sustainability

MDPI

Article

Life Cycle Assessment of Tomato Cultivated in an Innovative Soilless System

Maria Concetta Pedalà [1], Marzia Traverso [2,*], Simona Prestigiacomo [3], Antonio Covais [1] and Giovanni Gugliuzza [4]

[1] Circular S.R.L., Via Libertà 34, 90141 Palermo, Italy; mariaconcetta.pedala@circular.srl (M.C.P.); antoniocovais@gmail.com (A.C.)
[2] Institute of Sustainability in Civil Engineering, RWTH Aachen University, 52062 Aachen, Germany
[3] Department of Agricultural, Food and Forest Sciences, University of Palermo, Viale delle Scienze, Build. 4, 90128 Palermo, Italy; simona.prestigiacomo01@unipa.it
[4] CREA Research Centre for Plant Protection and Certification, c/o Dip. SAAF Unipa, Viale delle Scienze, Build. 4, 90128 Palermo, Italy; giovanni.gugliuzza@crea.gov.it
* Correspondence: marzia.traverso@inab.rwth-aachen.de

Abstract: The main goal of this study is to present the life cycle assessment results of an innovative closed-loop production system, called an agriponic system, used for producing tomatoes. In the study, this new system is presented, as well as its related environmental impacts generated for the production of the tomatoes. A life cycle assessment (according to ISO 14040) was applied to it, from seedling purchase and planting to harvest, using a functional unit of 1 ton of cherry tomatoes produced. SimaPro 9.3.0.3 software and the Ecoinvent database were used to analyze five impact categories. Plant growth emerged as the process unit with the highest impact, particularly for the ozone depletion potential (ODP), with a value of 0.00056 kgCFC-11eq, and for photochemical oxidation (POCP), with a value of 0.0784 kgC_2H_4eq impact categories. Greenhouse climate management presented a significant impact to the acidification potential (AP), with a value of 1.021 kgSO_2eq. Conversely, the phases of plant transplanting, harvesting, and crop disposal had positive impacts for all impact categories considered in the study, because they were very low. In conclusion, agriponic greenhouse tomato production is a sustainable process. This is due to fewer pesticides that are used, and to nutrient solution reuse.

Keywords: life cycle assessment; greenhouse; tomato; agriponic

Citation: Pedalà, M.C.; Traverso, M.; Prestigiacomo, S.; Covais, A.; Gugliuzza, G. Life Cycle Assessment of Tomato Cultivated in an Innovative Soilless System. *Sustainability* **2023**, *15*, 15669. https://doi.org/10.3390/su152115669

Received: 1 August 2023
Revised: 10 October 2023
Accepted: 18 October 2023
Published: 6 November 2023

1. Introduction

The global population is growing, leading to a corresponding increase in the demand for food. According to literature, the demand for agricultural products from 2005 to 2050 will increase by 100% [1]. The current systems for food production require large inputs of resources, presenting remarkable environmental impacts, and causing approximately 14% of global greenhouse gas emissions [2]. As much as 70% of global freshwater consumption [3], extracted and used worldwide, is allocated to the water needs of the agricultural sector. Approximately 40% of the global land surface is used for agriculture [4]. Every year, around 24 billion tons of fertile soil are lost due to intensive agricultural soil erosion [5]. Roughly 20–30% of the total environmental impact per individual can be attributed to food production and consumption [6]. Furthermore, with 66% of the world's population expected to live in cities by 2050, there has been an intensified push to modernize horticultural methods, in order to fulfill the demand from a population that is reaching close to 9 billion [7]. All growers are under pressure from declining arable land, growing urbanization, water shortages, and climate change. Thus, the agricultural sector causes climate change but, in turn, suffers from its effects. Among the new challenges facing farms today, the sustainability of agricultural production cycles is undoubtedly the most important, orienting European consumers, and becoming a fundamental requirement for companies to access EU aid.

A life cycle assessment (LCA) is defined as a "compilation and evaluation of the inputs, outputs, and the potential environmental impacts of a product throughout its lifecycle", and is a methodology that was established and standardized by the International Organization for Standardization [8,9]. It is used for calculating environmental impacts in a structured manner. Although the LCA was initially developed for industrial processes, it has found widespread application in various sectors, including agriculture and food production [10]. Vegetable cropping systems exhibit a wide variety of agricultural- and production-related environmental factors that have a significant influence on the inventory, on related on-field estimating techniques, and on resulting LCA outcomes.

Tomatoes represent one of the most important agricultural crops on a global scale, with a cultivated area in 2021 of approximately 5.16 million hectares, and an estimated worldwide production of 189.1 million tons [11]. Tomatoes are produced in the open field and in greenhouses. For fresh consumption, much of the production occurs inside greenhouses due to their longer production calendar, high yields, and good product quality. Inside greenhouses, cultivation is carried out in soil or in soilless systems, using artificial substrates. It is common for greenhouse cultivation to require higher energy inputs, such as heating or artificial lighting, in order to enhance production.

The productivity of tomatoes and, consequently, their life cycle assessment (LCA) impacts, are influenced by various factors, including the climate of the cultivation area, tomato variety, production cycle, cultivation system, etc. [12–15]. Many studies have been conducted on the LCA impacts of tomato production, considering greenhouse or open field cultivation methods [16–21].

The environmental impacts associated with tomato cultivation arise from various components, including the infrastructure (greenhouses, irrigation systems, water supply, and other equipment), production processes (seed and seedling production, cultivation in soil, above ground, open cycle, closed cycle), and the means of production (substrates, fertilizers, pesticides, water) [17,19,22]. Energy consumption is another significant factor that encompasses heating, cooling, lighting, and electricity requirements for automation, irrigation, and other purposes [23–29]. Lastly, waste management practices also play a role in the overall environmental impacts of tomato cultivation [21].

The production capacity of a greenhouse tomato plant is an important factor in the assessment of the impacts of cultivation. In fact, the environmental impact should be related not to the unit of area, but to the unit of product (how much energy is used to produce 1 kg of tomatoes) [30].

The identification of key areas for improvement, such as the optimization of water and nutrient management, has facilitated the development of innovative cultivation methods aimed at enhancing environmental sustainability in greenhouse tomato cultivation [17,21].

The aim of the present study was to investigate the environmental impacts of greenhouse-based production of tomatoes in an innovative closed-loop soilless system, denominated as "agriponic", using the life cycle assessment (LCA) methodology. The environmental analysis conducted in this case study generated results that can serve as a foundational "knowledge base" for enhancing awareness about the impacts of tomato production. These findings can also assist stakeholders in implementing sustainable production practices, with the objective of guiding producers towards more environmentally friendly production methods.

2. Materials and Methods

2.1. Cultivation System

Agriponics represents a soilless hybrid production system that combines features of aeroponic and nutrient film technique (NFT) systems. In this cultivation system, plants grow on closed channels where the root system develops while partially suspended in the air, while the rest of the plants are in contact with the channel's bottom. The nutrient solution is distributed at intervals by sprayers and is partially absorbed by the roots, while excess solution flows out into the channels. Therefore, root uptake occurs partially by sprayer (aeroponic) and partially by the film of leaching solution passing through (NFT) (Figure 1).

