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Assessing the Physical and Environmental Aspects of Greenhouse Cultivation: A Comprehensive Review of Conventional and Hydroponic Methods

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Abstract: Population growth has presented several challenges in terms of energy, food supply, and environmental protection. The agricultural industry plays a crucial role in addressing these challenges by implementing innovative technologies that optimize resource utilization, minimize environmental impacts, and increase food production. Among these technologies, greenhouse cultivation systems have garnered substantial attention due to their ability to create a controlled environment for crop growth, resulting in higher yields, improved quality, and reduced water usage. However, it is important to note that greenhouse cultivation technology is also one of the most energy-intensive sectors within agriculture, contributing significantly to global energy consumption. Despite this, the technology remains popular due to its efficiency in optimizing inputs, increasing production per unit area, enabling year-round crop production, and managing unfavorable environmental conditions such as pests, diseases, and extreme weather events. There are two primary greenhouse cultivation systems: conventional and hydroponic methods. Each system has distinct similarities and differences regarding energy consumption, crop production per unit area, and environmental impacts. In this study, we compare conventional and hydroponic greenhouse cultivation, analyzing various inputs such as temperature, light, and energy consumption. Our findings indicate that hydroponic systems, equipped with advanced control equipment and growth mediums, create optimal conditions for plant growth. Also, hydroponics offered 11 ± 1.7 times higher yields but required 82 ± 11 times more energy compared to those conventionally produced in some plant productions. Moreover, specific energy consumption increased by 17% compared to conventional cultivation for some vegetables. This information can be used to optimize energy usage, reduce costs, and promote sustainable crop production, thereby contributing to global food security and environmental sustainability.

Keywords: life cycle assessment; energy consumption; greenhouse structure; modeling

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1. Introduction

Today, the surging global population and the escalating demand for food have drawn significant attention from scientists and researchers towards the agricultural industry and energy consumption [1–3]. One of the key challenges in this field revolves around addressing the needs of a rapidly expanding global population and their growing demand for food [1,4,5]. Therefore, the goal to enhance food production through the development of new technologies should be a primary focus for researchers [1,6,7]. Improving energy consumption and associated costs in sustainable agriculture is crucial for preserving the environment, conserving natural resources, and maximizing economic benefits. This requires finding a balance between ensuring food security and minimizing environmental impact [2,8]. The greenhouse sector has become a growing interest within the agricultural industry, steadily progressing with each passing day [5,9]. One of the key benefits of this type of cultivation is its ability to produce crops outside the traditional growing season. This extended period of cultivation requires additional energy compared to traditional agricultural practices on farmlands. Traditional agriculture requires a large area under cultivation, natural minerals, and water, which reduces productivity. Also, weed removal requires a lot of effort and energy consumption that can reduce productivity (Table 1). Table 1 shows a brief comparison of two methods of farming in the open field and cultivation in the greenhouse.

Table 1. Comparison between traditional and hydroponic cultivation.

Open field cultivation	Greenhouse Cultivation
Large cultivation area is needed	Optimal use of water
The need for natural minerals	Off-season cultivation
Hard weed removal	Higher yield and nutrient content
Water wastage	Control of environmental conditions

Greenhouse cultivation includes two types: conventional and hydroponic (cultivation substrate in soil, and cultivation substrate in water-based nutrient solution, respectively). Conventional greenhouses can grow the plant in a soil bed with a controllable environment [10]; in fact, the vital environmental factors for plant growth can be kept at an optimal level to create a favorable climate inside the greenhouse [1,11,12]. Greenhouse cultivation is becoming more and more popular and today there are about 405,000 ha of greenhouses around the world [1,13]. Conventional greenhouse cultivation (cultivation substrate soil) has some disadvantages, including the need for a large area under cultivation that requires high concentrations of nutrients and pesticides [1,14,15]. In addition, chemical wastes and pollutants released during cultivation can have dangerous effects such as soil degradation, erosion, and pollution [1,16].

Hydroponic cultivation is a kind of cultivation where the plant is placed in a bed using air, water, or solids containing moisture instead of soil [17]. This cultivation provides better quality, has a higher yield, and nutrient content, and better consumption of fertilizer and water compared to conventional greenhouse [1]. Also, hydroponic cultivation is one of the most popular techniques. This method is clean and easy compared to the conventional manner [17,18]. Traditional agriculture requires a large area under cultivation, natural minerals, and water, which reduces productivity. Also, weed removal requires a lot of effort and energy consumption that can reduce productivity. Hydroponics can control the temperature, humidity, and irrigation level by a control system consisting of a microcontroller kit connected to a wireless sensor network (WSN) [17,19]. Hydroponics is a special and useful method for growing plants that can be used even in dry areas such as arid deserts [17,20]. Based on some comparisons between hydroponic and open-field cultivation, crop yield per unit area has been about 10 times higher than conventional cultivation on open land [21,22]. In arid or semi-arid areas, it is common to use low-quality water (high salt concentration) for agriculture because this is the only source available [23,24]. These waters contain a large amount of salt and sodium ions, which cause physical and chemical changes in soil structure and helps to destroy it [21,22]. As a result, it has a negative effect on the number of plant leaves, leaf surface, relative water content, and biomass, and it also reduces productivity [23,24]. Thus, hydroponic cultivation can become a significant strategy because the matric potential in this type of cultivation will not exist under the free energy of water and only includes the osmotic potential [23]. However, in conventional greenhouse cultivation, where the soil is the substrate for plant growth, both matric and osmotic potentials cause less water to be available for the plant [21,25].

In general, water salinity in the hydroponic method is less harmful than in conventional cultivation because of the constant amount of oxygenation (O_2) [26]. Therefore, agricultural production in greenhouse systems has both advantages and disadvantages. Its advantages include producing more than one type of product in a year, producing regardless of weather conditions, identifying the essential needs of plants and environmental effects, increasing production per unit area, implementing a marketing plan, and identifying target market demands; its disadvantages are the excessive use of local non-commercial energy sources [27] such as the energy of seed, livestock manure, and commercial energy sources such as machinery, irrigation water, diesel power, pesticides, fertilizers, and so on. Furthermore, inputs used in greenhouse structures, such as steel, polyethylene, and polycarbonate sheets, as well as the shape of the greenhouse buildings, can increase greenhouse gas (GHG) emissions and energy utilization compared to cultivation on agricultural land.

According to some studies [9,28], about 10% to 12% of the world's GHGs are released by the agricultural industry. It was found that agricultural production produces about 15% of the world's total CO_2 emissions. As a result, evaluating the amount of GHG emissions is another challenging topic in today's world. Life cycle assessment (LCA) is a method to analyze various goods and services in terms of environmental consequences [29]. This technique, which examines the extraction of raw materials until the end of their life, is very useful in the agricultural industry, especially in greenhouse cultivation [30]. The main aim of this approach (LCA) is to present a decision-backing system for beneficiaries in a plant's supply chain that plays a critical role in two types of hydroponic planting and conventional greenhouse cultivation [31]. Considering the ever-increasing growth of the population and the global need for food, as well as the need to preserve the environment and reduce energy consumption, investigating new cultivation methods and comparing them with each other is an essential need that researchers and farmers should pay special attention to.

Based on the above literature and the lack of similar research about energy consumption in two types of traditional greenhouse and hydroponic cultivation, there is a need for a total review with details to show the advantages and disadvantages of these two cultivation methods and provide examples to farmers. In this regard, comparing and evaluating the energy pattern, benefits, and drawbacks of conventional and hydroponic cultivation methods are among the main aims of this research.

2. Literature Review

2.1. Life Cycle Assessment (LCA)

LCA is a detailed approach to examining all the inputs, outputs, and total environmental effects in the production life cycle of a product and is very useful for different systems [29]. This method is very effective in solving problems such as the limitation of natural resources and the disadvantages of excessive use of energy resources [31–33]. There are two main methods for LCA, namely attributional life cycle assessment (ALCA) and consequential life cycle analysis (CLCA). The first approach (ALCA) emphasizes the dissimilarities between physical engineering characteristics and intrinsic emissions among products. In other words, ALCA is a retrospective procedure that offers a snapshot of average "status quo" circumstances. The second method (CLCA) goes beyond and analyzes the impacts of economic outcomes [34,35]; in fact, CLCA is a promising approach that evaluates the potential consequences of modifications within a product system, including any resulting market-mediated effects on the supply or demand of other product systems. As such, CLCAs can effectively analyze the impact of large-scale changes in the field crop industry, considering other relevant sectors and processes, such as biofuel production or the human and animal consumption of food [36]. Life cycle assessment (LCA) is a popular method for analyzing all aspects of a product's life cycle, including raw material extraction, processing, transportation, use, and end-of-life phases. The goal is to quantify cumulative resource demands and emissions over the whole life cycle [37]. Based on ISO 14040 and ISO 14044 standards, LCA includes four phases, including life cycle inventory, range and target, life cycle efficacy evaluation, and commentary [38–40]. Defining the objective and scope as the initial stage includes the functional unit, system boundary, influencing goals and categories. The system border determines what is included in the evaluation. The system frontier for ALCA is clearly defined while for CLCA there are insufficient principles. Practical units consider the quantitative feature of a commodity, effective categories examine the effect of diverse options, while the user usually determines goals [35,41]. Life cycle inventory (LCI) assesses the total environmental burden made at each step of a commodity's life cycle [31]. Data can be collected through questionnaires, reliable databases such as articles, and Ecoinvent 3. The life cycle impact assessment (LCIA) is obtained from environmental impacts by multiplying LCI outcomes by efficacy factors. The ultimate step is exegesis, which includes feedback to redefine the scope and target [35]. LCA is critical in the agriculture sector, especially in the greenhouse cultivation industry. To reduce environmental issues, it is necessary for managers of agricultural and food industries to carefully examine the behavior of agricultural systems, inputs, and outputs that affect nature. Therefore, LCA is a reference and a necessary method to examine environmental impacts and the entire supply chain which makes it possible to compare different production systems in terms of resource use performance and environmental impacts [37]. LCA is also very useful for agri-food systems to ensure food security in the world [42–44]. Research related to LCA plays a fundamental role in making decisions and identifying efficient energy production methods [31]. A limitation of LCA analysis is that its consequences are not comparable in different studies due to geographical location, border conditions, and manufacturing strategy. Geographical and manufacturing factors significantly impact the life cycle assessment (LCA) of agri-food systems. They influence the analysis through: Transportation and Distribution: Geographical location affects transportation distance and mode, impacting emissions and energy use. Resource Availability: Available water and land resources impact the environmental footprint of agri-food systems. Climate and Weather Conditions: Climate affects crop yields and pest infestations, altering resource consumption and environmental impacts. Energy Sources: Geographical location determines the energy mix and associated greenhouse gas emissions during manufacturing processes. Infrastructure and Technology: Availability of infrastructure and technological advancements can improve efficiency and reduce resource consumption. Waste Management: Geographical location and manufacturing processes influence waste management practices, affecting environmental impact and sustainability [45,46]. The LCA method has many applications in the agricultural industry. For example, Dias et al. [47] reported that the heat from fossil fuels accounts for half to four-fifths of the total effects of ozone layer destruction. LCA was used in the environmental impact assessment to evaluate the reduction potential for a pepper greenhouse cultivation [35,48]. Fertilizers and consumables in greenhouse construction are among the important factors in evaluating this method. Also, the environmental effects of the greenhouse roof and multi-tunnel greenhouses have been studied [49]. In another study, Bosona and Gebresenbet [50] used LCA to investigate the ambient effects of dried tomatoes and fresh tomatoes. The results showed that dried tomatoes have less environmental effects by reducing damage but consume more energy than fresh tomatoes. LCA is efficient in both types of conventional greenhouse and hydroponic cultivation. Hesampour et al. [9] used the LCA method in their research to investigate the energy–economy cycle and environmental effects in a cucumber greenhouse cultivation. Based on the results of the LCA, the direct emissions caused by the consumption of inputs include nitrogen oxides (NO_x) and carbon dioxide (CO_2) in the air, as well as lead (Pb), mercury (Hg), and copper (Cu) in the soil. In addition, indirect emissions include the production of chemical pesticides, chemical fertilizers, and greenhouse constructions. Martin-Gorriz et al. used the LCA approach to study the recycling of drainage effluents using Reverse Osmosis (RO) and Photovoltaic (PV) energy in hydroponic tomato cultivation, and to analyze six indicators of environmental effects related to water production and purification systems. The inputs used in this method were fertilizers, agricultural chemicals, electricity, water, machinery, materials, and irrigation infrastructures. As expected, LCA showed explicit results with leachate collection and treatment and the results of the sensitivity analysis showed how the effects are significantly reduced by using renewable energy and reducing the fertilizers. In this research, the LCA showed remarkable environmental benefits from wastewater recycling, and the hydroponic system helped to reduce the eutrophication of leachate effluents [2]. In another study, Ghasemi-Mobtaker et al. [33] used the LCA method and studied energy indicators in hydroponic fodder production and found the most efficient production method with a lower environmental impact. The results showed that the GHGs generated by the hydroponic fodder cultivation fertilizer were released only into the air. The NH_3 pollutant in the air was calculated to be 0.7 kg ton^{-1}, which was caused by chemical fertilizers. In this cultivation method, 10 kg ton^{-1} CO_2 pollutants entered the air that were generated by human labor. Heavy metals, including lead with 31,264.02 mg and mercury with 0.58 mg, had the highest and lowest emissions. The outcomes of LCA after normalization and weighting determined that most environmental emissions belong to the series of ecosystem detriments. Also, the results of investigating the types of energy in hydroponic fodder production showed that non-renewable fossil fuels consume the most energy [33]. Currently, many software programs have been designed and released for performing LCAs; most of them are commercial ones including SimaPro, Gabi, Umberto, Quantis Suite, EarthSmart, Sustainable Minds, and Enviance System. Among these, SimaPro has been widely used in agricultural studies including greenhouse cultivation [51].

