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The Life Cycle Assessment on Environmental Impacts of Greenhouse Crops: A Theoretical Review

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Abstract

Greenhouse crop production is fundamental to manage the worldwide demand for food. However, the required energy for controlling the temperature and humidity of the greenhouse may cause an environmental impact. The life cycle assessment is one of the most widely used management tools to help in assessing the environmental impact of a product over its whole life through four main steps: “goal and scope definition”, “life cycle inventory analysis”, “life cycle impact assessment”, and “interpretation”. This study offers a review of the prior literature to analyze different environmental impacts that can be monitored by the LCA technique in greenhouse crops according to three characteristics: the LCA phase, the type of cultivated product, and the locations and their climates. The results of prior literature about the adoption of LCA on greenhouses indicate that average global warming potential is lower in the case of cucumber and lettuce cultivation in comparison with other products, that SimaPro is the most used software to measure the environmental impacts of greenhouses through LCA, and that warmer climates lead reductions on environmental impacts of greenhouses.

Keywords: Greenhouse crop, LCA, Environmental impact, Climate, LCI, LCIA

1 Introduction

Around 30% of the worldwide greenhouse gas (GHG) emission is attributed to the food industry (1). At the same time, around one-third of the foods are lost during transit due to the far distance between food production companies and consumers (2). Greenhouse crop production can alleviate this waste of food due to transportation since this cultivation system helps in protecting the crops from difficult conditions and adverse climatology. As a consequence, greenhouse crop production is a recommendable way to satisfy the worldwide demand for food (3). In addition to transport distance reduction, there are other advantages concerning the use of greenhouses in comparison with open fields, such as yield increment and land usage reduction. Greenhouse crop is a widely known and long-standing technique in the agri-food sector since the major growth crops in the greenhouse are vegetables, fruits, and flowers (4). However, due to the controlled conditions (e.g., temperature, humidity, and light) that greenhouse crop production requires, the energy demand in greenhouses is higher than in the open fields. In fact, the energy cost is the second cost driver in the greenhouses after labor costs (5). Around up to 85% of the operating cost in greenhouses is attributed to heating (6). Further, the control of thermal and lighting conditions of the greenhouses involves not only a cost for agri-food companies that use this type of crops but also generates significant environmental impacts. For instance, the study of Dias et al. (7) about the tomato greenhouses in Canada found that heating with fossil fuels is responsible for 50% to 85% of the overall impact for global warming potential, ozone depletion, and respiratory effects. Consequently, the goal of a sustainable expansion of greenhouses must be focused on reducing energy consumption and, at the same time, increasing crop production (8). Several studies have evaluated the environmental impact of greenhouses by considering heating and cooling systems, lighting systems, dryer systems, among other causes (4, 6, 9, 10). Results indicated that different technological systems measure the environmental impact and energy consumption of greenhouses differently. Due to this lack of homogenization when results attempt to be compiled and summarized, it is essential to identify a management tool that measures environmental impact in a similar (or even unique) manner.

At this point, various management tools have been developed to evaluate the sustainability of products and technologies (11). The life cycle assessment (LCA) is one of the most widely used management tools in the agriculture sector (12). The LCA helps in assessing the environmental impact of a product over its whole life (12, 13). Companies use LCA as a method to analyze the procurement, environmental effect, and product design strategy (12, 14). Related to greenhouse crops, the LCA aims at providing a comprehensive view of environmental impacts specifically those related to energy consumption. From a management point of view, the LCA has several purposes such as financial decision making, improvement in the analysis of investment possibilities, and market claims (15).

Different studies have evaluated the environmental impact of various greenhouse cultivation systems in different geographical areas. A variety of classification criteria for both causes and consequences of the sources of environmental

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impacts exists in prior literature concerning LCA in greenhouse crops. For instance, Wang et al. (16) studied LCA in the plastic-greenhouse for the pepper production system in China, meanwhile, Torrellas et al. (17) analyzed LCA of a tomato crop in a multi-tunnel greenhouse in Almeria (Spain). This diversity shows there is insufficient conclusive summarization in the literature related to greenhouse crops and their environmental impacts. It should be noted that different methods of environmental assessment, crops, and location of cultivation cause different results and conclusions. Hence, this paper reviews prior literature about the environmental impact of greenhouses crops under the lens of LCA. The main objective of this work is to analyze different environmental impacts that can be monitored by the LCA technique in greenhouse crops, trying to homogenize the main results made by prior literature. In doing so, this study uses three different criteria for the analysis of environmental impacts generated in greenhouse production crops: first, the phases of LCA; second, the type of products that are cultivated in the greenhouses; and third, the climate conditions of the geographical area where the crops are yielded. Knowing what has been found in the literature about the environmental impacts of greenhouse production under these criteria is especially relevant since these classifications are often used in the managerial making decisions process about where and how to locate greenhouse plantations. Managers often assess the environmental impacts of greenhouse crops by comparing the environmental impact of the LCA phase, products, and climate areas for choosing the best one among them (18).

2 Literature review about LCA: definition, phases, and standardization

The LCA is a tool for analysis of the environmental impacts of a product throughout its entire life and assessment of its potential effects on the environment (13, 14, 19). The LCA evaluates the environmental aspects from cradle to grave, that is, the potential impacts from raw material acquisition through production, use, and disposal (20). In the case of the agri-food sector, is common to speak about the "cradle to gate" philosophy that mentions "cradle" as the origin of agricultural production and "gate" as the consumer's home (21). The main difference between "cradle to grave" and "cradle to gate "is that the environmental impacts are assessed from the creation to disposal in the consumer's gate (21, 22).

Several studies have categorized different types of LCA. For instance, according to Martin et al. (23), two main types of LCA exist: attributional and consequential. The attributional LCA highlights the physical engineering as well as emissions of products meanwhile the consequential LCA is more focused on the feedback caused by economic replies. This work is focused on how LCA is categorized into four main phases: (1) goal and scope definition, (2) life cycle inventory analysis, (3) life cycle impact assessment, and (4) interpretation. Table 1 explains the objective of each one of these phases and Figure 1 shows the links among the LCA phases. Related to the standardization of LCA, this management tool was standardized from 1990 by the coordination of the Society of Environmental Toxicology and Chemistry (SETAC). Also, the International Organization for Standardization (ISO) developed different types of standards and guidelines regarding LCA.

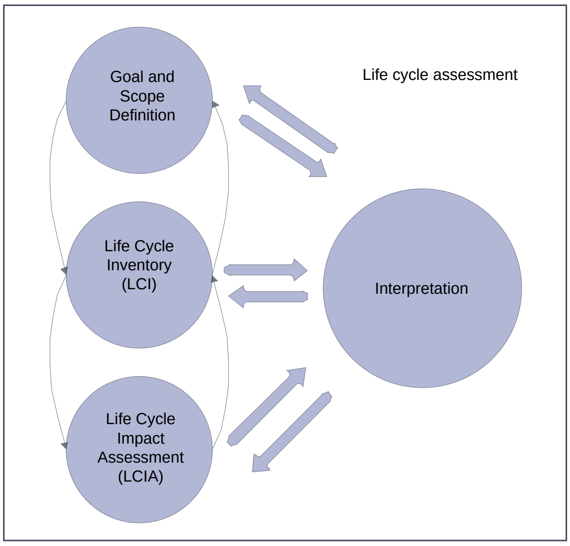

Figure 1: Phases of LCA
Source: adapted from Arvanitoyannis (1)

Table 1: The objective of LCA phases

Name of the phase	Definition/Objective	Example in the greenhouse sector
Goal and Scope definition	Including the system boundary and level of detail	Evaluating the environmental burden associated with crop production from cradle to gate or cradle to grave.
Life cycle inventory	An inventory of input/output data concerning the studied system	The input data such as greenhouse structure, water consumption, fertilizers, pesticide, electricity power, natural gas or petrol usage, etc.
Life cycle impact assessment	Provide additional information to assess the results of LCI	Analyzing the environmental impact of LCI on different categories such as the global warming potential (GWP), abiotic depletion potential (ADP), acidification potential (AP), eutrophication potential (EP), ozone layer depletion (ODP), human toxicity potential (HTP),
Interpretation	The results of the life cycle inventory and life cycle impact assessment are discussed following the goal and scope definition.	Discussing the environmental impact of different factors such as types of crops, scenarios, chemical fertilizers, energy sources, etc. Finally, giving the best option that reduces the environmental impacts in the greenhouse sector.