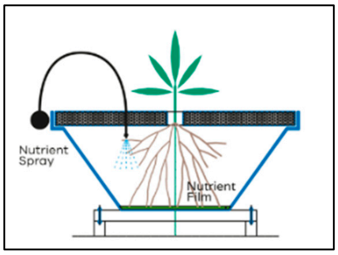

Figure 1. Cultivation channel section in the agriponic system.

Excess nutrient solution is collected as it flows to the base of the channels for subsequent filtration, sanitization, and integration with new solution, thereby creating a closed-loop system that allows for reuse of the nutrient solution.

The objective of the model is to enhance environmental sustainability by focusing on water conservation, minimizing waste, improving energy efficiency, and reducing the presence of pathogens and pests. Simultaneously, it ensures that the product meets high-quality standards.

2.2. Greenhouse

The agriponic system was installed inside an iron–plastic greenhouse in a commercial farm located in Ispica (RG), Italy (36°75′ N, 14°91′ E).

The pilot greenhouse consists of 5 modules, each with the following characteristics: 9 m wide, 90 m long, 2.5 m height at the eaves, and 3.5 m height at the ridge (Figure 2). It is equipped with manual side openings with insect netting to allow for ventilation of a confined environment. The study's unheated greenhouse was equipped with an emergency heating system and an external anti-freeze system that comes into action when the external temperature drops below 4 °C. In the spring, a shading net was located over the plastic covering.

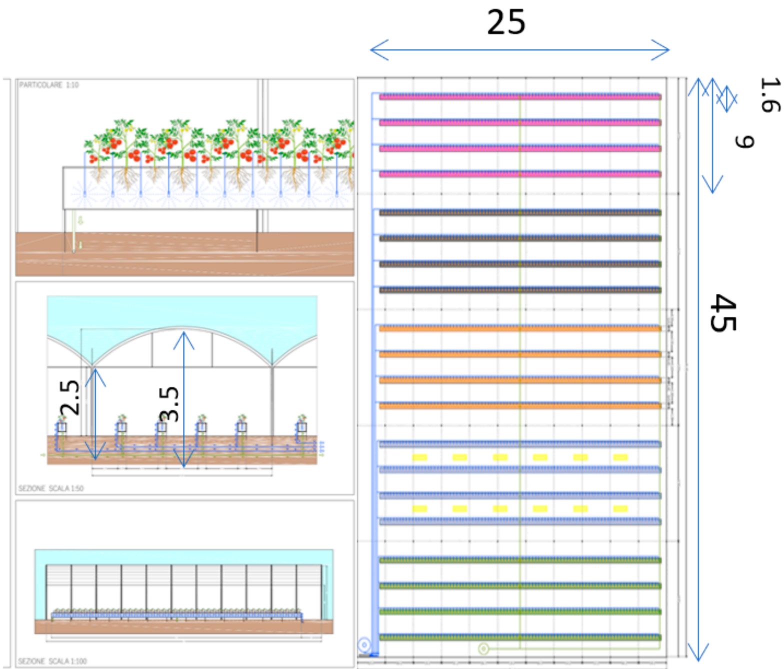

Figure 2. Greenhouse and cultivation channels in the agriponic system.

The pilot greenhouse presents a low technological level regarding its structure, but it is the most widespread approach used in southeastern Sicily for the cultivation of vegetables.

The agriponic cultivation system was composed of closed polystyrene channels (40 × 40 × 2500 cm) (Figure 2) allocated at a distance of 1.6 m from each other. The plants were placed on top of the channels at a distance of 28 cm. The nutrient solution (NS) was distributed by sprayers (one per plant), and the excess solution flowed out into the channels to a tank. (Figure 3).

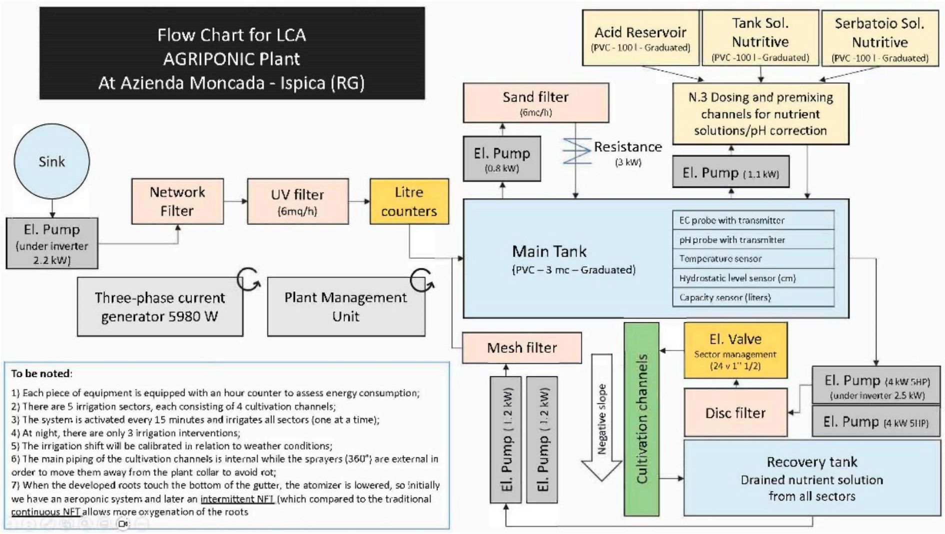

Figure 3. Operation of the greenhouse irrigation system.

2.3. *Tomatoes*

Forty-day-old cherry tomato seedlings (cv. Durillo, grafted into Optifort), grown in stone wool cubes (5 × 5 × 5 cm (Grodan@ ROCKWOOL B.V. Roermond, The Netherlands)), were transplanted on 29 December 2021, inside the greenhouse in the channels of the agriponic system. A planting density of 1.5 plants/m^2 was adopted. The plants were grown vertically, keeping 2 shoots per plant.

The NS was prepared by agro experts, in accordance with their experience on soilless agriculture systems.

The leached, collected, and disinfected NS was integrated (closed-loop) with new NS by fertigation on the basis of the pH and EC values.

2.4. *Irrigation System*

The water and nutrient solution cycle for the agriponic system is shown in Figure 3.

The nutrient solution (NS) distribution system involves the following steps: water is drawn from a well, filtered to remove impurities, and sent to the primary PVC tank that houses numerous sensors and probes. Then, the water is pumped to dosing channels where tanks filled with nutrient solution and acids mix with it. After this, the water is returned to the primary tank and sent through electric pumps to disc filters before being directed to cultivation channels via a solenoid valve. In the last phase of the system, the water is filtered once more and sent to a recovery tank that collects drained nutrient solutions from all areas. Electric pumps transport the substance to mesh filters before feeding it back into the primary tank.

