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Review

A Review of Hydroponics and Conventional Agriculture Based on Energy and Water Consumption, Environmental Impact, and Land Use

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Abstract: The increasing demand for food, the lack of natural resources and arable land, and the recent restrictions on energy consumption require an immediate solution in terms of agricultural activities. This paper's objective was to review hydroponics (a new soilless cultivation technology) and compare it with conventional agriculture (soil cultivation) regarding its environmental impact and water and energy consumption. The soil loss, the crop/soil contamination, and the greenhouse gas emissions were the criteria for the environmental comparison of conventional agriculture and hydroponics. As for resource consumption, the water consumption rates (L/kg), energy consumption rates (kWh), and energy required (kW) were the criteria for comparing conventional agriculture with hydroponics. Tomato and cannabis cultivation were used as case studies in this review. The review results showed that the advantages of hydroponics over conventional cultivation include zero-soil cultivation, land-use efficiency, planting environment cleanliness, fertilizer and resource saving, water consumption reduction, and conservation. The disadvantages of hydroponics versus conventional cultivation were found to include the high investment costs, technical know-how requirements, and higher amount of demanded energy.

Keywords: hydroponics; conventional agriculture; environment; water; land; energy; climate change; tomato; cannabis

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1. Introduction

The United Nations forecasts that the world population will reach approximately 9 billion by 2030 [1]. Other research indicates that the world population has doubled since 1960, while statistics indicate that the world's population will reach 9.8 billion people by 2050 [2]; the same predictions have been made by the World Food and Agriculture Organization of the United Nations (FAO) [3]. In the past 150 years, the world's population has grown by 8.7 billion [4]. In 2016, global hunger grew to affect 815 million people worldwide, confirming the fragile state of global food security [5], and by 2030 it is expected that global food demand will have increased by up to 50% [6]. From 2005 to 2015, the rate of undernourishment declined; more specifically, the rate of undernourishment in 2005 was 14.5%, while in 2015, it reached 10.6% [2]. According to the same research, 947.2 million and 785.4 million people were undernourished in 2005 and 2015, respectively [2]. The same research indicated that the rate of undernourishment remained almost constant from 2015 to 2018, at 10.6% (2015) and 10.8% (2018), while the number of undernourished people grew from 785.4 million people (2015) to 821.6 million people (2018), representing an increase of 4.6% [2]. In 1996, the World Food Summit (WFS) decided that all people should experience food security [7]. Access (via natural presence, financial resources, and as social human beings) to adequate, safe, and nutritious food for people to satisfy their needs for nutrition, ensuring a healthy and active life, is an inalienable right [7].

Since 2000, academic publications mentioning the term "conventional agriculture" have become more frequent; more than 70% of such articles were published in the last ten years, establishing the term "conventional agriculture" as a topic in the literature [8]. Conventional agriculture involves high inputs of pesticides, herbicides, fertilizers, and chemical drugs, which pollute the soil and cause severe risks to human health and the environment [9]. In contrast to conventional agriculture, hydroponics can increase production without the extensive disposal of chemicals into the environment [10]. The nutrient solutions used in hydroponics mainly contain soluble inorganic salts [11].

Conventional cultivation requires soil, in contrast to hydroponics, which is a soilless form of cultivation [12] whereby the crop is submerged in a nutrient solution [13] or different types of substrates [10]. The rising demand for accommodation and the urbanization of agricultural land due to population growth has increased the need for disposable arable land for food production [14]. This situation has arisen because the abrupt growth in the world's population has created a rapid increase in the demand for food production to meet people's nutritional needs [15]. Currently, the agricultural sector accounts for 11% of the world's land area, representing 1.5 billion hectares of land [16]. In contrast to conventional agriculture, hydroponics works in controlled environments and can provide higher annual yields [17], ensuring less land use than conventional agriculture.

Nowadays, the agricultural sector consumes 70% of the world's water withdrawn from aquifers, streams, and lakes and is ultimately responsible for 13.5% of global greenhouse gas emissions [16]. On the other hand, hydroponics saves up to 95% of irrigation water compared to conventional agriculture [18]. In the case of hydroponics implemented as part of a closed system, the water consumption and nutrient supply are reduced [19]. A study on lettuce yield that compared hydroponics with conventional agriculture showed that the water demands were 20 ± 3.8 L/kg/y and 250 ± 25 L/kg/y, respectively, for this crop [17].

For conventional agriculture in greenhouses, most energy is spent on meeting the heating needs [20], as well as cooling and lighting [21]. However, studies have proven that hydroponics has a higher energy consumption than conventional greenhouse cultivation. A helpful example is a study of a hydroponic greenhouse (in the Mediterranean climate zone) that was shown to consumes 2559 kWh/year to cover its electricity needs for cooling and heating [22]. The main characteristics of this greenhouse were: a surface area of 24 m^2, height of 3 m, south-east orientation, and polyurethane panel covering [22].

The main advantages of hydroponics are summarized as follows: reduced chemical application (fertilizers, pesticides, and improvers); soilless cultivation; and more efficient land use, i.e., better performance in terms of land surface area, less consumption, and improved water management. These advantages contribute to a lower environmental impact and make hydroponics an attractive crop cultivation method in a controlled environment. However, the high operational costs [23], extensive know-how requirements [24], and high initial investment costs [25] are disadvantages that cause many producer–growers to avoid hydroponics. This literature review clarifies the situation by comparing conventional agriculture with hydroponics in terms of environmental impact and water and energy consumption.

2. Methodology and Objectives

The agricultural sector must provide a solution to the current challenges regarding food security and ensure food of a high quality and sufficient quantity. In this review, conventional agriculture (soil cultivation) was compared to hydroponics (soilless cultivation). Hydroponics is an emerging technology applied, among others, in agricultural production; it is well-known in the agricultural sector and could become established as the first choice among growers. Conventional agriculture, i.e., soil cultivation, demands the availability of arable land, agricultural areas for planting, the supply of chemicals, and water consumption for irrigation. Conventional greenhouse cultivation demands the consumption of electrical energy. These demands result in the production of greenhouse emissions and climate change. These were the criteria employed for the comparison between conventional and hydroponic cultivation.

In this review, tomato and cannabis were used as example plants, and we provide data on conventional and hydroponic tomato and cannabis cultivation. Tomato is a well-known crop that has been extensively used for research purposes. The bibliographic reports on this crop are numerous and provided enough data for the reliable acquisition of information without large deviations. Additionally, hydroponics is extensively applied to tomato cultivation. Cannabis is a crop that, in recent years, has monopolized the research community's interest, mainly in the field of pharmacology. However, in many cases, the officially recorded data are minimal. This review aimed to collect as much official data as possible on conventional and hydroponic cannabis cultivation. It is essential to mention that cannabis is of particular interest due to its growing conditions, crop yield, and energy footprint.

From a search of the literature using the keywords 'conventional agriculture' and 'hydroponics' in combination, we identified a relatively limited number of sources addressing these two crops and examining criteria such as land, water, energy consumption and environmental impact. In addition, the analysis of two different plants, to which both cultivation methods (conventional and hydroponic) could be applied, was considered helpful for comparison purposes. The two cultivation methods were compared based on similar criteria. The impact of conventional agriculture on the environment and its consumption of water resources and energy for the heating and cooling of greenhouses were the criteria for comparing the two types of cultivation. These criteria were chosen because they could provide a useful comparison between the two types of cultivation.

2.1. Methodology

Data were collected from the recent and earlier literature, which ensured a more accurate and comprehensive approach to analysis. The search for bibliographic sources was carried out using keywords, either individually or in combination. The search keywords were: hydroponics, conventional agriculture, environment, soil, water, land, energy, greenhouse, heating, cooling, energy consumption, crop yield, tomato, and cannabis.

The search results were evaluated based on their relevance to the subject and the provision of useful information. In addition to the most recent publications, we also selected earlier bibliographic sources that were considered helpful in terms of the data and information they could provide. The information collection was based on topics related to hydroponics, conventional agriculture, and greenhouses. From the evaluated resources, 14% of the works used and referenced in this work were issued in the years 2000–2010, 22% in the years 2011–2015, and 60% from 2016 until now.

Data were grouped based on environmental impact (soil, land use, natural resources, and greenhouse gas emissions); water consumption; and energy consumed for heating and cooling. Additionally, we obtained essential data regarding the definition of hydroponics and its advantages and disadvantages as presented in this paper.

A case study of hydroponic and conventional tomato and cannabis cultivation was considered as an example. The example was used to compare hydroponics and conventional agriculture in terms of crop yield, planting density, greenhouse gas emissions, water usage, and energy consumption.

2.2. Objective

The objective of this paper was to identify several useful recent and older literature sources to provide the reader with helpful information regarding hydroponic and conventional cultivation. To achieve this objective, we present a great amount of data from the literature related to each component of the research topic. Data for arable land, crop and soil contamination, climate change, the consumption of natural resources, and greenhouse gases are provided for the environmental component. Data on the rates of water consumption are provided for the water component. Data on the rate (kWh) and quantity of energy (kW) consumption (for heating and cooling) are provided for the energy component. In addition, this paper's objective was to reach conclusions related to the advantages and disadvantages of hydroponics in comparison to conventional agriculture. Additionally, based on the comparison of two crops (tomato and cannabis), we aimed to demonstrate the usefulness of hydroponics in the cultivation of plants, fruits, and vegetables. The benefits of hydroponics in terms of the environment, water, arable land use, land-use efficiency, productivity, and chemical use were this study's primary concern.

3. Data Collected from the Existing Literature

3.1. The Impacts of Conventional Agriculture on the Environment

Conventional agriculture suffers from crucial disadvantages associated with the extensive use of resources, pesticides, fertilizers, and land, all of which must be intensified to meet increasing food production targets [26]. Currently, 38% of non-frozen land globally is at the disposal of crop production, which will rise continuously until 2050, reaching about 593 million hectares of land to meet the food needs of a constantly growing population [26]. The disadvantages of such land use include the destruction of ecosystems and the disturbance of the environmental balance.

Regarding the environmental balance, intensive cultivation at high yields is considered responsible for a loss of soil [27]. In addition, the transformation of the natural landscape and a significant reduction in arable land have been observed [28,29]. As a result, arable land for growing crops to serve individual needs can be located in areas that are not suitable for the cultivation of fruits and vegetables, such as those close to industrial areas [30], which leads to low-quality food production. An additional risk connected with soil cultivation is the presence of weeds, which are responsible for retarded productivity [31].

The consequences of cultivating intensive high-yield crops include a loss in biodiversity and global warming [32]. The food sector could contribute to a decrease in the global temperature of 2 °C by the restriction of greenhouse emissions, mainly through land management [33]. Reducing atmospheric greenhouse gases has become one of the most pressing environmental challenges of the 21st century. Agriculture alone accounts for 50% and 60% of global anthropogenic emissions of N_2O and CH_4, respectively [34], and soil is one of the primary emission sources. In order to effectively move towards reducing the sector's environmental impact, the adequate management of energy consumption is essential and is considered the leading indicator for sustainable development [35,36].

In the last few years, agricultural systems have undergone several changes related to not only equipment and the use of modified seeds but also the extensive use of pesticides and enhancers, the composition of which is inextricably linked to minerals and thus natural resources [37,38]. As a result, pesticides and fertilizers and the release of chemical waste and pollutants are responsible for soil degradation, erosion, and contamination [39] and water contamination [40]. Regarding natural resources and water, soil cultivation demands high-quality water and high-quantity natural resources [41].

All the data detailed above are summarized below in Table 1.

3.2. The Impacts of Conventional Agriculture on Water Resources

The supply of fresh and clean water plays a key role, as many countries with large populations have access to neither clean drinking water nor clean water for sanitation purposes, as reported by the United Nations [42]. The increasing population and its movement to urban centres have decreased the natural freshwater reservoirs and created a large amount of wastewater [43]. The United Nations world water development report provides data for wastewater treatment [44]. These data indicate that high-income countries treat around 70% of their wastewater, upper-middle-income countries almost 38%, lower-middle-income countries almost 28%, and low-income countries almost 8% [44]. The United Nations reported that by 2025, many countries and regions will face water scarcity, affecting almost 1.8 billion people [45].

Table 1. Areas of the environmental burden resulting from conventional agriculture.

Source	Sphere of Influence	Environmental Burden
Princeton Student Climate Initiative [26]	Reduction of arable land	Globally, 38% of non-frozen land is dedicated to crop production, which will continuously increase until 2050, reaching about 593 million hectares of land to meet the food needs of a constantly growing population.
Cortada et al. [28]; Dach and Starmans [29]	Reduction of arable land	The natural landscape is transformed, and the arable land is reduced significantly by conventional agriculture.
Princeton Student Climate Initiative [26]	Crop contamination/soil contamination	Conventional agriculture is associated with the extensive use of pesticides and fertilizers.
Alice Kici'nska and Justyna Wikar [30]	Crop contamination/soil contamination	There is arable land for growing crops located close to industrial areas.
Ezzahoui et al. [31]	Crop contamination/soil contamination	Soil cultivation is threatened by weeds, which are responsible for retarded productivity.
Tilman et al. [32]	Climate change	The intensification of high-yield crops is responsible for a lack of biodiversity and global warming.
IPCC [33]	Climate change	By reducing greenhouse emissions from the agricultural sector alone, global temperatures would be reduced by 2 °C.
Taki et al. [37]; Rafiee et al. [38]	Consumption of natural resources	Introducing machinery, modified seeds, pesticides, and enhancers has changed agricultural systems and increased their dependence on minerals.
Bakhtar et al. [41]; Princeton Student Climate Initiative [26]	Consumption of natural resources	Soil cultivation requires the extensive use of natural resources.
IPCC [34]	Greenhouse emissions	Agriculture accounts for 50% and 60% of global anthropogenic emissions of N_2O and CH_4, respectively, and soil is one of the primary emission sources.

According to the United Nations, 40% of the world's population will live in regions where the water supply will be deficient by 2025 [46]. This is a cause for great concern and reinforces the need for water recycling programs mainly in the agricultural sector, which is considered the largest consumer of fresh water (Table 2) [47]. Agriculture is the largest water consumer, with over 70% of this water being used for irrigation [48]. The large amounts of water required for irrigation [49] are considered one of the disadvantages of soil cultivation. According to FAO data [50], 30–40% of the world's food comes from irrigated areas that comprise only 17% of the total cultivated land. Agriculture is the primary consumer of water, with the industrial sector placed second, followed by domestic and recreational use [51]. At the same time, studies have reported that 80% of water resources are consumed by agriculture [52].