Source: Adapted from ISO 14044 (2006)

The most recent ISO standards for LCA are ISO 14040, ISO 14041, ISO 14042, ISO 14043, and ISO 14044. However, ISO 14040 and ISO 14044 can be considered as leading standards in LCA. It should be noted that the framework of both ISO and SETAC is similar but with some differences (25). Overall, SETAC was developed and specialized on issues that were more related to the highly populated areas of Europe, especially on pollutants. The ISO framework was more focused on the development of documents and working groups based on SETAC principles. Furthermore, other international organizations have developed programs and protocols for LCA. For instance, the World Resources Institute (WRI) and the World Business Council on Sustainable Development (WBCS) developed a protocol for LCA in 2011 which was focused on assessing the greenhouse gas emission of products. A published handbook by the joint research center of the European Commission entitled “International Reference Life Cycle Data System (ILCD)” (26) has prepared very detailed technical guidelines related to the LCA. Further, the standard PAS 2050 was prepared by the British Standards Institution (BSI) to standardize the life cycle analysis of GHG emissions of products.

3 Methodology of the systematic literature review

To know prior results on environmental impacts of greenhouse crops drawing upon the LCA method, this study has made a systematic literature review based on the proposed method by Denyer and Tranfield (2). A four-stage process was designed to answer the following research question: What have been the main results in prior literature on the environmental impact of greenhouse crops using LCA? Figure 2 shows the stages of the review process that was carried out. First, we searched studies published on electronic academic databases, such as Web of Science and Scopus, in the period 2005-2020. Second, we evaluated the available studies related to the research question, that is, the use of LCA to measure environmental impacts on greenhouse crops. The review process was designed based on published studies within the last 15 years (i.e. 2005-2020). The literature search was based on the documents which included all three following keywords “Greenhouse” and “LCA” and “crop” in the title, abstract, or keywords. By doing so, 141 documents were found and were reduced to 137 documents by applying the year limitation. Third, we assessed the important sections of prior literature, extracting the useful data, summarizing and comparing the achieved data, and reporting them in tables. After extensive analysis, the number of studies was reduced to 24 due to the rest of the studies were out of the scope of our research objective. At this point, we considered the environmental impacts that were assessed in each research work. Several publications evaluated other parameters that, being important, were not related to the question of this study. These (eliminated) studies were focused on the engineering and technical characteristics of greenhouses. For instance, some studies assessed solutions for environmental impacts on greenhouses by improving the water systems (28, 29), solar energy usage in the greenhouse (30), lighting systems (31), and structural design (32). However, they were not specifically focused on management implications of LCA on greenhouses, and, for this reason, we considered that these studies were out of our research scope and were removed from the final evaluation list. Finally, the last step was analysis and discussion about the key results based on prior literature. The distribution of final reviewed publications in different years demonstrated an upward trend for LCA in greenhouses crops, as Figure 3 shows.

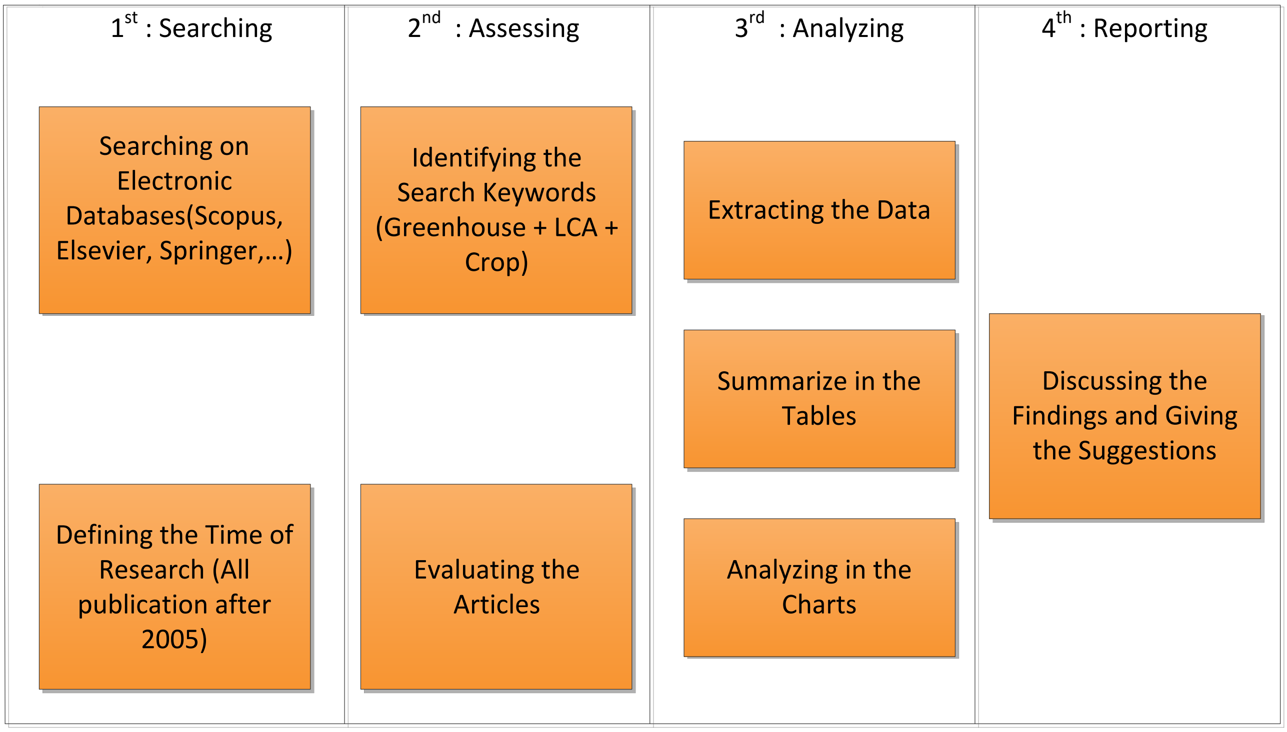

Figure 2: Stages of systematic literature review according to Denyer and Tranfield (2)
Source: adapted from Denyer and Tranfield (2)