2.2. Types of Cultivation in Greenhouses

2.2.1. Conventional Cultivation

Greenhouse cultivation is a method that controls the indoor cultivation environment and optimizes it for crop growth and development [52,53]. The controlled environment of the greenhouse provides the possibility of producing crops in diverse climates and seasons [10,54] (Figure 1).

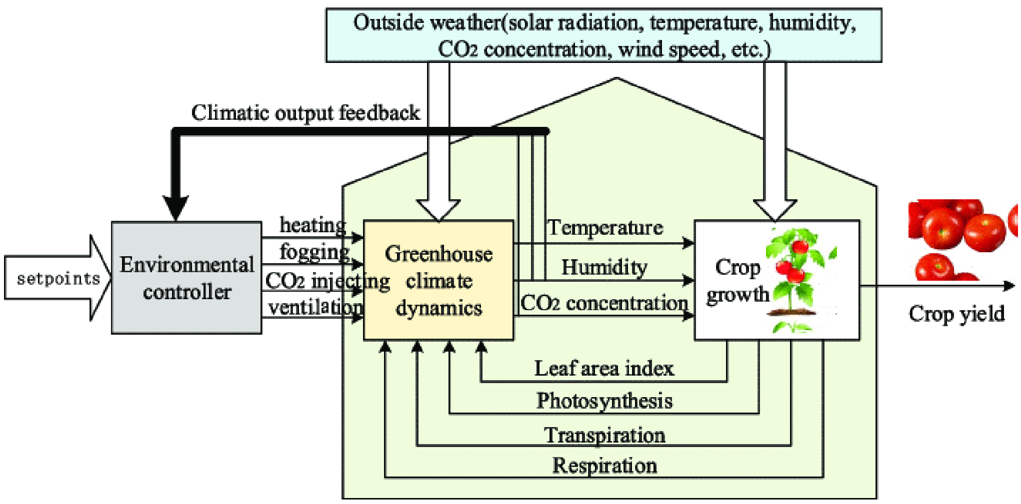


Figure 1. Conventional greenhouse system [54,55].

Controlling the cultivation environment increases the yield of the product and reduces the consumption of water and chemical pesticides [35]. In addition, this type of cultivation faces very difficult challenges, including a reduction in the soil fertility and crop productivity due to continuous cultivation [56–59]. The environmental situation required for the growth of plants includes regulating the temperature, moisture, and accessibility of light and water [10]. As a result, greenhouses are more energy-intensive than other sectors of agriculture [27,35]. Some agricultural products such as fruits, vegetables, and flowers are cultivated in greenhouses. Energy supply in the greenhouse is generally the second major expenditure of production after the labor cost, which accounts for 25% of the operational cost of large vertical fields in the United States [60]. Reducing energy demand to increase crop yield in greenhouse cultivation is recognized as a sustainable industry production goal [61]. Fuel and electricity are used to control the internal environment of the greenhouse, with the aim of performance and stabilizing quality improvement, but increasing the price of these resources has reduced the profits of farmers [52,62,63]. Excessive use of non-renewable energy sources such as diesel fuel causes negative environmental effects, including GHG emissions and energy consumption. The substitution of fossil fuels with renewable energy sources (RESs) plays an essential role in incrementing the quality of the living environment and reducing the emission of GHGs [64,65]. Therefore, increasing high-quality production to optimize energy and enhance the farmers' profits is a challenge for researchers. Hesampour et al. [9] investigated the cucumber fruit cultivation stages in a greenhouse from energy, economic, and environmental aspects of greenhouse cucumber production. Table 2 presents the energy equivalent of all the inputs in that study.

The essential information in this table is obtained through the questionnaire, databases Simapro version 7.2 (a sustainability software for analyzing sustainability performance through life cycle assessment (LCA), used globally by industry and academia) and Ecoinvent (a top LCI database with 17,000+ unique datasets covering various products, services, and processes), and previous studies. The data relating to the machinery can include the practical lifetime of the machine, the number of activity hours over the efficient lifetime and the growing season, as well as the weight of the machinery. The use of nitrogen fertilizer has harmful consequences, including global warming and the potential for acidification in the environment [66,67].

Table 2. Energy equivalent of all the inputs for greenhouse cucumber production.

Items	Energy Equivalent (MJ unit^{-1})	References
Human labor (h)	1.96	[68–70]
Diesel fuel (L)	56.31	[71]
Electricity (kwh)	11.93	[67,72]
Transportation (tone.km)	3.05	[73]
Chemical pesticides (kg)	101.2	[74]
Chemical fertilizer (kg)	-	
Nitrogen	78.1	[75]
Phosphate	17.4	[75]
Potassium	13.7	[76]
Micronutrients (kg)	120	[77]
Manure (kg)	0.3	[78]
Water (m^3)	1.02	[75]
Natural gas (m^3)	49.5	[79]
Machinery (kg)	62.7	
Nylon (kg)	17.91	[80]
Steel (kg)	27.73	[81]
Plastic general (kg)	90	
Cucumber (kg)	0.8	[82]

The usage of structural materials and phosphorus fertilizer in the potential of eutrophication is effective in reducing energy consumption in the greenhouse [9,83,84]. Extensive studies have been conducted in the field of energy consumption and the factors affecting it in conventional greenhouse cultivation. Table 3 shows some of these studies.

Table 3. Various studies conducted on energy consumption in conventional greenhouses.

Refs.	Titles	Purpose and Review	Results
[35]	Energy-efficient operation and modeling for greenhouses: A literature review	Existing strategies in energy efficiency control operations; Advanced simulations of greenhouse energy	The result showed that the cost and precision of sensors restrict the adoption of optimal controls by growers.
[85]	Manufacturing energy and greenhouse gas emissions associated with plastics consumption	Comparison of energy supply chain requirements; Greenhouse gas emissions caused by plastic production technologies; Development of bioplastic production technologies	The results indicated that commodity polymers, with a global consumption of 1 MMT per year, cause 3.2 quadrillion Btutus of energy and 104 MMT CO_{2e} of GHG emissions annually in the US alone.
[86]	Demand side management of energy consumption in a photovoltaic integrated greenhouse	Analysis of activities in greenhouse production and electrical equipment performance; Particle swarm optimization scheme; Analysis of the energy consumption program in the greenhouse	The results showed that the optimization plan is useful for directing production activities in greenhouses and building photovoltaic integrated greenhouse systems.
[87]	Modeling and experimental validation of heat transfer and energy consumption in an innovative greenhouse structure	Modeling and experimental evaluation of heat and mass transfer functions in a solar greenhouse with a thermal screen	The results revealed that implementing a thermal screen could decrease both the final cost and air pollution.
[88]	The potential contribution of food wastage reductions driven by information technology on reductions of energy consumption and greenhouse gas emissions in Japan	Analysis of the effects of food waste; Reducing energy consumption; Reducing greenhouse gas emissions	The results showed that the reduction of GHG emissions would be between 5.6 to 7.8 million tons of $CO_{2\text{-eq}}$ per year.
[89]	Methodologies of control strategies for improving energy efficiency in agricultural greenhouses	Systematic review of control strategies to improve energy efficiency in greenhouses (especially low-energy greenhouses)	The results showed that 60% of the selected articles on greenhouse climate management consider temperature and humidity as controlled parameters.
[9]	Energy-economic-environmental cycle evaluation comparing two polyethylene and polycarbonate plastic greenhouses in cucumber production (from production to packaging and distribution)	Investigation of energy flow, economic benefit, and environmental effects in cucumber greenhouse cultivation; Measurement with two methods of LCA and Cumulative Exergy Demand (CExD) considering different greenhouse structures	The LCA results showed that the main environmental impacts come from direct emissions due to input consumption (air: carbon dioxide (CO_2), and nitrogen oxides (NOx); soil: mercury (Hg), copper (Cu), and lead (Pb)) and indirect emissions induced by the production of chemical fertilizers, greenhouse structures, and chemical pesticides.
[90]	Impact of environmental factors on the energy balance of greenhouse for strawberry cultivation	Effects of solar greenhouses on strawberry cultivation in temperate regions; Energy required to heat the greenhouse; Experimental investigation of ambient temperature, solar radiation, and relative humidity	The result showed that passive solar heating may not suffice in cold regions with extended cloudy weather, requiring additional gas or electricity-based heating systems.

