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Environmental and Economic Performance of Greenhouse Cropping in the Mediterranean Basin: Lessons Learnt from a Cross-Country Comparison

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Abstract: In the Mediterranean region, the expansion of greenhouse horticulture has enabled the year-round supply of fresh vegetables. Compared to open field horticulture, this farming method can generate higher returns for farmers. However, it is often associated with significant environmental pressures. This research aims to pinpoint important opportunities for improvement of the environmental and economic performance of greenhouse farming in the Mediterranean region by showing the life cycle's environmental and economic impacts and by highlighting life cycle hotspots. This is achieved through the combined application of life cycle assessment and life cycle costing to four case studies (commercial greenhouses) spanning the Mediterranean Basin (Italy, Spain, Tunisia, and Turkey). The case study findings highlight the following environmental hotspots and related impacts: (i) fertigation management can generate up to 11,283 m^3/ha/year of water use impact; (ii) fertilizer leaching can generate up to 27 kg of N eq marine eutrophication impact; and (iii) crop protection treatments can generate up to 130,037 kg 1,4-DCB of terrestrial ecotoxicity impact. The large use of plastic materials (greenhouse and fertigation infrastructures) is an additional critical aspect due to manufacturing and disposal, contributing to eutrophication impact categories. Economic hotspots are related to greenhouse management (up to 35% total costs of production) and hired labor (up to 40% total costs of production). The lessons learnt from these case studies offer valuable insights into the sustainability challenges of greenhouse horticulture across the Mediterranean region. The hotspot analysis points to the need for targeted interventions to mitigate the most critical impacts while ensuring economic viability. This study enriches scientific understanding by examining different production and socioeconomic contexts, offering crucial insights for the advancement of sustainable practices in greenhouse agriculture such as the use of decision support systems to optimize input use.

Keywords: life cycle assessment; life cycle costing; hotspot analysis; normalization; protected horticulture; tomato

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1. Introduction

Over the past decades, greenhouse horticulture has developed enormously in the Mediterranean Basin due to its favorable climatic conditions (mild winters, high irradiance in autumn and winter), which have enabled year-round production without the need for large structural investments [1], thereby making greenhouse farmers very competitive in the market [2]. However, greenhouse farming creates significant environmental impacts, as it requires the consumption of significant amounts of production inputs (especially fertilizers and pesticides) and natural resources (mainly water for irrigation) to ensure optimal growing conditions for crops [3]. Understanding these impacts and the processes that primarily contribute to them (hotspots) can provide valuable information for optimizing the sustainability of greenhouse tomato production [4]. Mediterranean greenhouses for vegetable production share several common features (e.g., simple metal and plastic structures, no artificial lighting systems and low levels of technology, among others). However, management practices (e.g., in-soil vs. soilless cultivation, integrated pest management) are likely to differ across countries, due to specific aspects such as the diversity of climatic conditions (e.g., lack of water for irrigation due to long drought periods) and economic contexts, which affect the sustainability of greenhouse farming.

This study presents research carried out as part of the activities of the iGUESSmed project [5]. The aim of this research is to identify and suggest improvements to current greenhouse production systems in the Mediterranean Basin that have the potential to increase their environmental and economic sustainability. Three specific research questions (RQ) were identified to achieve the aim of the research, as follows:

RQ1: "What are the environmental and economic impacts of greenhouse production in different Mediterranean countries?"

RQ2: "What are environmental and economic hotspots?"

RQ3: "What recommendations can be derived from the analysis of case studies that may have potential implications for increasing the sustainability of greenhouse horticulture?"

The research questions are answered by developing a comparative life cycle assessment (LCA; ISO 14040-14044:2006 [6,7]) and life cycle costing (LCC; ISO 15686-5:2017 [8]), which are performed in case studies of tomato greenhouse production (RQ1) by carrying out hotspot analysis through contribution analysis and external normalization (RQ2) and identifying the lessons learnt from previous steps (RQ1, RQ2) that may generate useful implications beyond the case study level (RQ3). Tomato was chosen as a representative crop as it is the most widely grown and consumed fresh vegetable in the Mediterranean region and is also extensively exported [9]. The primary data (years 2022–2023) refer to real-world greenhouses that are reasonably representative at the regional level in Tuscany (Italy), Almería (Spain), Monastir (Tunisia), and Antalya (Turkey). The regions are level two areas under the nomenclature of territorial units for statistics for countries in the European Union (EU) and Turkey (EU candidate country) and a comparable area in Tunisia.

The case studies differ for cultivation methods (in-soil, soilless), irrigation water sources (rain harvesting system, well), and pest control methods (conventional, integrated pest management).

LCA and LCC (ISO 15686-5:2017) are widely used in the scientific literature, individually or together, to assess the overall sustainability of an agricultural practice or product. The two methods have been used together in different situations, such as evaluating the profitability of a bell pepper greenhouse using desalinized water for irrigation and nematode-resistant plants in Spain [10], evaluating the impacts of two different smart irrigation systems versus traditional irrigation in zucchini cultivation [11], and comparing the performance of five different crops raised in northern Italy [12]. This combination of LCA and LCC is also used for comparing different production systems [13] or systems under different climatic conditions [14]. However, there is a lack of comparative studies that consider similarities and the diversity of production systems in different countries of the Mediterranean Basin. Bridging this gap is of utmost importance for providing recommendations for policy makers and decision-makers on how to create pathways for sustainable greenhouse horticulture in Mediterranean countries and beyond by exploiting success factors and mitigating the diffusion of the practices with the most negative effects on the environment and the economic performance of farms.

This manuscript has three more sections. The next section details the methodological approach and data for the LCA and LCC. Assessment findings and hotspot analysis are presented in the Results section, which follows. Lessons learnt and their implications are presented in the Discussion section alongside the study limitations. Finally, the Conclusions provide the key take-home messages from this research, recommendations for policymakers and decision-makers on how to increase the sustainability of Mediterranean greenhouse production, and recommendations for advancing research.

2. Materials and Methods

An LCA study has interconnected mandatory steps: (1) goal and scope definition, including the identification of the system boundaries and the selection of the most suitable functional unit; (2) life cycle inventory analysis, based on the collection of all of the system's inputs and outputs; (3) life cycle impact assessment, in which the impacts are characterized; and (4) interpretation, to improve understanding of the study findings and derive recommendations, including contribution analysis. Optional steps are normalization and weighing. In this study, the normalization of characterized impacts is carried out. The same steps are followed for LCC, except for the life cycle impact assessment and normalization, which are not necessary as all data are already expressed in currency units [15]. The hotspot analysis was carried out by combining contribution analysis with the analysis of normalized impacts [16].

2.1. Goal and Scope Definition

The goal of this study is to assess the environmental and economic impacts of tomato production in greenhouses in different Mediterranean countries and under different management conditions. Production hotspots are identified by highlighting the contribution of life cycle stages and their constituting processes to impact categories [17]. Similarities and differences emerging from impact assessment and hotspot analysis are used for generating lessons learnt with implications for an international audience.