The irrigation frequency was set at 18 min during daylight, with an irrigation time of 18 s. A total irrigation volume of 302 m^3 was used.

2.5. Production Process Description

The tomato production process involved various stages, such as greenhouse preparation, transplanting, continuous nutritional support and treatments (plant growth), appropriate climatic management, and crop disposal.

First, the greenhouse was prepared; this phase lasted one month (November 2021 to December 2021). Then, raw materials for greenhouse production were purchased, i.e., the plants and fertilizers for plant growth. The tomato seedlings were planted in the greenhouse on raised supports; this phase lasted two days from 28 to 29 December 2021. From 28 December 2021 until the end of July (the period in which the harvest took place and then the crop was disposed of), nutritive solutions were distributed, followed by foliar applications as phytosanitary, fertilizer, and biostimulated treatments (from January 2022 until July 2022).

An emergency diesel heating system was installed inside the greenhouse, which goes into operation when the temperature inside the greenhouse drops below 4 degrees. A total of 50 L of diesel fuel was consumed during the considered time period.

On 31 July 2022, the total disposal of the crop took place. This detailed process highlights the complexity and dedication required for efficient and effective greenhouse tomato production.

2.6. Life Cycle Assessment

The methodology used to assess the environmental impacts is the life cycle assessment according to ISO 14040 (2006) [8] and ISO 14044 (2006) [9]. In accordance with ISO 14040 [8] and ISO 14044 [9], the procedure was standardized, and the main steps are outlined as follows: (1) goal and scope definition; (2) data collection and life cycle inventory; (3) impact assessment; and (4) interpretation. The following paragraphs explain how each phase of the LCA for this case study was conducted. The goal and scope aim to define, together with the main goal of the study and also all assumptions necessary, to characterize the case study and make the results reproducible. Indeed, in the goal and scope, the audience of the study, functional units, reference flow, system boundary, type and quality of data, impact categories analyzed, and software used must be defined.

The life cycle inventory presents all input and output data used in the study. The input and output data included all of the energy and materials entering into the system, and all of the emissions and materials/wastes and products going out of the system, respectively.

In a life cycle impact assessment, the inventory data are classified and assigned to the main impact categories considered in the study and presented in the goal and scope, and then throughout characterization of the model translated into impact categories. Most of the related studies, and also the current one, focused on the midpoint impact categories that translate the inventory into impacts. A further level of assessment would be to use endpoint impact categories, which further translate the impacts into damages to three main areas of protection: human health, ecosystem quality, and resource depletion. The current study focused on midpoint impact categories. The last phase, the interpretation, included sensitivity analysis and interpretation of the results.

In the following paragraphs, the case study and its related results are presented following the LCA methodology.

3. Results

3.1. A Life Cycle Assessment of a Tomato Produced in Agriponic Greenhouse

3.1.1. Goal and Scope

The goal of this study is to evaluate the environmental impacts, through mass and energy balances of each operation in-depth "from cradle to gate" analysis, of the production of fresh cherry tomatoes grown in greenhouses with agriponic systems. The life cycle of the tomato was considered in its various stages, from the purchase and planting of the tomato seedlings to the first harvest taking place. The functional unit (FU) considered in this study is 1 ton of harvested cherry tomatoes. The analyzed system boundary and the life cycle inventory are shown in Figure 4.

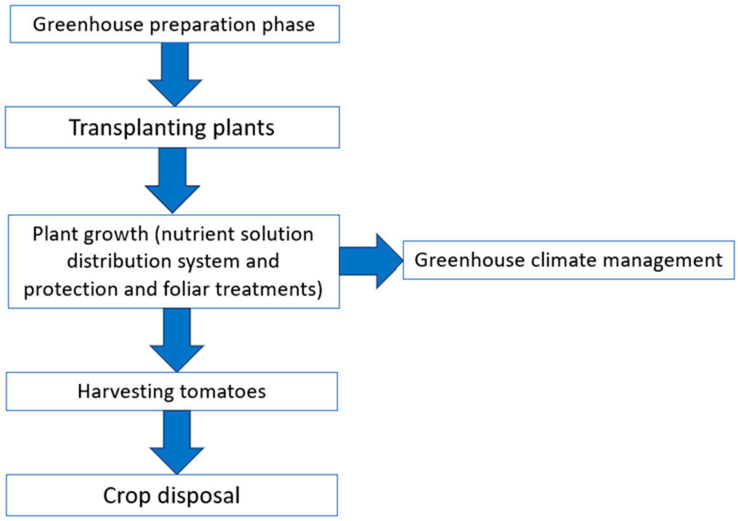

Figure 4. System boundary analyzed.

The description of the system boundary considers the inputs and outputs for each phase of the system. The inputs are any material and energy that is necessary to carry out the assessment of the environmental impact of the tomato production, while the outputs are the products or waste generated by the system.

The greenhouse system was analyzed in five phases, and the inputs and outputs for each phase are listed below.

Plant transplanting phase: Inputs include tomato plants, polypropylene wires, and clips made of PET used to make the tomato plants climb. Outputs include the polystyrene seed pots and their disposal.

Plant growth phase: During the plant growth phase, the inputs to the system include the water, fertilizers, pesticides, fungicide, foliar fertilizers, and electrical energy for pump operation. Meanwhile, the outputs are represented by PE fertilizer bags and pesticides, fungicide bottles, and the disposal of these items also taken into account. The distribution system for the nutrient solution and the defense and foliar treatment phase are also considered together in this phase.

Harvesting: In this phase, the total tomato plant production is considered.

Greenhouse climate management: Inputs include the square meters of shading net used in the greenhouse, and energy produced using diesel fuel to heat the greenhouse. The output is the CO_2 produced by diesel combustion.

Crop disposal: Outputs include PET clips, and polypropylene wires and their disposal.

In the context of the tomato study, the software SimaPro 9.3.0.3 and the Ecoinvent database were used to quantify the environmental impacts of tomato cultivation in terms of greenhouse gas emissions, water consumption, energy use, and other relevant indicators. These data were collected and analyzed using the CML baseline method, which is a commonly adopted approach for life cycle assessment that considers the environmental impacts throughout all stages of the product's life cycle.

3.1.2. Life Cycle Inventory Analysis

The life cycle inventory (LCI) is a critical step in assessing the environmental sustainability of greenhouse tomato production. It involves the comprehensive quantification of inputs and outputs associated with each stage within the system boundaries. It assumes great importance, as it determines the quality of the data utilized in the LCA analysis. A successful completion of this stage exerts a substantial influence on the overall dependability and precision of the sustainability evaluation for greenhouse tomato production.

Given the unique characteristics of each production process, also in the context of greenhouse tomato production, primary data pertaining to the various cultivation steps are acquired through questionnaires and personal interviews. These primary data play a vital role in constructing accurate mass and energy balances, which serve as the foundation for the inventory.