Table 3. *Cont.*

Refs.	Titles	Purpose and Review	Results
[91]	Thermo-environomic assessment of an integrated greenhouse with an adjustable solar photovoltaic blind system	Energy plus modeling as a greenhouse reference in rose cultivation; Validation of the developed greenhouse model with experimental site measurements; Investigating ambient temperature in the greenhouse with a photovoltaic system	The results showed that covering 19.2% of the roof can reduce natural gas consumption, electricity demand, and CO_2 emission by 3.57%, 45.5%, and 30.56 kgm^{-2} annually, without affecting plant canopy illumination levels.
[92]	Nanomaterials application in greenhouse structures, crop processing machinery, packaging materials, and agro-biomass conversion	Application of nanomaterials in agricultural products; Investigating nanotechnology in climate control and photosynthesis of plants in the greenhouse	The reviewed work indicated that nanotechnology has the potential to enhance agricultural production.
[52]	Energy-sustainable greenhouse crop cultivation using photovoltaic technologies	Examining the important aspects of greenhouse cultivation and the electricity required; Studying state-of-the-art photovoltaic systems in the greenhouse and their shading effects on plants; A vision for sustainable greenhouses with photovoltaic technologies	The results showed that solar cells can be used in greenhouses to generate electricity, but the shading from photovoltaic panels can impact plants below.

2.2.2. Hydroponic Cultivation

Hydroponic or liquid culture is one of the specialized methods for growing plants, which provides conditions for plant growth without soil (Figure 2) [56,93].

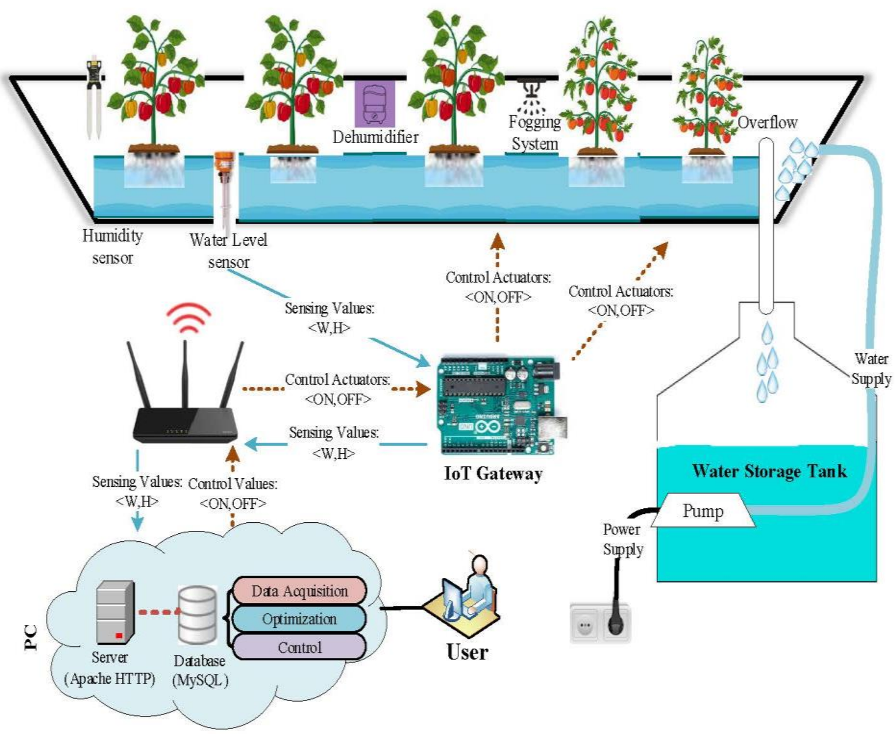


Figure 2. Hydroponic greenhouse system [93].

Hydroponics is a type of culturing method in which a nutrient solution is used instead of soil and can save the consumption of essential resources for crop growth [94]. This method will create the highest efficiency in a large space by delivering water to the thirsty roots of plants based on their needs, with the least amount of human energy and water resources [95]. The diet in hydroponic production is very optimal and based on the needs of the plant, which allows these products to have a better and healthier quality than their counterparts in soil cultivation. Because of the precise regulation of watering and feeding the plant, this method is superior to the traditional method [96–98]. Hydroponic cultivation is expanding dramatically to increase crop productivity, especially in developed countries such as China and the United States. Some agricultural products such as cucumber, lettuce, and tomato have been studied in this cultivation [99–101]. Researchers have concluded that hydroponic cultivation has various results on different crops and many types of research have been performed on energy consumption in this type of cultivation (Table 4) [56,102].

Table 4. Research conducted on energy consumption in hydroponic greenhouse cultivation.

Refs.	Titles	Purpose and Review	Results
[2]	Recycling drainage effluents using reverse osmosis powered by photovoltaic solar energy in hydroponic tomato production: Environmental footprint analysis	Measuring the environmental benefits and trade-offs of reverse osmosis integration; Recycling of greenhouse drainage effluents using photovoltaic solar system; Comparison of the environmental footprint of tomato production in two types of conventional and hydroponic cultivation; Comparison of three independent sources of irrigation	The results showed that using brackish groundwater as a substitute for desalinated seawater can reduce the global warming footprint by 27%.
[17]	Hydroponic and Aquaponic Farming: Comparative Study Based on Internet of things IoT technologies	Comparison of hydroponic and aquaponic cultivation systems; Using the automatic technology of the Internet of Things (IoT)	The results showed that implementing a depth-camera module in the system offered an advantage, and a mobile application to maintain the ecological balance of the environment.
[103]	Validation of a building energy model of a hydroponic container farm and its application in urban design	Validation of Energy Plus model in container hydroponic culture; Continuation of experiments for nine months and data collection; Studying energy consumption and its optimization	The results showed that stakeholders can reliably predict annual container farm energy use by representing plant–air interactions within EnergyPlus.
[1]	Autonomous greenhouse microclimate through hydroponic design and refurbished thermal energy by phase change material	Evaluation of the microclimate of hydroponic greenhouse cultivation without heating; Hydroponic design evaluation; Comparison of environmental conditions inside the greenhouse during the day and night	The results showed that hydroponic greenhouses offer better conditions than conventional ones, with temperatures above 18 °C and a humidity range of 20–35% during the day.
[104]	Hydroponic system and desalinated seawater as an alternative farm-productive	Comparison of energy consumption of lettuce production in two types of conventional and hydroponic greenhouse cultivation; Investigating the amount and emission of greenhouse gases; Comparison of different percentages of desalinated seawater for irrigation	The results showed that desalinated seawater with hydroponic systems can sustain agriculture but relies heavily on energy.

Table 4. *Cont.*

Refs.	Titles	Purpose and Review	Results
[21]	Comparison of soil and hydroponic cultivation systems for spinach irrigated with brackish water	Measurement of differences in the water status of spinach plants; Using brackish water to grow plants in covered soil, non-covered soil, and hydroponic cultivation system; Investigating the leaf water and osmosis potential of the product and also its regulation	The results showed that the spinach plant adjusts to salinity with adaptive strategies by increasing osmotic adjustment and leaf succulence, reducing leaf water potential. Sodium concentration in leaves and fresh weight are highest in hydroponic cultivation, especially with brackish water.
[56]	Evaluation of hydroponic systems for the cultivation of Lettuce (*Lactuca sativa* L., var. *Longifolia*) and comparison with protected soil-based cultivation	Investigating the suitability of hydroponic cultivation of lettuce in replacing greenhouse soil-based cultivation; Study of two hydroponic techniques including deep-water culture and nutrient film technique and compare them with conventional greenhouse cultivation; Using Tukey's test to investigate crop performance, water consumption and economy	The results indicated that hydroponic techniques outperformed soil-based systems with a higher yield, simplicity, ease of operation, economic feasibility, and nutritionally superior produce.
[33]	A new method for green forage production: Energy use efficiency and Environmental sustainability	Evaluating energy and water consumption in hydroponic fodder production; Study of environmental indicators	The results showed that despite the many benefits of hydroponic fodder on livestock nutrition, its greenhouse cultivation imposes many adverse environmental effects.

In this method, the plant's growing season is an effective parameter for the level of economic productivity of this type of cultivation. So, food production techniques are advancing, and hydroponic cultivation has proven that it does not have many of the problems associated with conventional greenhouse cultivation [1]. In a study about green fodder production by hydroponic method, energy consumption performance and environmental sustainability were investigated [33]. Physical input data used in greenhouses and the energy of each were obtained using a questionnaire from 18 greenhouses with green fodder production using the hydroponic method, as shown in Table 5.

Table 5. Input and output data of energy consumption in hydroponic cultivation method.

Items (unit)	Energy Equivalent (MJ unit^{-1})	References
Human labor (hr)	1.96	[70]
Stationary equipment (kg yr)	9	[80]
Natural gas (m^3)	49.5	[80]
Nitrogen fertilizer (kg)	66.14	[105]
Pesticides (kg)	199	[106]
Electricity (kWh)	11.93	[107]
Seed (kg)	14.7	[108]
Hydroponic Fodder Yield (kg)	1.66	[109]

The whole electricity consumption for greenhouse facilities, lighting, etc., was registered by phase meter. Natural gas is used to heat the indoor environment of the greenhouse and its amount can be calculated with a gas meter. To calculate fodder energy by the hydroponic culture method, in the first step, the amount of dry matter during the growth period was determined. Then, with the energy metabolism of fodder dry matter, the energy equal to hydroponic fodder was calculated [33]. The energy indices of Energy Ratio (ER), Energy Productivity (EP), and Net Energy (NE) were calculated by calculating the amount of input and output energy as follows [70,110]:

$$ER = \frac{OE}{IE} \tag{1}$$

$$EP = \frac{HFY}{IE} \tag{2}$$

$$NE = OE - IE \tag{3}$$

where ER is the energy ratio; OE and IE are output and input energies; EP is energy productivity; HFY is Hydroponic Fodder Yield and NE is Net Energy.

Various environmental factors are effective in greenhouse cultivation, both conventional and hydroponic, which are explained below. In this regard, Figure 3 shows some environmental factors that can be investigated in greenhouse cultivation.