Table 2. Consumption of water resources by conventional agriculture.

Source	Consumption of Water Resources
UNESCO [47]	The agricultural sector is considered the largest consumer of freshwater.
McDaniel et al. [48]	Agriculture is the largest water consumer, with over 70% of this water being used for irrigation.
Hardin et al. [49]	Large amounts of water are required for irrigation.
FAO [50]	Globally, 30–40% of food comes from irrigated areas that comprise only 17% of the total cultivated land.
Sathaiah and Chandrasekaran [51]	The main consumer of water is agriculture.
Sathaiah and Chandrasekaran [51]	Water availability for agriculture will be threatened by growing domestic and industrial demand. Water use for irrigation in 45 countries, accounting for 83% of the world's population, will have increased 22% from 1995 by 2025.
Martinez-Mate et al. [52]	Eighty percent of water resources are consumed by agriculture.
Fitton et al. [53]	Water depletion because of climate change has affected 11% of the world's rural land and 10% of global pastures.
Egbuikwem, Mierzwa, and Saroj [54]	The growing demand for water from the agricultural and industrial sectors is contributing to a worldwide water scarcity crisis.

According to Fitton et al. [53], 11% of the world's rural land and 10% of global pastures are affected by water scarcity because of the climate change. The growing demand for water in the agricultural and industrial sectors is contributing to a worldwide water scarcity crisis [54]. In the future, water availability for agriculture will be threatened by growing domestic and industrial demand, and water use for irrigation in 45 countries, accounting for 83% of the world's population, will have increased 22% from 1995 by 2025 [51].

3.3. The Impacts of Conventional Greenhouse Cultivation on Energy Consumption for Heating and Cooling

Rural development usually faces limitations related to resources, the environment, and energy conservation [55]. Environmental impact reduction, considered a crucial indicator for sustainable development, requires the adequate management of energy consumption [35]. In agriculture, cultivation in a controlled environment, such as a greenhouse, contributes to sustainable development and the production of food in areas with adverse climatic conditions [56]. In areas with high temperatures, greenhouse cultivation is affected by high solar and thermal loads, causing problems in the internal greenhouse environment that negatively affect the growth of crops [57]. On the other hand, low temperatures are responsible for the destruction of crops [58].

The internal greenhouse environment should provide optimal growing conditions. For this reason, the application of heating and cooling equipment, ventilation and misting systems, shading and lighting mechanisms, and CO_2 enrichment systems is necessary [7,59]. The heat trapped inside the greenhouse increases the temperature, which plays a key role; energy must be consumed to meet the greenhouse's needs, which are directly related to the temperature and indirectly to the covering materials, resulting in an increase in the consumption and operating costs [60]. In Saudi Arabia, 151.3 Wh/m^2 per day and 133.8 Wh/m^2 per day of energy are required in the first and third production cycle periods, respectively, to cover the cooling needs (Table 3) [61]. A study of a typical hydroponic greenhouse for tomato cultivation in North Greece proved that the annual cooling load was 95 kWh/m^2 per year [62]. In warmer areas, cooling greenhouses could amount to 50% of the total operating costs [63]. In Mediterranean regions, 100,000 kWh/y/ha is spent on cooling needs [64].

In northern climatic areas, the energy required for heating greenhouses increases significantly and could account for 65–85% of the total energy required for greenhouses operation [65]. A Michigan State University study [66] found that 88% of the energy consumed by a greenhouse is spent on heating. In another study conducted among growers in Sweden, it emerged that the cost of labor and the need for heating were the two highest costs, respectively [67]. Reaching the optimal temperature inside a greenhouse in a cold climate increases the energy consumption significantly, especially at night [68], representing 70–85% of the total operating cost [63]. A study on greenhouses in Serbia showed that 50% of the energy consumed was spent on heating [69]. The heating of Sweden's greenhouses is responsible for 15% of the total energy spent on the country's agricultural activities [70]. In some areas in Mexico where the temperature drops below 10 °C (which is the desirable limit for tomato cultivation), heating a greenhouse's air requires auxiliary equipment [71]. A study of a greenhouse in such a region of Mexico (the minimum temperature varying from 2.49 to 11.24 °C) showed that when the temperature was lower than 12 °C, an average of 3 h of heating per day was required, while in the period from June to September there was no need for heating [71]. The main characteristics of this greenhouse were: a surface area of 1050 m^2, a translucent polyethylene material on the walls and floor, and a polycarbonate material on the roof [71]. Under these conditions, the study showed that 32,228.76 kWh (for the 1050 m^2 greenhouse) was required annually to cover the heating needs [71]. Another study took place in an experimental greenhouse for cucumber cultivation in Tehran, having a total area of 40 m^2 and covered with a polycarbonate material [72]. The temperature inside the greenhouse was 25 °C during the day and 18 °C during the night for the cold season [72]. This research showed that the highest amount of thermal energy required for the heating of this greenhouse was 47.58 kWh/m^2 in January and July [72]. A conventional greenhouse in Sweden required 320 kWh/m^2 to cover its heating needs [73].

Heating and cooling require a high energy consumption of 65–85% [74,75], which has a great impact on not only the overall heating and cooling performance of the greenhouse but also the final configuration of the product's price that reaches the consumer [76]. The annual requirements for energy consumption correspond to 95.3% of the total energy, with 4.7% corresponding to the consumption of electricity [77]. Comparing greenhouses that use microclimate control systems with those that have minimal control climatic systems, it was found that in the former, the energy consumption is 8 to 12 times higher [78]. Thus, energy efficiency and the prudent consumption of energy are gaining the attention and concern of the global community [79].

As emerged from the official figures of the FAO [80], global food chains account for 30% of the total energy obtained from fossil fuels. Overall, 79.7% of the world's energy use is dominated by energy from fossil fuels [81]. Therefore, energy consumption could be the leading cause of environmental problems [82,83], such as global warming from greenhouse emissions; water, soil, and air pollution; soil fertility reduction; soil erosion; and resource depletion [84,85], and contribute 19–29% of the total annual greenhouse gas emissions [80]. Research on greenhouses in France demonstrated that the use of conventional energy sources by agricultural greenhouses is responsible for rising costs and environmental issues [86]. These rising costs and environmental issues are a crucial challenge for researchers, scientists, and investors, who are trying to find alternative sources of clean energy and energy-saving solutions to reduce agricultural greenhouses' dependence on non-renewable energy sources [86]. To succeed and ensure more sustainable rural development and prosperity, reducing the energy consumed by agricultural activities and improving the sector's energy efficiency are necessary [87]. Moreover, transitioning to a more sustainable, accessible, and secure energy system is vital [88]. In addition, fossil fuels should be replaced by an alternative energy source for the successful development of greenhouse structures [89].

Table 3. Energy consumption for cooling and heating from conventional agriculture.

Source	Consumption of Energy for Cooling and Heating
Buchholz [61]	In Saudi Arabia, 151.3 Wh/m^2 per day and 133.8 Wh/m^2 per day of energy are required for the first and third production cycle periods, respectively, to cover cooling needs.
Tataraki, Kavvadias, and Maroulis [62]	In greenhouses in Greece, the energy for cooling amounted to 95 kWh/m^2 per year.
Iddio et al. [63]	In warmer areas, cooling greenhouses could amount to 50% of the total operating costs.
Iddio et al. [63]	In cold climates, heating and cooling greenhouses amount to 70–85% of the total operation cost.
FAO [64]	In Mediterranean regions, 100,000 kWh/y/ha is spent on cooling.
Runkle and Both [65]	In greenhouses located in more northerly climates, the energy requirements to cover the demand for heating increase significantly, amounting to 65–85% of the total energy required to operate a greenhouse.
Lindberg, Go, and Runkle [66]	88% of the energy consumption of greenhouses is spent on heating.
Vadiee and Martin [67]	Research on growers in Sweden found that labor and heating were the two highest direct costs.
Benli [68]	Ensuring the optimal temperature inside greenhouses in cold climates, especially at night, increases energy consumption significantly.
Djevic and Dimitrijevic [69]	Greenhouses in Serbia spend 50% of their consumed energy covering heating needs.
Statistics [70]	Sweden's greenhouses use 15% of the total energy spent on the country's total agricultural activity to cover their indoor heating needs.
Aguilar-Rodriguez et al. [71]	The energy required for heating by a 1050 m^2 greenhouse in an area of Mexico where the temperatures are lower than 10 °C (except in the period from June to September) was estimated to be 32,228.76 kWh annually.
Banakar et al. [72]	The energy required by a 40 m^2 greenhouse in Tehran so that the temperature inside the greenhouse was 25 °C during the day and 18 °C during the night (for the cold season) was 47.58 kWh/m^2 in January and July.
Vadiee and Martin [73]	A conventional greenhouse in Sweden required 320 kWh/m^2 to cover its heating needs.
Ahmed et al. [74]; Yano and Cossu [75]	Heating and cooling require a high energy consumption of 65–85%.
Djevic and Dimitrijevic [76]	Heating and cooling have the highest impact not only on a greenhouse's overall (heating and cooling) performance but also on the final configuration of the product's price that reaches the consumer.
Vourdoubas [77]	The annual requirements for energy consumption correspond to 95.3% of the total energy, with 4.7% corresponding to electricity consumption.
Paris et al. [78]	Comparing greenhouses that use microclimate control systems with those employing minimal-control climatic systems, it was found that in the former, the energy consumption is 8 to 12 times higher.
FAO [80]	Global food chains account for 30% of the total energy obtained from fossil fuels.
FAO [80]	Energy consumption contributes 19–29% to the total annual greenhouse gas emissions.
The World Bank [81]	80% of the world's energy production comes from fossil fuels.
Cherni and Jouini [82]; Jiang and Lin [83]	The extensive use of energy has created environmental problems.
Marcelis and Heuvelink [86]	Research on greenhouses in France has shown that the rising costs and environmental issues that have resulted from the use of conventional energy sources by agricultural greenhouses are a challenge and a key issue to be addressed by researchers, scientists, and investors, who are trying to find alternative sources of clean energy, as well as energy-saving solutions, in order to reduce the dependence of agricultural greenhouses on non-renewable energy sources.
Alluvione et al. [87]	Reducing energy consumption from agricultural activity and improving energy efficiency ensures more sustainable rural development and prosperity.
World Economic Forum [88]	The transition to a more sustainable, accessible, and secure energy system is a necessity.
Jaramillo-Nieves and Del Río [89]	An alternative energy source should replace fossil fuels for the successful development of greenhouse structures.

3.4. Definition of Hydroponics

Huos et al. [90] characterized hydroponic systems as highly efficient industrial-type vegetable production systems. As an industrial system, hydroponics includes a control system, which is wirelessly connected to the corresponding sensors and responsible for temperature, humidity, and water-level control [31]. In addition, hydroponic systems are more industrialized and automated and can increase productivity while respecting the requirements for ecological development and balance, since they are based on facilities for ecological protection and environmental improvement, enhancing socio-economic development [91].

According to Seaman and Bricklebank [92], hydroponics refers to plant cultivation without soil. More specifically, hydroponics refers to the soilless, anhydrous growth of plants using a mixture of water and a nutrient solution perfectly adapted to a plant's needs [93]. In hydroponic cultivation, the supply of nutrients to the root system of a plant is not provided through the soil but is introduced through water [31]. In this cultivation method, water is used as a solvent for the supply of nutrients [94]. The hydroponic method uses nutrient solutions containing water and nutrients [95]. Table 4 presents the definitions of hydroponics with references. In conclusion, food production techniques must be applied, and hydroponic cultivation stands out as an essential answer to many problems related to the conventional methods of cultivation in greenhouses [20].

Table 4. Definitions of hydroponics.

Source	Definition of Hydroponics
Ezzahoui et al. [31]	In hydroponics, the means for nutrient supply is water, not soil.
Ezzahoui et al. [31]	Hydroponics uses control systems to manage the temperature, humidity, and water level conditions.
Huo et al. [90]	Hydroponics is an efficient, industrial-style vegetable production system.
Seaman and Bricklebank [92]	Hydroponics is soilless plant cultivation.
Christie [93]	Hydroponics is the soilless, anhydrous growth of plants using a mixture of water and nutrient solutions perfectly controlled according to the needs of the plants.
Rakoczy [94]	In hydroponics, the plants are grown in a solution of mineral nutrients using water as a solvent.
Sharma et al. [95]	Hydroponics is a cultivation method in which vegetables are grown without soil but in nutrient solutions.

Hydroponics is soilless plant cultivation, applied worldwide to produce fruits and vegetables [96]. It is a combined cultivation method which provides an effective solution to the problems of conventional agriculture. The industrialization and automation offered by its equipment work positively to increase productivity by creating controlled conditions for the introduction of the required nutrients in terms of quality and quantity, precisely meeting the needs of each plant. The solutions contribute to the limited use of fertilizers and pesticides, reducing pollutants and soil and water contamination and generating products of high quality and nutritional value. The controlled use of water makes hydroponics an ideal solution not only for arid regions but also for reducing water consumption generally, presenting a cultivation method that responds to the concern for effectively securing water resources.

4. Advantages and Disadvantages of Hydroponic Cultivation

4.1. Advantages of Hydroponic Cultivation

Many countries have adopted hydroponic cultivation systems to serve their needs, with Latin America, Brazil, and Mexico considered the most prominent users [97]. Hydroponics as a production method is advanced and promotes large-scale cultivation in the absence of soil [98], ensuring the increased production of many crops at significantly higher yields through vertically accumulated trays to provide more space [99]. Hydroponic systems are efficient, industrial-type vegetable production systems. A plant's growth rate in hydroponic cultivation is 30–50% faster than in soil cultivation [100]. For example, the growth rate of lettuce via hydroponics is 11 times higher than via conventional cultivation (Table 5) [17]. Food production by hydroponic methods is a well-known technique and its application is increasing worldwide [101], ensuring higher quantities in a shorter crop cycle and high-quality, high-nutritional-value products. This phenomenon has resulted from ever-increasing production, which has allowed the development of crop diversification and higher profits for producers [102]. This fact is important because it represents economic efficiency, which is the central goal of farmers [27,103]. The numerous products generated by hydroponic cultivation, the industrialization of its systems, the automation offered by its equipment, its applicability in smaller areas, and the increase in productivity make it an economically viable alternative food production investment [104].