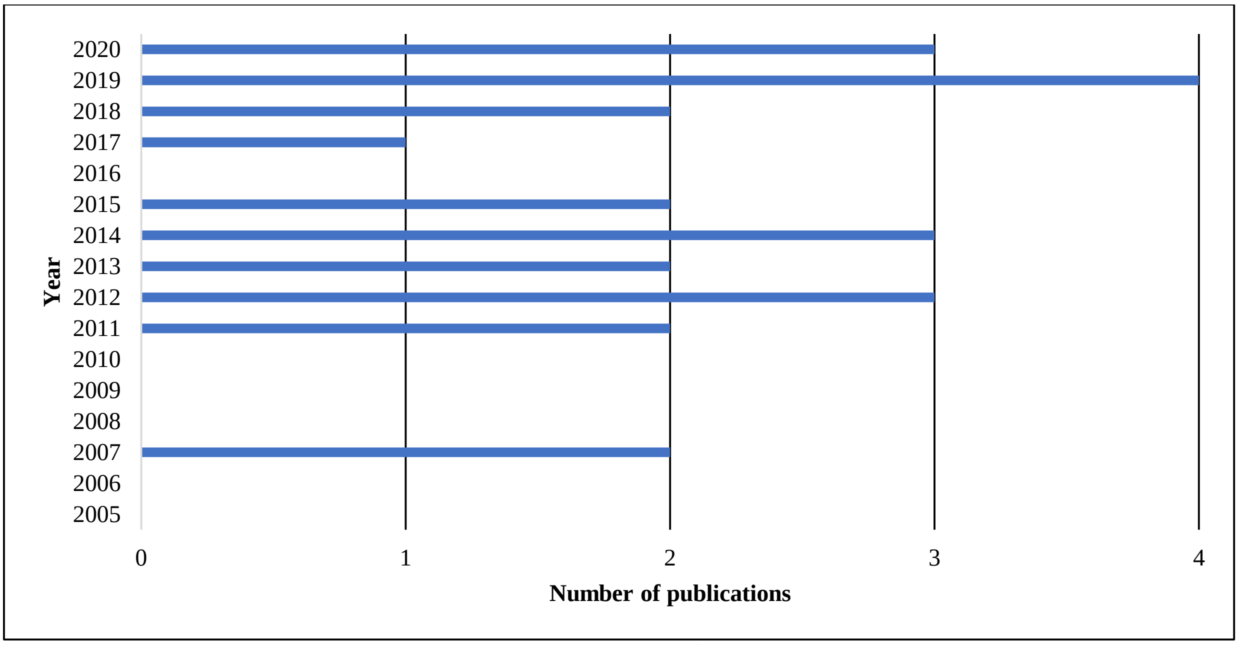

Figure 3: Time distribution of documents

4 Classification criteria for environmental impacts in LCA of greenhouse crops

Greenhouse cultivation is a suitable method for protecting crops from adverse weather conditions and this is one of the reasons why it is a widely used form of cultivation. Indeed, the worldwide extension of greenhouse crops was estimated at around 500,000 hectares (33). To homogenize results of prior literature on environmental impacts of greenhouse crops, LCA could serve as a tool because it has been widely used by researchers to evaluate the effects on the environment of greenhouses. Further, LCA also serves to compare the production of the greenhouses with two (or more) different crop scenarios such as open fields. For instance, Martínez-Blanco et al. (34) found that using a fraction of compost instead of mineral fertilizers is a proper method for tomato cultivation in both greenhouses and open fields.

According to Torrellas et al. (35) in the specific case of greenhouse production, there are seven main types of environmental impacts that are measured through the LCA: structure, auxiliary equipment, fertilizers, climate control systems, pesticides, waste management, and transportation. However, these environmental impacts can vary in function of different characteristics such as methods of environmental assessment, types of crops, types of products, the geographical location of cultivation, and external conditions, among other criteria. At this point, it is important to note that our work has considered three criteria for analyzing different environmental impacts: LCA phases, types of products, and climate conditions. However, it is essential to highlight that other impacts linked to LCA exist, such as the soil, landscape, urban planning, or the socio-economic environment. This work is focused on the three prior mentioned criteria.

4.1. LCA phases as a criterion for analysis of environmental impacts on greenhouse crops

According to Arvanitoyannis (24), the four main phases of LCA are goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and interpretation (see Figure 1).

4.1.1. Goal and Scope

Four aspects are determined in this first phase of the LCA process: the aim of the study, anticipated products, system boundaries, and functional unit (FU) (36). First, the aspects “aim of the study” and “anticipated products” refer to the reason for carrying the study. Related to the “aim of the study” prior literature has mainly focused on the environmental impact of tomato cultivation on greenhouses (e.g., 37, 38). Second, system boundaries refer to the selected input and output based on the goal of the study. Most prior studies have selected cradle to gate as a boundary, which means assessment of the environmental impact of products from resource extraction to transportation. Further, prior literature has paid special attention to fertilizer and pesticide production and transportation (e.g., 34, 39). Finally, related to FU, in the case of agriculture studies, due to its multifunctional feature, three main FU have been reported in prior studies: hectare per year, the physical unit of mass, and energy (kg, tonne, MJ, etc)as well as monetary currency unit (40). Most studies in the literature have selected physical and land units as FU. Several goals and scopes, FU, and system boundaries of prior literature are summarized in Table 2.

Table 2: How to measure Phase 1 of LCA by prior literature

Reference	Goal and scope	FU	boundary inputs
Russo, Scarascia Mugnozza (3)	Environmental impacts of cut flowers and pot plants.	100 cut stems	N/A
Muñoz, Antón (4)	Environmental impact of tomatoes production in Mediterranean greenhouses and open fields.	1 kg	Agrochemical production such as fertilizers and pesticides, the production and use of energy for agricultural purposes

			such as the machinery and irrigation systems, and the agricultural phase.
Martínez-Blanco, Muñoz (5)	Environmental impact of crop cultivation using i) mineral fertilizers ii) compost +mineral fertilizer.	1 Ton	Preparation & transportation of organic waste, compost production, mineral fertilizers production, compost transportation, mineral fertilizers, irrigation, Phytosanitary substances, Irrigation, Nursery plant, Greenhouse structure, Greenhouse management
Boulard, Raeppel (6)	Environmental impact of the crop in plastic house, glasshouse, and polytunnel.	1 kg	Extraction and preparation of the raw materials, energy for infrastructure and production, manufacture of structures and equipment, transport of system inputs, disposal of waste and structures at the end of the activity, packaging.
Torrellas, Antón (7)	Environmental impact of crop production in a multi-tunnel greenhouse.	1 Ton	Manufacture of components, transport of materials, materials disposal and greenhouse management (water, fertilizers, pesticides, and electricity consumption), greenhouse structure, auxiliary equipment, climate control system, fertilizers, pesticides, and waste management.
Cellura, Longo (8)	Indirect environmental impact related to energy source generation, water, and raw materials supply for the protected crop in Italy.	1000kg for packaged tomato	Production and transportation of construction materials and chemicals (fertilizers, manures, and pesticides), production and transportation of energy sources (diesel) and water, use of energy, water, and materials during the crop treatments and harvesting, agriculture machines, and the waste disposal, packaging and transports.
Torrellas, Antón (9)	Evaluating the environmental and economic of various types of greenhouse in Europe.	1 tonne for tomato and 1000 stems for rose	Greenhouse components, transport of materials, and greenhouse operations (water, fertilizers, pesticides, and energy consumption), infrastructure, climate control system, auxiliary equipment, fertilizers, pesticides, and waste management.
Khoshnevisan, Rafiee (10)	Comparing the environmental impact of strawberry cultivation in the greenhouse and open field.	1 ton	Fertilizer and pesticide production from raw materials, harvested strawberries.
Sahle and Potting (11)	Environmental burden of rose cultivation in Ethiopian greenhouses.	20 stems	Greenhouse plastic, planting material, fertilizer, acids, pesticide, water, post-harvest chemicals, packaging materials, diesel, and electricity, waste treatment is included for most inputs.
Khoshnevisan, Rafiee (12)	The environmental impact of cucumber and tomato cultivation in the greenhouse.	1 Tonne and 1 Hectare	Fertilizer production, pesticide production, harvested, greenhouse plastic, materials for planting, fertilizer, acids, pesticide, water, agricultural machinery, diesel fuel, natural gas, and electricity crops.
Bojacá, Wyckhuys (13)	Environmental impact of tomatoes production.	1 ton	the extraction of raw materials, fossil fuel production, fertilizer and pesticide production, steel production, plastics production, and transport of materials, including materials disposal.
Romero-Gámez, Audsley (14)	Assessing the environmental impact of lettuce and escarole as well as improving cultivation techniques, structure, and equipment to minimize the environmental burden.	1 tonne	Solid residues, atmospheric emissions and emissions to water, changing nitrogen fertilizer application rates, packaging and transport
Bartzas, Zaharaki (15)	Comparison of the conventional fertilizers and waste compost i) Cultivation the lettuce in the open field of Italy, ii) Cultivation of lettuce in the greenhouse of Italy iii) Cultivation of barley in the open field of Spain, iv) Cultivation of lettuce in greenhouse, Spain.	1 kg	Compost production, compost transportation, nursery production, nursery transportation, waste production, waste transportation, fertilizer production and transport, pesticide production and transport, agricultural machinery, and irrigation system.
Sanyé-Mengual, Oliver-Solà (16)	Environmental assessment of rooftop greenhouse.	1 kg	construction material extraction, construction materials preparation, construction material transportation, construction greenhouse, maintenance, auxiliary water equipment, auxiliary energy equipment, fertilizer, pesticide, substrate, packaging, and distributing
Dias, Ayer (17)	Environmental burden of tomato cultivation in the greenhouse of Ontario.	1 kg	Greenhouse infrastructure, seedling production, climate control (electricity generation for lighting and ventilation and the production and combustion of natural gas and bunker fuel for heating), tomato cultivation (pesticides, fertilizers, and growing medium), on-site packaging, and waste related to greenhouse operations