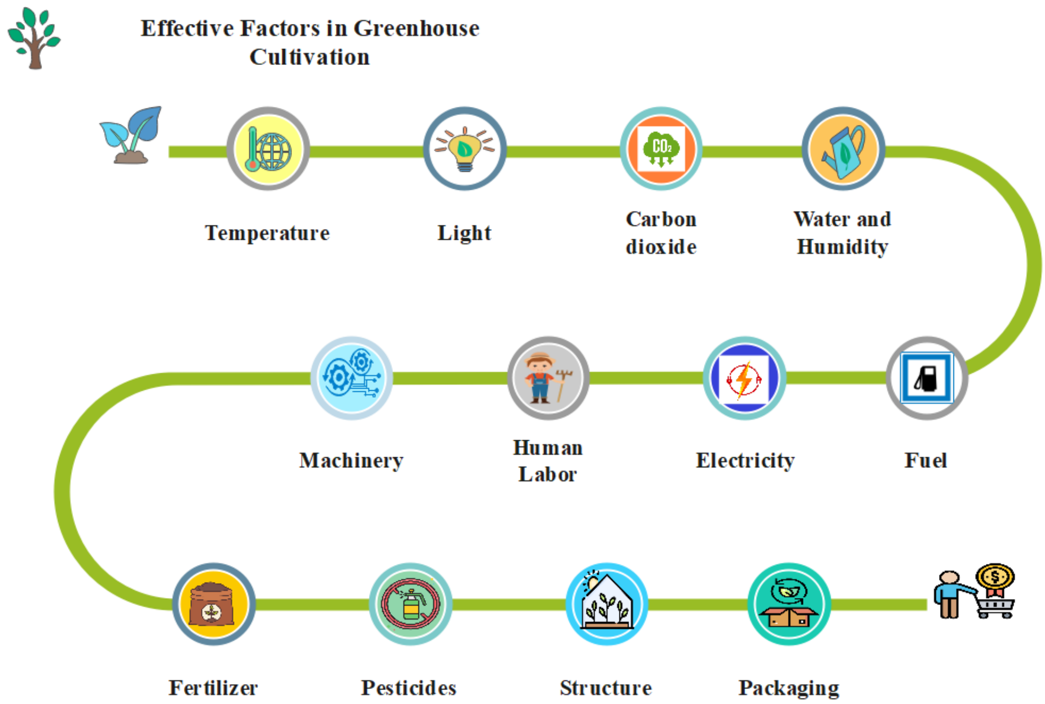


Figure 3. Some effective environmental factors in greenhouse cultivation [81].

2.3. All the Inputs in the Greenhouse

2.3.1. Structure

The structures of greenhouses are different and they can be divided in terms of shape and structure, application, and type of materials used in the building. Greenhouses with a glass roof or plastic cover are among the most widely used materials [27,111,112]. Glass greenhouses are very expensive, but they have high resistance compared to other types of greenhouses. In addition, the high ability to pass light and heat in cold seasons or cold regions increases production efficiency. Greenhouses with plastic covers are usually cheaper and more economic, but they are not durable [63,113]. There are various structures for greenhouses along with their advantages and disadvantages which are listed in Table 6 [114].

Hesampour et al. [9] studied the energy–economy–environmental cycle of two greenhouses with polyethylene and polycarbonate covers for cucumber production. A comparison of two greenhouse structures (the first type, polyethylene roof covering, and the second type, polyethylene roof covering and polycarbonate walls) showed that in the greenhouse with polycarbonate walls, energy consumption is higher.

This causes higher costs to be allocated in input data in the second species of the greenhouse. The highest input energy consumption was due to the covering of the walls and roof of the greenhouse, which was about 72.23%. The contribution of polyethylene used in the roof of the greenhouse was 39.90% and the contribution of polycarbonate applied in the walls was 32.33%. The total energy amounts consumed in the first and second greenhouses were 14,811.13 and 17,451.73 MJ (1000 $m^2)^{-1}$, respectively. In this research, the share of variable costs was 47.14% for the first type of greenhouse and 28.44% for the second type of greenhouse, while the fixed costs were 52.85% and 55.71%, respectively. The total fixed costs of the first and second kinds of greenhouses were also 104.72 and 111.49 \$ ton^{-1}, respectively. The assessment of economic and energy indices showed that the compound index of energy intensity for the first type of greenhouse is 80.26 and for the second type is 77.07 MJ \$$^{-1}$. They concluded that the first kind of greenhouse utilizes less energy and has lower expenses than the second kind. For the sustainable development of greenhouse production, it is necessary to adhere to two principles. Firstly, greenhouse equipment must be appropriate and compatible with the environment. Secondly, the condition must be controllable, and it is vital to use environmentally friendly inputs in greenhouse cultivation and reduce the consumption of chemical fertilizers. The researchers estimated the life cycles of various agricultural crops, including tomatoes, peppers, and watermelons [33]. The results indicate that the utmost of the pollutants depend on the greenhouse structures. Also, greenhouses that do not need a heating system have less environmental impacts [115]. Liebman et al. [103] conducted research on the validation of the building energy model in a hydroponic container system. Using the Energy Plus model, they were able to validate it in the hydroponic container farm in Massachusetts, USA, within nine months by collecting data. This validation was performed in a portable container for vertical hydroponic cultivation with artificial light. One of the significant advantages of this kind of cultivation container is its portability and its use in unused environments regardless of harsh weather conditions. The results of the calibrated energy model reached an average normalized bias error of 3%. Also, the root-mean-square error (RMSE) was 11%. The results showed that according to the plant–air exchange with the Energy Plus model and the performance modeling of the cooling coefficient and considering the outside air temperature, the annual energy consumption in these systems can be predicted.

Table 6. Characteristics of different types of greenhouse structures along with their advantages and disadvantages.

References	Structural Shapes	Picture	Properties	Advantages	Disadvantages
[116]	Lean-to greenhouse		Suitable for the side of a building; One or two rows at 12 ft	Close to the water and electricity facilities of the building; Lower cost of materials; Needs a small space; Fewer support requirements for the roof	Limited space for plant growth; Lack of exposure to sufficient light; Difficulty controlling the temperature due to the sides of the wall
[117]	Ridge and furrow greenhouse		It has a structure similar to the A-frame structure that drains extra snow and rain; It is cheap to make and can be made with only basic materials; Very little use of wooden and plastic covers	Sufficient space for plant growth; Energy saving and automation; Increasing the life of the structure by discharging excess snow and rain	Needs a large piece of land to set up; High setup cost

Table 6. *Cont.*

References	Structural Shapes	Picture	Properties	Advantages	Disadvantages
[118]	Even span greenhouse		This design is suitable for a backyard; It can increase the size; Sufficient sunlight penetration due to the high transparent coating surface	Flexible design in the size of the structure; Suitable for carrying many plants; An ideal structure that maintains temperature uniformity; Additional snow and rain drainage due to the A-shaped roof	Expensive setup cost; Needs a dedicated heating system
[119]	Gothic arch greenhouse		Flexible in the size of the greenhouse structure; The pointed roof of the greenhouse eliminates the use of trusses in its structure	No need for trusses; Easy drainage of snow and rain; Can be made in different sizes	Compared to other types of greenhouses, it requires more materials for construction; Air circulation to the corners is difficult
[100]	Uneven span greenhouse		One of the roofs of the structure is longer than the other; Suitable for hilly areas that receive more light from the sun	Penetration of more sunlight into the greenhouse; It prevents the wind; Strong and durable structure	Not suitable for flat areas

2.3.2. Temperature and Fuel

The transparency of the greenhouse roof and the covering materials inside its walls make the sunlight penetrate completely into the greenhouse and block the heat leakage to the outside [120]. For this reason, the temperature inside the greenhouse will be higher than the temperature outside (Figure 4) [63,112]. During the day, thermal energy is stored in the walls and soil, then over the night, it is released in the greenhouse [121–123]. Temperature is a key and effective factor in the growth of plants, and it is required to create a uniform environment inside the greenhouse [90,124,125]. In the winter, the sudden decrease in temperature and sunlight time can cause damage to the products, which expands the use of new technologies in heating systems [90].

New technologies independent of fossil energy for heating greenhouses are progressing. For example, storing thermal energy in the summer season and then releasing it in the winter is one of these methods [123]. The heating systems inside the greenhouses increase the initial production investment [126], so with their setup and installation, depending on the size and location of the greenhouse, the initial costs rise and constitute about 30 to 60% of the total capital costs [127].

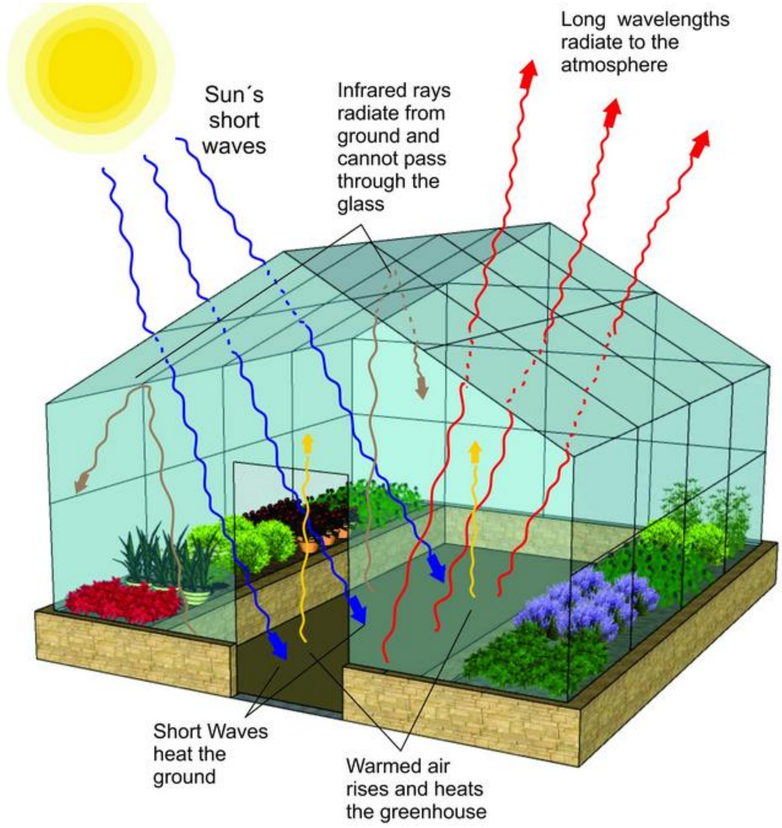


Figure 4. The cycle of solar radiation to the greenhouse [93].

In addition, almost 70–80% of the total energy utilization in the greenhouse is due to the heating system [90,101]. In this regard, reducing thermal losses can decrease the operating cost of thermal systems. During cold seasons, heating systems consuming fossil fuels or grid electricity supplies the required temperature inside the greenhouse [126] and allows the setting up of greenhouses in cold-climate locations and the production of quality crops [52,122,128]. It is clear that in cold areas with low radiation potential, the amount of energy used to regulate the temperature in the greenhouse will increase. Therefore, areas with moderate climates can be better options for building greenhouses. This energy is provided by electric heat pumps or steam boilers and by burning fuel [129–131]. Additionally, the amount of energy consumption increases with rising latitude due to the plant's need for heating and light [132–134]. By investing more and providing new equipment for heating, the amount of energy consumption can be reduced, requiring a dynamic and low-risk economy. On the other hand, during summer, along with high radiation, the temperature inside the greenhouse significantly increases, causing a wide range of morphoanatomical, physiological, and biochemical changes in the plant. These changes decrease the growth of plants and greatly reduce the economic yield [52,135]. Among the cooling methods, reducing the penetration of sunlight into the greenhouse by whitening the roof, plastic nets, and thermal plates is less expensive, and easier compared to other methods [136–138]. The passive cooling, that includes natural ventilation, shading and reflection, and forced ventilation, fans, and foggers are other methods of cooling in greenhouses (Figure 5) [132,139,140]. The fuel consumption in greenhouses is spent on the heating system to provide an appropriate temperature inside the greenhouse. However, according to the preservation of the environment and reduction of fossil fuel consumption, it is recommended to use renewable fuels for heating inside the greenhouses [120]. Usually, the ideal temperature for plant growth is 25 °C, which decreases in the cold seasons of the year; the heating system starts working automatically, then turns off after optimizing the temperature [9,141]. The amount of fuel consumption is calculated as follows [9,141]:

$$F_c = F_{hr} \times T \quad (4)$$

where F_c is the fuel consumption of agricultural activities ($Lton^{-1}$); F_{hr} is the required fuel ($L\,h^1$) and T is the working time of machinery ($h\,ton^{-1}$).