The functional unit is the occupation of 1 hectare of greenhouse tomato production for 1 year. The selection of an area-based functional unit emphasizes the impacts of greenhouse cultivation in the case studies and enables the delivery of recommendations to improve the overall sustainability of the protected cultivation systems in the reference regions [18]. Primary data refer to the year 2022. Commercial greenhouse management is not subject to relevant changes across the years. Farmers adopt the same cultivation cycles for the same crop species in the same geographical locations. Fertigation management does not change, nor does substrate management in soilless systems. There might be just minor adaptations in input use to meet climate conditions.

2.1.1. Case Studies

Tuscany, Italy (43°07′30″ N; 10°38′24″ E)

This greenhouse is part of a family-owned farm and is operated with the aid of hired labor (two family members and three hired workers). The greenhouse surface is 0.67 ha with a density of three plants/m^2, with chemical pest management. The irrigation water is from a private well. There are two annual production cycles (293 days). The commercial yield is 159.3 t/ha. Tomatoes (cv. Pisanello) are sold to local retailers; the average producer price is 1.44 €/kg. The distinctive characteristics of the Tuscany case study are soilless cultivation (open loop) in coir pith substrate bags and the use of emergency heating in winter through a diesel heating system (emergency heating: 14 nights during the study period). The frame includes galvanized steel arches with concrete anchorage and plastic (LDPE) covering. The floor is covered with plastic (PP) mulch. Ventilation is managed through roof windows and side openings (manually operated). Openings include plastic (HDPE) insect nets. The drip irrigation system includes a plastic (PVC) distribution system, five nutrient tanks, a fertigation control unit, and a pump that draws water from the farm well. The substrate is replaced every 2 years; exhausted coir pith is reused on the farm (soil spreading). Metal and paper are delivered (100%) to dedicated recycling plants; 50% of plastic is recycled.

The test site is representative of the sector in Tuscany due to the type of greenhouse, soilless production method, agronomic practice, and type of value chain [15]. Tuscany hosts key greenhouse farming districts, which greatly contribute to the domestic production of fresh vegetables and the local economy [19,20].

Almería, Spain (36°51′46″ N, 2°17′04″ W)

This greenhouse is part of a family-owned farm and operated with the aid of hired labor (two family members and three hired workers). The greenhouse surface (in soil cultivation) is 0.8 ha with a density of two plants/m^2 and IPM (biological control). Irrigation water comes from a private well. It has a single and short annual production cycle (112 days), which takes full advantage of favorable spring conditions. The greenhouse is used for growing another crop during the autumn–winter period. The commercial yield is 127 t/ha. The cultivated crop is cluster tomato with Emperador rootstock. Fresh tomatoes are sold to local retailers; the average producer price is 0.69 €/kg. Every 3 years, a soil treatment with sheep manure is conducted to enhance nutrient availability in the soil. The greenhouse consists of a steel frame with concrete anchorage and a double-layer LDPE roof. Ventilation is facilitated through roof and side openings (electronically operated), shielded by HDPE insect nets. Fertigation is managed via drip irrigation, regulated by an automated Venturi system. Metals and paper are entirely (100%) recycled in dedicated plants; 50% of plastic and concrete are recycled.

The greenhouse is of the Parral type, i.e., the most widespread greenhouse structure in Spain, especially in Almería where crops are grown on the typical *enarenado* (sand-mulched) soils [21,22].

Monastir, Tunisia (35°45′18″ N, 10°49′16″ E)

This greenhouse is part of a family-owned farm and operated with the aid of hired labor (one family member and six seasonal workers). The greenhouse surface (in-soil cultivation) is 0.15 ha with a density of 1.6 plants/m^2 and chemical pest management. The greenhouse is equipped with a plastic artificial pond for rainwater harvesting. It has a single annual production cycle (225 days). The commercial yield is 157.8 t/ha. Tomatoes (cv. Pai Pai) are sold to local retailers; the average producer price is 0.48 €/kg. The greenhouse structure is made of a galvanized steel frame with concrete anchorage and LDPE coverage. The floor is covered with PP mulch cloth. Ventilation openings on the roof and side walls are manually operated and covered with HDPE insect nets. Fertigation is ensured by a drip irrigation system with a pumping unit. Half of the water needs are supplied by the farm well and the rainwater collection pond, which is constructed with PVC sheeting. The rest is from a public dam system. Metals and paper are completely recycled (100%); 50% plastic and concrete are recycled.

Monastir is the major producer of the greenhouse horticulture crops of Tunisia, both in terms of covered surface and quantity of products, especially tomatoes (25% domestic production). The test site is representative of the Monastir greenhouse sector due to the typical greenhouse structure and production practice [23,24]. Water for irrigation comes from the Nebhana dam, water drilling, and rainwater harvesting systems. Due to drought, irrigation water quotas of the Nebhana dam have recently been reduced, and well water quality has decreased; therefore, a growing number of farmers have used water harvesting systems [25].

Antalya, Turkey (36°58′13″ N, 30°56′08″ E)

The greenhouse analyzed is part of a family farm operated with the aid of hired labor (one family member and six seasonal workers). The greenhouse surface (in-soil cultivation) is 0.42 ha with a density of 2.5 plants/m^2 and chemical pest management. Irrigation water comes from a private well. There are two annual production cycles (275 days). The commercial yield is 147.4 t/ha. The cultivated variety is cluster tomatoes that are sold to local retailers; the average producer price is 0.34 €/kg. The greenhouse frame is made of galvanized steel with concrete anchorage and an LDPE cover. Ventilation is supported by roof and side openings (electronically operated), screened by HDPE insect nets. Fertigation is managed through a drip irrigation system, regulated by an automated Venturi system. Metals and paper are recycled (100%); other materials are landfilled.

Antalya has the largest greenhouse horticulture surface and is the first producer of the horticultural crops of Turkey. The test site is representative for Antalya due to the greenhouse type and surface (average surface in Antalya is 0.4 ha), as well as for farming practice [26].

2.1.2. System Boundaries

Similar to most agricultural LCA and LCC studies [13,14], system boundaries are cradle-to-gate, i.e., ranging from the manufacturing of production inputs to the delivery of marketable tomatoes at the farm gate (Figure 1).