The hydroponic growing method is flexible, and there are opportunities for its improvement using simplified models; such an attempt was made by Bradley and Marulanda [105]. They presented a simplified hydroponic model that required 25% of the land area used by soil cultivation for immediate hunger reduction [105]. Large cultivation areas are considered a disadvantage of conventional crops [17,106]. The combination of automatic fertilization and automatic soil control represents a benefit of hydroponics, because it ensures a clean planting environment and saves space due to the vertical production of multiple layers [107]. This allows better performance with the least possible land use [20]. Hydroponic cultivation methods using 10% less land, according to Barbosa et al.'s (2015) comparative lettuce production study, resulted in eleven-times higher yields than conventional cultivation methods [17]. Hydroponics is important for agriculture globally as an opportunity for cultivation in areas with no access to soil [97]; hence, it is applied in areas with adverse climatic conditions and a lack of arable land, producing food without soil [41]. These characteristics and benefits make hydroponics viable for urban areas [108]. Additionally, the phenomenon of growing crops in areas that could be expropriated is common, but hydroponics offers investment stability and reduces the high risks of this practice [109]. Finally, the benefits of soilless cultivation to soil protection are remarkable [110].

Hydroponic cultivation is prevalent in the modern agricultural world [95] as a clean and easy method compared to the traditional types of cultivation [31]. The absence of soil makes the crops quite clean, removing the need for washing [111]; at the same time, this agricultural system faces a low risk of contamination [112]. Additionally, hydroponics can effectively control the use of not only water but also fertilizers and chemicals [113], which are applied to combat diseases and pests [20]. On the other hand, conventional agriculture uses pesticides and nutrients extensively, which is another disadvantage of conventional crops [17,106]. Therefore, hydroponics is safer than open-field cultivation because it can apply natural barriers against specific bacterial agents and reduce contamination factors [114]. Hydroponic products are grown without pesticides, prompting consumers to trust them more and be willing to spend more on their acquisition, thus creating food security [115]. According to Russo and Scarascia Mugnozza [116], hydroponic cultivation in a greenhouse dramatically reduces the environmental impact compared to greenhouse soil cultivation due to the use of pesticides and fertilizers.

The advantages of this system are summarized as follows: the better control of plant nutrition, the more efficient use of space, and the possibility of reducing the application of fertilizers [108]. Hydroponics supports innovative, sustainable, and environmentally friendly crops [117], presenting a lower environmental impact and lower greenhouse gas emissions [20]. In addition, the benefits of hydroponic technology mean that their environmental impact and pollution rates are lower than their sewage disposal rates [118]. According to Martinez-Mate et al. [52], the gas emissions of soil crops and hydroponics crops are 0.23 kg CO_2 equivalent and 0.11 kg CO_2 equivalent, respectively. An existing study found that in terms of raw materials, using wood instead of zinc-coated steel structures definitely has environmental benefits, but using recycled plastics for pipes, grow benches, and containers also works very well [116].

Wastewater reuse is also considered to be extremely important in environmental protection and balance, as wastewater reuse reduces the pollution load in rivers, groundwater, and soil and provides a reliable water supply throughout the year [50]. Water recycling in the agricultural sector requires adequate and economically efficient approaches [54]. In hydroponics, treated wastewater and domestic wastewater, as a nutrient medium, are a viable solution [119]. Water saving and the possibility of reusing water [120] are considered vital features and benefits of hydroponic cultivation. A study by Grewal et al. [118] demonstrated that crops such as cucumber and tomato can be grown using 33% drainage water.

Another benefit of hydroponics is its ability to act as a subsystem in aquaponic systems. In recent years, aquaponics has become an exciting vegetable production approach for application near urban centres with minimal water consumption [121,122]. As a combination of aquaculture and hydroponics, it provides an environmentally and economically sustainable food production system by uniting two systems that normally operate independently [123–126]. This combined system (hydroponics and aquaculture) serves more directly the recycling of wastewater, as the output of one part of the system (wastewater) is used as the input (nutrients) of the other by creating the necessary conditions for the biological cycle [127]. The FAO [128] described aquaponics as a promising and fast-growing food production sector that already produces 50% of human-consumed fish and vegetables. The simultaneous recovery of nutrients makes aquaponics one of the most promising sustainable food production methods for the future [129].

Hydroponics, even as an independent method of food production, is considered more effective at optimizing resources than soil cultivation [130]. For example, the water resources are better managed, only 10% of water resources are used compared to conventional cultivation methods [131]. In hydroponics, the water consumption is seven times lower than in conventional greenhouse production and four times lower than in open-field cultivation [132]. As a result, hydroponics is self-sustainable and environmentally friendly [131]. According to Trang and Brix [133], the two main characteristics of hydroponics are the high efficiency of water use and its design plasticity.

Table 5. Advantages of hydroponic cultivation.

Source	Sector	Advantages of Hydroponics
Barbosa et al. [17]	Better land use	Reduction in land use by 10%.
Barbosa et al. [17]	Higher crop yield	Eleven-times higher lettuce yield with hydroponic cultivation.
Baddadi et al. [20]	Irrigation water saving/fertilizer saving	Hydroponics allows the controlled and efficient use of water, fertilizers, and chemicals.
Baddadi et al. [20]	Better land use	Better performance, less land use.
Baddadi et al. [20]	Lower environmental impact	Lower environmental impact and greenhouse gas emissions.
Bakhtar et al. [41]	Better land use	Hydroponics is applied in areas with adverse climatic conditions and a lack of arable land, producing food without soil.
Martinez-Mate et al. [52]	Lower environmental impact	Comparing soil crops and hydroponics crops, the gas emissions were 0.23 kg CO_2 equivalent and 0.11 kg CO_2 equivalent, respectively.
Sharma et al. [95]	Clean cultivation	Hydroponics is one of the most popular methods of modern cultivation, with its main characteristics being that it is clean and easy.
Croft et al. [97]	Better land use	Hydroponics is important for agriculture globally as an opportunity for cultivation in areas with no access to soil.
Müller et al. [98]	Better land use	Hydroponics as a production method is advanced and promotes large-scale cultivation without soil.
Link [99]	Higher crop yield/high-quality food	Hydroponics allows the multiplication of the number of crops to obtain higher yields.
Link [99]	Better land use	Hydroponics allows vertical crop cultivation and saves land use.
Joshi and Joshi [100]	Higher crop yield	The growth rate is 30–50% faster in hydroponic culture than in soil.
Borges and Dal'Sotto [102]	Higher crop yield/high-quality food/economic viability	Ever-increasing production allows the upward trend of crop diversification and higher profits for producers.
Souza, Toesca Gimenes, and Binotto [104]	Economic viability	Hydroponics ensures the financial viability of the investment and is an attractive alternative food production solution.
Bradley and Marulanda [105]	Better land use	Hydroponics responds to global hunger while using 25% less land than soil cultivation.
Wada [107]	Clean cultivation/better land use	Hydroponics ensures a clean planting environment and saves space due to vertical multi-layer production.

Table 5. *Cont.*

Source	Sector	Advantages of Hydroponics
Rufí-Salís et al. [108]	Nutrition control/better land use/fertilizer saving	Hydroponics provides better plant nutrition control and more efficient land use and saves on fertilizers.
Rufí-Salís et al. [108]	Better land use	Hydroponics is a sustainable system of agriculture for urban areas.
Orellano et al. [109]	Better land use/economic viability	Hydroponics is a solution to the growing of crops on land that could be expropriated, providing investment stability and protecting growers from the high risks involved in this activity.
NOSB [110]	Clean cultivation	Hydroponics, as a soilless cultivation method, offers greater protection.
Coolong [111]	Clean cultivation	Hydroponics, as a soilless cultivation method, makes crops exceptionally clean without washing.
Lopez-Galvez et al. [112]	Clean cultivation	Low risk of soil and crop contamination.
Hussain et al. [113]	Clean cultivation/fertilizer saving	Hydroponics allows the efficient consumption of fertilizers and the reduced use of chemicals to control pests and diseases.
Orozco et al. [114]	Lower environmental impact/clean cultivation	Hydroponics is safer than open-field cultivation because it can apply natural barriers against specific bacterial agents and reduce contamination factors.
Phew et al. [115]	Lower environmental impact/clean cultivation	Hydroponic products are grown without pesticides, prompting consumers to trust them more and be willing to spend more on their acquisition, thus creating food security.
Russo and Scarascia Mugnozza [116]	Lower environmental impact	In terms of raw materials, using wood instead of zinc-coated steel structures has environmental benefits, but using recycled plastics for pipes, grow benches, and containers also works very well.
Russo and Scarascia Mugnozza [116]	Lower environmental impact/fertilizer saving	Hydroponic cultivation in a greenhouse greatly reduces the environmental impact compared to greenhouse soil cultivation due to the use of pesticides and fertilizers.
Li et al. [117]	Lower environmental impact	Hydroponics supports innovative, sustainable, and environmentally friendly crops.
Grewal et al. [118]	Lower environmental impact	Hydroponics is a beneficial technology with much lower environmental impacts and pollution rates, including effective sewage disposal.
Grewal et al. [118]	Irrigation water saving	Hydroponic cucumber and tomato crop cultivation could use 33% drainage water.
Sutar et al. [119]	Irrigation water saving	Hydroponics can apply treated sewage water, using household sewage as a nutrient medium.
Carmassi et al. [120]	Irrigation water saving	Hydroponics provides water savings and the possibility of reusing water.
Zou et al. [121]; Love et al. [122]	Better land use/irrigation water saving/nutrition control	Aquaponics is an interesting combined system of hydroponics and aquaculture for the production of vegetables near urban centres with minimal water consumption.
König et al. [123]; Goddek et al. [124]; Xie and Rosentrater [125]; Tyson et al. [127]; Adler et al. [126]	Lower environmental impact/irrigation water saving/fertilizer saving/nutrition control	Aquaponics combines aquaculture and hydroponics, providing an environmentally and economically sustainable food production system compared to the independent operation of the systems.
FAO [128]	Higher crop yield	Aquaponics is a promising and rapidly growing food production sector, already producing 50% of the fish and vegetables consumed by humans.
Suhl et al. [129]	Nutrition control/fertilizer saving	The simultaneous recovery of nutrients makes aquaponics one of the most promising sustainable food production methods for the future.
Gwynn-Jones et al. [130]	Optimization of natural resource use	Hydroponics is more efficient at optimizing resources than soil cultivation.
Alshrouf [131]	Lower environmental impact/irrigation water saving	Hydroponics is a self-sustainable and environmentally friendly system, using 10% less water in comparison to conventional agriculture.
Romeo, Blikra Vea, and Thomsen [132]	Irrigation water saving	Water consumption in hydroponics is seven times lower than in conventional greenhouse production and four times lower than in open-field cultivation.
Trang and Brix [133]	Irrigation water saving/nutrition control	Hydroponics is characterized by a high efficiency of water use and design plasticity.

4.2. Disadvantages of Hydroponic Cultivation

Despite the numerous advantages of hydroponics, there are some disadvantages related to the high initial investment required, meaning that interested farmers should be cautious at first [104]. The annual requirements for energy consumption amount to 95.3% of the total energy, whereas 4.7% of the total energy is dedicated to electricity needs (Table 6) [77]. The initial high investment, the high energy expenditure, the requirements for special technical knowledge, and the need for continuous assistance and monitoring may prevent the adoption of this cultivation method [134].

Table 6. Disadvantages of hydroponic cultivation.

Source	Sector	Disadvantages of Hydroponics
Vourdoubas [77]	Higher energy consumption	The annual requirements for energy consumption correspond to 95.3% of the total energy, with 4.7% corresponding to electricity consumption.
Souza, Toesca Gimenes, and Binotto [104]	High initial investment	Hydroponics requires a high initial investment.
Muñoz [134]	High initial investment/higher energy consumption/required know-how	Hydroponics requires a high initial investment, high energy expenditure, special technical knowledge, and continuous assistance and monitoring.

5. Case Study of Hydroponic Tomato and Cannabis Cultivation versus Conventional Cultivation Method

5.1. Tomato Crop Production Performance

The crop yield is one of the critical elements in the evaluation of hydroponic cultivation against conventional cultivation. Hydroponic tomatoes are harvested after 45 days for varieties with smaller fruits and 70 days for those with larger fruits [135], while 60–100 days are required in open-field cultivation [136]. Hydroponics also demonstrates an increased production in kilograms per hectare compared to conventional cultivation, as it can accommodate more cultivated plants per square meter of surface area. Unfortunately, no official sources can provide data on the production quantity in tonnes of individual hydroponic crops. However, the literature can provide an average production quantity in tons per hectare for hydroponic cultivation. This average production depends on conditions such as the effective management of space and equipment, the assurance of a suitable cultivation environment (forming a microclimate), and the appropriate quantity of nutrients in the solution. For example, Rosa-Rodriguez et al. [137] compared closed hydroponic systems to open ones, observing an increased production of hydroponic tomatoes with more than 13.5 kg per m^3 of consumed water. Each tomato plant could produce 20 to 90 tomatoes or 4.54 to 13.61 kg of tomatoes as long as the climatic conditions for plant growth and the environmental factors positively impacted its development [138]. With an average yield of 9.075 kg per tomato plant and a planting density of 12 plants per m^2, hydroponic cultivation could yield 108.9 kg/m^2 tomatoes [139].

5.2. Greenhouse Gas Emissions of Tomato Cultivation

Regarding greenhouse gas emissions, research has shown that open-field cultivation contributes 37%, mainly from agrochemicals, and cultivation in greenhouses contributes 22%, due to infrastructure [140]. Several studies have identified that the emission of CO_2 is a result of the energy requirements for heating greenhouses internally, which are dependent on the growing needs of each crop [141–143] in the area where the hydroponics project is implemented. However, nitrogen fertilizers, used extensively in hydroponic cultivation (mainly in hydroponic tomato cultivation), produce more N_2O emissions than open-field cultivation; tomato cultivation contributes, on average, cumulative N_2O emissions of 2.3 kg N_2O–N ha^{-1} yr^{-1} [144]. A study on greenhouse gas emissions and, more specifically,

N_2O emissions resulting from hydroponic tomato cultivation in a greenhouse in Germany showed daily emissions of N_2O 58 ± 31 gr N_2O–N ha^{-1} day^{-1} [145]. Another study conducted in a greenhouse in Germany presented similar results, identifying the highest emissions in November and calculating an average of 31 gr N_2O–N ha^{-1} day^{-1} [146]. Nevertheless, hydroponics remains a promising approach in terms of greenhouse gas emissions, as it absorbs carbon from the air without interfering with the land (since the plants grow in water) [147]. Additionally, hydroponics reduces carbon emissions in three ways: the crops are grown in closed structures, more plants are produced and consumed in the same place (which reduces transportation requirements), and carbon reuse is involved (which is still under research) [147].