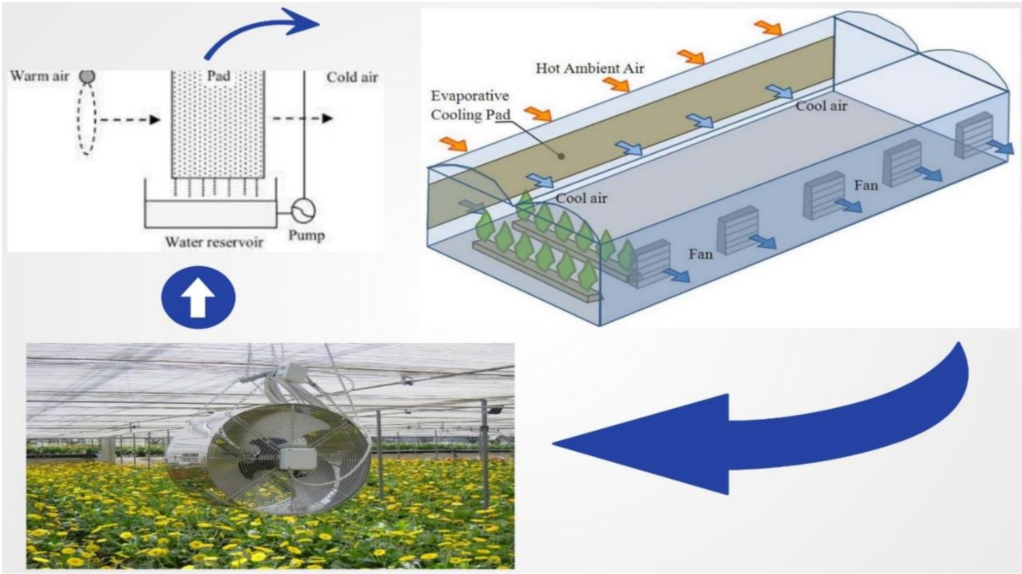


Figure 5. The new cooling technology system (Pad-fan evaporative cooling in greenhouses) [142].

Based on the study by Gorriz et al. [2] on the environmental effects of the use of drainage effluent recycling that occurs by RO and PV energy in the hydroponic cultivation system, it was found that leachate treatment technology in the hydroponic cultivation system compared to the sanded soil cultivation system shows a significant reduction in eutrophication (72%), but a significant increase in fossil fuel consumption by 43% due to the use of additional infrastructure and equipment. In addition, 37% in global temperature and 32% acidification were obtained. Among the inputs used in the cultivation systems, including the structure of the greenhouse, the production of fertilizers, and the use of electricity for fertilization, it has the highest environmental burden. In this study, three irrigation water types, including desalinated seawater with low electrical conductivity (EC), two mixtures of underground water, and desalinated water with medium and high EC, were used. Comparing irrigation with three types of water, results showed that global warming is significantly reduced (27%) by partially replacing desalinated seawater with saline groundwater. Moreover, the sensitivity analysis demonstrated a considerable reduction in environmental impacts. In the study by Baddadi et al. [1], significant results were achieved in the design and construction of a microclimate in a greenhouse with a hydroponic system and regenerated thermal energy. The performance of this hydroponic greenhouse was evaluated without conventional heating methods and results indicated that the hydroponic greenhouse provides better environmental conditions than conventional greenhouses. During the day, temperatures inside the greenhouse reached above 18 °C, and the temperature difference between outside and inside the greenhouse was 6 °C. Also, the relative humidity was in the range of 20–35% during the day and 70–85% during the night. According to the new heating system in it, other parameters were also measured. The night temperature after heating reached over 15 °C and the daytime temperature reached mostly over 32 °C in comparison with the conventional heating method; a better performance was achieved in raising the internal temperature of the greenhouse, especially under harsh and nighttime weather conditions. In general, this research revealed that in the comparison between conventional and hydroponic greenhouse cultivation methods, the second method guarantees better quality, more nutrient content, higher yield, and efficient use of water and fertilizer. Khammayom et al. [90] conducted a study on the effect of environmental factors on energy balance in strawberry planting in the greenhouse, and in this research, different factors including relative humidity, sunlight, and ambient temperature were experimentally investigated. The results of this study showed that the highest difference in temperature between the inside and outside air of the greenhouse during the evaluation period is 16.4 °C and the maximum decline of sunlight via a lucid vinyl sheet is about 30% compared to the surroundings solar radiation. The monthly heat demand of the greenhouse was calculated in the range of 60.0 and 327.6 MJ/(m^2.month), and during the coldest month of the year, January, the highest amount of energy was consumed to heat the greenhouse.

2.3.3. Light

One of the important sources of energy for plant growth is sunlight. Plants convert sunlight into biochemical energy through photosynthesis [65,143] (Figure 6), which is biologically transmitted in the food chain. Chlorophyll molecules in photosystems absorb the photon energy of sunlight. The photosystem converts the photonic energy into chemical types for storage in the plant [144]. Solar radiation usually extends to longer wavelengths, which provides the energy needed for plant growth [65], but excessive heat will increase the internal temperature of the greenhouse, which hurts the conditions for optimizing plant growth; furthermore, plants' photosynthesis usually occurs in wavelengths between 400 and 700 nanometers [52,145–147].

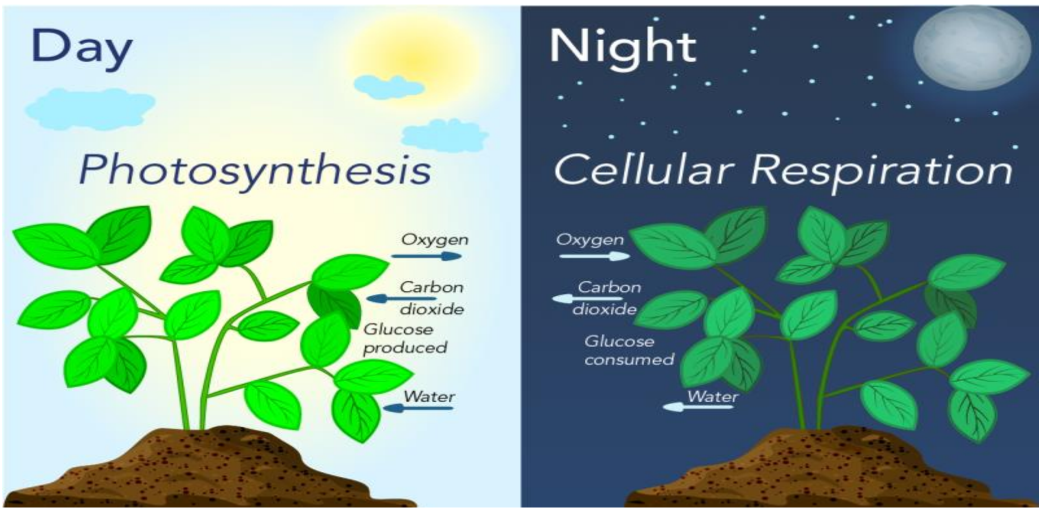


Figure 6. Photosynthetic cycle of plants during the day and night [143].

Covering materials on the roof of the greenhouse cause reflection or emission of a part of the sunlight waves to the outside environment. Therefore, the radiation in the greenhouse environment is usually less than outside. But for crops such as tomatoes that need a large amount of sunlight, the roof of the greenhouse is designed in such a way that it transmits the lightest to the plant [113]. In general, factors such as plants' needs and geographic region are very effective in the shape of the greenhouse and the amount of lighting in the greenhouse's interior environment. Weather conditions and seasonal changes can affect the amount of sunlight entering the greenhouse, and therefore, the use of artificial light is very crucial to control the amount of light required by plants for photosynthesis. Controlling the internal parameters of the greenhouse is significantly effective in energy consumption. Lighting control has become a critical issue for high energy efficiency and plant productivity in greenhouse cultivation, particularly with the enhanced use of supplementary lighting [148,149]. Plant growth in controlled greenhouse conditions is influenced by three parameters of light, including light spectrum, light intensity, and duration of light exposure [150,151]. Experiments were conducted on these three characteristics affecting plant growth, as in the study of Leontavich and Bobro [146,152]. In this study, the intensity of different 49 μmol $m^{-2}s^{-1}$ and 98 μmol $m^{-2}s^{-1}$ lights in 12 h of illumination was investigated in the hydroponic production of barley fodder. The results showed that the maximum efficiency is achieved in the light intensity of 49 μmol m^{-2} s^{-1} in the amount of 14 kg m^{-2}. Lower light intensity can reduce the level of chlorophyll and prevent the growth of leaves. On the other hand, too much light intensity causes heat stress in the plant and overall yield loss [153,154]. In another study, El-Deeba et al. [146,155] investigated the effect of different time durations of light including 8, 12, 16 and 24 h day^{-1} in constant light intensity of 38 μmol m^{-2} s^{-1} on barley fodder production. The consequences showed that in the period of 12–16 h day^{-1}, the highest yield (15 kg) was obtained, and in the period of 24 h day^{-1}, the yield decreased by 1.04 kg. Therefore, optimal light focusing on the quality, quantity, and frequency of plant exposure to light is mandatory for efficient growth and development [156]. Various light sources are used as supplementary light in the controlled greenhouse system. One of the light control methods in the greenhouse is measuring the photosynthetic photon flux density (PPFD) from solar light, which is called the dynamic control of light-complementary growth. In recent studies, the parallel particle swarm optimization algorithm has been used to solve the problem of light intensity optimization in greenhouses [35,157]. The purpose of this is to discover the most suitable locale and number of LED lamps based on the plant's need for light and to reduce energy consumption. The use of LED systems consumes 82.6% and 54.2% less energy compared to fluorescent and incandescent lamps, respectively [157]. In another study, a complementary dynamic control of LED lamps was proposed based on the PPFD setting point and PPFD measurement from received solar radiation [150]. Two continuous low-light and off tactics were considered for energy expending, and optimized crop growth with the first strategy led to 20% energy saving. A demand response strategy and real-time pricing used for lighting control of greenhouses in Denmark resulted in 18–25% thrifts in electricity expenses [35,158].