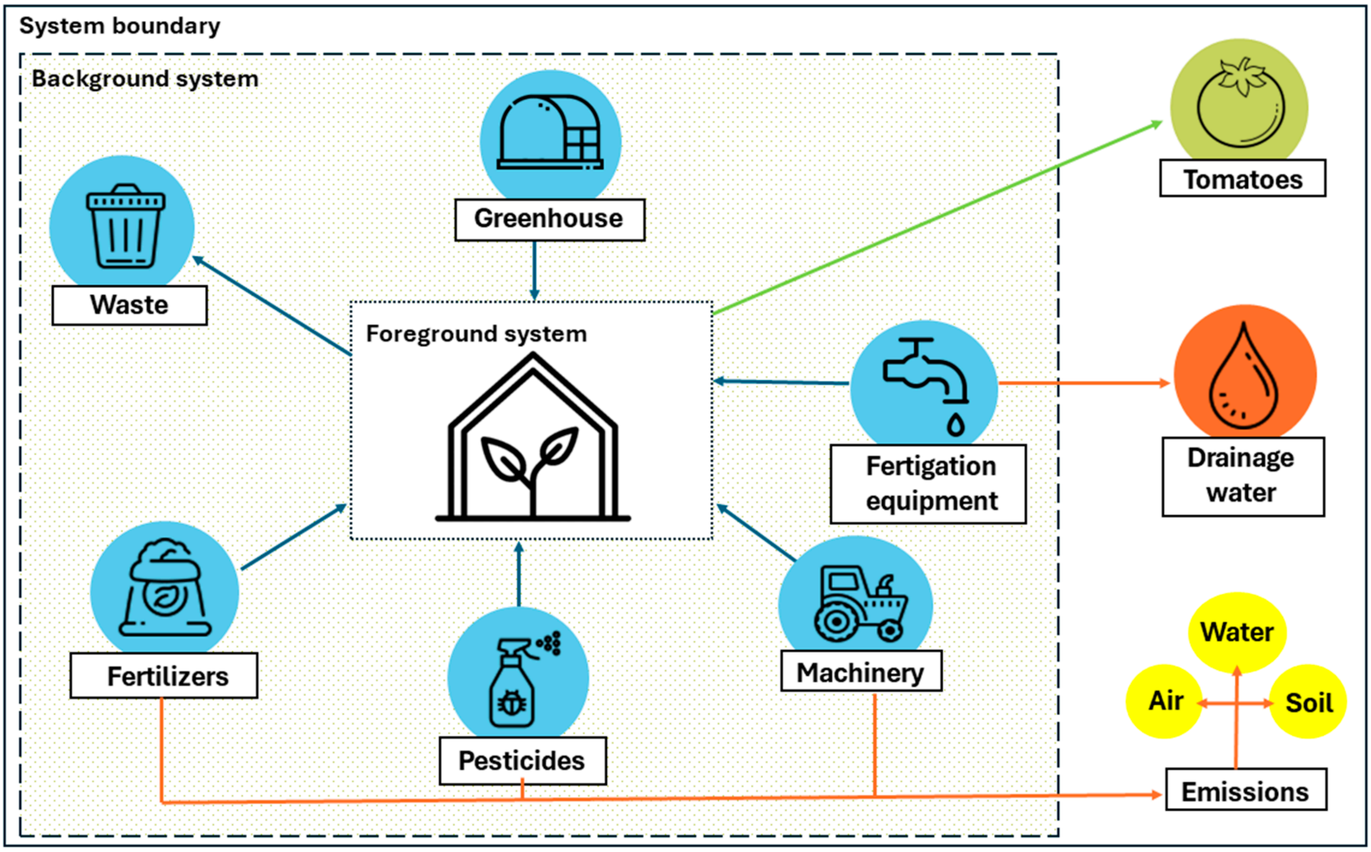

Figure 1. System boundaries of cradle-to-gate life cycle assessment and life cycle costing in the case studies. Source: Authors' own elaboration.

Life cycle stages are identified to facilitate the comparison with similar literature [15] and for the identification of hotspots, i.e.: (i) greenhouse, including building materials, covering materials, and plant supports; (ii) fertigation system, including pipes, tanks, fertigation control unit, artificial pond, etc.; (iii) machinery, including sprayers, tractors, tillers, etc.; (iv) fertilizers; (v) pesticides, including chemical and organic pesticides, useful insects, and traps; and (vi) waste, which includes materials at the end of their useful lives. Background stages refer to input production and end-of-life management (materials), as well as their outputs to the environment, i.e., indirect emissions. The foreground stage includes the consumption of production inputs to cultivate tomatoes and produce the commercial yield. This stage includes all field operations and direct emissions to the environment.

2.2. Life Cycle Inventory Analysis

This phase consists of the compilation and quantification of all inputs and outputs of the system under study, following the cutoff approach. Under this approach, waste is considered the farmer's responsibility (polluter pays the principle), and the use of the recycled products is considered burden free, being raw material for other processes (to avoid double counting) [27].

Background data, including indirect emissions to air, water, and soil, are from the Ecoinvent®3.8 [28] and Agri-footprint®4.0 [29] databases. Missing processes are sourced from the literature [15,30,31]. The primary data for foreground processes are from interviews with farmers and advisors at the case study level. In the Almería case study, live organisms for biological control under IPM are produced in an insect factory. The data used to model this process and related indirect emissions were provided by the producer (located in Italy).

2.2.1. Materials and Resources

Tables 1 and 2 show, respectively, the quantities of materials used and the costs for the farmers in the four case studies.

Table 1. Life cycle inventory: annual material and resource inputs quantities for one hectare of greenhouse. a.i. = active ingredient. * Nutrients from manure treatment are included. Source: Authors' own elaboration.

Inputs (ha/year)	Unit	Case Studies			
		Tuscany	Almería	Monastir	Antalya
Concrete	m^3	5.0	3.9	2.5	5.0
Metals	kg	881	1248	1257	2082
Plastics	kg	1900	1499	7459	2095
Electronic component	kg	9.5	0.1	1.2	0.2
Growing substrate	kg	2604	-	-	-
Agricultural machinery	kg	180	2000	1470	5053
Fuel	L	1986	127	1050	365
Water	m^3	10125	5142	6160	13,170
Electricity	kWh	777	431	1800	6481
N	kg	1282	603 *	377	1485
K_2O	kg	2072	1057	707	2525
P_2O_5	kg	484	460	464	853
Other nutrients	kg	1056	1179	312	664
Chemical pesticides (a.i)	kg	7.1	5.7	8.6	1.7
Biopesticides (a.i.)	Kg	2.2	3.8	0.2	0.3

Table 2. Life cycle cost inventory. * This is considered as a separate item, being available in one out of four case studies. ** For the Almería case study, this includes the service of the treatment of *enarenado* soil with sheep manure every 3 years. Source: Authors' own elaboration.

Production Stages	Breakdown of Costs	Price (€/ha/year)			
		Tuscany	Almería	Monastir	Antalya
Greenhouse infrastructure	Investment (construction materials and transport, project design)	14,733	6542	6280	4266
	Investment (heating system and transport) *	3518	-	-	-
	Maintenance	6191	1041	359	1766
	Consumables and packaging	29,733	17,129	17,287	3272
	Transport (consumables only)	49	29	208	19
	Electricity	53	637	-	139
Fertigation system	Investment	3780	3514	2729	1648
	Maintenance	1682	2207	469	1199
	Electricity	64	350	360	21
	Substate	15,000	-	-	-
	Water tax	-	-	288	-
Machinery	Investment (rent or purchase)	1100	1100	1541	368
	Fuel and maintenance	657	193	726	200
Fertilizers	Consumables (and transport)	14,592	10,308	2587	13,107
	Manure treatment (every 3 years)	-	929	-	-
Pesticides	Chemical consumables (and transport)	1844	2500	1185	342
	Biocontrol consumables	1190	1241	1026	-
Waste	Waste management and demolition	547	585	1188	1337
Labor and services	Labor **	52,060	27,531	11,326	6665
	Advisory services, taxes, and administration	8500	1630	984	60

For half of the year, the Almería greenhouse is used for another crop; both the quantities and costs of materials needed to build the greenhouse and those of the fertigation system were reduced by 50% in this study. All the examined greenhouses feature a steel framework, secured by concrete plinths, and are covered with plastic roofing (low density polyethylene), which is typically replaced every 3 years. These structures are multi-bay greenhouses, with roof apertures shielded by plastic (high density polyethylene) insect nets. The significant plastic usage observed in the Monastir case primarily stems from the plastic bottom (polyvinyl chloride) of the rainwater harvesting pond that has a lifespan of five years. The fertigation system used in greenhouses with soil cultivation is simple and consists of a set of pipes and injectors operated by a pump, while an electronic irrigation control unit is used in the Tuscany greenhouse. In addition, cultivation in the Tuscany greenhouse is conducted directly in bags of substrate, eliminating the need for large agricultural machinery. The significant fuel consumption in this configuration comes mainly from diesel heating pumps. The higher fertilizer consumption in greenhouses in Tuscany and Antalya is justified by the higher planting density.