5.3. Water Use for Tomato Cultivation

The study of Nederhoff and Stanghellini [148] identified significant differences in the water consumed by open-field and hydroponic tomato cultivation, depending on the climatic conditions of each season. The same study [148] indicated a water consumption of 300 L/m^2 or 60 L/kg during the growing season in the field, while for greenhouse cultivation, the water consumption decreased to 20 L/kg, reaching as low as 12.5 L/kg (with an average of 15 L/kg). Hydroponics and high-tech greenhouses set water consumption at 4 L/kg [148]. A study on controlled-environment cultivation [149] showed that vertical hydroponic farms reduce water consumption by 70 to 95%. According to Venter [150], hydroponic cultivation uses 10 to 16% of the water required for conventional cultivation.

5.4. Energy Inputs for Tomato Cultivation

In the field, tomato cultivation requires 0.8 MJ of energy per harvested kg, in contrast to intensive cultivation sites that require electricity and fuel for producing synthetic fertilizers and pesticides and for machinery operation and irrigation [151]. A study on the energy inputs required for greenhouse tomato cultivation in regions of Turkey proved that the total energy input for the production of 57,905.1 kg ha^{-1} tomatoes was 61,434.5 MJ ha^{-1} [152], without any reference to soil cultivation or hydroponics. Considering that one tomato weighs about 125 gr, the total energy required for the growth of a single tomato in a region such as Almería (a city in southeast Spain) is 460–875 kcal, in contrast to colder climates that require 40 to 150 times more energy input [151].

Table 7 presents a comparison between tomato cultivation in soil and without soil, summarizing data collected from the literature regarding crop yields, the density of plants, greenhouse gas emissions, water usage, and energy inputs.

Table 7. Hydroponic and soil tomato cultivation case studies.

Tomato Cultivation	Soil	Sources	Hydroponics	Sources
Crop yield (tonnes/ha)	36.98	Our World in Data [153]	280–300 up to 650–700	Hydroponics Systems [154]
Recommended density (plants/m^2)	2 to 3.7	Calpas [155]	10 to 14	Savvas et al. [156]
Greenhouse gas emissions per kilogram ($kgCO_2eq$ per hectare)	8.24	de Jesus Pereira, Filho, and La Scala Jr. [157]	n/a	
Greenhouse gas emissions per kilogram of food product ($kgCO_2eq$ per kilogram)	2.09	Our World in Data [158]	n/a	
Water usage (L/kg)	60	Hydroponics Systems [154]	22 (greenhouses without recycling), 10 (greenhouses with recycling), 4 (high-tech greenhouses)	Hydroponics Systems [154]
Energy input (megajoule/harvested kg)	0.8	Smil [151]	4	Antón and Muñoz [159], Torrellas et al. [160]

5.5. Introduction to the Cultivation of Cannabis

The global production of medical cannabis has reached USD 6822.21 million [161], while estimations show an increase in the global market production in the distant future. This makes research into this crop, mainly regarding its improved cultivation, even more attractive. However, the data collected to compare the hydroponic and soil cultivation of cannabis were obtained from literature sources at a research level. The cultivation of medical cannabis is characterized by the microclimate conditions of the internal cultivation space.

Most reports on cannabis cultivation (in soil or soilless) concern greenhouse structures rather than open-field cultivation, due to the legislation in many states permitting cannabis cultivation for medical purposes only in indoor cultivation areas. Therefore, the data collected and described herein pertain to soil cultivation in greenhouses and hydroponics. The need to control indoor cultivation is inextricably linked to the climatic conditions outside the greenhouse, as these interact with the indoor environment in such a dynamic system. It is essential to mention that most of the data included below, especially those related to energy consumption, are directly related to the climatic conditions of the plant's growth area. Additionally, greenhouse gas emissions depend on the energy consumed, which means that the energy required for the growth of each plant is directly linked to the corresponding emissions.

5.6. Cannabis Crop Production Performance

According to Janatová et al.'s [162] study, the average yield is 21.02 $\pm$ 3.33 gr/plant, and the average yield value (for all genotype cycles) per square meter ranges from 138.59 to 231.08 gr/m^2. As crop yield is a crucial indicator of production, many growers measure the yield of their crops and keep statistical records. According to the Cannabis Business Times [163], 72% of United States growers collect data on their crops, indicating a crop yield of 39.5 gr/ft^2. Cannabis has many varieties, and each presents individual characteristics and needs. Whether hydroponic or soil cultivation is chosen does not make much difference in terms of quality and yield; however, hydroponic cultivation shows excellent results in terms of feeding and water management, as the margin of error is significantly reduced [164]. The main advantages presented by the hydroponic cultivation of medical cannabis are summarized as follows: a higher yield, faster growth rate, increased plant hydration control, and the elimination of the need to repot the plant [165]. The hydroponic cultivation of medical cannabis ensures that the plant's automated growth remains highly competitive in commercial terms for those growers who want to invest in the medical cannabis industry, and it is projected that cannabis production will reach USD 66.3 billion by 2025 [165].

5.7. Cannabis Crop Planting Density

Various studies have been conducted worldwide regarding the most effective density of cannabis plants per square meter. The average value is 16–20 plants per square meter [166]. However, other studies have suggested 10–20 [167], 15 [168], and even 1–2 plants per square meter [169]. According to Jan et al. [170], plants cultivated at a lower density show better growth than those at a higher density per square meter of surface area. Regarding the performance of the hydroponic cultivation of medical cannabis, various studies have been conducted; Jin, Jin, and Chen's [171] study demonstrated an average yield of 687 gr/plant of dry product. According to Knight et al. [172], a successful hydroponic cultivation cycle of cannabis can yield 881 gr/plant of dry product; however, a study conducted in New Zealand showed that 18 plants could yield an average of 687 gr/plant of dry product. On the other hand, the hydroponic cultivation of cannabis can increase the yield by up to 20% compared to soil cultivation [173], with the advantages of hydroponics including a faster rate of plant growth and an increased yield [171].

5.8. Greenhouse Gas Emissions from Growing Cannabis

The energy requirements for the growing conditions of the cannabis crop shape the greenhouse gas emissions from cannabis cultivation. Regarding the hydroponic cultivation of cannabis, no data have emerged providing the kilograms of CO_2 produced per kilogram or even per hectare of product. Notably, most studies have reported the greenhouse gas emissions from the indoor cultivation of cannabis. Indoor cultivation refers to controlled-environment cultivation (such as in vertical farms, plant factories, and greenhouses), which is not conventional cultivation. However, it is unclear whether these greenhouse emissions results emerged from hydroponics or other technologies such as aeroponics, aquaponics, and aquaculture. A Colorado State University study reached the following conclusions: for the indoor cultivation of cannabis in the United States, the greenhouse gas emissions range from 2283.00 to 5184.00 $kgCO_2eq/kg$ of dried flower; for open-field cultivation, the greenhouses gas emissions are 22.7 $kgCO_2eq/kg$ of dried flower; and for conventional greenhouse cultivation they are 326.6 $kgCO_2eq/kg$ of dried flower, which is due to electricity consumption only [174]. Another study on greenhouse gas emissions from cannabis cultivation [175] reported that eastern O'ahu in Hawaii has the highest greenhouse gas emissions at 5184.00 $kgCO_2eq$ per kg of dried flower, while in southern California the figure is 2288.00 $kgCO_2eq$ per kg of dried flower. O'Hare et al.'s [176] study determined a value of 4409.25 $kgCO_2eq$ per kg of dry flower. Notably, glass-wall greenhouses produce lower greenhouse gas emissions ($kgCO_2eq$ per kg of dried flower) because of the lower electricity demands compared with other indoor cultivation methods [175].

5.9. Use of Water to Grow Cannabis

In outdoor cultivation, cannabis requires a significant amount of water (22.7 L of water per plant per day), which is more than other crops [177,178]. Another paper identified an amount of 8557 L/m^2 per day for the open-field cultivation of cannabis [179]. Contrarily, in indoor cultivation, the water consumption is lower (6.52 L/m^2), with hydroponic cultivation and recycling systems clearly showing better yields [180]. Another study provided a figure of 8.96 L/m^2 per day, or 22.7 L/plant per day, for open-field cultivation [181], while indoor cultivation required 7.334 L/m^2 per day [182]. One advantage of hydroponic crops over conventional crops is that they consume much less water, relying on systems and equipment that enable water recirculation and reuse. Research on the hydroponic cultivation of cannabis identified a reduction in water use by up to 90% [164]. Regarding the significant issue of water in hydroponic cultivation, cannabis crops in hydroponic cultivation systems need 3912 L/m^2 to 6519 L/m^2 of water; on the other hand, open-field cultivation demands 4889 L/m^2 to 8192 L/m^2 for the flowering period of the plant [183].

5.10. Energy Inputs for Cannabis Cultivation

Research on the indoor cultivation of cannabis shows that the required energy is 6074 kWh per kilogram, with 50% of this energy covering the heating, ventilation, and air conditioning needs and 33% of this energy covering the lighting needs [181]. According to another study, the electricity consumption for cannabis cultivation is greater than 150 kWh/ft^2 per year, being required for the adjustment of the growing conditions, such as the temperature, humidity, and lighting, for each stage of the plant's development [184]. According to Cannabis Business Times research [185], 56% of all survey participants (growers) reported that the largest percentage of energy was used for heating, ventilation, and air conditioning; 54% lighting; and 50% temperature and humidity control equipment.

Table 8 presents a comparison between cannabis cultivation in soil and without soil, summarizing data collected from the literature concerning crop yields, the density of plants, greenhouse gas emissions, water usage, and energy inputs.

Table 8. Hydroponic and soil cannabis cultivation case studies.

Cannabis Cultivation	Soil	Sources	Hydroponics	Sources
Crop yield (gr/m^2)	138.59 to 231.08	Janatová et al. [162]	274.8	Jin, Jin, and Chen [171]
Crop yield (gr/plant)	21.02	Janatová et al. [162]	881	Knight et al. [172]
Recommended density ($plants/m^2$)	16 to 20	Vanhove, van Damme, and Meert [166]	15	Caulkins [186]
Greenhouse gas emissions per kilogram of product ($kgCO_2eq$ per kilogram)	2000 to 5000	Fox [175]; Webster [187]	n/a	
Water usage during growing season (L/m^2 per day)	15.97	Cannabis Control Commission [180]	6.52	Cannabis Control Commission [180]
Energy input (kWh/kg yield)	6074.00	Zheng, Fiddes, and Yang [181]; Mills, 2012 [188]	n/a	

6. Discussion

6.1. Summary of Results

This study presented the impacts of conventional agriculture and hydroponics on the environment, water, and energy. All data were collected from studies published in the academic literature. The results of this search were compared to demonstrate the value and efficiency of each cultivation method.

- Conventional agriculture occupies 38% of the total land used on the planet [26]. Hydroponic cultivation manages land more effectively, reducing the required arable land [20,109] by 10% [17] to 25% [105]. In addition, vertical production ensures a reduction in cropland [99,107]. Hydroponics, as a soilless cultivation method, can be applied in areas without arable land [41,97,98] and urban centres [108,121,122].
- Hydroponic cultivation with less land use shows a better yield than conventional cultivation [17,99,102,128]. Hydroponic cultivation presents 30–50% faster growth rates [100]. The crop yield depend on the plant type, but in any case, hydroponic yields are higher than those of conventional agriculture.
- Conventional agriculture accounts for 13.5–29% [16,80] of total greenhouse gas emissions. Hydroponic cultivation shows lower gas emissions [20,147], with up to 52.2% lower CO_2 emissions [52].
- Conventional agriculture is responsible for the extensive consumption of fertilizers and pesticides [9,26,37–40,116]. According to reports, 136.82 kg of fertilizers [189] and 2.66 kg of pesticides [190] are applied per hectare of arable land worldwide. Hydroponics allows the efficient and reduced consumption of chemicals [20,108,113,116,123–127,129], while the nutrient medium is based on soluble mineral salts [11].
- Conventional agriculture is responsible for climate change due to chemical use, large areas of arable land, and the consumption of water resources [32,33,53].
- Conventional agriculture consumes 70% of the world's water resources [48]. Hydroponic cultivation shows a 33% reduction in water consumption [118].
- A disadvantage of hydroponic cultivation is the high initial investment cost due to equipment [104,134] and the necessary acquisition of a high level of technical know-how [134].
- Conventional greenhouse cultivation requires a high expenditure of electrical energy mainly to cover heating and cooling, while 61.42% of the electricity expended worldwide comes from fossil fuels [191].

A case study of tomato and cannabis crops was used to compared conventional and hydroponic cultivation. In the case of tomatoes, the comparison between conventional and hydroponic cultivation was based on crop yield, planting density, greenhouse gas emissions, and energy inputs. It was noted that for energy inputs, the geographical location of the greenhouse largely shaped the energy requirements due to the climate and (in the case of conventional agriculture) soil factors. The results of this case study demonstrated the following:

- The crop yield depends on both the planting density and the plant growth rate. In the case of hydroponic tomato cultivation, the planting density (plants/m^2) is four times higher, and the growth rate is 30–40% [192] higher than in conventional agriculture. The yield of hydroponic tomato cultivation is, on average, seven times higher in tonnes/ha compared to that of conventional cultivation.
- The water consumption for hydroponic tomato cultivation was 22 L/kg [154], which was three times lower than that of conventional cultivation.
- The greenhouse gas emissions in $kgCO_2$ eq/kg from conventional agriculture arose from the use of fertilizers and pesticides; the consumption of water; the exploitation of the soil; and the consumption of electricity, produced for the most part by fossil fuels, for heating and cooling the greenhouses. Hydroponics, as a cultivation method without the use of soil that involves nutrient solution consumption, markedly lower

water consumption, and indoor application presents a lower percentage of emissions, though we were unable to precisely determin this figure from the literature.