2.3.4. Carbon Dioxide

Carbon dioxide (CO_2) concentration plays an important and critical role in plant photosynthesis. Usually, this concentration fluctuates in the greenhouse environment during the day and night based on photosynthesis and plant respiration. In fact, during the day, the concentration of CO_2 in the greenhouse environment is at a high level due to plant respiration and the release of CO_2 at night [52,159]. The low concentration of CO_2 limits the amount of photosynthesis of the plant, even if there is enough light at the disposal of the plant. In addition, air conditioning in the greenhouse environment plays a vital role in the concentration of CO_2, temperature, and humidity [160]. The expansion of closed and semi-closed greenhouses (Figure 7) is increasing due to the increment in the concentration of CO_2, the reduction in the use of pesticides, and the energy and water savings [133,161,162]. Air conditioning is one of the main components of closed greenhouses (a kind of greenhouse with no ventilation, which means that excess sensible and latent heat must be removed) to regulate the temperature of the indoor environment [132,163]. CO_2 concentration is one of the important factors for plant growth and photosynthesis [164]. Thus, CO_2 enrichment can be used in the indoor environment of the greenhouse to increase product yield. According to the study by Lin et al. [164], the CO_2 concentration is calculated as:

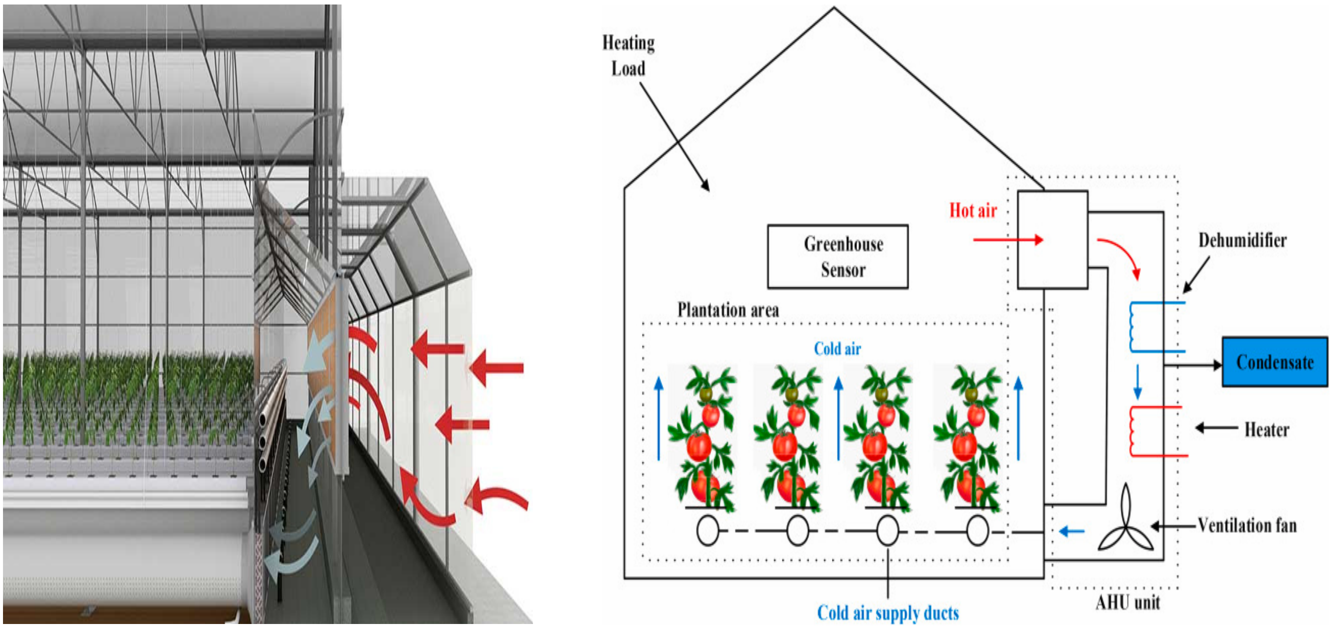
$$\frac{dC_{air}}{dt} = \frac{1}{h}\left(C_{inj} - C_{ass} - C_{vent}\right) \tag{5}$$

where C_{air} is CO_2 concentration inside the greenhouse; C_{inj} is CO_2 injection; C_{ass} is CO_2 assimilation; and C_{ass} is the changes in CO_2 concentration due to ventilation. C_{ass} and C_{vent} can be calculated from the following relations:

$$C_{ass} = 2.2 \times 10^{-3} \frac{1}{1 + \frac{0.42}{C_{air}}} \left(1 - e^{-0.003(Q_{sun} + P_E)}\right) \tag{6}$$

$$C_{vent} = g_v(C_{air} - C_{out}) \tag{7}$$

where Q_{sum} is incoming radiation from the sun; g_v is the ventilation rate; P_E is the power of lighting; and C_{out} is the CO_2 concentration outside the greenhouse.



(**A**) (**B**)

Figure 7. Two types of greenhouse structure: (**A**) closed greenhouse; (**B**) semi-closed greenhouse.

The concentration of CO_2 accessible to the plant should be based on the plant's requirements, because amounts of CO_2 concentration that are too high or too low reduce the plant's yield and make photosynthesis difficult [165]. The method of CO_2 enrichment is found to increase the productivity of plants gown in greenhouses [166]. By increasing the amount of CO_2 from 340 to 1000 ppm (parts per million), most plants perform pure photosynthesis. The concentration of CO_2 in the outside air is usually 400 ppm, which is higher than the level of CO_2 inside the greenhouse; then, CO_2 enrichment is essential [167]. In the study of Hans Peter Kläring [35,165], it was shown that providing CO_2 for plant photosynthesis in the greenhouse increased the yield by 35% compared to greenhouses where this was not conducted. Also, the optimal time to inject CO_2 is when the intensity of sunlight and the temperature inside the greenhouse are low, such as early morning. Another issue that is principal about CO_2 is the emission rate of this gas by the inputs and outputs of greenhouse cultivation. In the study of Hesampour [9], the emission coefficient of CO_2 gases from human power in conventional greenhouse cultivation was found to be 0.7 to the air.

These distribution coefficients in inputs such as diesel fuel, natural gas, human labor, and electricity are as follows (Table 7).

Table 7. The values of the distribution coefficients of the input data.

Inputs	Diesel Fuel (kg MJ^{-1})	Natural Gas (kg $(m^3)^{-1}$)	Human Labor (kg. man-h^{-1})	Electricity (kg. kwh^{-1})
CO_2 emissions to air	74.5	0.0133	0.07	0.58

In this research, two methods were proposed to adjust the temperature inside the greenhouse. The first method uses diesel fuel and the second one uses natural gas. The amount of CO_2 emission in these two methods, causing an increase in global heat, is as follows (Table 8).

Table 8. The amount of CO_2e missions and the effect of global warming.

Environmental Impact	Unit	Method 1		Method 2	
		Characterization	Normalization	Characterization	Normalization
Global warming	Kg CO_2 eq	888.55	3.44×10^{-9}	1983.43	7.7×10^{-9}

Based on the study by Nabavi-Pelesaraei [168] on rice cultivation, the universal warming indicator was calculated as 8413.24 kg CO_2, in which the two factors of farm activities and natural gas for drying played a significant role. This index, which is imputed to the vast use of natural gas, is two to four times higher than other research studies. In another study conducted by Khanali [169] for the production of edible oil, chemical and animal fertilizers had the greatest effect on the global warming indicator, which was 2991.822 kg CO_2. These indicators show that greenhouse cultivation has less effect on global warming than rice field cultivation and edible oil production. The global warming index is one of the most important metrics (the measure of greenhouse gases produced in the atmosphere that causes environmental problems) in the CML-IA baseline V3.01/the Netherlands, which calculated the amount of this emission (CO_2) in the first method to be 888.55 and in the second method, 1983.43 kg CO_2 ton^{-1}. The amount of CO_2 produced from natural gas is estimated at 1.8862 kgm^{-3}, according to the United States Environmental Protection Agency [91]. Iran's Ministry of Energy also calculated the amount of CO_2 emissions as 660.65 $grkWh^{-1}$ of electricity production [170]. In another study by Alinjad [91] conducted on the environmental thermal evaluation of a one-fabric greenhouse system with adjustable PV technology, the results showed that by covering 19.2% of the roof and without significant change in the canopy over the plants, the annual consumption of natural gas, electricity used and the amount of CO_2 emission decreased by 3.57%, 45.5%, and 3.56 kg/m^3, respectively. Based on the study of M. A. Martinez-Mate [104] on hydroponic system irrigation with desalinated seawater in low-water areas, it was found that the emission of GHGs in the hydroponic system (0.11 $kgCO_{2eq}kg^{-1}$) is lower than the soil cultivation system (0.23 $kgCO_{2eq}kg^{-1}$). In this study, the calculation of regional GHG emissions and specific GHGs based on each product weight unit is as follows:

$$\text{Arial GHG emissions } \left(\text{kgCO}_{2eq}\ \text{ha}^{-1}\right) = \frac{\text{Total GHG emissions } \left(\text{kgCO}_{2eq}\right)}{\text{Farmland (ha)}} \tag{8}$$

$$\text{Specific GHG emissions } \left(\text{kgCO}_{2eq}\ \text{ha}^{-1}\right) = \frac{\text{Total GHG emissions } \left(\text{kgCO}_{2eq}\right)}{\text{Yield } \left(\text{kg ha}^{-1}\right)} \tag{9}$$

Table 9 shows the CO_2 emission coefficients in hydroponic greenhouse cultivation inputs [104].

Table 9. Carbon dioxide emission coefficients in hydroponic system cultivation inputs.

Inputs	CO_2 Gas Emissions	Unit	Sources
Diesel	0.07	kg CO_2eq MJ^{-1}	[171]
Electricity	0.210	kg CO_2eq kWh^{-1}	
Machinery and irrigation systems			-
PVC sheet	5.7	kg CO_2eq m^2	[172]
Steel	1.76	kg CO_2eq m^2	[173]
PE	2.2	kg CO_2eq m^2	[172]
PVC	3.0	kg CO_2eq m^2	[172]
Copper	6	kg CO_2eq m^2	[172]
Fertilizers			[174]
N	1.3	kg CO_2eq kg^{-1} N	-
P_2O_2	0.2	kg CO_2eq $kg^{-1}P_2O_5$	-
K_2O	0.15	kg CO_2eq $kg^{-1}K_2O$	-
Pesticides			[174]
Fungicides	3.9	kg CO_2eq kg^{-1}	-
Insecticides	5.1	kg CO_2eq kg^{-1}	-
Herbicides	6.3	kg CO_2eq kg^{-1}	-

2.3.5. Water and Humidity

In recent years, with the changes in climatic conditions as well as the indiscriminate use of water resources, the irrigation of crops has faced many problems. Climate change in the form of temperature increase, frequent periods of drought, unpredictable weather patterns, and poor management of water resources has created a serious threat [56,175–177]. Therefore, innovations in irrigation technology especially in agriculture are rapidly expanding. One of these methods is the use of closed greenhouses. The roof of the greenhouse is a protection that prevents raindrops from reaching the leaves of plants, flowers, and fruits and is a factor in disease prevention. In addition, the structure of the greenhouse prevents runoff of soils and crops during heavy rains. So, irrigation inside the greenhouse is crucial. The hydroponic cultivation method is highly regarded and can optimize water consumption (Figure 8) [178]. In this method, irrigation and water circulation in the greenhouse are conducted with an electric pump. Also, the nutrients in the water are provided to the roots of the plants. This process helps the optimal growth of plants by controlling water and nutrients [99,179,180].

Figure 8. Irrigation systems in hydroponic cultivation [178].