The economic inventory is compiled from the farmer's perspective and includes material costs as well as labor costs, overhead, insurance costs, and taxes (Table 2).

The labor force includes two full-time farm family members in each case and a variable number of seasonal workers. The Labor price includes the wages of hired workers and pension contributions for family workers. The monetary value of all economic indicators is expressed in euros (€), using the average exchange rate for the year 2022 to convert prices from non-EU countries.

2.2.2. Direct Emissions

Direct emissions are calculated for machinery, fertilizers, and pesticides through emission factors (Tables 3 and A2).

Table 3. Calculation of direct emissions to air, water, and soil. Source: Authors' own elaboration.

Emissions	Formulas	Description	Source
Machinery (to air)			
CO, HC, NO_x CO_2, CH_4, NH_3, SO_2 $PM_{2.5}$	$=ER_{CO,HC,NOx} \times ot$ $=DC \times EF_{CO2,CH4,NH3,SO2}$ $=EF_{PM2.5} \times 0.854 \times MP \times ot$	ER = reference emissions from field operation (g/h); ot = operation time (hours) DC = diesel consumption EF = emission factor (g/kg_{diesel}) MP = mean power during fieldwork	[32]
Fertilizers (to water)			
N_2O NH_3 NO_x	=1.25% of N_f =2% of N_f =0.21 × emissions of N_2O	N_f = total N applied with fertilizers (kg/ha)	[32]
Fertilizers (to soil)			
NO_3 K_2O	$=0.3 \times N_f$ $=K_{pl} \times (K_l/100)$	K_{pl} = amount of potentially leachable potassium oxide (kg/ha) K_l = leaching coefficient	[33,34]
Pesticides			
To air To water To soil	=5% total a.i. =8.5% total a.i. =76.5% total a.i.	a.i. = active ingredient (g/ha)	[35–37]

The combustion of diesel fuel during machinery use for field operations is mainly responsible for the release of climate active gases, but it is also mainly responsible for the increase in fine particulate matter formation, eutrophication, and acidification. The calculation of emissions in the air from agricultural machinery is based on [32]. Only the most relevant types of exhaust gases according to the existent literature were calculated [38,39].

Fertilizer consumption can significantly affect the environmental impact in terms of air acidification, eutrophication, and photochemical oxidant formation [40]. Emissions of NH_3, N_2O, and NO_x to the air and of NO_3 to water were calculated based on [32–34]. Due to the rapid adsorption and fixation in the soil and the absence of rainfall for a controlled environment, phosphate is leached little and in rather long times, so it is not a potential danger for groundwater contamination [34]. Additionally, phosphates were not considered in the calculation of emissions as in similar research [41]. Therefore, water emissions of potassium, calculated based on [34], were considered.

Direct emissions from pesticides were calculated only for active chemical ingredients that have effects on toxicity, especially freshwater toxicity [42]. A variety of chemical active ingredients are used in the case studies (see Table A1). Direct emissions to the air were calculated as 5% of the total applied quantity by assuming that the applications are carried out with closed windows [37]. Emissions to other compartments were calculated based on [35,36] by assuming that 76.5% is emitted to soil, and 8.5% is emitted to water. Active ingredient residual on the crop (biomass and fruit) are not considered, being beyond the set system boundaries.

2.3. Life Cycle Impact Assessment

In the LCA, direct and indirect emissions are classified into impacts and characterized based on the selected impact assessment method. In this study, we use ReCiPe 2016 midpoint (H), as it is suitable for EU and non-EU countries [43].

The following impact categories were considered for their relevance to greenhouse horticulture [15,44]: climate change, fine particulate matter formation, terrestrial acidification, freshwater eutrophication, marine eutrophication; terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity, human non-carcinogenic toxicity and water consumption.

In the LCC, there is no life cycle impact assessment. We used three distinct economic impact indicators: total cost of current production (TCOP); net present value (NPV) calculated over the life cycle of the greenhouse (20 years) with a 10% interest rate; and profitability index (PI), a dimensionless indicator for the efficiency of the investment over time [15]. PI is calculated as the ratio of NPV to investment costs: profitable case studies have PI > 1.

2.4. Interpretation, Normalization, and Hotspot Analysis

The calculated environmental and economic impacts are analyzed in a comparative way, using normalized data to understand the ranking of impact categories. Contribution analysis is used to identify the life cycle stages and the relative processes, which generate the highest shares of impacts per each impact category. In the LCC, this is performed for the TCOP indicator and enables a more meaningful comparison of the case studies. Normalization is an optional step in LCA that aims to evaluate the environmental impacts identified during the analysis in a more understandable and interpretable way. During an LCA, several impacts are identified and quantified, each expressed in specific units of measurement, thereby preventing impact ranking. Normalization provides a baseline of the pressure on the environment for each category of environmental impact, allowing the quantities in each category to be translated into relative contributions to the overall average [45]. The normalized results are then comparable to each other and help to communicate more clearly the scale and significance of these impacts in a broader context [46]. A commonly used reference value is the average annual environmental load of a country or continent divided by the number of inhabitants. in this study, we used the World (2010) H reference normalization factor, embedded in the ReCiPe 2016 method.

Hotspot analysis results from the combination of contribution analysis and normalization. They deliver indications about the prioritization of intervention to mitigate the impact on the most relevant impact categories (normalization) and the life cycle stages and relative processes toward which this intervention should be primarily directed [16].

3. Results

3.1. Impact Assessment

The environmental impacts of each case study are shown in Table 4.

Table 4. Absolute life cycle assessment results. Functional unit (1 ha). CC = climate change, PM = fine particulate matter formation, AC = terrestrial acidification, FE = freshwater eutrophication, ME = marine eutrophication; TET = terrestrial ecotoxicity, FET = freshwater ecotoxicity, MET = marine ecotoxicity, HCT = human carcinogenic toxicity, HnCT = human non-carcinogenic toxicity, and WC = water consumption. Source: Authors' own elaboration.