The data required for studying the greenhouse tomato production system encompass several key aspects:

- Water consumption;
- Electricity consumption associated with pumps;
- Fertilizer usage;
- Irrigation period and duration;
- Waste generation.

After gathering the data through the questionnaires, they were entered into SimaPro 9.3.0.3 software for analysis. The materials and products utilized in the greenhouse were examined by referring to the databases available in the software. In this case, the Ecoinvent database, developed by a Swiss research organization, was utilized. Ecoinvent is a comprehensive life cycle inventory database specifically designed to facilitate diverse sustainability assessments.

The input and output data for the various stages received through the questionnaires were entered into the software. They concern the main process units considered in the system Below are the input and output data corresponding to each stage of the system considered, Table 1 shows the quantities used. Plant transplanting phase: The input data include the number of tomato plants, while the output data include the quantity of plastic materials, specifically the amount of polystyrene used for 88 seed pots.

Table 1. Input and output data of the various phases of the system considered.

Phase System	Input	Quantity	Output	Quantity
Plant transplanting phase	Tomato plants Polypropylene wires Clips (PET)	1760 5.2 kg 2.6 kg	Polystyrene seed pots Polypropylene PET	166.8 kg 5.2 kg 2.6 kg
Plant growth	Water Nitric Acid Monopotassium phosphate Nitro 34 Chelated iron Microelement mix Potassium sulphate Magnesium sulphate Magnesium nitrate Electricity Vermitec Intrepid Costar Oikos Oberon Armicab Ridomil Cidely Top Sprintene Algalive Agrialgae Zolfo Pro 20-20-20 Plantafol Dentamet	66.8 m^3 28 kg 5.2 kg 1.3 kg 0.42 kg 0.77 kg 9.85 kg 5.23 kg 5.23 kg 457.226 kWh 0.014 kg 0.55 kg 0.252 kg 0.083 kg 0.021 kg 0.180 kg 0.215 kg 0.015 kg 0.049 kg 0.070 kg 0.102 kg 0.098 kg 0.070 kg 0.012 kg	Bags of fertilizers in PE Fertilizer bottles and plant protection	2.8 kg 12.86 kg

Table 1. *Cont.*

Phase System	Input	Quantity	Output	Quantity
Plant growth	Laser Epik Labin CU Flipper	0.007 kg 0.031 kg 0.015 kg 0.138 kg		
Harvesting			Tomato fruits	1 ton
Greenhouse climate management	Shading net Diesel	1600 m^2 42 kg		
Crop disposal			Clips (PET) Polypropylene wires	2.6 kg 5.2 kg

Raw materials purchase phase: The input data include information about the tomato plants, such as the type of tomato grown, where they were purchased, the number of seedlings acquired, and the distance traveled by the vehicle to transport them to the greenhouse. For mineral fertilizers, the input data comprise the types of fertilizers used and their quantities. These inputs are considered to be part of the nutrient solution distribution system, as it involves the fertilizers used for tomato plant growth.

Nutrient solution distribution system phase: The input data include the amount of nutrient solution in the tanks, the total water consumption for irrigation and nutrient solution, and the energy usage for pumps and artificial light. The output data entered pertain to the amount of polyethylene (PE) used for the fertilizer bags.

Defense and foliar treatment phase: The input data encompass the acaricides, insecticides, fungicides, and fertilizers used in the greenhouse, along with their quantities and water consumption. The output data collected pertain to the number of bottles used.

Greenhouse climate management phase: The input data involve the square meters of shading net used, and the liters of diesel consumed for greenhouse heating.

Crop disposal phase: The input data include the number of clips and wire length used to support the growth of the tomato plants. The output data primarily relate to the amount of plastic materials used, particularly from the pesticide bottles.

With regard to the fertilizers, acaricides, insecticides, and fungicides used during production, since the names of the products used could not be found in SimaPro, the various active ingredients present in the product used were included; the following tables (Tables 2 and 3) show the active ingredients contained in each product.

Table 2. Active principal ingredients of acaricides, insecticides, fungicides, and fertilizers used.

Product	Active Principal Ingredients	Notes
Vermitec	Abamectine	Acaricide
Intrepid	Pure methoxyfenozide 1,2-benzisothiazolin-3-one	Insecticide
Costar	Bacillus thuringiensis	Biological insecticide
Oikos	Azadirachtin A	Insecticide
Oberon	Spiromesiphene	Insecticide
Armicab	Potassium bicarbonate	Fungicide
Ridomil	Metalaxyl-M Copper metal (from oxychloride)	Fungicide
Cidely Top	Pure diphenoconazole Pure cyflufenamid	Fungicide

Table 2. *Cont.*

Product	Active Principal Ingredients	Notes
Sprintene	Flavonic glucosides Oxycoumarins Group B vitamins Anthocyanins Nicotinic acid Micro-nutrients in chelated form (Fe, Zn, Mn, Co) Boron (B)	Biostimulant/Organic fertilizer
Algalive	Organic nitrogen (N) Organic carbon of biological origin Organic substance with a molecular weight <50 kDa	Biostimulant/Organic fertilizer
Agrialgae	Free L-amino acids Total nitrogen Organic nitrogen Nitric nitrogen P_2O_5 K_2O	Biostimulant/Organic fertilizer
Zolfo Pro	Nitrogen (N) total Soluble organic nitrogen (N) Sulphur (S) total Organic carbon of biological origin	Mineral fertilizer
20-20-20 Plantaflo	Total nitrogen Total phosphoric anhydride (P_2O_5) Water-soluble potassium oxide (K_2O) Water-soluble boron (B) Water-soluble copper (Cu) chelated with EDTA Water-soluble iron (Fe) chelated with EDTA Manganese (Mn) chelated with water-soluble EDTA Zinc (Zn) chelated with water-soluble EDTA	Mineral fertilizer
Dentament	Water-soluble copper (Cu) Zinc (Zn) soluble in water	Mineral fertilizer
Laser	Pure spinosad (QUALCOVA active)	Mineral fertilizer
Epik	Pure acetamiprid	Biological insecticide
Labin CU	Water-soluble copper	Organic fungicide
Flipper	Potassium salts of fatty acids (C14–C20)	Biological insecticide

Table 3. Active principal ingredients of mineral fertilizers used.

Product	Active Principal Ingredients
Monopotassium phosphate	Phosphoric anhydride (P_2O_5) Phosphorus Potassium oxide (K_2O) Potassium
Nitro 34	Total nitrogen (N) Nitrogen (N) nitric Nitrogen (N) ammonia
Chelated Iron	Water soluble iron (Fe) Iron (Fe) chelated with EDTA

3.1.3. Impact Assessment Results

The elaboration of the inventory data was performed through LCA SimaPro 9.3.0.3 software, in agreement with the reference standard for LCA (i.e., ISO 14040-14044). The

CML baseline was used to classify and characterize the inventory results in the impacts categories.