Bosona and Gebresenbet (18)	The environmental impact of tomato cultivation in Sweden greenhouse.	1 tonne	Manure application, irrigation, weed management, harvesting, sorting, washing, drying, packaging,
Wang, Liu (19)	Environmental impact of pepper cultivation in the plastic greenhouse.	1 hectare and 1 tonne	Fertilizers production and transportation, pesticide production and transportation, structural materials preparation and transportation, fuels, soil preparation, irrigation, harvesting.
Zarei, Kazemi (20)	The goal of this study is to evaluate the environmental impact of tomato and cucumber cultivation in the open field and greenhouse.	1 tonne and 1 hectare	N based fertilizer, P based fertilizer, K based fertilizer, farmyard manure, plastic, diesel fuel, electricity, natural gas, applying farmyard manure, land preparing, planting or transplanting, fertilizing and spraying, harvesting
Canaj, Mehmeti (21)	Environmental impact of tomato cultivation in the greenhouse of Albania.	1 ha	Agricultural operations, fertilizer application, nutrients environmental fate, plant protection products application and related environmental fate, irrigation, and land occupation and transformation processes for the production of electricity, chemicals, fuels, materials, and infrastructure.
Yelboğa (22)	Environmental impact of the production of the grafted tomato seeding in Turkey.	single grafted tomato	Energy, fertilizers, pesticides, disinfectants, peat, perlite, vermiculite, inserts, trays, grafting sticks, clips, plastic sheeting, packaging used in production.
Naderi, Dehkordi (23)	Environmental impact of bell pepper cultivation in the greenhouse of Iran.	1 tonne	Energy, seed production, machinery production, fertilizer production, chemical production, electricity production, tilling, planting, fertilizing, spraying, irrigation, harvesting
ADSAL, ÜÇTUĞ (24)	Environmental impact of banana cultivation in greenhouses of Turkey under different scenarios.	2 tonnes	Fertilizer, pesticide, electricity for equipment, irrigation, packaging, energy for water heater, retail.
Maham, Rahimi (25)	Environmental impact of organic tomato cultivation in the greenhouse and its vitamin C content using organic fertilizers.	1-tonne tomato, mg of vitamin C/100g	Electricity, greenhouse structure, growth media, seeding, fertilizer, water, seeding, fertilization, irrigation, pruning, harvesting, sorting, and packaging.
Maaoui, Boukchina (26)	Environmental burden of soilless cherry tomato cultivation in greenhouse	1 tonne	Energy, fertigation, pesticides, transport, crop maintenance, and climate control system, greenhouse setting-up, waste treatment.

2.1.2 Life-Cycle Inventory

The second phase of LCA is the life cycle inventory which quantifies the input materials, energy, and environmental emission. The method of cultivation such as open field or greenhouse, soilless or soil-based, organic, or conventional can affect how LCI is developed. Also, in the LCI phase, other factors such as the location of cultivation, type of crop, packaging, and distribution have been reported by prior studies (56). At this point, it is essential to note that LCA can be computed without and with software. Focusing on LCI using specific software to quantify the inputs, different software has been developed, such as SimaPro, GaBi, Umberto, open LCA, eBalance, EIME, Quantis Suite, Team 5, and REGIS. In the case of the software GaBi, more than 60 developers provided over 4000 LCI profiles. These profiles are compiled based on ISO standards for LCA such as ISO 14044, ISO 14064, and ISO 14025. SimaPro, another LCA software for the collection, analysis, and monitoring of the environmental performance of products and services, is compiled based on ISO 14040 (57). Another of the most commonly used LCA databases is the software EcoInvent. Prior research that has analyzed how companies have developed LCI is focused on whether they have used primary and secondary data in doing so. Related to LCI analysis, prior works have achieved the primary data from questionnaires, experimental field measurement, available literature review, and face-to-face interviews with farmers. The secondary data were achieved through professional databases such as EcoInvent, LCA food DK, BUWAL 250, and IDEMAT 2001. Related to studies that have used secondary data about LCI, most researchers have used different versions of SimaPro for LCA analysis. In the case of greenhouses studies, SimaPro and GaBi have been the most commonly used LCA software, being the percentage of using 88% and 12% respectively (XX)

4.1.3 Life Cycle Impact Assessment and interpretation

The life cycle impact assessment (LCIA) is the third phase of LCA in which the results of the inventory are interpreted in terms of environmental impact (58). The LCIA is a way for a better understanding of the environmental impact (59). This phase consists of a compulsory step in which the LCI results are translating to some categories of environmental impacts. According to Khoshnevisan et al. (40), the most common categories of environmental impacts for greenhouses are:

- Global warming potential (GWP),
- Abiotic depletion potential (ADP),
- Acidification potential (AP),
- Eutrophication potential (EP),
- Ozone layer depletion (ODP),
- Human toxicity potential (HTP), and
- Photochemical oxide potential (POP).

Prior literature has used this classification of environmental impacts on greenhouses according to LCA methods for comparative purposes. Specifically, three main comparisons emerge from prior studies on phase LCIA. First, LCIA results help in comparing the environmental impact of two (or more) products. For instance, Khoshnevisan et al. (40) reported that the GWP, ADP, AP, EP, ODP, HTP, and POP of tomatoes are less than cucumber around 47%, 34%, 41%, 57%, 33%, 40%, and 33%, respectively. They conclude that using less energy in greenhouse tomato production compared to cucumber production is the main reason for the reduction in environmental impact (40). Similarly, Zarei et al. (51) also compared the environmental impact of cucumber and tomato, concluding that the environmental impact of tomato is less than cucumber around 7% and 1% in terms of GWP, and ODP, respectively, but the ADP, AP, EP, HTP, and POP of tomato are higher than cucumber around 5%, 5.5%, 14%, 2%, and 5%, respectively concluding that the higher impact of tomato compared to cucumber is due to using more natural gas. Cellura et al. (44) assessed the environmental impact of pepper, melon, tomato, cherry tomato, and zucchini, concluding that the energy consumption for 1ton production of zucchini is 79% higher than tomato production.

Second, LCIA results help in comparing the environmental impact of the same product, but in two different crop situations. For instance, Bosona and Gebresenbet (21) compared the environmental impact of greenhouse tomato cultivation in a fresh and dry situation, reporting that the GWP of dry tomato is around 15% less than a fresh tomato and concluding that dry tomato is more environmentally friendly compared to the fresh tomato due to reducing losses in the drying process. Adsal et al. (54) compared the environmental impact of banana in greenhouses under three different scenarios for heating the irrigation water: usual systems, natural gas, and biogas. They concluded that using biogas is environmentally promising for banana cultivation.

Finally, LCIA results help in determining the best conditions (internal and external) to reduce the environmental impact of greenhouse crops. For instance, Boulard et al. (43), who analyzed the environmental impact of plastic and glass greenhouses in France, reported that heating the off-season production has the main environmental impact, concluding that the environmental impact per kilogram of tomato in heated crops is around 4.5 times higher than unheated crops. Similarly, Romero-Gámez et al. (48) identified that the more environmental impact of lettuce and escarole production is related to the structure of greenhouse, auxiliary systems, and fertilizers.