Impact Categories	Unit	Tuscany	Almería	Monastir	Antalya
CC	kg CO_2 eq	34,393	28,678	54,087	53,818
PM	kg $PM_{2.5}$ eq	75.6	74.4	150	124
AC	kg SO_2 eq	257	136	390	206
FE	kg P eq	15.5	14.7	36.6	33.6
ME	kg N eq	36.2	14.5	15.3	35.5
TET	kg 1,4-DCB	211,211	175,547	167,203	328,531
FET	kg 1,4-DCB	3806	2169	2453	3799
MET	kg 1,4-DCB	3663	2901	3077	5022
HCT	kg 1,4-DCB	3589	7440	8305	14,617
HnCT	kg 1,4-DCB	50,749	39,999	53,139	67,593
WC	m^3	8276	3475	3775	11,283

The results show that the non-EU case studies have higher average impacts than the EU case studies. The Antalya case study shows above-average impacts in almost all categories except for terrestrial acidification, where it shows lower impacts than both the Tuscany (by about one-fifth) and Monastir (by about half) case studies. In this comparison, the Antalya case shows maximum impacts in the categories of human toxicity, ecotoxicity, and water consumption. In contrast, the Monastir greenhouse shows considerable impacts in climate change (slightly higher than those of the Antalya greenhouse), fine particulate matter formation, terrestrial acidification, and freshwater eutrophication (almost double that of the EU cases). The Tuscany greenhouse shows average values comparable to those of the Almería greenhouse, although with notable peaks in marine eutrophication (more than twice as high as the Almería and Monastir cases) and freshwater ecotoxicity (about one-third higher than the Almería and Monastir cases) due to high fertilizer consumption. Terrestrial acidification and water consumption also show high average values in the comparison, while the category of human carcinogenic toxicity is the lowest among the cases analyzed (four times lower than the Antalya greenhouse and about two times lower than the other cases). Finally, the greenhouse in Almería showed the lowest impacts in the categories CC (only 2% lower than Tuscany), AC (about two and a half times less than Monastir), FE (half as much as Monastir), ME (equal to the case in Antalya and less than half the impacts of the other two cases), and WC (about three times less than Antalya).

Table 5 illustrates the values of the economic indicators for each case study.

Table 5. Life cycle costing indicators. TCOP = total cost of production; NPV = net present value (20 years); PI = profitability. Source: Authors' own elaboration.

Economic Indicators	Unit	Tuscany	Almería	Monastir	Antalya
TCOP	€/ha/yr	155,332	77,436	48,543	34,408
NPV	€/ha (20 years)	463,123	254,007	162,013	90,759
PI	(20 years)	1.28	1.59	1.26	1.05

Higher annual costs are found in EU greenhouses, particularly notable in the Tuscany case. Here, the inclusion of an emergency heating system and the adoption of soilless cultivation significantly escalate the initial investment. However, this investment is balanced by robust production and favored by the extension of the production cycle and higher planting density, as well as the sale of a niche variety that is priced higher than other tomato varieties. In particular, the Almería case study shows the most favorable profitability index in the long run (20 years), followed by the Tuscany and Monastir case studies. The Antalya case study shows the lowest PI, that is, the efficiency of the investment over time, compared to the other cases analyzed.

3.2. Hotspot Analysis

Hotspot analysis shows that fertilizer, greenhouses, and machinery are the life cycle stages that contribute most to the impacts characterized, though with some differences in each case study (Figure 2).

In the Tuscany case study (Figure 2a), fertilizers are clearly a hotspot, affecting most of the selected impact categories, predominantly the TET (77%) and ME (73%) categories. These impacts are mainly due to the production and extensive use of nitrogen- and phosphorus-based fertilizers. Direct emissions given by use affect mainly the ME category (97% of contribution) and the PM (36%), AC (26%), and CC (22%) categories. The transportation of materials and construction of the greenhouse impact several categories, particularly HCT (53%) and secondarily CC (21%). Contributing most to these impacts are the industrial processes for plastic covers. Direct emissions of chemical pesticides mainly impact the FET (31%), MET (6%), and TET (1%) categories, while their production has a negligible impact. The fertigation system is the largest contributor to WC, but it also has impacts on ME (21%) and AC (16%) due to the production of plastic materials (pipes and microtubes, tanks, and plant supports), steel structures, and substrates. As a soilless crop, it does not require tillage machinery, so the impacts of agricultural machinery are limited. Direct emissions from machinery impact the AC (96% of the total contribution), PM (84%), and CC (14%) categories, with the remaining impact coming from industrial production. Waste contributes most to the FE category (32%), influenced mainly by the disposal of plastics. The production, transportation, and use of the emergency heating system, which was turned on for about 14 nights in the year analyzed, have little influence on the total impacts. In fact, it shows larger contributions in the HCT category (6% of total impacts) and an average of 1% contribution in the other impact categories.