- A higher percentage of the energy input for conventional agriculture in greenhouses is dedicated to cooling and heating. Hydroponic cultivation presents five times higher energy requirements in MJ/harvested kg compared to conventional cultivation.

Similarly, in the case of cannabis, the comparison between conventional and hydroponic cultivation was based on crop yield, planting density, greenhouse gas emissions, and energy inputs. As far as the energy inputs are concerned, the geographical location is still important. The results of this case study demonstrated the following:

- Hydroponic cannabis cultivation yields 1.5 times more gr/m^2 and 40 times more gr/plant than conventional agriculture. Thus, the plant growth rate in hydroponic cultivation is higher, and a greater mass of products can be obtained from an equal planting area.
- The water consumption for hydroponic cannabis cultivation is 2.5 times lower than for conventional cultivation.
- The greenhouse gas emissions from conventional greenhouse cultivation arise from the use of fertilizers and pesticides; the consumption of water; the exploitation of the soil; and the consumption of electricity, produced to a large extent from fossil fuels, for greenhouse heating and cooling. The greenhouse gas emissions from hydroponics were not precisely determined by the literature.
- In conventional greenhouse cultivation, energy inputs for cooling and heating represent 50–56% of the total consumption. However, there were no clear reports in the literature regarding the energy inputs for hydroponic cannabis cultivation.

As emerged from the literature review and the case study, hydroponics presents benefits related to:

Soilless cultivation:

- Cultivation in inaccessible, barren, and arid areas, including urban agriculture close to industrial areas.
- Better land use and lower environmental impact. No soil stress and pollution.
- A much lower transmittance of diseases and pests from the soil.
- The reduced use of chemicals for soil fertility and pest extermination.
- Biodiversity protection.
- Eliminating poverty in urban areas, providing new jobs, and elevating production.

More efficient land use:

- A higher density of plants per square foot.

Higher crop yield:

- A higher density of plants combined with a higher growth rate, yielding a highger mass (kg) of harvested product per plant and per square foot.
- Higher production using less land.
- Reduced crop cycles.
- Eliminating hunger.

Pesticide free:

- Soil protection.
- Clear culture, high nutritional value.
- The protection of natural resources.
- Lower greenhouse gas emissions.
- Reduction in operating costs and benefits for the consumer.

Low water consumption:

- High crop yield with lower water consumption.
- The protection of natural resources.
- Lower environmental impact.

- Cultivation in arid areas.
- The possibility of the reuse of treated wastewater.
- The operation of a closed water recirculation system.
- Self-sustaining system.

The low emission of greenhouse gases due to:

- Chemical use not required.
- Low water consumption.
- Controlled environment.
- Short transportation chain as a result of urban agriculture.
- No soil contamination by chemicals that end up in water runoff through rainwater.
- The reuse of treated wastewater.

Disadvantages:

- Higher energy consumption via electricity to cover the heating and cooling requirements.
- Higher energy consumption via electricity to meet the lighting requirements.
- Higher energy consumption via electricity to cover equipment operation requirements (pump, ventilation, inverter, fan, etc.).
- Higher energy consumption via electricity to meet humidity control requirements.
- Skilled work and know-how requirements.
- High investment cost.

6.2. Suggestions

The integration of renewable energy sources into agriculture would reduce agriculture's dependence on fossil fuels. Renewable energy could replace the consumption of electricity for heating and cooling, which are the fundamental requirements of a greenhouse's microclimate. Moreover, renewable energy could cover the additional energy consumption for equipment and automated operation. In addition, renewable energy is a solution to not only the planet's energy restrictions but also the environmental limitations of fossil fuels and natural resources use.

Educational programs for training and imparting knowledge would be very beneficial. The cooperation between the market and universities would make hydroponic technology more well-known. Seminars and training centers would help professionals in the hydroponics sector to improve their knowledge. In addition, technical knowledge about hydroponic mechanical equipment and research into new construction materials would reduce the high initial investment cost. The acquisition of know-how for the application of hydroponics systems and the operation of the related equipment, as well as research (mechanical and technical) into new materials for the construction of hydroponics projects, would create new jobs for mechanics, chemists, agronomists, and academic staff.

6.3. Future Work

The recent COVID-19 pandemic, which is still ongoing, has highlighted many limitations in various areas of daily life. Production systems and food play a crucial role in human wellbeing and survival. Food production systems provide not only food for humans but also jobs. It would be exciting and instrumental in the future to conduct research into the pandemic and its impact on the agricultural sector. Possible research topics include:

- How the global crisis resulting from the pandemic has affected the agricultural sector in terms of conventional cultivation practices.
- How hydroponics, as an emerging agricultural technology, could offer solutions to the limitations created by the global pandemic crisis in conventional agriculture.
- The added value of hydroponics to the sustainability of agricultural production in times of pandemic, focusing on the implications of the COVID-19 pandemic.
- How the COVID-19 pandemic affected natural and water resources, energy, and the environment, and how conventional agriculture and hydroponics could respond to these challenges to ensure food security.

- In contrast to conventional agriculture, new cultivation technologies are increasingly relevant. Hydroponics, aquaponics, and aquaculture are among these technologies. A comparison between these appraoches would be useful for future works.
- Cannabis is a crop that, in recent years, has monopolized the research community's interest, mainly in the field of pharmacology. However, in many cases, the officially recorded data are minimal. The literature provides few data related to the electrical energy consumption of hydroponic cannabis. Data related to the electrical consumption of different indoor hydroponic cannabis systems would be very useful. In addition, further work on the greenhouse gas emissions emitted by the hydroponic cultivation of cannabis would be very valuable.
- Hydroponic indoor cultivation includes greenhouses, plant factories, and vertical farms. In the case of energy consumption from hydroponics, the existing literature does not specify the energy requirements of each geographical location. Future work in this field would be interesting.

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References

1. United Nations. *World Population Prospects: The 2000 Revision—Highlights*; ESA/P/WP.165; United Nations: New York, NY, USA, 2001; Available online: http://enerpedia.net/images/2/2c/Wpp2000h.pdf (accessed on 28 November 2022).
2. Gorjian, S.; Calise, F.; Kant, K.; Ahamed, M.S.; Copertaro, B.; Najafi, G.; Zhang, X.; Aghaei, M.; Shamshiri, R.R. A Review on Opportunities for Implementation of Solar Energy Technologies in Agricultural Greenhouses. *J. Clean. Prod.* **2021**, *28*, 124807. [CrossRef]
3. Food and Agriculture Organization. The Future of Food & Agriculture: Alternative Pathways to 2050—Summary Version. Available online: https://www.fao.org/3/CA1553EN/ca1553en.pdf (accessed on 15 April 2022).
4. Heilig, G. World Population Prospects: Analyzing the 1996 UN Population Projections. Available online: https://core.ac.uk/download/pdf/33896352.pdf (accessed on 18 May 2021).
5. Food and Agriculture Organization. The State of Food Security and Nutrition in the World Building Resilience for Peace and Food Security. 2017. Available online: https://www.fao.org/3/I7695e/I7695e.pdf (accessed on 17 March 2021).
6. Food and Agriculture Organization. Energy-smart Food for People and Climate: Issue Paper. 2011. Available online: https://www.fao.org/3/i2454e/i2454e.pdf (accessed on 2 April 2021).
7. Hassanien, R.H.E.; Li, M.; Dong Lin, W. Advanced Applications of Solar Energy in Agricultural Greenhouses. *Renew. Sustain. Energy Rev.* **2016**, *54*, 989–1001. [CrossRef]
8. Sumberg, J.; Giller, E.K. What is 'conventional' agriculture? *Glob. Food Secur.* **2022**, *32*, 100617. [CrossRef]
9. Chausal, N.; Saxena, J. Chapter 15—Conventional versus organic farming: Nutrient status. In *Agronomic Soil Management Practices*; Elsevier: Amsterdam, The Netherlands, 2021; pp. 241–254. [CrossRef]
10. Velazquez-Gonzalez, R.S.; Garcia-Garcia, A.L.; Ventura-Zapata, E.; Barceinas-Sanchez, J.D.O.; Sosa-Savedra, J.C. A Review on Hydroponics and the Technologies Associated for Medium- and Small-Scale Operations. *Agriculture* **2022**, *12*, 646. [CrossRef]
11. Ramazzotti, S.; Gianquinto, G.; Pardossi, A.; Muñoz, P.; Savvas, D. *Good Agricultural Practices for Greenhouse Vegetable Crops*; Food and Agriculture Organization: Rome, Italy, 2013; Available online: https://www.fao.org/3/i3284e/i3284e.pdf (accessed on 12 October 2022).
12. Savvas, D. Hydroponics: A modern technology supporting the application of integrated crop management in greenhouse. *Food Agric. Environ.* **2003**, *1*, 80–86.
13. Maharana, L.; Koul, D.N. The emergence of Hydroponics. *Yojana* **2011**, *55*, 39–40.
14. Heredia, N.A. *Design, Construction, and Evaluation of a Vertical Hydropoinc Tower*; CORE: London, UK, 2014; Available online: https://core.ac.uk/download/pdf/20074627.pdf (accessed on 13 May 2021).

15. Sims, R.; Flammini, A.; Puri, M.; Bracco, S. *Opportunities for Agri-Food Chains to Become Energy-Smart*; Food and Agriculture Organization: Rome, Italy, 2015; Available online: https://www.fao.org/3/i5125e/i5125e.pdf (accessed on 18 May 2021).
16. Food and Agriculture Organization. *The State of the World's Land and Water Resources for Food and Agriculture—Managing Systems at Risk*; Food and Agriculture Organization Publications: Rome, Italy, 2011; Available online: https://www.fao.org/3/i1688e/i1688e.pdf (accessed on 2 April 2021).
17. Barbosa, G.; Gadelha, F.; Kublik, N.; Proctor, A.; Reichelm, L.; Weissinger, E.; Wohlleb, G.; Halden, R. Comparison of Land, Water, and Energy Requirements of Lettuce Grown Using Hydroponic vs. Conventional Agricultural Methods. *Int. J. Environ. Res. Public Health* **2015**, *12*, 6879–6891. [CrossRef]
18. Karaşahin, M. Effects of different applications on dry matter and crude protein yields in hydroponic barley grass production as a forage source. *Ziraat Fak. Derg. Süleyman Demirel Univ.* **2014**, *9*, 27–33.
19. Langenfeld, N.J.; Pinto, D.F.; Faust, J.E.; Heins, R.; Bugbee, B. Principles of Nutrient and Water Management for Indoor Agriculture. *Sustainability* **2022**, *14*, 10204. [CrossRef]
20. Baddadi, S.; Bouadila, S.; Ghorbel, W.; Guizani, A. Autonomous Greenhouse Microclimate through Hydroponic Design and Refurbished Thermal Energy by Phase Change Material. *J. Clean. Prod.* **2019**, *211*, 360–379. [CrossRef]
21. Ahamed, S.; Sultan, M.; Shamshiri, R.R.; Rahman, M.; Aleem, M.; Balasundram, K.S. Present status and challenges of fodder production in controlled environments: A review. *Smart Agric. Technol.* **2022**, *3*, 100080. [CrossRef]
22. Bouadila, S.; Baddadi, S.; Skouri, S.; Ayed, R. Assessing heating and cooling needs of hydroponic sheltered system in mediterranean climate: A case study sustainable fodder production. *Energy* **2022**, *261*, 125274. [CrossRef]
23. Jan, S.; Rashid, Z.; Ahmad Ahngar, T.; Iqbal, S.; Abbass Naikoo, M.; Majeed, S.; Ahmad Bhat, T.; Gul, R.; Insha Nazir, I. Hydroponics—A Review. *Int. J. Curr. Microbiol. Appl. Sci.* **2020**, *9*, 1779–1787. [CrossRef]
24. Sonneveld, C. Effects of Salinity on Substrate Grown Vegetables and Ornamentals in Greenhouse Horticulture. Ph.D. Thesis, University of Wageningen, Wageningen, The Netherlands, 2000. Available online: https://edepot.wur.nl/121235 (accessed on 13 October 2022).
25. Sardare, M.D.; Admane, S.V. A review on plant without soil-Hydroponics. *Int. J. Res. Eng. Technol.* **2013**, *2*, 299–304.
26. PSCI. The future of farming: Hydroponics. 2020. Available online: https://psci.princeton.edu/tips/2020/11/9/the-future-of-farming-hydroponics (accessed on 1 November 2021).
27. Su, Y.; Li, C.; Wang, K.; Deng, J.; Shahtahmassebi, A.R.; Zhang, L.; Ao, W.; Guan, T.; Pan, Y.; Gan, M. Quantifying the Spatiotemporal Dynamics and Multi-Aspect Performance of Non-Grain Production during 2000–2015 at a Fine Scale. *Ecol. Indic.* **2019**, *101*, 410–419. [CrossRef]
28. Cortada, U.; Hidalgo, M.C.; Martínez, J.; Rey, J. Impact in Soils Caused by Metal (Loid)S in Lead Metallurgy. The Case of La Cruz Smelter (Southern Spain). *J. Geochem. Explor.* **2018**, *190*, 302–313. [CrossRef]
29. Dach, J.; Starmans, D. Heavy Metals Balance in Polish and Dutch Agronomy: Actual State and Previsions for the Future. *Agric. Ecosyst. Environ.* **2005**, *107*, 309–316. [CrossRef]
30. Kicińska, A.; Wikar, J. Ecological Risk Associated with Agricultural Production in Soils Contaminated by the Activities of the Metal Ore Mining and Processing Industry—Example from Southern Poland. *Soil Tillage Res.* **2021**, *205*, 104817. [CrossRef]
31. Ezzahoui, I.; Abdelouahid, R.A.; Taji, K.; Marzak, A. Hydroponic and Aquaponic Farming: Comparative Study Based on Internet of Things IoT Technologies. *Procedia Comput. Sci.* **2021**, *191*, 499–504. [CrossRef]
32. Tilman, D.; Cassman, K.G.; Matson, P.A.; Naylor, R.; Polasky, S. Agricultural Sustainability and Intensive Production Practices. *Nature* **2002**, *418*, 671–677. [CrossRef]
33. IPCC. Land is a Critical Resource, IPCC Report Says. 2019. Available online: https://www.ipcc.ch/2019/08/08/land-is-a-critical-resource_srccl/ (accessed on 6 April 2022).
34. IPCC. *Climate Change 2007: The Physical Science Basis*; Cambridge University Press: Cambridge, UK, 2007; p. 996. Available online: https://www.ipcc.ch/site/assets/uploads/2018/05/ar4_wg1_full_report-1.pdf (accessed on 6 April 2022).
35. Taki, M.; Rohani, A.; Rahmati-Joneidabad, M. Solar Thermal Simulation and Applications in Greenhouse. *Inf. Process. Agric.* **2018**, *5*, 83–113. [CrossRef]
36. Tzilivakis, J.; Warner, D.J.; May, M.; Lewis, K.A.; Jaggard, K. An Assessment of the Energy Inputs and Greenhouse Gas Emissions in Sugar Beet (Beta Vulgaris) Production in the UK. *Agric. Syst.* **2005**, *85*, 101–119. [CrossRef]
37. Taki, M.; Abdi, R.; Akbarpour, M.; Mobtaker, H.G. Energy inputs–yield relationship and sensitivity analysis for tomato greenhouse production in Iran. *J. Agric. Eng.* **2013**, *15*, 59. Available online: https://cigrjournal.org/index.php/Ejounral/article/view/2095/1701 (accessed on 19 October 2021).
38. Rafiee, S.; Mousavi Avval, S.H.; Mohammadi, A. Modeling and Sensitivity Analysis of Energy Inputs for Apple Production in Iran. *Energy* **2010**, *35*, 3301–3306. [CrossRef]
39. Stanghellini, C.; Kempkes, F.L.K.; Knies, P. Enhancing Environmental Quality in Agricultural Systems. *Acta Hortic.* **2003**, *609*, 277–283. [CrossRef]
40. Zhang, L.X.; Song, B.; Chen, B. Emergy-Based Analysis of Four Farming Systems: Insight into Agricultural Diversification in Rural China. *J. Clean. Prod.* **2012**, *28*, 33–44. [CrossRef]
41. Bakhtar, N.; Chhabria, V.; Chougle, I.; Vidhrani, H.; Hande, R. IoT Based Hydroponic Farm. 2018. Available online: https://ieeexplore.ieee.org/document/8748447 (accessed on 17 October 2022). [CrossRef]