The impact categories that were considered in the greenhouse study were the following:

- Global warming potential (GWP 100a);
- Ozone layer depletion potential (ODP);
- Photochemical oxidation potential (POCP);
- Acidification potential (AP);
- Eutrophication potential (EP).

Table 4 shows the results obtained with regards to characterization for the impact categories considered for each stage of the greenhouse production process analyzed.

Table 4. Values of global warming potential (GWP100a), ozone layer depletion (ODP), photochemical oxidation potential (POCP), acidification potential (AP), eutrophication potential (EP) for each phase of the system considered.

Impact Category	Unit	Total	Transplanting Plants	Plant Growth	Harvesting	Greenhouse Climate Management	Crop Disposal
Global warming potential (GWP 100a)	Kg CO_2 eq	562.29	10.45	402.02	0.34	144.46	5.02
Ozone layer depletion (ODP)	Kg CFC-11 eq	0.00058	1.93×10^{-6}	0.00056	3.66×10^{-8}	2.54×10^{-5}	4.67×10^{-9}
Photochemical oxidation (POCP)	Kg C_2H_4 eq	0.096	0.001	0.078	5.37×10^{-5}	0.017	1.81×10^{-6}
Acidification potential (AP)	Kg SO_2 eq	2.73	0.04	1.67	0.002	1.02	6.047×10^{-5}
Eutrophication potential (EP)	Kg PO_4---eq	0.66	0.007	0.43	0.001	0.23	1.15×10^{-5}

The following graphs (Figures 5–9) show for each phase the trends of the impact categories considered.

Based on the results obtained (Table 4), a comprehensive analysis of the impact categories reveals significant environmental implications associated with different phases of the system. Notably, the plant growth phase has the highest impacts for all impact categories, followed by greenhouse climate management.

With regard to the normalization phase, the following table (Table 5) shows the normalized values, compared to European values, of the impact categories taken into account in the study conducted for each stage of the system considered.

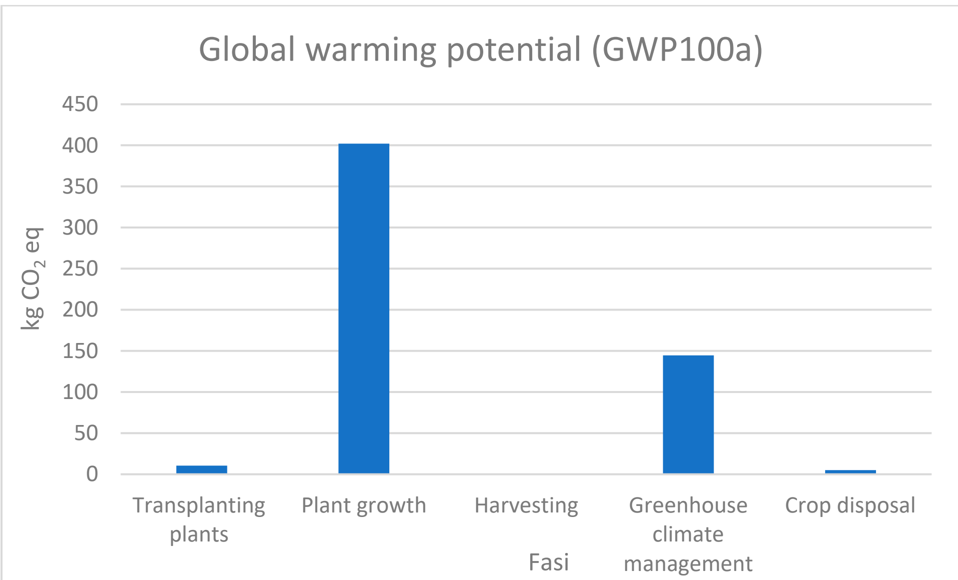

Figure 5. GWP 100a trends.

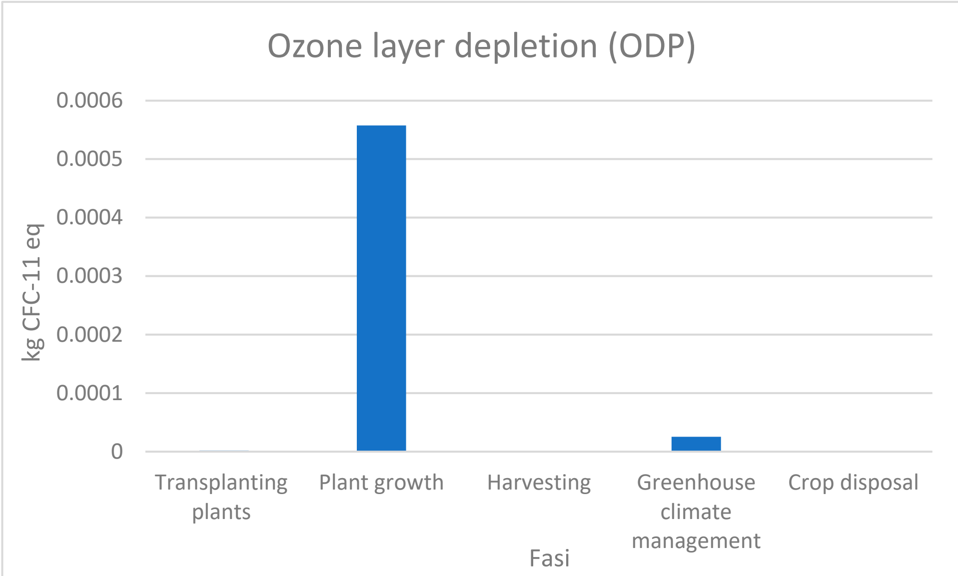

Figure 6. ODP trends.

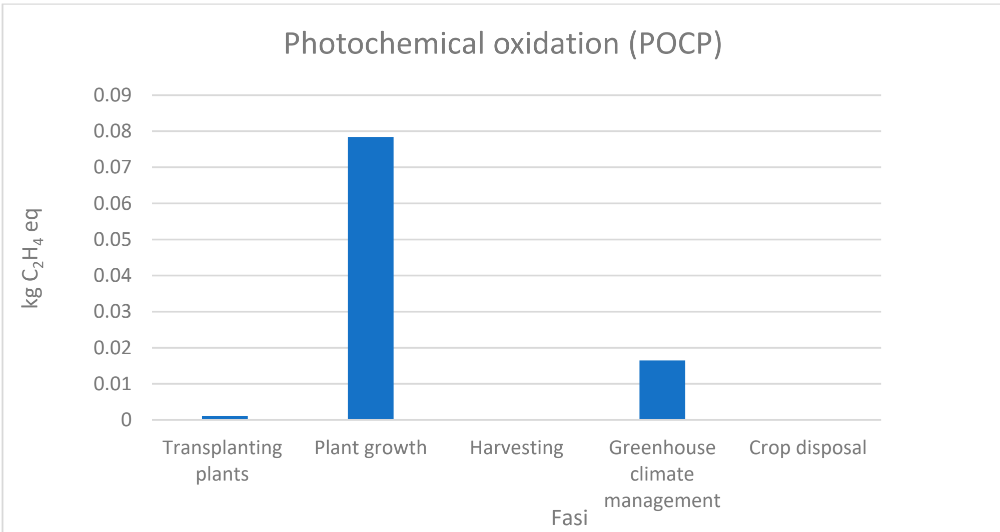

Figure 7. POCP trends.