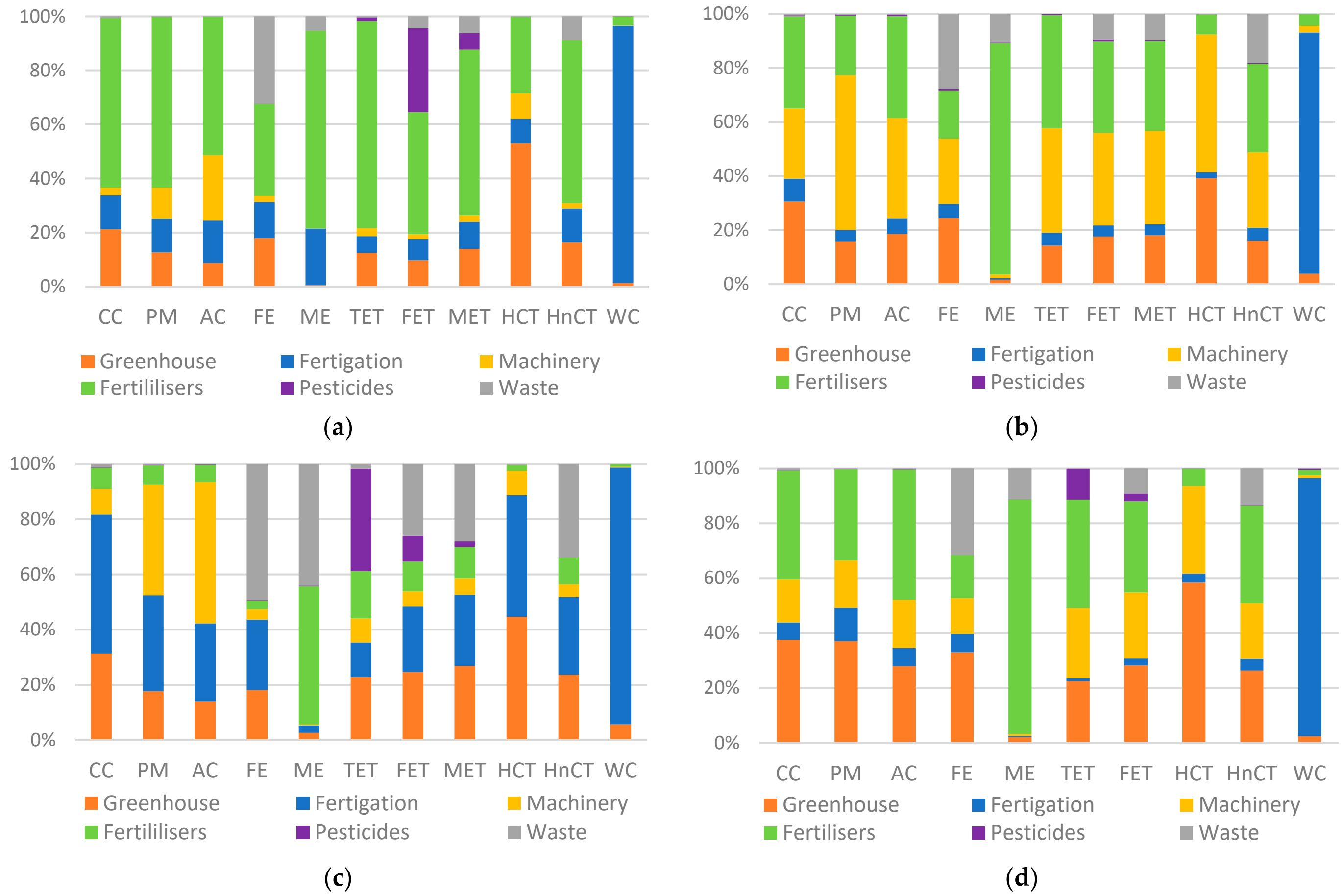

Figure 2. Comparative contribution analysis. (**a**) Tuscany, (**b**) Almería, (**c**) Monastir, and (**d**) Antalya. Source: Authors' own elaboration.

In the Almería case study (Figure 2b), as in the Tuscany case study, fertilizers are a hotspot with high contributions, especially in the categories ME (86%), TET (42%), and AC (38%) categories. Impacts in ME derive 98% from direct emissions, as well as 23% of the contribution in CC, while other impacts come mainly from industrial production. Agricultural machinery is another hotspot, with the greatest impact in the PM (57%) and HCT (51%) categories. Of these contributions, only 67% of PM and 55% of HCT are due to direct emissions from machinery. The construction and maintenance of greenhouses have significant impacts on HCT (39%) and CC (31%), mainly due to the transportation of materials and the industrial processes for creating plastic materials and steel structures. The use of IPM strategies leads to negligible environmental impacts in the pesticide stage. The fertigation system is simple, with few elements, and causes low environmental impacts compared to the other process steps except for water consumption (WC). Waste contributes to the categories FE (28%), HnCT (18%), and aquatic ecotoxicity (11%), especially from the disposal treatments of plastic materials.

In the Monastir case study (Figure 2c), waste is a hotspot, both because of the large amount of plastic going to landfills and because of the great distance of disposal points from the greenhouse. It particularly affects the ME and FE categories (44 and 49%, respectively), but also HnCT (34%) and aquatic ecotoxicity (about 28% in MET and 26% in FET). Emissions from agricultural machinery also contribute particularly to the PM and AC categories (51 and 40%, respectively), with more than 90% of the contribution coming from direct greenhouse emissions. The fertigation system affects mainly the CC category (50%), due to other plastic production (pipes, rain harvesting systems, etc.), and of course the WC category (93%). The production of greenhouse materials as well as their transportation and use contribute to most impact categories, with peaks in HCT (45%) FET, and MET (both about 27%). Direct emissions from fertilizer use have the main impact on ME (50%), resulting from the extensive use of manure and potassium sulfate. The chemical pesticides used show high contributions to the TET category (37%) and moderate content in the FET and MET categories (9 and 2%, respectively). Of this contribution, 88% in MET to 99% in TET depended on direct emissions from their use in greenhouses.

Fertilizers are also a hotspot in the Antalya case study (Figure 2d), where they show high contributions, especially in the categories ME (86% of the total impact), 98% of which comes from direct emissions; and AC (47%) and CC (40%), mainly from nitrogen fertilizer production processes. The transportation of materials and greenhouse maintenance are also hotspots, having high impacts in most categories, with peaks of CC and PM (both about 37%). Emissions from the use of agricultural machinery also have a fair amount of impact in many categories in this case study, with high values in many impact categories, particularly ecotoxicity (from 24% in FET to 26% in TET) and human toxicity (about 32% in HCT). Of these impacts, however, only 21% in PM and 18% in AC come from direct emissions from machinery, with the remaining contribution coming from industrial manufacturing and maintenance processes. Because there is not a real recycling system, all waste (plastics, concrete, and steel) is disposed of in landfills, leading to impacts in the FE (31%), ME (11%), and HnCT (13%) categories. The fertigation system is simple, with few elements, and causes low environmental impacts (averaging 5%, peaking at 12% in PM) compared to the other process steps, except for water consumption (94%). Pesticides show impacts in all categories of ecotoxicity, particularly in TET with an 11% contribution.

Figure 3 shows the economic contributions of each phase to the TCOP of greenhouses.

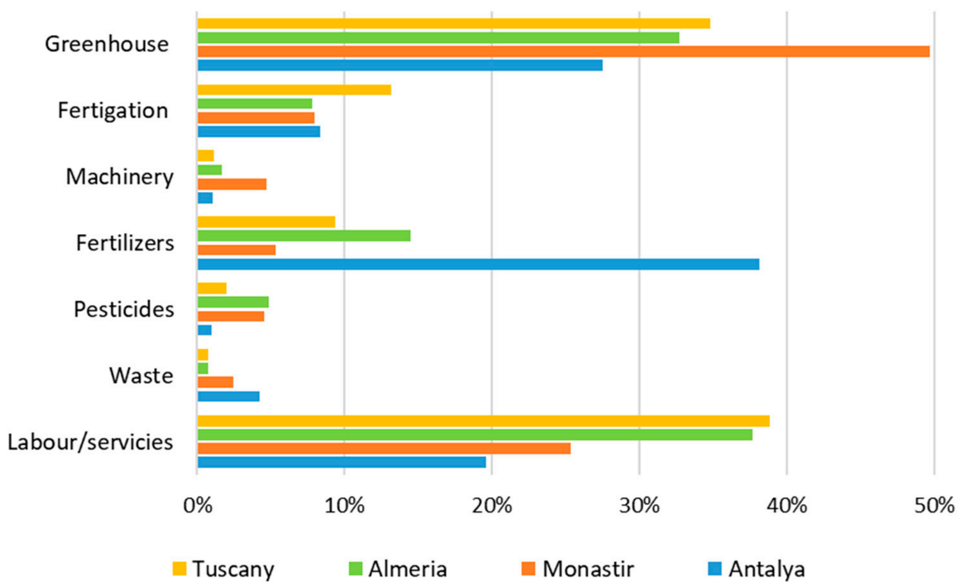

Figure 3. Contribution analysis of the total costs of production. Source: Authors' own elaboration.

In the Tuscany and Almería case studies, labor and services is the most significant economic hotspot, accounting for around 40% of TCOP, followed by the costs included in the greenhouse phase (about 35% of TCOP). In the case of Monastir, about 50% of the annual costs come from the greenhouse, while in the case of Antalya, it is the cost of fertilizers that weighs the most (38% of TCOP).