42. United Nations. *Groundwater Making the Invisible Visible*; United Nations Educational, Scientific and Cultural Organization: Paris, France, 2022; Available online: https://www.unesco.org/en/articles/groundwater-making-invisible-visible-2022-and-beyond (accessed on 2 June 2022).
43. Yadav, R.K.; Chiranjeevi, P.; Sukrampal; Patil, S.A. Integrated Drip Hydroponics-Microbial Fuel Cell System for Wastewater Treatment and Resource Recovery. *Bioresour. Technol. Rep.* **2020**, *9*, 100392. [CrossRef]
44. United Nations. *The United Nations World Water Development Report 2017: Wastewater: The Untapped Resource*; United Nations Educational, Scientific and Cultural Organization: Paris, France, 2017; Available online: https://www.unwater.org/publications/world-water-development-report-2017/ (accessed on 2 April 2021).
45. United Nations. *Coping with the Water Scarcity: Challenge of the Twenty-First Century*; United Nations Educational, Scientific and Cultural Organization: Paris, France, 2007; Available online: https://www.fao.org/3/aq444e/aq444e.pdf (accessed on 26 March 2021).
46. EPA. Guidelines for Water Reuse: US-EPA. 2012. Available online: https://www3.epa.gov/region1/npdes/merrimackstation/pdfs/ar/AR-1530.pdf (accessed on 26 March 2021).
47. United Nations. *Water in a Changing World: The United Nations World Water Development Report*; United Nations Educational, Scientific and Cultural Organization: Paris, France, 2009; Available online: https://unesdoc.unesco.org/ark:/48223/pf0000181993 (accessed on 31 May 2022).
48. McDaniel, R.L.; Munster, C.; Nielsen-Gammon, J. Crop and Location Specific Agricultural Drought Quantification: Part III. Forecasting Water Stress and Yield Trends. *Trans. ASABE* **2017**, *60*, 741–752. [CrossRef]
49. Hardin, C.; Mehlitz, T.; Yildiz, I.; Kelly, S.F. Simulated performance of a renewable energy technology—Heat pump systems in semi-arid California greenhouses. *Acta Hortic.* **2008**, *797*, 347–352. [CrossRef]
50. FAO. *Coping with Water Scarcity an Action Framework for Agriculture and Food Security*; Food and Agriculture Organization Publication: Rome, Italy, 2012; Available online: http://www.fao.org/docrep/016/i3015e/i3015e.pdf (accessed on 26 March 2021).
51. Sathaiah, M.; Chandrasekaran, M. A Bio-Physical and Socio-Economic Impact Analysis of Using Industrial Treated Wastewater in Agriculture in Tamil Nadu, India. *Agric. Water Manag.* **2020**, *241*, 106394. [CrossRef]
52. Martinez-Mate, M.A.; Martin-Gorriz, B.; Martínez-Alvarez, V.; Soto-García, M.; Maestre-Valero, J.F. Hydroponic System and Desalinated Seawater as an Alternative Farm-Productive Proposal in Water Scarcity Areas: Energy and Greenhouse Gas Emissions Analysis of Lettuce Production in Southeast Spain. *J. Clean. Prod.* **2018**, *172*, 1298–1310. [CrossRef]
53. Fitton, N.; Alexander, P.; Arnell, N.; Bajzelj, B.; Calvin, K.; Doelman, J.; Gerber, J.S.; Havlik, P.; Hasegawa, T.; Herrero, M.; et al. The Vulnerabilities of Agricultural Land and Food Production to Future Water Scarcity. *Glob. Environ. Change* **2019**, *58*, 101944. [CrossRef]
54. Egbuikwem, P.N.; Mierzwa, J.C.; Saroj, D.P. Evaluation of Aerobic Biological Process with Post-Ozonation for Treatment of Mixed Industrial and Domestic Wastewater for Potential Reuse in Agriculture. *Bioresour. Technol.* **2020**, *318*, 124200. [CrossRef]
55. Wu, J.; Ge, Z.; Han, S.; Xing, L.; Zhu, M.; Zhang, J.; Liu, J. Impacts of Agricultural Industrial Agglomeration on China's Agricultural Energy Efficiency: A Spatial Econometrics Analysis. *J. Clean. Prod.* **2020**, *260*, 121011. [CrossRef]
56. Kumar, K.S.; Tiwari, K.N.; Jha, M.K. Design and Technology for Greenhouse Cooling in Tropical and Subtropical Regions: A Review. *Energy Build.* **2009**, *41*, 1269–1275. [CrossRef]
57. Misra, D.; Ghosh, S. Thermal Modelling and Performance Assessment of a Circular Greenhouse with Solar Chimney Assisted Ventilation and Fog Cooling. *Agric. Eng. Int. CIGR J.* **2018**, *3*, 1. Available online: https://cigrjournal.org/index.php/Ejounral/article/view/4741/2886 (accessed on 6 May 2021).
58. Von Zabeltitz, C. *Integrated Greenhouse Systems for Mild Climates*; Springer: Berlin/Heidelberg, Germany, 2011.
59. Radojevic, N.; Kostadinovic, D.; Vlajkovic, H.; Veg, E. Microclimate Control in Greenhouses. *FME Trans.* **2014**, *42*, 167–171. [CrossRef]
60. Baneshi, M.; Gonome, H.; Maruyama, S. Wide-Range Spectral Measurement of Radiative Properties of Commercial Greenhouse Covering Plastics and Their Impacts into the Energy Management in a Greenhouse. *Energy* **2020**, *210*, 118535. [CrossRef]
61. Buchholz, M. *The New Generation of Greenhouses. Saving Water and Improving Nutrition: Unlocking the Potential of Protected Agriculture in the Countries of the Gulf Cooperation Council*; Food and Agriculture Organization Publications: Cairo, Egypt, 2021; p. 97. Available online: https://www.fao.org/3/cb4070en/cb4070en.pdf (accessed on 22 June 2022).
62. Tataraki, K.G.; Kavvadias, K.C.; Maroulis, Z.B. Combined Cooling Heating and Power Systems in Greenhouses. Grassroots and Retrofit Design. *Energy* **2019**, *189*, 116283. [CrossRef]
63. Iddio, E.; Wang, L.; Thomas, Y.; McMorrow, G.; Denzer, A. Energy Efficient Operation and Modeling for Greenhouses: A Literature Review. *Renew. Sustain. Energy Rev.* **2020**, *117*, 109480. [CrossRef]
64. Food and Agriculture Organization. *Unlocking the Potential of Protected Agriculture in the Countries of the Gulf Cooperation Council—Saving Water and Improving Nutrition*; Food and Agriculture Organization Publications: Cairo, Egypt, 2021; Available online: https://www.fao.org/3/cb4070en/cb4070en.pdf (accessed on 22 June 2022).
65. Runkle, E.; Both, A. *Greenhouse Energy Conservation Strategies*; Extension Buletin E3160; Michigan State University: East Lansing, MI, USA, 2011.
66. Lindberg, H.; Go, A.; Runkle, E. *How Do I Use Less Energy to Heat My Greenhouse?* Michigan State University: East Lansing, MI, USA, 2021; Available online: https://www.canr.msu.edu/news/how-do-i-use-less-energy-to-heat-my-greenhouse (accessed on 6 October 2022).

67. Vadiee, A.; Martin, V. Energy Management Strategies for Commercial Greenhouses. *Appl. Energy* **2014**, *114*, 880–888. [CrossRef]
68. Benli, H. A Performance Comparison between a Horizontal Source and a Vertical Source Heat Pump Systems for a Greenhouse Heating in the Mild Climate Elaziğ, Turkey. *Appl. Therm. Eng.* **2013**, *50*, 197–206. [CrossRef]
69. Djevic, M.; Dimitrijevic, A. Energy Consumption for Different Greenhouse Constructions. *Energy* **2009**, *34*, 1325–1331. [CrossRef]
70. Statistik, S.O. *Energy Use in Greenhouses*; Statistics Sweden Center: Stockholm, Sweden, 2010.
71. Aguilar-Rodriguez, E.R.; Flores-Velazquez, J.; Ojeda-Bustamante, W.; Rojano, F.; Iñiguez-Covarrubias, M. Valuation of the Energy Performance of a Greenhouse with an Electric Heater Using Numerical Simulations. *Processes* **2020**, *8*, 600. [CrossRef]
72. Banakar, A.; Montazeri, M.; Ghobadian, B.; Pasdarshahri, H.; Kamrani, F. Energy analysis and assessing heating and cooling demands of closed greenhouse in Iran. *Therm. Sci. Eng. Prog.* **2021**, *25*, 101042. [CrossRef]
73. Vadiee, A.; Martin, V. Energy Analysis and Thermoeconomic Assessment of the Closed Greenhouse—The Largest Commercial Solar Building. *Appl. Energy* **2013**, *102*, 1256–1266. [CrossRef]
74. Ahamed, M.S.; Guo, H.; Tanino, K. Energy Saving Techniques for Reducing the Heating Cost of Conventional Greenhouses. *Biosyst. Eng.* **2019**, *178*, 9–33. [CrossRef]
75. Yano, A.; Cossu, M. Energy Sustainable Greenhouse Crop Cultivation Using Photovoltaic Technologies. *Renew. Sustain. Energy Rev.* **2019**, *109*, 116–137. [CrossRef]
76. Djevic, M.; Dimitrijevic, A. Greenhouse Energy Consumption and Energy Efficiency. Available online: http://baer.uni-ruse.bg/papers_v5/2004_v5_01.pdf (accessed on 7 April 2021).
77. Vourdoubas, J. Overview of Heating Greenhouses with Renewable Energy Sources a Case Study in Crete—Greece. *J. Agric. Environ. Sci.* **2015**, *4*, 70–76. [CrossRef]
78. Paris, B.; Vandorou, F.; Balafoutis, A.T.; Vaiopoulos, K.; Kyriakarakos, G.; Manolakos, D.; Papadakis, G. Energy Use in Greenhouses in the EU: A Review Recommending Energy Efficiency Measures and Renewable Energy Sources Adoption. *Appl. Sci.* **2022**, *12*, 5150. [CrossRef]
79. Aydin, M.E.; Keleş, R. A Multi Agent-Based Approach for Energy Efficient Water Resource Management. *Comput. Ind. Eng.* **2020**, *151*, 106679. [CrossRef]
80. Food and Agriculture Organization. *Early Warning Early Action Report on Food Security and Agriculture*; Food and Agriculture Organization Publications: Rome, Italy, 2019; Available online: https://www.fao.org/3/ca6372en/CA6372EN.pdf (accessed on 23 March 2021).
81. The World Bank. World Bank Open Data. 2014. Available online: https://data.worldbank.org/indicator/EG.USE.COMM.FO.ZS (accessed on 6 October 2022).
82. Cherni, A.; Essaber Jouini, S. An ARDL Approach to the CO2 Emissions, Renewable Energy and Economic Growth Nexus: Tunisian Evidence. *Int. J. Hydrog. Energy* **2017**, *42*, 29056–29066. [CrossRef]
83. Jiang, Z.; Lin, B. China's Energy Demand and Its Characteristics in the Industrialization and Urbanization Process. *Energy Policy* **2012**, *49*, 608–615. [CrossRef]
84. Beccali, M.; Cellura, M.; Iudicello, M.; Mistretta, M. Resource Consumption and Environmental Impacts of the Agrofood Sector: Life Cycle Assessment of Italian Citrus-Based Products. *Environ. Manag.* **2009**, *43*, 707–724. [CrossRef]
85. Naderi, S.; Ghasemi Nejad Raini, M.; Taki, M. Measuring the Energy and Environmental Indices for Apple (Production and Storage) by Life Cycle Assessment (Case Study: Semirom County, Isfahan, Iran). *Environ. Sustain. Indic.* **2020**, *6*, 100034. [CrossRef]
86. Marcelis, L.F.M.; Heuvelink, E. *Achieving Sustainable Greenhouse Cultivation*, 1st ed.; Burleigh Dodds Science Publishing: Cambridge, UK, 2019. [CrossRef]
87. Alluvione, F.; Moretti, B.; Sacco, D.; Grignani, C. EUE (Energy Use Efficiency) of Cropping Systems for a Sustainable Agriculture. *Energy* **2011**, *36*, 4468–4481. [CrossRef]
88. World Economic Forum. Shaping the Future of Energy, Materials and Infrastructure. Available online: https://www.weforum.org/system-initiatives/shaping-the-future-of-energy (accessed on 31 May 2022).
89. Jaramillo-Nieves, L.; Del Río, P. Contribution of Renewable Energy Sources to the Sustainable Development of Islands: An Overview of the Literature and a Research Agenda. *Sustainability* **2010**, *2*, 783–811. [CrossRef]
90. Huo, S.; Liu, J.; Addy, M.; Chen, P.; Necas, D.; Cheng, P.; Li, K.; Chai, H.; Liu, Y.; Ruan, R. The Influence of Microalgae on Vegetable Production and Nutrient Removal in Greenhouse Hydroponics. *J. Clean. Prod.* **2020**, *243*, 118563. [CrossRef]
91. Zhang, L.; Yang, J.; Li, D.; Liu, H.; Xie, Y.; Song, T.; Luo, S. Evaluation of the Ecological Civilization Index of China Based on the Double Benchmark Progressive Method. *J. Clean. Prod.* **2019**, *222*, 511–519. [CrossRef]
92. Seaman, C.; Bricklebank, N. Soil-free farming. *Chem. Ind. Mag.* **2011**, *19*. Available online: http://www.soci.org/Chemistryand-Industry/CnI-Data/2011/6/Soil-free-farming (accessed on 6 May 2022).
93. Christie, E. Water and Nutrient Reuse within Closed Hydroponic Systems. Master's Thesis, Department of Mechanical Engineering, Georgia Southern University, Statesboro, GA, USA, 2014. Available online: https://digitalcommons.georgiasouthern.edu/etd/1096 (accessed on 2 April 2021).
94. Rakocy, J.E. Chapter 14: Aquaponics-Integrating Fish and Plant Culture. In *Aquaculture Production Systems*, 1st ed.; Tidwell, J., Ed.; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2012; pp. 344–386. [CrossRef]
95. Sharma, N.; Acharya, S.; Kumar, K.; Singh, N.; Chaurasia, O.P. Hydroponics as an Advanced Technique for Vegetable Production: An Overview. *J. Soil Water Conserv.* **2018**, *17*, 364. [CrossRef]