Table 5. Values of impact categories normalized to European values for each stage considered in the system.

Impact Category	Total	Transplanting Plants in Aeroponics	Plant Growth	Harvesting	Greenhouse Climate Management	Crop Disposal
Global warming potential (GWP 100a)	1.119×10^{-10}	2.080×10^{-12}	8.0003×10^{-11}	6.762×10^{-14}	2.875×10^{-11}	9.986×10^{-13}
Ozone layer depletion (ODP)	6.549×10^{-12}	2.156×10^{-14}	6.242×10^{-12}	4.0099×10^{-16}	2.847×10^{-13}	5.231×10^{-17}
Photochemical oxidation (POCP)	1.132×10^{-11}	1.213×10^{-13}	9.252×10^{-12}	6.334×10^{-15}	1.945×10^{-12}	2.134×10^{-16}
Acidification potential (AP)	9.695×10^{-11}	1.290×10^{-12}	5.933×10^{-11}	6.684×10^{-14}	3.626×10^{-11}	2.147×10^{-15}
Eutrophication potential (EP)	5.027×10^{-11}	5.438×10^{-13}	3.259×10^{-11}	8.097×10^{-14}	1.706×10^{-11}	8.704×10^{-16}

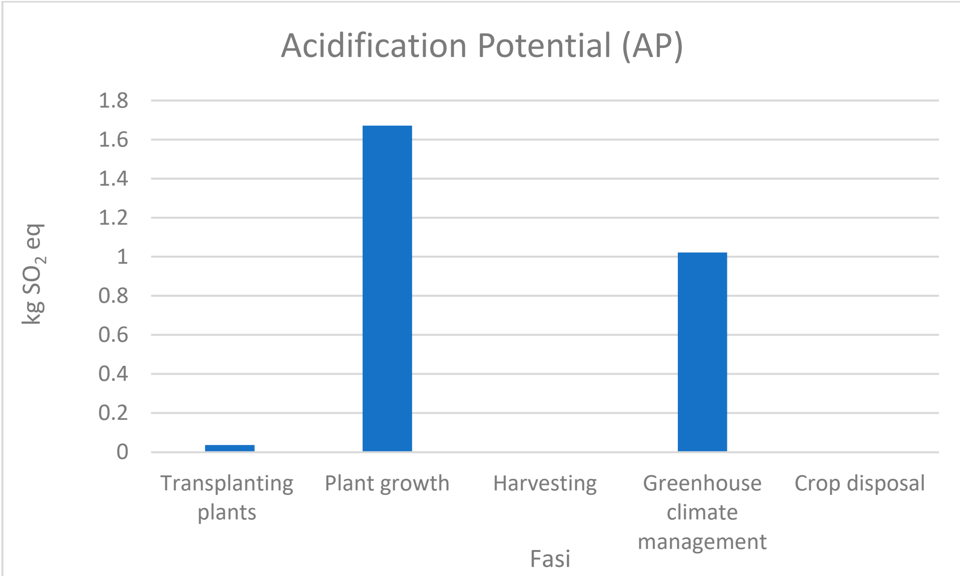

Figure 8. AP trends.

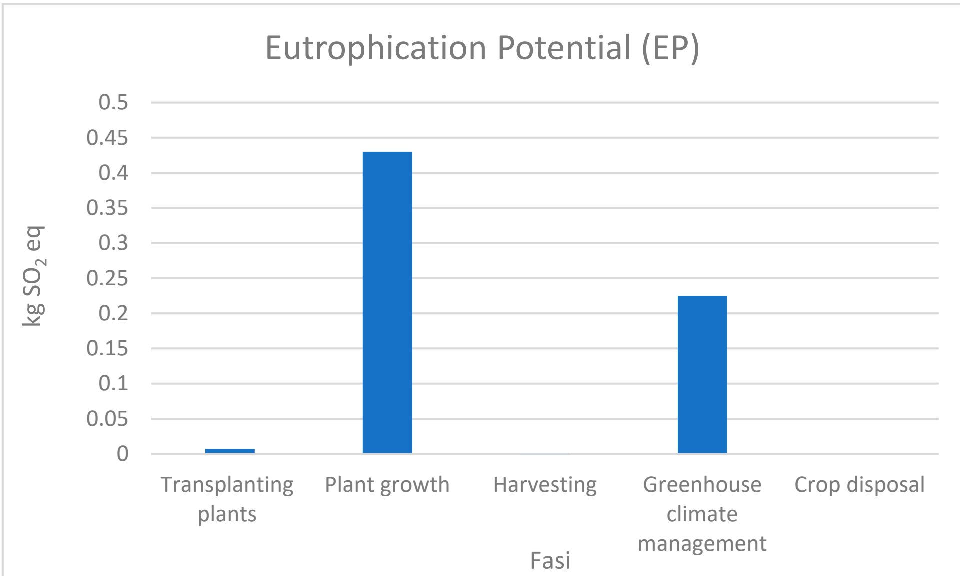

Figure 9. EP trends.

Based on the results obtained from the normalization LCA study on greenhouse tomato production (Table 5) and the analysis of the graph (Figure 10), it is evident that the phases with the highest environmental impacts are the plant growth phase and the climatic management phase of the greenhouse. These two phases contribute significantly to the overall environmental footprint due to the use of fertilizers, plant protection products, electrical energy for operating pumps used in nutrient solution distribution and plant protection, and the utilization of diesel fuel for heating the greenhouse when required.

Moreover, as depicted in the graph (Figure 10), the phases of aeroponic plant transplanting, harvesting, and crop disposal demonstrate minimal impacts across all of the considered impact categories in the study, indicating their relative insignificance in terms of environmental effects.

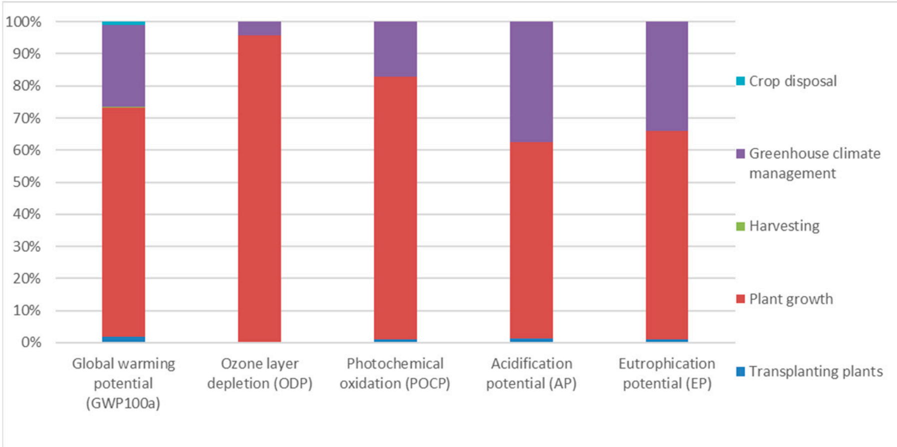

Figure 10. Trends of the various impact categories for the system phases.