In all case studies consumables have the greatest contribution to the greenhouse phase (53% in Tuscany, 68% in Almería, 71% in Monastir, and 34% in Antalya), followed by the initial investment and construction costs (28%, 26%, 27%, and 45%, respectively). Additional relevant costs originate from seasonal labor, i.e., 65% in Tuscany, 68% in Almería, 84% in Monastir, and 96% in Antalya. The remaining annual costs are due to the payment of pension contributions for family workers, taxes, and consulting services to agronomists. For the soilless fertigation system observed in the Tuscany case study, the main cost is coir pith bags (substrate). The use of beneficial insects and other biological control systems in Almería account for about one-third of the costs for crop protection.

Table 6 shows the normalized impact assessment results.

Table 6. Normalized impacts, Recipe 2016 World normalization factors (midpoint, H). CC = climate change, PM = fine particulate matter formation, AC = terrestrial acidification, FE = freshwater eutrophication, ME = marine eutrophication; TET = terrestrial ecotoxicity, FET = freshwater ecotoxicity, MET = marine ecotoxicity, HCT = human carcinogenic toxicity, HnCT = human non-carcinogenic toxicity, and WC = water consumption. Source: Authors' own elaboration.

Impact Categories	Tuscany	Almería	Monastir	Antalya
CC	4	4	7	7
PM	3	3	6	5
AC	6	3	10	5
FE	24	23	56	52
ME	8	3	3	8
TET	14	12	11	22
FET	151	86	97	151
MET	84	67	71	116
HCT	348	722	806	1419
HnCT	2	1	2	2
WC	31	13	14	42

The normalized values show that greenhouse tomato production primarily affects certain impact categories, with HCT being the most impacted, followed FET and MET. These impacts predominantly stem from the industrial production of inputs: HCT from steel production and FET and MET from fertilizer production. However, it should be noted that in the LCA analyses, there is a bias whereby the normalization factors often favor the toxicity categories. For this reason, in this study, the impact categories placed just below were also examined (WC and FE).

4. Discussion

The study findings show that commercial greenhouses across the Mediterranean region differ in their major environmental impacts while sharing hotspots.

The EU case studies have higher long-term profitability (PI) than non-EU case studies. However, TCOP findings (TCOP) show that labor is a significant hotspot in the EU case studies. Non-EU case studies show a different pattern due to the lower impact of labor costs. In Monastir, annual costs were primarily driven by greenhouse construction investments and expenditures on 'consumable' materials such as bumblebee hives and plant support materials, while in the Antalya case, the recent increase in the fertilizer prices [47] has contributed substantially to the increase in annual costs in the case study examined, consequently decreasing the return on investment.

As shown in Figure 4, fertilizers emerge as environmental hotspot in all case studies.

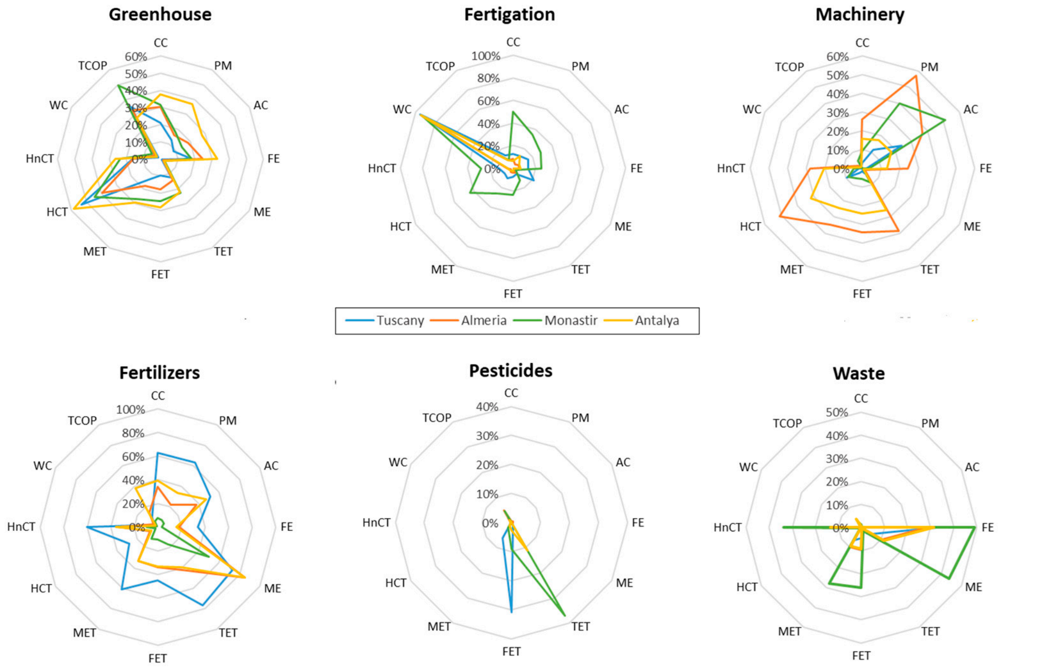

Figure 4. Life cycle stage contribution to environmental and economic impacts. CC = climate change, PM = fine particulate matter formation, AC = terrestrial acidification, FE = freshwater eutrophication, ME = marine eutrophication; TET = terrestrial ecotoxicity, FET = freshwater ecotoxicity, MET = marine ecotoxicity, HCT = human carcinogenic toxicity, HnCT = human non-carcinogenic toxicity; WC = water consumption; TCOP = total costs of production (TCOP). Source: Authors' own elaboration.

The main consequence is the potential increase in freshwater eutrophication. This is a relevant impact, due to direct emissions to water through nutrient leaching and plastic disposal at end-of-life. The Antalya case study demonstrates the worst environmental and economic performances. The excessive use of fertilizers beyond plant needs caused significant environmental impacts, particularly in categories such as marine eutrophication and acidification. In addition, the greenhouse's high dependence on this input (much higher than in the other cases examined) makes it highly vulnerable to market fluctuations. This suggests that the transition to sustainability production would require adopting systems aimed at optimizing inputs (water and fertilizer) and replacing, as far as possible, plastic components with materials that are more easily recyclable or have a longer useful lives [15]. Both soil and soilless systems could benefit from the introduction of digital technology such as decision support systems based on climate and crop sensors and Internet of Things, which is a cost-effective solutions to improve the management of production inputs in greenhouse farming [48]. The use of decision support systems can enable the optimization of fertilizer distribution and water consumption by continuously monitoring the actual needs of the crop [49,50]. Such targeted calibration of inputs would reduce both the environmental impact and the cost of purchasing fertilizer, making the system more efficient and sustainable over time. For such solutions to be adopted on a large scale, targeted incentives and training programs are needed to raise awareness and promote the adoption of sustainable agricultural practices.

The case study developed in Tuscany shows good economic and environmental performances due to the use of soilless cropping. This finding suggests that the soilless farming system has emerged as a viable alternative to reduce production-related environmental impacts. Soilless cropping systems demonstrate several advantages, such as higher yields, greater planting intensity, and better weed control [51], as well as better control over water and nutrient dosing. However, it is worth noting that soilless cultivation generally involves higher initial investment costs than traditional soil-based methods, which may be a barrier to their diffusion [15]. To maximize the benefits of soilless cropping, a technology upgrade is needed to enable drainage water reuse [52]. Reusing drainage water through closed loop fertigation or cascade cropping can mitigate FE and ME further by preventing nitrogen and phosphorus emissions to water [53]. Cheaper, more durable, or recyclable/reusable substrate materials should be used as well [15]. Soilless cropping might contribute to the reduction of the impacts from the use of agricultural machinery as no soil preparation is required. Agricultural machinery has emerged as a significant source of impacts in which cultivation occurs in soil; its impact is significantly lower in substrate cultivation, which does not require soil tillage.