4.2. Type of product as a criterion for analysis of environmental impacts on greenhouse crops

The prior literature assessed different types of crops in different areas and scenarios. The percentage of crop types by-products among 33 available crops analyzed by prior literature is shown in Figure 4. Most of the cultivated vegetables in Mediterranean greenhouses are tomato, pepper, cucumber, melon, and watermelon (60). These vegetables can be grown in a greenhouse with medium thermal equipment. As shown in Figure 4, tomato is the most studied product category in the literature about the environmental impacts of greenhouses using LCA. Tomato cultivation in greenhouses is very common due to its easy growth and huge yield (61). Nevertheless, although many studies have analyzed the environmental impacts of tomato cultivation in greenhouses using LCA, not all of them have focused on the same production characteristics. Several studies have focused on analyzing how the type of greenhouse used is related to environmental impacts of tomato cultivation: the open fields (42) the glasshouses, plastic houses, or polytunnel (43), or the rooftop greenhouses and multi tunnel systems (50). It is important to note that the environmental impact of plastic or glasshouse is significantly greater than polytunnel. However, the environmental impact of a multi tunnel system is greater than the rooftop greenhouses.

Further, other studies have focused on environmental impacts of tomato cultivation by geographical areas highlighting that tomato cultivation in greenhouses could be located in multiple places worldwide, such as Colombia (47), Sweden (21), Albania (37), Turkey (52), Tunisia (55), Canada (38), among others. Several studies analyzed tomatoes along one or more crops to assess and compare the environmental impact. For instance, Torellas et al. (45) analyzed the environmental impact of tomato and rose crops in hot and cold weather in Europe.

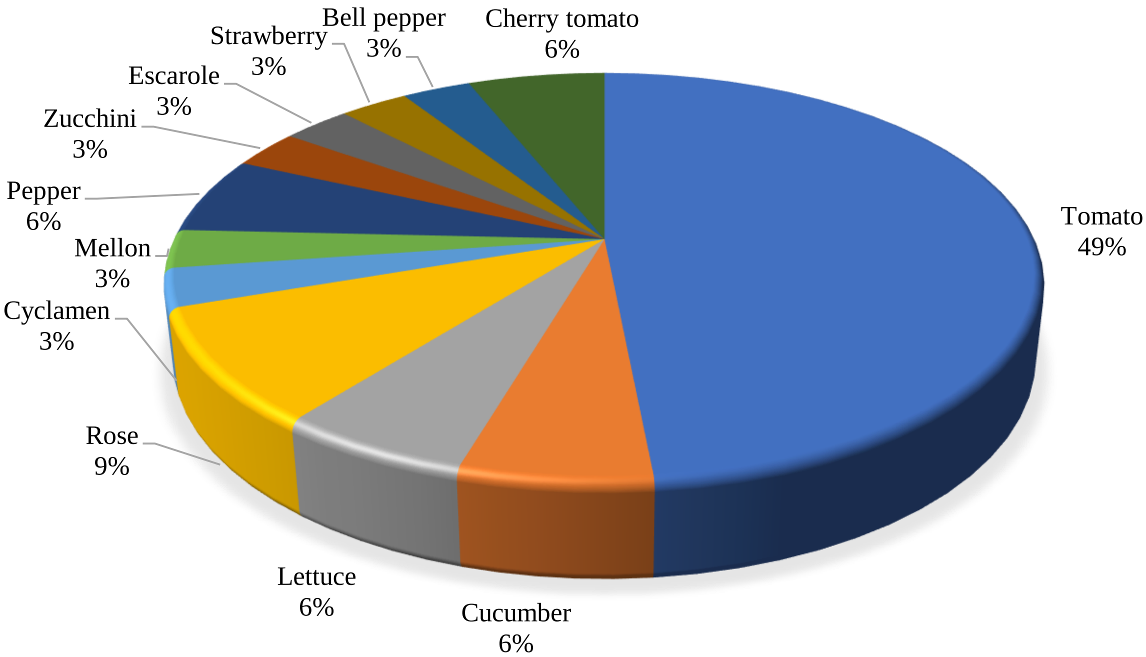

Figure 4: Percentage of crop types evaluated in prior literature using LCA (analyzed by this study)

Cellura et al. (44) assessed the environmental impact of tomatoes, cherry tomatoes, peppers, melons, and zucchini in tunnel and pavilion greenhouses. Khoshnevisan et al. (40) and Zarei et al. (51) evaluated the environmental impact of greenhouse tomato and cucumber production using LCA in different areas of Iran. Besides tomato, the environmental impact of other crops also has been assessed using LCA. Regarding the flowers, Russo et al. (41) and Sahle and Potting (46) assessed the environmental impact of rose cultivation in Italy and Ethiopia, respectively. Several researchers evaluated the environmental impact of some types of vegetables such as lettuce, escarole, and barley (48, 49) as well as pepper and bell pepper cultivation in greenhouses of Iran (16) and China (53). Regarding fruit production in the greenhouse, the environmental impact of strawberry (39) and banana (54) were evaluated.

Related to the environmental impact factors (e.g., GWP, AP, EP, ODP) the most reported data are related to the tomato, the lettuce, the escarole, the banana, the cucumber, and the cherry tomato (42, 48, 49). The summary of prior literature in terms of environmental impact for different crops is shown in Figure 5. It should be noted that these figures (i.e., GWP, AP, EP, and ODP) are based on the most analyzed factors by previous research. However, only a few studies reported other impact categories like HTP and POP, and for this reason, these measures of environmental impacts were not reported in our study. In sum, it is difficult to compare exhaustive results on environmental impacts in greenhouses among different studies due to differences in types of the greenhouse, climate, and boundary conditions of LCA. However, a more general comparison of prior studies of LCA in greenhouse crops revealed two main conclusions. On the one hand, the average environmental impact of greenhouses is lower in the case of cucumber, lettuce, and escarole cultivation compared to the other crops. It should be noted that the reported data vary for different types of crops (Figure 4). On the other hand, the tomato has been considered in different types of greenhouses and climates under different scenarios of cultivation. The results concerning tomatoes demonstrate that there is a lack of knowledge regarding the environmental impact of a lot of crops and more studies are required to evaluate the environmental impact of different crops in greenhouses (not just tomatoes). One of the reasons that may explain the lack of studies on other types of products (and the large number of studies on tomato cultivation) is that tomato is a highly demanded and mass-consumed food (21, 34) whose cultivation, however, is not widespread in all geographical regions. The tomato must be grown in very specific conditions of temperature, humidity, etc., and, therefore, requires cultivation in greenhouses so that this product can be consumed worldwide.

