk density of approximately 70 kg · m⁻³. The same authors report that the CO₂ eq emission factor for sheep wool is −24 kg CO₂ converted to 1 m³ of wool with a bulk density of 80 kg · m⁻³. When stored, used wool substrate undergoes mineralization, which results in CO₂ emissions of 120 kg of CO₂ · m⁻³. When used for fertilization, the amount of CO₂ emissions from the substrate is comparable to GHG emissions from organic fertilizers. For the purpose of calculating the emission value of the used substrate, the guidelines contained in the IPCC 2006 [47] document were used. Consequently, the amount of CO₂ eq emissions from the wool substrate used for fertilization purposes is 54 kg CO₂ m⁻³. Since the waste was directed to another branch of production, the level of GHG emissions from the wool substrate was considered to be zero in this study. The energy demand for the production of 1 m³ of peat is 3120 MJ. This requires GHG emissions of 168 kg CO₂ eq. Half of the CO₂ emissions from the use of peat for horticultural substrates is due to the emission of this gas during postproduction waste disposal. Approximately 10% of total emissions are related to the extraction and processing of peat [48]. The carbon footprint for the production of 1 ton of tomato in plastic greenhouse cultivation, taking into account the boundaries of the cradle-to-grave system, was 9400 kg of CO₂ eq [49]. In Swedish greenhouses, the amount was 3300 kg of CO₂ eq per 1 ton of tomatoes [50]. In the case of carrots, the value was 550,000 CO₂ eq. Cellura et al. [51] report the total greenhouse effect potential of cherry tomatoes in Italy to be 1290 kg of CO₂ · Mg⁻¹, with a water use efficiency of 77 m³ · Mg⁻¹.

of yield. Most of the greenhouse gases emitted in plastic greenhouse cultivation show energy consumption for heating and maintaining the water recirculation system [52]. These authors indicate that, in plastic greenhouse cultivation, the consumption of fertilizing nitrogen is several times lower and that the consumption of other fertilizers and pesticides is approximately 50% lower per unit of product mass. A very important element that affects the level of GHG emissions from plastic greenhouse cultivation is their emission from nitrogen fertilizers that are not assimilated by plants. In this research, the efficiency of nitrogen fertilization was approximately 5 kg N per 1 Mg of produced commercial crop. Khoshnevisan et al. [36] obtained slightly lower values in the production of cucumbers, approximately 4 kg · kg N per 1 Mg. Based on the level of balance method, the level of nitrogen utilization by plants was considered to be approximately 50%. Nitrogen unused by plants is a significant source of environmental burden, both as a source of the greenhouse effect and the cause of water eutrophication [45,53].

Currently, the substrates most often used in soilless cultivation in the European Union countries apart from mineral wool are coconut fibers, peat, sawdust, bark, perlite, and wood shavings [39]. The production of horticultural substrates also uses dedicated plant cultivations, such as sphagnum, willow, or reed, as well as local waste materials from various production branches.

A good horticultural substrate should have good air and water properties, a high water capacity, and a low sorption potential [54]. It should also be phytosanitary, resistant to crushing, cost-effective, and obtainable locally. With proper logistics and the development of inexpensive methods of processing greasy wool into a professional horticultural substrate, it is possible to build a raw material base for the growing plastic greenhouse production in many countries. The fat contained in grease wool increases the longevity of this material as a substrate for soilless crops. However, the development of soilless crops based on sheep wool must be related to the development of precise irrigation and fertilization technology.

The sheep population in Central Asia is estimated at over 22 million. Most of the wool obtained is waste, which is either illegally landfilled or burned. Taking into account the wool yield efficiency of 3 kg per one sheep, the obtained wool can provide substrates for more than 12,000 ha of greenhouse crops. In the republic of Kyrgyzstan and Uzbekistan, as well as other countries of central Asia, a relatively dynamic development of modern vegetable production has been observed. This triggers the need for changes in both plant production technology and the approach to product quality and safety management [55–57]. The intensification of vegetable production increases the demand for horticultural substrates. Traditional crops in this region use non-standardized substrates made of locally available materials, such as straw and plant waste (bean husks). Plant production with professional substrates is costly. Most of the substrates are imported from the Netherlands. Sheep wool is a waste product of sheep farming, and it is quite remarkable from the point of view of carbon sequestration. Sheep convert the organic carbon contained in plants into wool, which contains almost 50% of the weight of this element. Sheep graze in large areas with unfavorable climatic conditions, making very good use of food resources. In the long run, there will be an increasing number of areas with a water deficit, and, therefore, the size of the sheep population will increase. Due to the properties of wool fibers, the share of this raw material in textile production is only 1.5%. There is a large supply of this raw material, not only in mountainous areas but also in vast arid areas, and there are rational reasons to use it as a material for the production of horticultural substrates. The literature resources offer information on the possibility of using wool or other keratin-containing products as fertilizers or substrates for horticultural production. Slamič and Jug [33] point to the beneficial effect of wool substrate on the growth and development of plants in plastic greenhouse cultivations. However, during wool mineralization, there could be an oversupply of elements, mainly nitrogen. The rapid decomposition of wool is a favorable phenomenon in terms of its use for fertilization [32]. Greasy wool, not mechanically processed, contains significant amounts of fats that limit the growth of