The findings show that the soilless fertigation system and the rainwater harvesting system have the potential to increase the impacts related to the use of plastic materials due to increased emissions from background industrial manufacturing and landfilling. Increasing the recycling rate can exploit the potential of water saving approaches by significantly reducing their environmental impacts, which requires targeted policy intervention [54]. However, evidence from the Monastir case study suggests that negative environmental impacts outweigh the water saving benefits of the rainwater harvesting system, which supplies just 3% of fertigation water. This suggests that technological development is needed to address the drought emergency, which is projected to increase in the coming years, especially in the most arid regions of the Mediterranean Basin. This requires special attention by policy makers as the current adaptation policies and interventions that have been adopted are not proceeding at the same speed that climate risks are evolving [55] There is a need for alternative strategies, such as reusing treated wastewater, improving irrigation technologies, and adopting drought-resistant crop varieties, to effectively address the challenges of water scarcity [56].

The Almería case study shows the best results from both an environmental and economic impact perspective, largely due to favorable climate conditions, ensuring abundant production with a short production cycle and allowing the greenhouse to be exploited for other production during the rest of the year. In addition, the use of IPM offers significant environmental advantages over traditional chemical control approaches, despite greater management costs. These findings point to the importance of incentivizing and supporting this practice through targeted policies. Support is needed for specific decision support systems that enable real-time monitoring and knowledge sharing among users [57].

5. Conclusions

The aim of this study was to assess the environmental and economic impacts of common tomato growing practices in Mediterranean greenhouses. The life cycle analyses of these four commercial greenhouses revealed higher environmental impacts and lower economic returns in the non-EU cases than in the European cases (soilless and short-cycle soil). The key findings show that the main impacts focus on water consumption, peaking at 11,283 m^3/year in the Antalya case study, and freshwater eutrophication, reaching a maximum of 37 kg P eq in the Monastir case study. Fertilizers were identified as a hotspot, with direct emissions mainly affecting marine eutrophication, with a maximum of 30 kg N eq in the Antalya case study. Agricultural machinery also contributes to the impacts, mainly through the formation of particulate matter during use, reaching a maximum of kg $PM_{2.5}$ eq in the case of Monastir. The extensive use of plastics heavily affects the impacts, especially in production (maximum of 12,586 kg 1,4-DCB) and disposal (maximum of 18 kg P eq), particularly in the case of Monastir.

The findings of this research show that there is a need for policy support to encourage soilless cultivation and water-saving technology, as well as more focused fertilizer management and integrated pesticide control. Boosting sustainable greenhouse horticulture can enable rural development in both EU and non-EU countries, as it is a profitable farming system with relevance for the export market.

The combination of LCA and LCC is a valuable avenue for delineating pathways toward enhanced sustainability within greenhouse farming systems. However, absolute values should be considered with caution. This study's limitations include the bounded geographic and temporal scope of the primary data, the reduced number of case studies, and the reliance on simplified models for calculating emissions. The comparative nature of this study reduces in part the importance of these limitations, as the research results focus on the existing and potentially improvable critical points that can be achieved with respect to the observed situation. These limitations underscore the need for further research to deliver more comprehensive assessments to foster the diffusion of the most suitable technologies for the different farming contexts in the Mediterranean region. Future research should encompass a wider array of farm characteristics, either through observed data or simulations, to ensure broader applicability and relevance. From a methodological perspective, there is a need for more homogeneous approaches to LCA and LCC to facilitate the derivation of external validity from case studies and related recommendations.

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Conflicts of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as potential conflicts of interest.

Nomenclature

AC	Terrestrial acidification
CC	Climate change
EU	European Union
FE	Freshwater eutrophication
FET	Freshwater ecotoxicity
HCT	Human carcinogenic toxicity
HnCT	Human not carcinogenic toxicity
IPM	Integrated Pest Management
LCA	Life cycle assessment
LCC	Life cycle costing
ME	Marine eutrophication
MET	Marine ecotoxicity
NPV	Net Present Value
PI	Profitability Index
PM	Fine particulate matter formation
TCOP	Total Cost of Production
TET	Terrestrial ecotoxicity
WC	Water consumption

Appendix A

The following tables show additional data used for inventory building.

Table A1. Detailed inventory of the pesticides analyzed for each case study. (*) biopesticides. Source: Authors' own elaboration.

Case Study	Active Ingredient (a.i)	g (a.i)/ha
Tuscany	*Bacillus thuringiensis* var. *kurstaki* (*)	2150.0
	Chlorantraniliprole	116.7
	Copper oxychloride	2886.3
	Cyprodinil	416.7
	Deltamethrin	29.9
	Emamectin benzoate	23.8
	Fludioxonil	277.8
	Indoxacarb	66.7
	Metaflumizone	244.4
	Methomyl	268.6
	Methoxyfenozide	500.0
	Spinosad	128.9
	Sulfoxaflor	26.4
Almería	Azoxistrobine	200.0
	Bacillus amyloliquefaciens (*)	3750.0
	Cimoxanile 45%	500.0
	Sulfur	5000.0
Monastir	Abamectin	162.1
	Chlorantraniliprole	364.2
	Copper	800.4
	Copper sulfate	533.6
	Emamectin Benzoate	26.7
	Flubendiamide	40.0
	Flupyradifurone	68.4
	Folpet	1200.6
	Fosetyl-Al	1600.8
	Mancozeb	133.4
	Metalaxyl-M	1217.3
	Orange essential oil (*)	235.3
	Spinosad	353.8
	Sulfur	2134.4
Antalya	Abamectin	24.0
	Ametoctradine	642.9
	Cyprodinil	120.5
	Dimetomorf	483.3
	Emamectin benzoate	238.1
	Fludioxonil	80.4
	Orange essential oil (*)	280.0
	Spinetoram	17.1
	Spirotetramat	107.9

Table A2. Emissions from fertilizer and agricultural machinery for each case study. Source: Authors' own elaboration.

Emissions (kg/ha)	Case Studies			
	Tuscany	Almería	Monastir	Antalya
Machinery (to air)				
HC	1.1	1.1	3.5	0.04
NO_x	12.5	12.1	39.6	0.47
CO	1.6	1.5	4.9	0.06
CO_2	346.3	676.7	2735.5	9.73
SO_2	0.1	0.2	0.9	0.003
CH_4	0.014	0.028	0.113	0.0004
NH_3	0.002	0.004	0.018	0.0001
$PM_{2.5}$	4.6	27.4	45.9	0.08
Fertilizers (to air)				
N_2O	16.0	7.5	4.7	18.6
NH_3	25.6	12.0	7.5	29.7
NO_x	3.4	1.6	1.0	3.9
Fertilizers (to soil)				
NO_3	384.7	179.5	113.1	445.5
K_2O	2.6	0.04	0.05	0.9

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