Humidity inside the greenhouse can affect the respiration and infectious diseases of plants. If the surrounding air is dry, the stomata in the plant are closed and reduce the rate of respiration; as a result, the exchange of CO_2 between the leaves and the air is limited and the photosynthesis rate of the plant decreases. Therefore, controlling the humidity inside the greenhouse is necessary [52,181]. Lucas Leal in [21] compared the conventional greenhouses with hydroponic cultivation systems with spinach irrigation with saline water; it was found that the use of saline water in agriculture requires the use of compatible cultivation systems. In this study, cultivation in covered soil, without cover, and with a hydroponic system using brackish water (EC is equal to 0.8, 1.5, 3.0, 4.5, 6.0, and 7.5 dsm^{-1}) was used. A total of 38 days after planting the product, leaf water potential, osmotic potential of the product and systems were determined, as well as other factors such as osmotic regulation, water consumption, water consumption efficiency, leaf freshness, and leaf sodium content and yield. Water salinity in the hydroponic system increased the fresh weight of plant leaves. Plastic cover reduced the effects of water salinity by 16% compared to uncovered soil. The hydroponic cultivation system was least affected by water salinity, and the highest water consumption was related to uncovered soil, which reached over 58%. The results indicated that the hydroponic cultivation system is the most suitable system for cultivation, especially for irrigation with saline water. In another research study by Maliqa Majid [56], the hydroponic system for lettuce cultivation was evaluated and it was compared with conventional soil-based cultivation. In this study, two hydroponic techniques, i.e., cultivation in deep water and the nutrient film technique (NFT), were evaluated and compared with the soil-based cultivation method under controlled conditions. Product yield, water consumption, and economy criteria were selected to evaluate the efficiency of planting methods, which were significant at the 0.05 level in Tukey's test. The deep-water culture system was chosen as the most favorable method in terms of plant growth because it reduced the duration of growth to 15 days. In the deep-water culture (DWC) system, the crop yield increased due to high photosynthesis. Also, the two hydroponic techniques enhanced the yield of the crop in a short period in terms of nutrition compared to the soil cultivation method ($p < 0.05$). The NFT had the most water savings of 64% compared to another two methods. According to the indicators of economic analysis, the two hydroponic techniques performed better than soil-based systems, and the profit–cost ratio was greater than 2. Among the three tested techniques, the DWC technique had the best yield in controlled crop planting conditions due to its simplicity, easy operation, higher yield, economic feasibility, and better nutritious crops. Similar research by Guilherme L. Barbosa (Barbosa et al. 2015) compared conventional soil-based cultivation with hydroponic NFT in lettuce production (kg m^{-2}) and water usage. Conventional production yielded 3.9 kg $m^{-2}y^{-1}$ of produce, with a water usage of 250 $Lkg^{-1}y^{-1}$, while NFT production was 41 kg $m^{-2}y^{-1}$ with a water usage of 20 L $kg^{-1}y^{-1}$. In another study, Mate [104] investigated energy consumption and GHG reduction in the hydroponic cultivation system using desalinated seawater for lettuce crops in southern Spain. In this study, two conventional greenhouse and hydroponic methods were compared and three different percentages (0%, 50%, and 100%) of desalinated water were considered. The use of a hydroponic system increased the yield, water consumption efficiency, and emission of specific GHGs according to soil cultivation. However, specific energy consumption raised by 17% compared to soil cultivation (3.61 MJ kg^{-1} versus 4.23 MJ kg^{-1}) production. Also, the emission of GHGs in the hydroponic system (0.11 kg CO_2eq kg^{-1}) was significantly reduced compared to the conventional cultivation system (0.23 kg CO_2eq kg^{-1}). The advancement of replacing conventional water sources with desalinated seawater linearly increased the amount of energy consumption and GHG emissions in both cultivations. It was concluded that using renewable energy (biofuels, solar energies, etc.) can reduce GHG emissions by 9% in hydroponic systems and 2% in soil cultivation systems, although the hydroponic system was less sensitive to this replacement. Finally, the results showed that considering the limited water resources, desalinated seawater along with the hydroponic cultivation system can be a valuable method for sustainable agriculture with high production, although it is highly dependent on energy.

2.3.6. Electricity

The electricity in the greenhouse is used to extract water from the well to irrigate crops. The irrigation system in greenhouse cultivation is a drip that spreads water throughout the greenhouse system by using electric pumps. Additionally, electricity is also used to drive air conditioning systems to regulate the temperature and humidity of the greenhouse environment [74]. By controlling the environmental conditions of the greenhouse with the use of electricity, it is possible to boost the yield and quality of the crops (Figure 9). Hence, reducing electricity consumption to achieve optimal environmental conditions is an important issue in greenhouse cultivation [91,182–184].

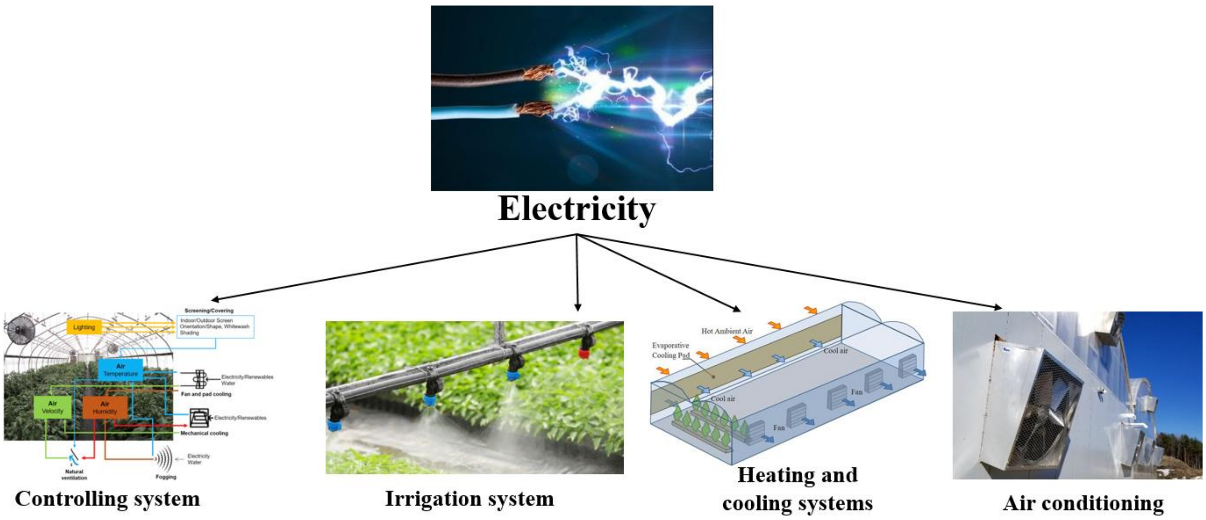


Figure 9. Applications of electricity in a greenhouse system [9].

The quantity of air per minute needed is multiplied by the whole area structure of the greenhouse to determine the number of required fans inside the greenhouse environment, and its result is compared with the amount of airflow of the fans. Equation (10) can be used to calculate the amount of electricity consumed by water extraction device from the well in the greenhouse [9,185]:

$$\mathrm{E}_e = \frac{g \times \rho \times H \times \phi}{\varepsilon_1 \varepsilon_2} \tag{10}$$

where $\mathrm{E_e}$ is the useful life of equipment (hr); g is the gravitational acceleration ($\mathrm{m(s^2)^{-1}}$); ρ is the density of water ($\mathrm{kg\ m^{-3}}$); H is the dynamic well head (m); ϕ is the flow rate of water ($\mathrm{m^3 ton^{-1}}$); ε_1 is pumping yield (ranging from 0.7 to 0.9); and ε_2 is efficiencies (0.25–0.30 for a diesel engine and 0.18–0.22 for an electromagnet pump).

In the study conducted by Hesampour et al. [9] on the cucumber greenhouse cultivation, electricity was the second most energy-consuming input data with the consumption of 558.32 MJ $\mathrm{ton^{-1}}$, which constituted 8.43% of the whole input data. This electricity was used to exploit and dispense water from the well in the irrigation strip and to ventilate the environment inside the greenhouse. One of the proofs of the increase in fuel and electricity consumption in greenhouses is the failure to replace the greenhouse cover during their effective life. By using advanced irrigation systems, the installation of awnings, the design and proper location of windows, and the amount of electricity consumption can be saved. In another study conducted by Ghasemi-Mobtaker et al. [33] on the hydroponic cultivation of fodder, the amount of consumed electricity was obtained as 33.5% of the total input energy which was used to supply energy to the fixed equipment of the greenhouse. Electricity was used to illuminate artificial lights in greenhouses for the photosynthesis of plants. In hydroponic culture, lighting systems are usually inefficient and have high electricity consumption, as a result of using light-emitting diodes in hydroponic culture. They can significantly reduce electricity consumption. Also, using a transparent cover for the greenhouse such as glass can provide the light needed for plants' photosynthesis and is very useful in reducing electricity consumption [186].

2.3.7. Human Labor

Human labor energy includes the amount of work completed by the manpower, from planting to harvesting, as well as packaging crops. Unsustainable and traditional production raises the activity of human resources, causing serious musculoskeletal tribulations for them [9,187,188]. The equipment used in greenhouses is very effective in the amount of manpower used for planting and harvesting. The use of more control equipment in the indoor environment of greenhouses reduces the need for human resources. In the study by Hesampour et al. [9], energy-economic indicators and environmental impacts in conventional greenhouse cultivation for cucumber production were investigated. In this study, human labor was calculated as 49.39%. Human labor in product packaging was a major part of energy input. This energy input was used for packing, sorting, and transporting the products to the market. Making these activities mechanized, especially product sorting, can significantly reduce input energy and increase product precision and quality. The most expensive input is related to the labor contribution of 15.94% (7.87 \$ ton^{-1}) to variable expenditures for diesel fuel-based systems. In the study by Ghasemi-Mobtaker et al. [33], the efficiency of energy consumption and environmental sustainability in the hydroponic production of fodder was investigated. It was found that human labor causes the release of 10 $kg.ton^{-1}$ pollutants into the air. And in barley production, CO_2 emissions by human labor to air was about 11 kg ton^{-1} which, when using a sprinkler irrigation system, this emission is reduced by about 50%. Labor cost is generally the first overhead expenditure in the greenhouse production of and after that, the second overhead expenditure is energy [35,60].

2.3.8. Machinery

Various machines and equipment are used in greenhouse cultivation that require information such as the beneficial life of the device, the number of activities accomplished by the device, and the device weight to calculate the energy consumption [74]. The energy and share of each machine or equipment can be calculated from Equation (11) [9]:

$$M_E = E_m \times \frac{W}{E_e} \times Q_h \tag{11}$$

where M_E is machinery energy (MJ ton^{-1}); E_m is the coefficient of machine's energy (MJ kg^{-1}); W is the weight of the machine (kg); E_e is the useful life of equipment (h); and Q_h is hours of machine working via an agricultural season.