96. Giordani, T.; Fabrizi, A.; Guidi, L.; Natali, L.; Giunti, G.; Ravasi, F.; Cavallini, A.; Pardossi, A. Response of tomato plants exposed to treatment with nanoparticles. *EQA—Int. J. Environ. Qual.* **2012**, *8*, 27–38. [CrossRef]
97. Croft, M.M.; Hallett, S.G.; Marshall, M.I. Hydroponic Production of Vegetable Amaranth (*Amaranthus cruentus*) for Improving Nutritional Security and Economic Viability in Kenya. *Renew. Agric. Food Syst.* **2017**, *32*, 552–561. [CrossRef]
98. Muller, A.; Ferré, M.; Engel, S.; Gattinger, A.; Holzkämper, A.; Huber, R.; Müller, M.; Six, J. Can Soil-Less Crop Production Be a Sustainable Option for Soil Conservation and Future Agriculture? *Land Use Policy* **2017**, *69*, 102–105. [CrossRef]
99. Link, C. Assessing the Potential Environmental Impacts of Controlled Environment Agriculture in Detroit and the Future of This Industry Based on Local Food Trends. 2017. Available online: https://dash.harvard.edu/bitstream/handle/1/33826456/DUSTON-DOCUMENT-2017.pdf?sequence=1&isAllowed=y (accessed on 26 September 2022).
100. Joshi, N.; Joshi, A. *Green Spaces: Create Your Own*, 1st ed.; Notion Press Inc.: Chennai, India, 2018.
101. Hickman, G.W. International Greenhouse Vegetable Production—Statistics a Review of Currently Available Data on the International Production of Vegetables in Greenhouses. Cuesta Roble (Oak Hill) Consulting: Mariposa, CA, USA. Available online: http://cuestaroble.com/statistics.htm (accessed on 18 May 2021).
102. Borges, R.; Cardoso, T.; Sotto, D. Análise Econômico—Financeira de um Sistema de Cultivo Hidropônico. 2016. Available online: http://www.custoseagronegocioonline.com.br/numero3v12/OK%2012%20hidroponia.pdf (accessed on 20 June 2022).
103. Zhang, L.-X.; Hu, Q.-H.; Wang, C.-B. Emergy Evaluation of Environmental Sustainability of Poultry Farming That Produces Products with Organic Claims on the Outskirts of Mega-Cities in China. *Ecol. Eng.* **2013**, *54*, 128–135. [CrossRef]
104. Souza, S.V.; Gimenes, R.M.T.; Binotto, E. Economic Viability for Deploying Hydroponic System in Emerging Countries: A Differentiated Risk Adjustment Proposal. *Land Use Policy* **2019**, *83*, 357–369. [CrossRef]
105. Bradley, P.; Marulanda, C. Simplified hydroponics to reduce global hunger. *Acta Hortic.* **2001**, *554*, 289–296. [CrossRef]
106. Killebrew, K.; Wolff, H. Environmental impacts of agriculture technologies. *Evans Sch. Policy Anal. Res.* **2010**. Available online: https://econ.washington.edu/sites/econ/files/old-site-uploads/2014/06/2010-Environmental-Impacts-of-Ag-Technologies.pdf (accessed on 17 October 2022).
107. Wada, T. Chapter 1.1 Theory and Technology to Control the Nutrient Solution of Hydroponics. In *Plant Factory Using Artificial Light*; Anpo, M., Fukuda, H., Wada, T., Eds.; Elsevier: Amsterdam, The Netherlands, 2019; pp. 5–14. [CrossRef]
108. Rufí-Salís, M.; Calvo, M.J.; Petit-Boix, A.; Villalba, G.; Gabarrell, X. Exploring Nutrient Recovery from Hydroponics in Urban Agriculture: An Environmental Assessment. *Resour. Conserv. Recycl.* **2020**, *155*, 104683. [CrossRef]
109. Orellano, V.; Azevedo, P.F.; Saes, M.S.; Nascimento, V.E. Land Invasions, Insecure Property Rights and Production Decisions. *J. Agric. Econ.* **2015**, *66*, 660–671. [CrossRef]
110. Giacomini, D.G.; Moyer, J. Production Standards for Terrestrial Plants in Containers and Enclosures (Greenhouses)—Formal Recommendation by the National Organic Standards Board (NOSB) to the National Organic Program (NOP). 2010. Available online: https://www.ams.usda.gov/sites/default/files/media/NOP%20Final%20Rec%20Production%20Standards%20for%20Terrestrial%20Plants.pdf (accessed on 13 May 2021).
111. Coolong, T. *Hydroponic Lettuce*; University of Kentucky Cooperative Extension Services: Lexinton, KY, USA, 2012.
112. Lopez-Galvez, F.; Gil, M.I.; Pedrero-Salcedo, F.; Alarcón, J.J.; Allende, A. Monitoring Generic *Escherichia coli* in Reclaimed and Surface Water Used in Hydroponically Cultivated Greenhouse Peppers and the Influence of Fertilizer Solutions. *Food Control* **2016**, *67*, 90–95. [CrossRef]
113. Imtiaz Hussain, M.; Ali, A.; Lee, G.H. Performance and Economic Analyses of Linear and Spot Fresnel Lens Solar Collectors Used for Greenhouse Heating in South Korea. *Energy* **2015**, *90*, 1522–1531. [CrossRef]
114. Orozko, L.; Rico-Romero, L.; Escartin, E.F. Microbiological Profile of Greenhouses in a Farm Producing Hydroponic Tomatoes. *J. Food Prot.* **2008**, *71*, 60–65. [CrossRef]
115. Fu, T.-T.; Liu, J.-T.; Hammitt, J.K. Consumer Willingness to Pay for Low-Pesticide Fresh Produce in Taiwan. *J. Agric. Econ.* **2008**, *50*, 220–233. [CrossRef]
116. Russo, G.; Scarascia Mugnozza, G. LCA Methodology Applied to Various Typology of Greenhouses. *Acta Hortic.* **2005**, *691*, 837–844. [CrossRef]
117. Li, G.; Tao, L.; Li, X.; Peng, L.; Song, C.; Dai, L.; Wu, Y.; Xie, L. Design and Performance of a Novel Rice Hydroponic Biofilter in a Pond-Scale Aquaponic Recirculating System. *Ecol. Eng.* **2018**, *125*, 1–10. [CrossRef]
118. Grewal, H.S.; Maheshwari, B.; Parks, S.E. Water and Nutrient Use Efficiency of a Low-Cost Hydroponic Greenhouse for a Cucumber Crop: An Australian Case Study. *Agric. Water Manag.* **2011**, *98*, 841–846. [CrossRef]
119. Sutar, K.A.; Wadkar, S.; Kiran, G.; Jadhav, S.; Turambekar, V. Study on Use of Waste Water in Hydroponic System instead of Nutrient Solution. *Int. J. Res. Appl. Sci. Eng. Technol.* **2018**, *6*, 2035–2039. [CrossRef]
120. Carmassi, G.; Incrocci, L.; Maggini, R.; Malorgio, F.; Tognoni, F.; Pardossi, A. Modeling Salinity Build-up in Recirculating Nutrient Solution Culture. *J. Plant Nutr.* **2005**, *28*, 431–445. [CrossRef]
121. Zou, Y.; Hu, Z.; Zhang, J.; Guimbaud, C.; Wang, Q.; Fang, Y. Effect of Seasonal Variation on Nitrogen Transformations in Aquaponics of Northern China. *Ecol. Eng.* **2016**, *94*, 30–36. [CrossRef]
122. Love, D.C.; Uhl, M.S.; Genello, L. Energy and Water Use of a Small-Scale Raft Aquaponics System in Baltimore, Maryland, United States. *Aquac. Eng.* **2015**, *68*, 19–27. [CrossRef]
123. Konig, B.; Junge, R.; Bittsanszky, A.; Villarroel, M.; Komives, T. On the Sustainability of Aquaponics. *Ecocycles* **2016**, *2*, 26–32. [CrossRef]

124. Goddek, S.; Delaide, B.; Mankasingh, U.; Ragnarsdottir, K.; Jijakli, H.; Thorarinsdottir, R. Challenges of Sustainable and Commercial Aquaponics. *Sustainability* **2015**, *7*, 4199–4224. [CrossRef]
125. Xie, K.; Rosentrater, K. Life Cycle Assessment (LCA) and Techno-Economic Analysis (TEA) of Tilapia-Basil Aquaponics. In Proceedings of the 2015 ASABE International Meeting, New Orleans, LA, USA, 26–29 July 2015. [CrossRef]
126. Adler, P.R.; Harper, J.K.; Wade, E.M.; Takeda, F.; Summerfelt, S.T. Economic Analysis of an Aquaponic System for the Integrated Production of Rainbow Trout and Plants. *Int. J. Recirc. Aquac.* **2000**, *1*, 15–34. [CrossRef]
127. Tyson, R.V.; Treadwell, D.D.; Simonne, E.H. Opportunities and Challenges to Sustainability in Aquaponic Systems. *HortTechnology* **2011**, *21*, 6–13. [CrossRef]
128. Food and Agriculture Organization. *The State of World Fisheries and Aquaculture—Opportunities and Challenges*; Food and Agriculture Organization Publications: Rome, Italy, 2014; Available online: https://www.fao.org/3/i3720e/i3720e.pdf (accessed on 26 March 2021).
129. Suhl, J.; Dannehl, D.; Kloas, W.; Baganz, D.; Jobs, S.; Scheibe, G.; Schmidt, U. Advanced Aquaponics: Evaluation of Intensive Tomato Production in Aquaponics vs. Conventional Hydroponics. *Agric. Water Manag.* **2016**, *178*, 335–344. [CrossRef]
130. Gwynn-Jones, D.; Dunne, H.; Donnison, I.; Robson, P.; Sanfratello, G.M.; Schlarb-Ridley, B.; Hughes, K.; Convey, P. Can the Optimisation of Pop-up Agriculture in Remote Communities Help Feed the World? *Glob. Food Secur.* **2018**, *18*, 35–43. [CrossRef]
131. AlShrouf, A. Hydroponics, Aeroponic and Aquaponic as Compared with Conventional Farming. *Am. Acad. Sci. Res. J. Eng. Technol. Sci.* **2017**, *27*, 247. Available online: https://core.ac.uk/download/pdf/235050152.pdf (accessed on 6 April 2022).
132. Romeo, D.; Vea, E.B.; Thomsen, M. Environmental Impacts of Urban Hydroponics in Europe: A Case Study in Lyon. *Procedia CIRP* **2018**, *69*, 540–545. [CrossRef]
133. Trang, N.T.D.; Brix, H. Use of Planted Biofilters in Integrated Recirculating Aquaculture-Hydroponics Systems in the Mekong Delta, Vietnam. *Aquac. Res.* **2012**, *45*, 460–469. [CrossRef]
134. Muñoz, H. Hydroponics Manual: Home-Based Vegetable Production System. Inter-American Institute for Cooperation on Agriculture (IICA): San Jose, Costa Rica. Available online: https://repositorio.iica.int/handle/11324/11648 (accessed on 8 March 2022).
135. NoSoilSolutions. How to Grow Hydroponic Tomatoes. Available online: https://www.nosoilsolutions.com/grow-hydroponic-tomatoes/ (accessed on 28 June 2022).
136. Old Farmer's Almanac. Tomatoes. Available online: https://www.almanac.com/plant/tomatoes (accessed on 23 June 2022).
137. La Rosa-Rodríguez, R.D.; Lara-Herrera, A.; Trejo-Téllez, L.I.; Padilla-Bernal, L.E.; Solis-Sánchez, L.O.; Ortiz-Rodríguez, J.M. Water and Fertilizers Use Efficiency in Two Hydroponic Systems for Tomato Production. *Hortic. Bras.* **2020**, *38*, 47–52. [CrossRef]
138. Volente, G. How Many Tomatoes Can 1 Plant Produce? Greenhouse Today. Available online: https://www.greenhousetoday.com/how-many-tomatoes-can-1-plant-produce/ (accessed on 22 June 2022).
139. Fayezizadeh, M.R.; Ansari, N.A.Z.; Albaji, M.; Khaleghi, E. Effects of Hydroponic Systems on Yield, Water Productivity and Stomatal Gas Exchange of Greenhouse Tomato Cultivars. *Agric. Water Manag.* **2021**, *258*, 107171. [CrossRef]
140. Heller, M. *Food Product Environmental Footprint Literature Summary—The Oregon Sustainability Board a Report*; Center for Sustainable Systems, University of Michigan: Ann Arbor, MI, USA, 2017.
141. Gruda, N.; Bisbis, M.; Tanny, J. Impacts of Protected Vegetable Cultivation on Climate Change and Adaptation Strategies for Cleaner Production—A Review. *J. Clean. Prod.* **2019**, *225*, 324–339. [CrossRef]
142. Gruda, N.; Bisbis, M.; Tanny, J. Influence of Climate Change on Protected Cultivation: Impacts and Sustainable Adaptation Strategies—A Review. *J. Clean. Prod.* **2019**, *225*, 481–495. [CrossRef]
143. Cuce, E.; Harjunowibowo, D.; Cuce, P.M. Renewable and Sustainable Energy Saving Strategies for Greenhouse Systems: A Comprehensive Review. *Renew. Sustain. Energy Rev.* **2016**, *64*, 34–59. [CrossRef]
144. Karlowsky, S.; Gläser, M.; Henschel, K.; Schwarz, D. Seasonal Nitrous Oxide Emissions from Hydroponic Tomato and Cucumber Cultivation in a Commercial Greenhouse Company. *Front. Sustain. Food Syst.* **2021**, *5*, 626053. [CrossRef]
145. Halbert-Howard, A.; Häfner, F.; Karlowsky, S.; Schwarz, D.; Krause, A. Evaluating Recycling Fertilizers for Tomato Cultivation in Hydroponics, and Their Impact on Greenhouse Gas Emissions. *Environ. Sci. Pollut. Res.* **2021**, *28*, 59284–59303. [CrossRef]
146. Nerlich, A.; Karlowsky, S.; Schwarz, D.; Förster, N.; Dannehl, D. Soilless Tomato Production: Effects of Hemp Fiber and Rock Wool Growing Media on Yield, Secondary Metabolites, Substrate Characteristics and Greenhouse Gas Emissions. *Horticulturae* **2022**, *8*, 272. [CrossRef]
147. EdenGreen Technology. Carbon-Negative Farming: Is Hydroponics the Solution? 2021. Available online: https://www.edengreen.com/blog-collection/carbon-negative-farming (accessed on 23 June 2022).
148. Nederhoff, E.; Stanghellini, C. Water use efficiency of tomatoes—In greenhouses and hydroponics. *Pract. Hydroponics Greenh.* **2010**, *115*, 1321. Available online: https://edepot.wur.nl/156932 (accessed on 3 November 2022).
149. Engler, N.; Krarti, M. Review of Energy Efficiency in Controlled Environment Agriculture. *Renew. Sustain. Energy Rev.* **2021**, *141*, 110786. [CrossRef]
150. Venter, G. Hydroponic Water Requirements. Farmer's Weekly SA: Johannesburg, South Africa, 2017. Available online: https://www.farmersweekly.co.za/agri-technology/farming-for-tomorrow/hydroponic-water-requirements/ (accessed on 28 June 2022).
151. Smil, V. *How Much Energy Does It Take to Grow a Tomato?* IEEE Spectrum: Piscataway, NJ, USA, 2021; Available online: https://spectrum.ieee.org/how-much-energy-does-it-take-to-grow-a-tomato (accessed on 22 June 2022).
152. Ozkan, B.; Ceylan, R.F.; Kizilay, H. Energy Inputs and Crop Yield Relationships in Greenhouse Winter Crop Tomato Production. *Renew. Energy* **2011**, *36*, 3217–3221. [CrossRef]