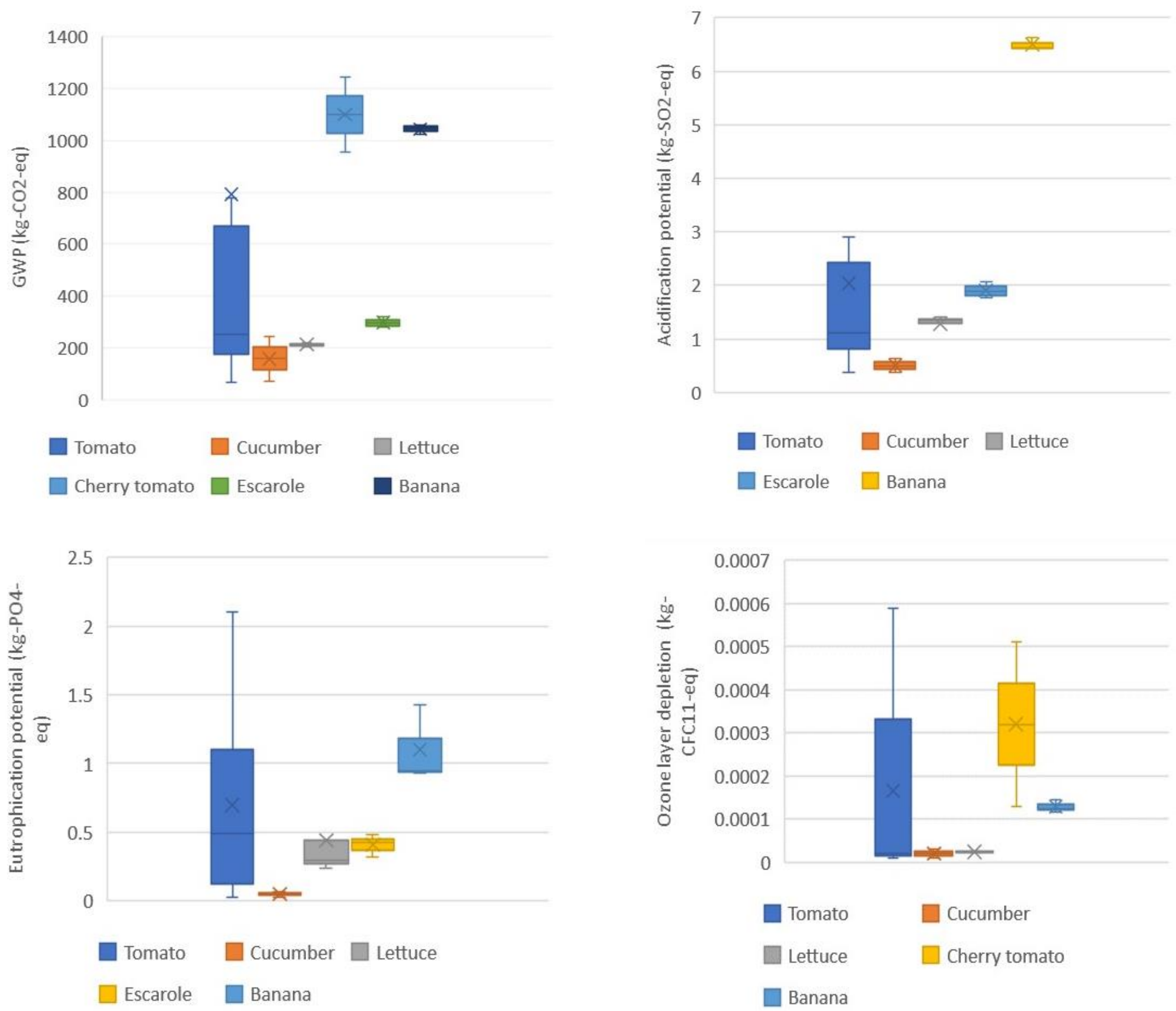

Figure 5: The environmental impact factors of different crops (analyzed by this study)

Due to its importance, the study of the environmental impacts of tomato cultivation in greenhouses has monopolized much of the academic research, to the detriment of the study of other types of products. Figure 5 will be helpful for the researcher to compare their results with the available literature.

4.3. Locations and climates as a criterion for analysis of environmental impacts on greenhouse crops

Several natural conditions of the territory are essential to analyze when considering the environmental impact of the greenhouse such as soil, existing vegetation, geology, etc. However, this study aims to evaluate the effect of climates on the environmental impact of the greenhouse. We focus on this because the local climate of the geographical area where the greenhouse is located can affect its cost, quality of production, energy, and environment (60). Thus, it is essential to consider the geographic location and climate of the greenhouse while considering its environmental impact using LCA. To do so, the Köppen-Geiger climate classification (K-G classification) was applied to determine the climate of available locations in the literature. Following Marin et al. (62), according to the K-G classification, the main climates are categorized as (A) equatorial, (B) arid, (C) warm temperate, (D) snow, and (E) polar. These five main climates are subcategorized based on precipitation and temperature. For instance, the code "Bsk" means an "arid climate with summer dried precipitations and cold arid temperatures", meanwhile the code "Cfa" means "a warm climate with fully humid precipitation and hot summer temperature". Figure 6 shows this classification and the interpretation of the codes.

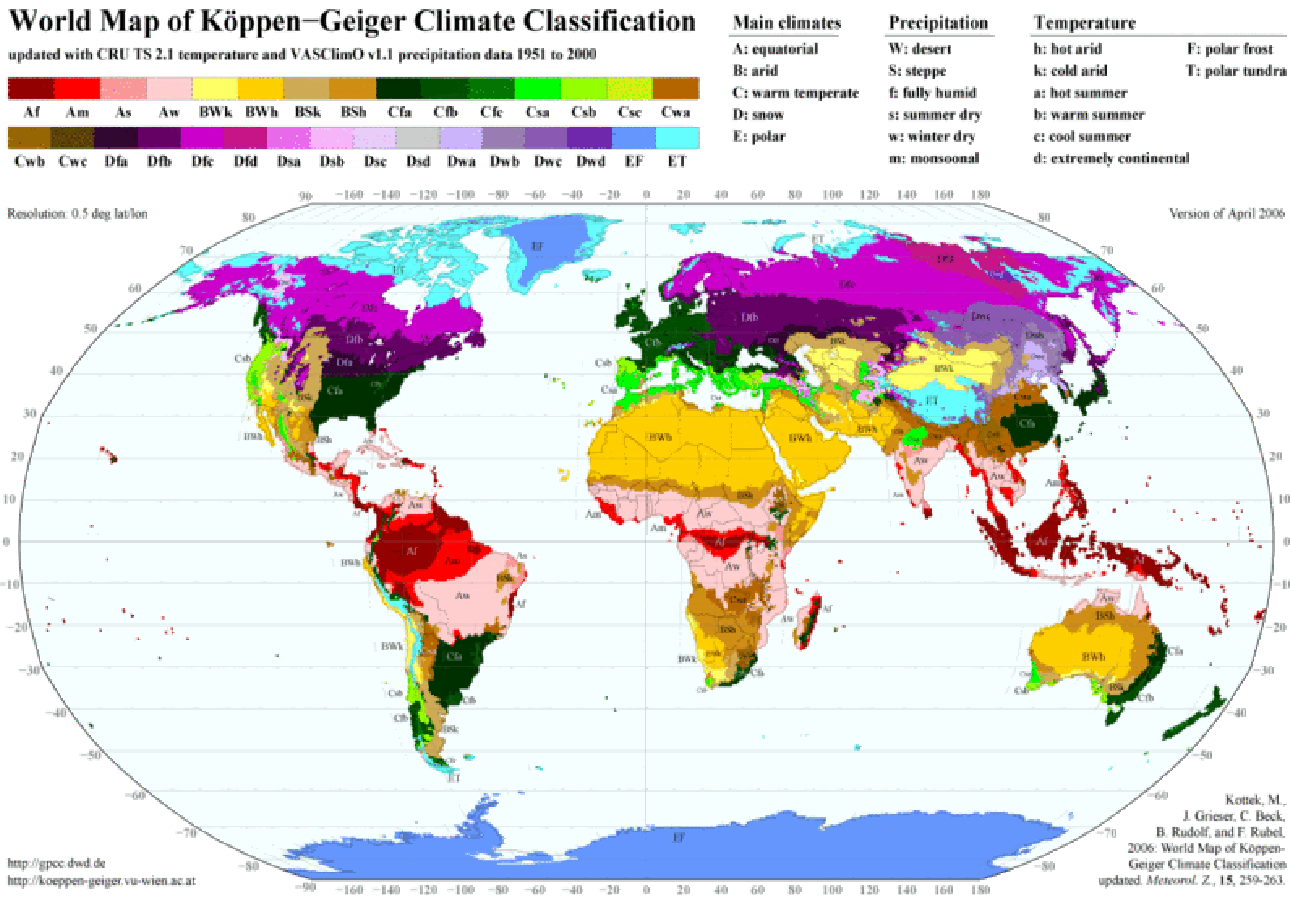

Figure 6: The Köppen-Geiger climate classification
Source: Marin et al. (27)