3.1.4. Interpretation

The interpretation phase is the final step of the LCA process, where the results obtained from the impact analysis are analyzed and interpreted. The main conclusions are summarized below.

Considering the five impact categories studied and the different phases of tomato cultivation, it is evident that the plant growth phase has the greatest environmental impact across all of the impact categories. This phase involves the use of fertilizers, phytopharmaceuticals, and pesticides for plant growth, along with significant electricity consumption for pump operation.

In terms of the GWP, the plant growth phase is the primary contributor to environmental impacts. The use of pumps powered by electricity for nutrient solution distribution during this phase is a key factor. It would be beneficial to explore the use of renewable energy sources to power the pumps. Additionally, the greenhouse climate management phase, which involves diesel fuel-based heating, also has notable impacts. Exploring alternative heating methods for the greenhouse would be desirable.

The plant growth phase has the highest environmental impact in the ODP category. The use of fertilizers and pesticides during this phase contributes to the impacts. The greenhouse climate management phase also has some environmental impacts, although these are relatively lower. Finding alternative heating methods for the greenhouse instead of relying on diesel would be desirable. The phases of aeroponic plant transplanting, harvesting, and decommissioning have minimal impacts.

In terms of the POCP, which assesses air pollution, the plant growth phase has the most significant environmental impact due to the use of fertilizers and pesticides. The greenhouse climate management phase, which involves diesel fuel-based heating, also contributes to environmental impacts. However, the impacts of the aeroponic plant transplanting, harvesting, and decommissioning phases are not high. The acidification potential, which measures acid rain, is primarily influenced by the plant growth and greenhouse climate management phases. On the other hand, the phases of aeroponic plant transplanting, harvesting, and crop disposal do not have significant impacts.

The eutrophication potential, which assesses water eutrophication caused by excessive nutrients, indicates that the plant growth phase contributes the most to water pollution, specifically due to the presence of phosphorus. This phase has the greatest environmental impact in this category. The greenhouse climate management phase also has relatively high impacts.

In conclusion, the interpretation of the LCA results for greenhouse tomato production highlights the significance of the plant growth phase and the greenhouse climate management phase in terms of their environmental impacts.

4. Discussion and Conclusions

The LCA results for greenhouse tomato production highlight the significance of the plant growth phase and the greenhouse climate management phase in terms of their environmental impacts. Indeed, these two phases are the most relevant in terms of absolute impact categories, as well for the normalized results to European values.

This LCA study has been applied for the first time to this innovative greenhouse system, and the results are unique. Moreover, it has already allowed for the elaboration of some suggestions to improve the environmental performance in the first implementation following the concept of eco-design. These suggestions are summarized in the following paragraphs.

It is essential for future applications to minimize the use of plastic materials: it is advisable to explore alternative materials used for seed pods, fertilizer bottles, and greenhouse components, in order to reduce the reliance on plastic. Utilizing materials that have lower environmental impacts, or are made from recycled plastics, can be beneficial.

In addition, it could be helpful to try to seek sustainable heating alternatives. To mitigate CO_2 emissions associated with greenhouse heating, it is essential to explore alternative heating sources beyond diesel. Incorporating sustainable heat sources such as renewable energy or efficient heating systems can significantly reduce greenhouse gas emissions.

A further option for eco-friendly transportation is to use low-emission vehicles, and to reduce reliance on diesel fuel for transportation. This strategy can help to minimize CO_2 emissions during the transportation of tomato crops.

Despite the plant growth phase being the most environmentally impactful, it is important to recognize the advantages offered by aeroponic cultivation in terms of its environmental sustainability. Aeroponics offers several advantages, including the utilization of smaller amounts of water compared to other plant cultivation systems (reducing water usage by an impressive 98%) which is particularly relevant for south European areas that have water scarcity issues. It also reduces labor costs, and allows for expansion of the root system without restrictions. This method enables direct and ample oxygen absorption, and ensures rapid and consistent delivery of nutrient-rich mist, creating an optimal environment for root growth [22]. This is possible due to the precise control of nutrient inputs provided to the system, enabling a more efficient use of water, nutrient solutions, and pesticides [23,24]. Regulating these inputs based on the specific needs of the plants reduces waste and minimizes the negative impacts associated with their use.

Furthermore, since aeroponic cultivation does not require the use of soil, this method is an alternative for people with limited spaces to grow plants, and offers additional environmental benefits. By reducing the dependence on soil, the risks of soil degradation and pest infestations are limited, which in turn reduce the need for fungicides, herbicides, and insecticides. This characteristic also helps to minimize the impacts resulting from land use change, one of the main causes of environmental degradation. As a result of these characteristics, aeroponics is particularly beneficial in regions where the soil conditions are unsuitable for traditional plant growth. Additionally, thanks to the controlled environment in which they are grown, the plants can be cultivated throughout the year, regardless of the external weather and conditions.

Finally, to further reduce the environmental impacts of aeroponic plant cultivation, it is crucial to adopt renewable energy sources to power the pumps that distribute the nutrient solution. Using electricity from sustainable sources helps reduce greenhouse gas emissions and the consumption of non-renewable resources.

In conclusion, despite the plant growth phase representing a significant impact in aeroponic plant cultivation, its intrinsic characteristics offer numerous environmental advantages [22]. The precise control of nutrient inputs, reduction in land use, and the adoption of renewable energy sources are just some of the aspects that make aeroponic cultivation a more sustainable and eco-friendly method for greenhouse tomato production.

Author Contributions: Methodology, M.T.; Investigation, M.C.P.; Data curation, G.G.; Writing—review & editing, S.P.; Project administration, A.C.; Funding acquisition, G.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Project IN.TE.S.A.—Innovation dans les Technologies à support d'un développement Soutenable de l'Agro-Industrie—co-financed by FESR under the ENI Italy–Tunisia 2014–2020 cross-border cooperation program (www.italietunisie.eu), grant number C54I19001630005.

Institutional Review Board Statement: Not relevant for this study.

Informed Consent Statement: Not applicable.

Data Availability Statement: All the data are been reported in the manuscript.