153. Our World in Data. Crop Yields—Yields Across the World—Fruits and Vegetables, Tomato Yields. Available online: https://ourworldindata.org/grapher/tomato-yields (accessed on 20 June 2022).
154. Hydroponic Systems. Advantages of Tomato Growing in Hydroponic Systems. Available online: https://hydroponicsystems.eu/advantages-of-tomato-growing-in-hydroponic-systems/ (accessed on 22 June 2022).
155. Calpas, J. Tomato Plant Propagation in Commercial Greenhouse Tomato Production. Available online: https://www.alberta.ca/tomato-plant-propagation-in-commercial-greenhouse-tomato-production.aspx (accessed on 28 September 2022).
156. Savvas, D.; Gianquinto, G.; Tuzel, Y.; Gruda, N. Soilless culture. In *Good Agricultural Practices for Greenhouse Vegetable Crops: Principles for Mediterranean Climate Areas*; Food and Agriculture Organization Publications: Rome, Italy, 2013; pp. 303–354. Available online: https://www.fao.org/3/i3284e/i3284e.pdf (accessed on 6 June 2022).
157. De Jesus Pereira, B.; Filho, A.B.C.; La Scala, N., Jr. Greenhouse Gas Emissions and Carbon Footprint of Cucumber, Tomato and Lettuce Production Using Two Cropping Systems. *J. Clean. Prod.* **2021**, *282*, 124517. [CrossRef]
158. Our World in Data. Environmental Impacts of Food Production—Greenhouse Gas Emissions per Kilogram of Food Product. Available online: https://ourworldindata.org/environmental-impacts-of-food (accessed on 21 June 2022).
159. Antón, A.; Muñoz, P. Integrated preventive environmental strategy in greenhouse production. In *Good Agricultural Practices for Greenhouse Vegetable Crops: Principles for Mediterranean Climate Areas*; Food and Agriculture Organization Publications: Rome, Italy, 2013; p. 565. Available online: https://www.fao.org/3/i3284e/i3284e.pdf (accessed on 6 June 2022).
160. Torrellas, M.; Antón, A.; Ruijs, M.; García Victoria, N.; Stanghellini, C.; Montero, J.I. Environmental and Economic Assessment of Protected Crops in Four European Scenarios. *J. Clean. Prod.* **2012**, *28*, 45–55. [CrossRef]
161. Allied Medical Research. Medical Cannabis Market by Product Type (Buds/Marijuana Flower and Cannabis Extracts), Application (Chronic Pain, Mental Disorders, Cancer, and Others), and End User (Pharmaceutical and Research & Development Centers): Global Opportunity Analysis and Industry Forecast, 2021–2030. 2021. Available online: https://www.alliedmarketresearch.com/request-sample/14619 (accessed on 27 June 2022).
162. Janatová, A.; Fraňková, A.; Tlustoš, P.; Hamouz, K.; Božik, M.; Klouček, P. Yield and Cannabinoids Contents in Different Cannabis (*Cannabis sativa* L.) Genotypes for Medical Use. *Ind. Crops Prod.* **2018**, *112*, 363–367. [CrossRef]
163. Cannabis Business Times. Measuring Yield. Available online: https://www.cannabisbusinesstimes.com/article/measuring-yield/ (accessed on 27 June 2022).
164. Sholl, L. Hydroponic vs. Soil Cannabis Cultivation—Royal Queen Seeds. Available online: https://www.royalqueenseeds.com/blog-hydroponic-vs-soil-cannabis-cultivation-n718 (accessed on 28 June 2022).
165. Labbate, E. Hydroponic Growing Systems & Quality Control for Medical Marijuana. Available online: https://www.climatecontrol.com/blog/hydroponic-growing-systems/ (accessed on 29 June 2022).
166. Vanhove, W.; Van Damme, P.; Meert, N. Factors Determining Yield and Quality of Illicit Indoor Cannabis (*Cannabis* spp.) Production. *Forensic Sci. Int.* **2011**, *212*, 158–163. [CrossRef]
167. Backer, R.; Schwinghamer, T.; Rosenbaum, P.; McCarty, V.; Eichhorn Bilodeau, S.; Lyu, D.; Ahmed, M.B.; Robinson, G.; Lefsrud, M.; Wilkins, O.; et al. Closing the Yield Gap for Cannabis: A Meta-Analysis of Factors Determining Cannabis Yield. *Front. Plant Sci.* **2019**, *10*, 495. [CrossRef]
168. Toonen, M.; Ribot, S.; Thissen, J. Yield of Illicit Indoor Cannabis Cultivation in the Netherlands. *J. Forensic Sci.* **2006**, *51*, 1050–1054. [CrossRef] [PubMed]
169. Johnson, R. *Hemp as an Agricultural Commodity*; Congressional Research Service: Washington, DC, USA, 2018; Available online: https://sgp.fas.org/crs/misc/RL32725.pdf (accessed on 29 June 2022).
170. Jan, J.Y.; Xiujie, S.; Wu, L.L.; Mohyuddin Mirza, M. Developing BMPs for Medical Cannabis Crops. Grow Opportunities: For Canadian Cannabis Producers. Available online: https://www.growopportunity.ca/developing-bmps-for-medical-cannabis-crops-31243/ (accessed on 27 June 2022).
171. Jin, D.; Jin, S.; Chen, J. Cannabis Indoor Growing Conditions, Management Practices, and Post-Harvest Treatment: A Review. *Am. J. Plant Sci.* **2019**, *10*, 925–946. [CrossRef]
172. Knight, G.; Hansen, S.; Connor, M.; Poulsen, H.; McGovern, C.; Stacey, J. The Results of an Experimental Indoor Hydroponic Cannabis Growing Study, Using the "Screen of Green" (ScrOG) Method—Yield, Tetrahydrocannabinol (THC) and DNA Analysis. *Forensic Sci. Int.* **2010**, *202*, 36–44. [CrossRef]
173. Sholl, L. Understanding Cannabis Yield per Plant—Royal Queen Seeds. Available online: https://www.royalqueenseeds.com/blog-how-much-weed-can-you-really-produce-per-plant-n1246 (accessed on 28 June 2022).
174. Manning, A. Insatiable demand for cannabis has created a giant carbon footprint. 2021. Available online: https://engr.source.colostate.edu/insatiable-demand-for-cannabis-has-created-a-giant-carbon-footprint/ (accessed on 27 June 2022).
175. Magazine, S.; Fox, A. Growing an Ounce of Pot Indoors Can Emit as Much Carbon as Burning a Full Tank of Gas. Available online: https://www.smithsonianmag.com/smart-news/growing-ounce-pot-indoors-can-emit-much-carbon-burning-full-tank-gas-180977240/ (accessed on 4 December 2021).
176. O'Hare, M.; Sanchez, D.L.; Alstone, P. *Environmental Risks and Opportunities in Cannabis Cultivation—Report, BOTEC Analysis Corporation*; I-502 Project#430–5d; University of California: Berkeley, CA, USA, 2013.
177. Chaitanya, S. A Reconsideration of Cannabis Water Use—Ganjier. Available online: https://www.ganjier.com/2021/06/14/a-reconsideration-of-cannabis-water-use/ (accessed on 28 June 2022).

178. Butsic, V.; Brenner, J.C. Cannabis (Cannabis Sativa or C. Indica) Agriculture and the Environment: A Systematic, Spatially-Explicit Survey and Potential Impacts. *Environ. Res. Lett.* **2016**, *11*, 044023. [CrossRef]
179. Drotleff, L. Cannabis Requires More Water than Commodity Crops, Researchers Say. Available online: https://mjbizdaily.com/cannabis-requires-more-water-than-commodity-crops-researchers-say/ (accessed on 16 June 2022).
180. Cannabis Control Commission. Guidance on Best Management Practices for Water Use. Available online: https://mass-cannabis-control.com/wp-content/uploads/2019/04/Guidance-on-Best-Management-Practices-for-Water-Use.pdf (accessed on 27 June 2022).
181. Zheng, Z.; Fiddes, K.; Yang, L. A Narrative Review on Environmental Impacts of Cannabis Cultivation. *J. Cannabis Res.* **2021**, *3*, 1–10. [CrossRef]
182. Wilson, H.; Bodwitch, H.; Carah, J.; Daane, K.; Getz, C.; Grantham, T.E.; Butsic, V. First Known Survey of Cannabis Production Practices in California. *Calif. Agric.* **2019**, *73*, 119–127. [CrossRef]
183. Greentechnology. Water and Cannabis: Use, Waste and Conservation. Available online: https://www.green-technology.org/gcsummit18/images/Water-Cannabis.pdf (accessed on 29 June 2022).
184. Kolwey, N. A budding Opportunity: Energy efficiency best practices for cannabis grow operations–SWEEP. Available online: https://www.swenergy.org/data/sites/1/media/documents/publications/documents/A%20Budding%20Opportunity%20%20Energy%20efficiency%20best%20practices%20for%20cannabis%20grow%20operations.pdf (accessed on 27 June 2022).
185. Cannabis Business Times. Energy Spending. Available online: https://www.cannabisbusinesstimes.com/article/energyspending/ (accessed on 27 June 2022).
186. Caulkins, P.J. Estimated Cost of Production for Legalized Cannabis Estimated Cost of Production for Legalized Cannabis. Available online: https://www.rand.org/content/dam/rand/pubs/working_papers/2010/RAND_WR764.pdf (accessed on 14 June 2022).
187. Webster, G.; Emily Henderson, B.S. Analyzing the Carbon Footprint of Cannabis. Available online: https://www.azolifesciences.com/article/Analyzing-the-Carbon-Footprint-of-Cannabis.aspx (accessed on 27 June 2022).
188. Mills, E. The Carbon Footprint of Indoor Cannabis Production. *Energy Policy* **2012**, *46*, 58–67. [CrossRef]
189. Our World in Data. Fertilizers—Fertilizer Use per Hectare of Cropland. Available online: https://ourworldindata.org/grapher/fertilizer-use-in-kg-per-hectare-of-arable-land (accessed on 14 October 2022).
190. Our World in Data. Pesticides—Pesticide Use per Hectare of Cropland. Available online: https://ourworldindata.org/grapher/pesticide-use-per-hectare-of-cropland?tab=chart (accessed on 14 October 2022).
191. Our World in Data. What Share of Electricity Comes from Fossil Fuels? *Share of Electricity Production from Fossil Fuels.* Available online: https://ourworldindata.org/grapher/share-electricity-fossil-fuels?tab=chart (accessed on 14 October 2022).
192. Supraja, K.V.; Behera, B.; Balasubramanian, P. Performance Evaluation of Hydroponic System for Co-Cultivation of Microalgae and Tomato Plant. *J. Clean. Prod.* **2020**, *272*, 122823. [CrossRef]