Table 3: Studies of environmental impacts in warm areas

Reference	Location	Type of climate
Torrellas et al. (7) Torrellas et al. (9)	Almeria, Spain	
Muñoz et al. (4)	Maresme, Spain	Cfa
Bartzas et al. (15)	Albenga, Italy	
Adsal et al. (54)	Aamur, Turkey	
Russo et al. (3)	Bari, Italy	
Torrellas et al. (9)	Netherlands Hungary	Cfb
Boulard et al. (6)	Rhone Valley, France Brittany, France	
Bosona and Gebresenbet (18)	Sweden	

Regarding the comparison between different climate areas, we found that, in the equatorial climate, Bojacá et al. (47) evaluated the environmental impact of tomatoes in Alto Ricaurte, (Colombia) and found that the global warming potential (GWP) for 1 ton of tomato production in the greenhouse was 74 kg- CO2-eq, meanwhile Maaoui et al. (55) analyzed the cherry tomato in the greenhouse of an arider area, in Chenchou (Tunisia), and the reported GWP for 1 ton of crop production in this climate is in the range of 65.2 to 5200 kg-CO2-eq. Results from prior literature indicated that most of the studies about greenhouses have been done in warm temperature climates (see Figure 7). Further, Table 3 shows the different studies that evaluated the environmental impacts of greenhouse crops in diverse geographical areas with warm temperatures.

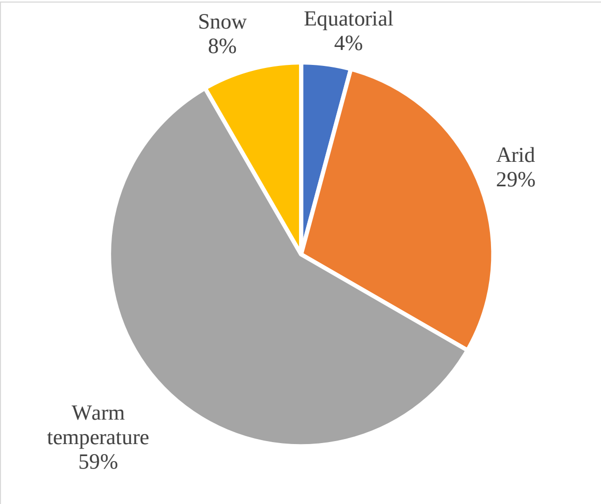

Figure 7: The percentage of reported impact categories in different climates (analyzed by this study)
Source: Analyzed by this study

Nevertheless, prior literature has hypothesized that the more usage of auxiliary heating systems in the greenhouse of cold weather locations could lead to higher global warming potential (63), but the results showed that the warm temperature area has the highest GWP compare to the other climates. It may be attributed to the different types of crops, different sources of energy for heating, different types of soil, various geology, and different selected boundaries of LCA by researchers. For instance, a nursery which is an important parameter in GWP has not been considered in all studied and just a few researchers evaluated it like Ref. (34, 49, 52). It is interesting to note that focusing just on tomato, as the most reported crop, these results change (Figure 9). The highest GWP was related to the snow areas compared to the equatorial, arid, and warm temperatures (Which were analyzed by this study). The correlation between average air temperatures of greenhouse location and the average GWP for different climates is shown in Figure 10. The results indicated that the coldest weather has more potential for CO_2 emission. This study proposed a correlation between the average air temperature of greenhouse location and global warming potential as follow:

$$GWP = 3.923T_{av}^2 - 182.34\, T_{av} + 2155.3 \qquad (R^2 = 0.89)$$

It is clearly indicated that the air temperature of greenhouse location can affect its environmental impact.

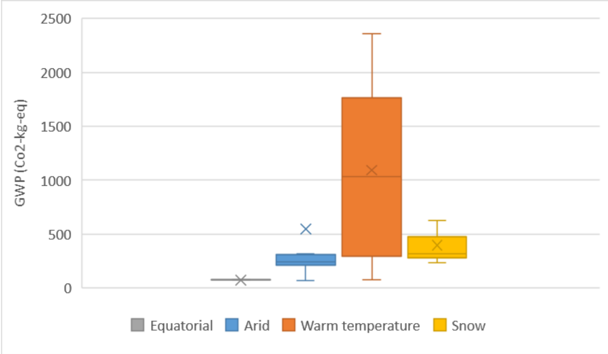

Figure 8: The reported GWP in different climates (analyzed by this study)
Source: Analyzed by this study

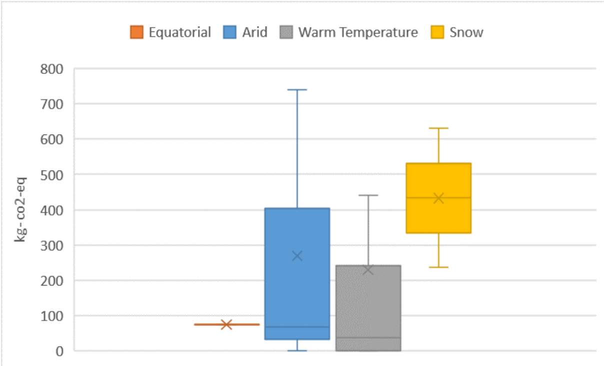

Figure 9: The reported GWP of tomato production in different climates (analyzed by this study)
Source: Analyzed by this study

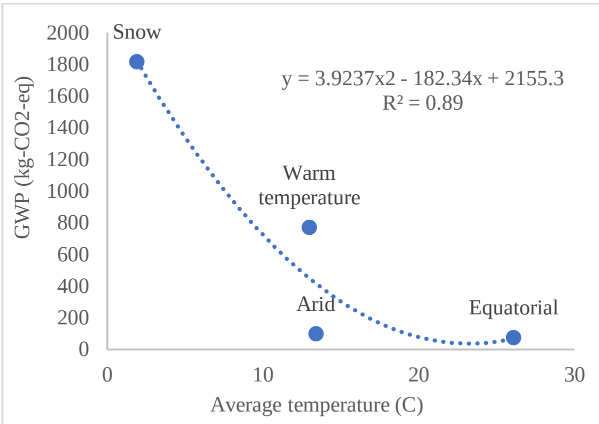

Figure 10: The relation between GWP and air temperature of tomato production (analyzed by this study)
Source: Analyzed by this study

5 Conclusions and Discussion

This work summarizes the studies that have used LCA as a method for environmental impacts assessment of cultivation in greenhouses. Overall, different studies reveal different environmental impacts on crop production in greenhouses, depending on the research objective on which they are focused. Several factors such as the structure of greenhouses, fertilizers, pesticides, irrigation, and energy for heating systems are usually mentioned in prior literature to analyze the causes of the environmental impacts of greenhouses. In this work, we focus on three types of variables that can be measured to know the environmental impact of greenhouse crops under the lens of LCA: the LCA phases, the type of product, and the climate conditions. Our literature review concludes that according to the LCA phase:

1. the environmental impact of tomatoes was the most analyzed in research focused on the "goal and definition" phase,
2. in the life cycle inventory phase, the software SimaPro and GaBi were used around 88% and 12% respectively for analyzing environmental impacts of greenhouses, and
3. the life cycle impact analysis and interpretation phase, in the greenhouses, presented a wide variety of non-homogenized results.