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

References

1. Tilman, D.; Balzer, C.; Hill, J.; Befort, B.L. Global food demand and the sustainable intensification of agriculture. *Proc. Natl. Acad. Sci. USA* **2011**, *108*, 20260–20264. [CrossRef] [PubMed]
2. Beach, R.H.; DeAngelo, B.J.; Rose, S.; Li, C.; Salas, W.; DelGrosso, S.J. Mitigation potential and costs for global agricultural greenhouse gas emissions. *Agric. Econ.* **2008**, *38*, 109–115. [CrossRef]
3. UNESCO. *World Water Assessment Programme. The United Nations World Water Development Report 2021: Valuing Water*; United Nations: New York, NY, USA, 2021; Available online: https://www.unwater.org/publications/un-world-water-development-report-2021 (accessed on 31 July 2023).
4. United Nations Convention to Combat Desertification. *The Global Land Outlook*, 2nd ed.; UNCCD: Bonn, Germany, 2022.
5. FAO and ITPS. *The Status of the World's Soil Resources (Main Report)*; FAO and ITPS: Rome, Italy, 2015.
6. Poore, J.; Nemecek, T. Reducing food's environmental impacts through producers and consumers. *Science* **2018**, *360*, 987–992. [CrossRef] [PubMed]
7. United Nations Department of Economic and Social Affairs, Population Division. *World Population Prospects 2022: Summary of Results*; DESA/POP/2022/TR/NO. 3; United Nations: New York, NY, USA, 2022.
8. *ISO 14040*; Environmental Management. Life Cycle Assessment. Principles and Framework, 2nd ed. International Organization for Standardization: Geneva, Switzerland, 2006.
9. *ISO 14044*; Environmental Management—Life Cycle Assessment—Requirements and Guidelines. International Organization for Standardization: Geneva, Switzerland, 2006.
10. Perrin, A.; Basset-Mens, C.; Gabrielle, B. Life cycle assessment of vegetable products: A review focusing on cropping systems diversity and the estimation of field emissions. *Int. J. Life Cycle Assess.* **2014**, *19*, 1247–1263. [CrossRef]
11. FAOSTAT. FAO Stat. Database. 2021. Available online: http://www.fao.org/faostat (accessed on 17 July 2023).
12. Naseer, M.; Persson, T.; Hjelkrem, A.G.R.; Ruoff, P.; Verheul, M.J. Life cycle assessment of tomato production for different production strategies in Norway. *J. Clean. Prod.* **2022**, *372*, 133659. [CrossRef]
13. Pineda, I.T.; Lee, Y.D.; Kim, Y.S.; Lee, S.M.; Park, K.S. Review of inventory data in life cycle assessment applied in production of fresh tomato in greenhouse. *J. Clean. Prod.* **2021**, *282*, 124395. [CrossRef]
14. Solimene, S.; Coluccia, D.; Bernardo, A. Environmental Impact of Different Business Models: An LCA Study of Fresh Tomato Production in Italy. *Sustainability* **2023**, *15*, 10365. [CrossRef]
15. Tamburini, E.; Pedrini, P.; Marchetti, M.G.; Fano, E.A.; Castaldelli, G. Life cycle based evaluation of environmental and economic impacts of agricultural productions in the Mediterranean area. *Sustainability* **2015**, *7*, 2915–2935. [CrossRef]
16. Bosona, T.; Gebresenbet, G. Life cycle analysis of organic tomato production and supply in Sweden. *J. Clean. Prod.* **2018**, *196*, 635–643. [CrossRef]
17. Canaj, K.; Mehmeti, A.; Cantore, V.; Todorović, M. LCA of tomato greenhouse production using spatially differentiated life cycle impact assessment indicators: An Albanian case study. *Environ. Sci. Pollut. Res.* **2020**, *27*, 6960–6970. [CrossRef] [PubMed]
18. Payen, S.; Basset-Mens, C.; Perret, S. LCA of local and imported tomato: An energy and water trade-off. *J. Clean. Prod.* **2015**, *87*, 139–148. [CrossRef]
19. Torrellas, M.; Antón, A.; López, J.C.; Baeza, E.J.; Parra, J.P.; Muñoz, P.; Montero, J.I. LCA of a tomato crop in a multi-tunnel greenhouse in Almeria. *Int. J. Life Cycle Assess.* **2012**, *17*, 863–875. [CrossRef]
20. Russo, G.; Scarascia Mugnozza, G. LCA methodology applied to various typology of greenhouses. In Proceedings of the International Conference on Sustainable Greenhouse Systems—GREENSYS 2004, Leuven, Belgium, 12–16 September 2004; Volume 691, pp. 837–844.
21. Anton, A.; Montero, J.I.; Munoz, P.; Castells, F. LCA and tomato production in Mediterranean greenhouses. *Int. J. Agric. Resour. Gov. Ecol.* **2005**, *4*, 102–112. [CrossRef]
22. Lakhiar, I.A.; Gao, J.; Syed, T.N.; Chandio, F.A.; Buttar, N.A. Modern plant cultivation technologies in agriculture under controlled environment: A review on aeroponics. *J. Plant Interact.* **2018**, *13*, 338–352. [CrossRef]

23. Kumari, R.; Kumar, R. Aeroponics: A review on modern agriculture technology. *Indian Farmer* **2019**, *6*, 286–292.
24. AlShrouf, A. Hydroponics, aeroponic and aquaponic as compared with conventional farming. *Am. Sci. Res. J. Eng. Technol. Sci.* **2017**, *27*, 247–255.
25. Cellura, M.; Longo, S.; Mistretta, M. Life Cycle Assessment (LCA) of protected crops: An Italian case study. *J. Clean. Prod.* **2012**, *28*, 56–62. [CrossRef]
26. Irabien, A.; Darton, R.C. Energy–water–food nexus in the Spanish greenhouse tomato production. *Clean Technol. Environ. Policy* **2016**, *18*, 1307–1316. [CrossRef]
27. Nordenström, E.; Guest, G.; Fröling, M. LCA of Local Bio-chp Fuelled Greeenhouses Versus Mediterranean Open Fiel Tomatoes for Consumption in Northern Scandinavia. In Proceedings of the Linnaeus ECO-TECH '10, Kalmar, Sweden, 22–24 November 2010; pp. 475–484.
28. Elings, A.; Kempkes, F.L.K.; Kaarsemaker, R.C.; Ruijs, M.N.A.; Van de Braak, N.J.; Dueck, T.A. The energy balance and energy-saving measures in greenhouse tomato cultivation. In Proceedings of the International Conference on Sustainable Greenhouse Systems—Greensys 2004, Leuven, Belgium, 12–16 September 2004; Volume 691, pp. 67–74.
29. Ghasemi, F.; Vílchez, V.F.; Asadi, I. The Life Cycle Assessment on Environmental Impacts of Greenhouse Crops: A Theoretical Review. *J. Environ. Treat. Technol.* **2022**, *10*, 35–46.
30. Tuomisto, H.L.; Hodge, I.D.; Riordan, P.; Macdonald, D.W. Does organic farming reduce environmental impacts?—A meta-analysis of European research. *J. Environ. Manag.* **2012**, *112*, 309–320. [CrossRef] [PubMed]