2.3.9. Fertilizer and Pesticides

In closed greenhouses, the use of fertilizer and water can be saved with optimal plant growth [139,189]. There are different types of fertilizers, among which granular fertilizers are less used because water-soluble fertilizers are more desirable in greenhouse cultivation. Based on the research [9,48], nitrogen fertilizers played a significant role in global warming and the acidification of potential indices. Additionally, phosphorus fertilizers in the eutrophication potential, as well as the materials used in the structure of the greenhouse, are effective in reducing the energy consumption. Three different elements in the composition of fertilizers including Potassium oxide (K_2O), Nitrogen (N), and Phosphorus pentoxide (P_2O_5) are essential in plant growth stages. Equation (12) is used to calculate the energy of fertilizer based on these three elements, and it is equal to the energy of the micronutrient [9].

$$E_f = W_f \times E_k \tag{12}$$

where E_f is the fertilizer energy (MJ ton^{-1}); W_f is weight of fertilizer (kg ton^{-1}) and E_k is existing energy in fertilizer (MJ kg^{-1}).

One of the features of the greenhouse cultivation system is its closed structure and covering materials that prevent insects from invading crops. Thus, it reduces the consumption of pesticides and saves energy [52,112]. To calculate the energy consumption through chemical poisons, it is essential to define the amount of the effective substance in kg/lit of poison [141]. Ibtissame Ezzahoui [17] evaluated hydroponic culture and compared this cultivation with aquaponic culture. Aquaponic culture, which is a combination of hydroponic cultivation and aquaculture, reduces the infectious diseases of insects and pests, and by removing most of the pesticides, they reduce the level of toxicity. This study showed that aquaponic culture, which includes hydroponic cultivation, as a global method in the future, has more advantages, including organic plant cultivation and optimal fish breeding, and also provides the possibility of plant cultivation in any harsh environmental conditions, which saves money and energy consumption.

2.3.10. Energy Indicators

Energy indicators show energy yield in the production procedure [68]. Energy ratio, energy efficiency, net energy efficiency, and specific energy are energy indicators as [9]:

$$\text{Energy Ratio} = \frac{\text{output energy}\left(\text{MJha}^{-1}\right)}{\text{input energy}\left(\text{MJha}^{-1}\right)} \tag{13}$$

$$\text{Specific Energy} = \frac{\text{input energy}\left(\text{MJha}^{-1}\right)}{\text{Yield}\left(\text{kgha}^{-1}\right)} \tag{14}$$

$$\text{Energy Productivity} = \frac{\text{Yield}\left(\text{kgha}^{-1}\right)}{\text{input energy}\left(\text{MJha}^{-1}\right)} \tag{15}$$

$$\text{Net Energy Gain} = \text{output energy}\left(\text{MJha}^{-1}\right) - \text{input energy}\left(\text{MJha}^{-1}\right) \tag{16}$$

Production costs in each greenhouse are divided into two fixed and variable costs. Fixed costs include structure and equipment, and variable costs contain manpower expenditure, fuel, pesticides, fertilizers, and electricity [9]. One of the methods to diminish energy utilization is to use PV panels, which provide electricity by the sun and play a vital role in the production of clean and sustainable energy [7,91]. Various software is used for their modeling and analysis of energy systems, including TRANSYS version 2018, PV*SOL version 2023, and PVSyst version 7.4, while the two software of TRANSYS and Energy Plus version 23.2.0 are more widely used. This system (PV panels) is applicable in both conventional and hydroponic cultivation in the greenhouse. A PV system consists of solar panels that include solar cells and can produce electrical power [190]. There are semiconductors and organic and inorganic molecules in the solar cell matrix of PV systems [52]. Using renewable energy sources can reduce greenhouse gas emissions [37,191]. In photovoltaic systems, some subjects, such as creating a balance between the consumption of solar energy for the photosynthesis of plants and solar panels [52], the shading rate of this system on greenhouse plants, applications, and the possibility of using this system, are the main challenges for researchers [52]. In the last decades, glass and plastic have been the most usable coverage in a conventional greenhouse. Comparing these two coverings shows that glass is more resistant to environmental parameters, but the cost of plastic covering is cheaper and needs to be replaced every few years [192,193]. Also, due to flexibility, curved shapes such as arcs can be created in plastic covers [194–196]. Greenhouses with glass covers are usually made of flat sheets. So, large glass panels with minimal shading are used in greenhouse frame structures [113,193]. Khammayom et al. [90] studied the effect of environmental factors on energy equivalence in a strawberry greenhouse culture. From the results, it was found that the heating system allocates approximately 70% to 80% of the total energy consumption in the greenhouse. In this study, four factors including greenhouse cover, indoor temperature, floor, and greenhouse plants were essential to consider in the energy balance under the stable conditions of strawberry cultivation in the greenhouse [197]. The origin of the incoming energy flow to the greenhouse is solar radiation and the heat losses caused by covering materials, ventilation and the ground indicate the outgoing energy flow. The energy balance in this research based on the first law of thermodynamics can be calculated through Equation (17).

$$Q_{rad} = Q_c + Q_{gr} + Q_v \tag{17}$$

where Q is the heat loss (W); rad is radiation; c is covering material; gr is ground; and v is ventilation. It is assumed that heat loss from the greenhouse is in winter when the solar radiation is low. Therefore, the total rate of heat loss through covering materials, ventilation exhaust, and ground can be calculated as follows [90,198]:

$$Q_{total} = Q_c + Q_{gr} + Q_v \tag{18}$$

$$Q_c = U_c A_C (\theta_{i,j} - \theta_{amb,j}) \tag{19}$$

$$Q_{gr} = U_{gr} A_{gr} (\theta_{i,j} - \theta_{amb,j}) \tag{20}$$

$$Q_v = 0.33 A_{ch} V (\theta_{i,j} - \theta_{amb,j}) \tag{21}$$

where U_C is the heat transfer coefficient of the coverage material (W $m^{-2}K^{-1}$); A_c is the whole area of the envelopment material (m); $\theta_{i,j}$ is inside air temperature at time distance (°C); θ_{amb} is the air temperature of the surrounding at the time interval of j (°C); U_{gr} is the ground thermal transition coefficient (W $m^{-2}K^{-1}$); A_{gr} is the plantation area (m^2); A_{ch} is the air variation per hour (1 h^{-1}); and V is the volume of the greenhouse (m^3). The amount of U_c belongs to several agents, including the size of the greenhouse, the type and thickness of the coverage material, the characteristics of the heating system, and the wind velocity. Hence, the capacity of U_c was empirically considered between the range of 6.0 and 8.0 (W $m^{-2}K^{-1}$) [199]. The results showed that the highest heat energy demand of 327.6 MJ m^{-2} is obtained in January, which is the coldest month of the year with a temperature of −4.4 °C and the lowest thermal energy demand of 60.0 MJ m^{-2} is obtained in November. Estimating the required energy of the greenhouse can be a worthy source of information for the energy demand of the heating and cooling systems, as well as useful for energy costs. In the research completed by Mollin and Martin [200], the energy performance in a vertical hydroponic cultivation system was evaluated. In this study, the cultivation of basil plants in two types of plastic and paper pots with a hydroponic vertical cultivation system in the Grunska area located in the south of Stockholm, Sweden, was investigated. The energy consumption for the basil hydroponic cultivation was investigated in heat, ventilation and light input data. A number of electric radiators were used for heating, which operated 12 h a day and the ventilation was checked assuming 24 h of operation during a day. For lighting, blue and red LEDs were used with 12 h of exposure during the day. The energy calculation was performed by multiplying the number of diodes by their effect (W) and the number of annual hours of use. Other energy consumption details such as the total number of units and effect figures were provided by Grunska, Sweden. In that study, two types of plastic and paper vases were used, and the energy consumption analysis showed that the annual energy consumption in paper vases (286,000 MJ) is less than that of plastic vases (296,000 MJ). In addition, the energy consumption for each basil plant or each functional unit in the paper pot was 4.81 MJ and for the plastic pot was 4.9 MJ. Comparing the energy of the growth surface showed that each square meter was 16.7 GJ for the paper pot and 17.1 GJ for the plastic pot. In this research, the first energy consumption process accounted for horticultural soil, where paper pots accounted for 48% of the total energy consumption and plastic pots accounted for 47%. The lighting system had the second share of the total energy consumption, which was 33% in the paper pot and 32% in the plastic pot. Also, the energy demand for the lighting system in the vertical hydroponic cultivation of basil had the highest amount of greenhouse gas production. Energy consumption in vertical hydroponic farms is more than in conventional greenhouse cultivation due to the use of lighting systems. In the Grunska region of Sweden, where this research was conducted, the annual energy consumption for heating, ventilation, and lighting was 3285 MJ m^{-2}.

3. Conclusions

The use of greenhouse cultivation technology is rapidly expanding as a viable method to produce high-quality agricultural products outside of traditional growing seasons. Among the various methods employed in greenhouse cultivation, hydroponics has garnered significant attention from researchers and farmers due to its unique and state-of-the-art approach. This study aims to comprehensively investigate and compare factors influencing conventional and hydroponic greenhouse cultivation scenarios. The results demonstrate that hydroponic cultivation, utilizing advanced control equipment and superior culture substrates, provides optimal conditions for plant growth. In comparison to conventional greenhouse cultivation, hydroponics requires less fertilizer, pesticides, and water due to the precise control over their distribution. The use of renewable energy in these two methods of greenhouse cultivation can reduce the emissions by up to 9% in hydroponics and 2% in conventional cultivation. The results of LCA in hydroponic cultivation after normalization and weighting determined that the most environmental emissions belong to a set of ecosystem damages. Also, the results of LCA in conventional greenhouse cultivation showed that the main environmental effects of direct emission were caused by input consumption (air: carbon dioxide (CO_2) and nitrogen oxides (NOx); soil: mercury (Hg), copper (Cu) and lead (Pb)) and indirect emissions from the production of chemical fertilizers, greenhouse structures and chemical pesticide. Overall, the hydroponic cultivation system, with its precise environmental control, results in better quality, higher yields, and optimal use of water and fertilizer. While the initial investment cost for hydroponic cultivation is higher in comparison to conventional methods, it significantly reduces energy losses. Further examination of data, such as greenhouse temperature, structure, and carbon dioxide concentration, revealed no significant differences between the two cultivation methods. Moreover, the type of cultivation did not impact energy consumption significantly. However, it should be noted that more advanced equipment used in the greenhouse would require additional electricity and fuel for operation. To fully optimize hydroponic cultivation, experts and farmers in this field are advised to expand their practices based on geographical location, available resources, and initial capital. While the initial capital investment for hydroponics may be higher, it can be mitigated by selecting an appropriate greenhouse location and utilizing renewable energy sources. Although conventional greenhouse cultivation requires less investment, it is less energy efficient compared to hydroponic methods. In conclusion, adopting hydroponic cultivation in greenhouse settings ensures sustainable and efficient production, optimized energy consumption, and efficient resource utilization. The findings from this study provide valuable insights for researchers, farmers, and investors in the greenhouse cultivation industry, emphasizing the need for ongoing research on energy optimization and life cycle assessments of hydroponic systems to ensure long-term sustainability.

4. Future Suggestions

- Expanding hydroponic cultivation using renewable energy is suggested to reduce the initial investment and energy consumption according to the environmental conditions.
- Farmers are advised to develop hydroponic cultivation techniques to produce high-quality products, profit more, and reduce energy losses.
- Researchers in agriculture and environmental science should conduct further research on energy-efficient and eco-friendly techniques for conventional greenhouse and hydroponic farming.

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