Concerning the type of product, prior literature indicates that the environmental impact of tomato cultivation is the most analyzed type of product in the greenhouse crops, especially compared to other types of products such as cucumber, pepper, melon, cherry tomato, or zucchini. This fact has facilitated the comparison of different studies regarding the cultivation of tomatoes, but it also demonstrated the lack of knowledge regarding the environmental impact of other crops. Finally, related to climate conditions, the colder weather needs more heating equipment which may increase environmental impacts related to the global warming potential and harmful gases (10). As a consequence, prior literature shows that, due to fewer energy requirements for heating, environmental impacts in greenhouses, under the measures of LCA, tend to be lower in the case of warmer climates. In general terms, this review highlights that the research boundary, location, and crops are different but some common points emerge when prior results are summarized and sorted. Managers of the agriculture sector who are interested in starting a greenhouse crop should be noted that LCA literature indicates that the average GWP is lower in the case of cucumber and lettuce cultivation in comparison with other products. However, it should be noted that it may be changed case by case based on the type of structure and climate of greenhouse location. The most common software to measure environmental impacts of greenhouses using LCA is SimaPro, and that even though the environmental impacts of greenhouse plantations are very varied, hot climates favor the reduction of environmental impacts when locating greenhouses. Thus, the main theoretical contribution of this review is that, even though one of the main limitations of LCA is that the achieved results from different studies are not easily comparable due to different crops and geographical location, external conditions, and production strategy (64), we attempt to homogenize results from prior literature to help managerial decision making about the best choice for reducing environmental impacts when greenhouse crop production is planned. This work is not exempt from limitations. First, we have used three types of variables to organize all the information related to the LCA of the environmental impacts of greenhouse crops. Future studies could select different variables or units of measure in doing so, such as type of crop, structure, and type of greenhouse, auxiliary equipment, fertilizers, climate control systems, pesticides, waste management, transportation (Torrellas, Antón, and Montero, 2013), among others. Second, we selected just the studies that used LCA as an assessment tool for the environmental impact of the greenhouse, but other studies evaluated the environmental impact and energy consumption in the greenhouse by using other tools, simulation software, and programming. Finally, it would be interesting to analyze not only the environmental impact of greenhouses but also, in conjunction with the environmental perspective, the economic impact of this type of crop. Future studies will be in charge of elaborating this comparison in terms of environmental impacts as well as economic figures.

Ethical issue

Authors are aware of and comply with, best practices in publication ethics specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. Authors adhere to publication requirements that submitted work is original and has not been published elsewhere in any language. Also, all procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. All procedures performed in this study involving animals were following the ethical standards of the institution or practice at which the studies were conducted.

Competing interests

The authors declare that no conflict of interest would prejudice the impartiality of this scientific work.

Authors' contribution

All authors of this study have a complete contribution for data collection, data analyses, and manuscript writing.

References

1. Arvanitoyannis IS. ISO 14040: life cycle assessment (LCA)–principles and guidelines. Waste management for the food industries. 2008:97-132.
2. Denyer D, Tranfield D. Producing a systematic review. 2009.
3. Russo G, Scarascia Mugnozza G, De Lucia Zeller B, editors. Environmental improvements of greenhouse flower cultivation by means of LCA methodology. International Symposium on High Technology for Greenhouse System Management: Greensys2007 801; 2007.
4. Muñoz P, Antón A, Nuñez M, Paranjpe A, Ariño J, Castells X, et al., editors. Comparing the environmental impacts of greenhouse versus open-field tomato production in the Mediterranean region. International Symposium on High Technology for Greenhouse System Management: Greensys2007 801; 2007.
5. Martínez-Blanco J, Muñoz P, Antón A, Rieradevall J. Assessment of tomato Mediterranean production in open-field and standard multi-tunnel greenhouse, with compost or mineral fertilizers, from an agricultural and environmental standpoint. Journal of cleaner production. 2011;19(9-10):985-97.
6. Boulard T, Raeppel C, Brun R, Lecompte F, Hayer F, Carmassi G, et al. Environmental impact of greenhouse tomato production in France. Agronomy for Sustainable Development. 2011;31(4):757.
7. Torrellas M, Antón A, López JC, Baeza EJ, Parra JP, Muñoz P, et al. LCA of a tomato crop in a multi-tunnel greenhouse in Almeria. The International Journal of Life Cycle Assessment. 2012;17(7):863-75.
8. Cellura M, Longo S, Mistretta M. Life Cycle Assessment (LCA) of protected crops: an Italian case study. Journal of cleaner production. 2012;28:56-62.
9. Torrellas M, Antón A, Ruijs M, Victoria NG, Stanghellini C, Montero JI. Environmental and economic assessment of protected crops in four European scenarios. Journal of Cleaner Production. 2012;28:45-55.
10. Khoshnevisan B, Rafiee S, Mousazadeh H. Environmental impact assessment of open field and greenhouse strawberry production. European journal of Agronomy. 2013;50:29-37.
11. Sahle A, Potting J. Environmental life cycle assessment of Ethiopian rose cultivation. ScTEn. 2013;443:163-72.
12. Khoshnevisan B, Rafiee S, Omid M, Mousazadeh H, Clark S. Environmental impact assessment of tomato and cucumber cultivation in greenhouses using life cycle assessment and adaptive neuro-fuzzy inference system. Journal of cleaner production. 2014;73:183-92.
13. Bojacá CR, Wyckhuys KA, Schrevens E. Life cycle assessment of Colombian greenhouse tomato production based on farmer-level survey data. Journal of Cleaner Production. 2014;69:26-33.

14. Romero-Gámez M, Audsley E, Suárez-Rey EM. Life cycle assessment of cultivating lettuce and escarole in Spain. Journal of cleaner production. 2014;73:193-203.
15. Bartzas G, Zaharaki D, Komnitsas K. Life cycle assessment of open field and greenhouse cultivation of lettuce and barley. Information Processing in Agriculture. 2015;2(3-4):191-207.
16. Sanyé-Mengual E, Oliver-Solà J, Montero JI, Rieradevall J. An environmental and economic life cycle assessment of rooftop greenhouse (RTG) implementation in Barcelona, Spain. Assessing new forms of urban agriculture from the greenhouse structure to the final product level. The International journal of life cycle assessment. 2015;20(3):350-66.
17. Dias GM, Ayer NW, Khosla S, Van Acker R, Young SB, Whitney S, et al. Life cycle perspectives on the sustainability of Ontario greenhouse tomato production: Benchmarking and improvement opportunities. Journal of Cleaner Production. 2017;140:831-9.
18. Bosona T, Gebresenbet G. Life cycle analysis of organic tomato production and supply in Sweden. Journal of cleaner production. 2018;196:635-43.
19. Wang X, Liu B, Wu G, Sun Y, Guo X, Jin Z, et al. Environmental costs and mitigation potential in plastic-greenhouse pepper production system in China: A life cycle assessment. Agricultural Systems. 2018;167:186-94.
20. Zarei MJ, Kazemi N, Marzban A. Life cycle environmental impacts of cucumber and tomato production in open-field and greenhouse. Journal of the Saudi Society of Agricultural Sciences. 2019;18(3):249-55.
21. 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. Environmental Science and Pollution Research. 2019:1-11.
22. Yelboğa MNM. LCA Analysis of Grafted Tomato Seedling Production in Turkey. Sustainability. 2019;12(1):1-16.
23. Naderi SA, Dehkordi AL, Taki M. Energy and environmental evaluation of greenhouse bell pepper production with life cycle assessment approach. Environmental and Sustainability Indicators. 2019;3:100011.
24. ADSAL KA, ÜÇTUĞ FG, ARIKAN OA. Environmental life cycle assessment of utilizing stem waste for banana production in greenhouses in Turkey. Sustainable Production and Consumption. 2020.
25. Maham SG, Rahimi A, Subramanian S, Smith DL. The environmental impacts of organic greenhouse tomato production based on the nitrogen-fixing plant (Azolla). Journal of Cleaner Production. 2020;245:118679.
26. Maaoui M, Boukchina R, Hajjaji N. Environmental life cycle assessment of Mediterranean tomato: case study of a Tunisian soilless geothermal multi-tunnel greenhouse. Environ Dev Sustainability. 2020:1-22.
27. Marin P, Saffari M, de Gracia A, Zhu X, Farid MM, Cabeza LF, et al. Energy savings due to the use of PCM for relocatable lightweight buildings passive heating and cooling in different weather conditions. ENERG BUILDINGS. 2016;129:274-83.