microorganisms and protect it against rapid decomposition. Therefore, it seems justified to use greasy wool as a raw material for the production of horticultural substrates, as demonstrated in this research. Broda et al. [58] found that sheep wool has a longer period of decomposition than other materials used in the production of geomembranes, which is advantageous for creating soilless substrates. Moreover, sheep wool is hydrophobic, which has a positive effect on the air–water properties of the substrate and the conditions for plant growth, which is favorable from the point of view of the fertilization process and the maintenance of plant health. Although the hydrophobic nature of the substrate is not desirable in soilless crops, with a proper irrigation strategy based on frequent irrigation at low amounts, satisfactory production results can be obtained [59]. Dannehl et al. [20] point out that, with time, sheep wool becomes more hydrophilic, which forces a change in the approach to irrigation technology. In the present experiment, water was found to persist evenly throughout the mats, albeit in smaller amounts. The addition of wool to the organic and mineral components of substrates changes their chemical and physical properties. Górecki and Górecki [60] point to the possibility of using wool as a substrate for the production of fertilizers with a controlled release of nutrients. The grease wool microbiome does not pose a phytosanitary threat, which is crucial for the use of this material in plant cultivation. Jeliashkov [61] and Zheljaskov [62] found a positive effect of adding wool to various substrates on the growth of herbs in different periods. A positive fertilizing effect was observed just one month after the application of wool as a fertilizer. The authors emphasize that the elements contained in wool are released into the environment over an extended period of time, during which the wool is mineralized, and the elements are activated. The addition of wool also increases the microbial activity of the soil, which translates into an increased fertility and production capacity of the substrate. Górecki and Górecki [60] found a positive effect of the addition of wool to substrate in the production of vegetables. The increase in the yield of tomatoes and eggplants resulted from both the improvement of the physical properties of the substrate and the increased supply of nutrients. However, Slamič and Jug [33] found a higher growth rate of lettuce on sheep wool than on mineral wool and a slightly lower growth rate than on a soil-based substrate. The authors found that the root weight and biomass of lettuce plants grown on sheep wool were approximately 20% higher than those grown on mineral wool. The uptake of elements from the substrate did not differ significantly between the mineral wool, sheep wool, and soil at the same amounts of nutrients.

4. Conclusions

1. The use of sheep wool as a substrate in the hydroponic cultivation of cucumbers did not require the changing of irrigation and fertilization techniques. This resulted in a reduction in the obtained yield of approximately 10% compared to the mineral wool substrate.
2. Using sheep wool as a substrate reduced water consumption by about 13% per biomass yield.
3. Within the accepted system boundary, the use of the sheep wool substrate reduced the greenhouse effect by 83 kg CO₂ eq · Mg^{−1} of commercial yield.
4. The use of the sheep wool did not increase the phytosanitary risk of the cultivated plants.
5. The use of sheep wool as a substrate for soilless plastic greenhouse cultivation is a rational solution for the development of waste-free methods of food production.

Author Contributions: Conceptualization, M.K., M.N., J.S., P.N. and M.C.; methodology, M.K., M.N., J.S., A.A., H.G. and M.C.; software, M.K., M.N., A.A., J.S. and M.C.; validation, Z.G.-S., H.G., A.A. and P.N.; formal analysis, Z.G.-S. and M.K.; investigation, M.K., M.N., J.S. and A.A.; resources, H.G., Z.G.-S. and H.G.; data curation, M.N., M.K. and J.S.; writing—original draft preparation, M.K., M.N., J.S. and P.N.; writing—review and editing, Z.G.-S., H.G. and A.A.; visualization, M.N., M.K. and J.S.; supervision, Z.G.-S., H.G., and A.A.; project administration, Z.G.-S.; funding acquisition, M.N. All authors have read and agreed to the published version of the manuscript.

Funding: The publication was financed by a subsidy for the Cracow University of Economics (057/ZZE/2022/POT) and the University of Agriculture in Krakow.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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