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Tracing the root of the evil in the carbon footprint of tomato production: Implications for optimization process and policy formulation

THEODOROS MARKOPOULOS*, DIMITRIOS N. KAZIOLAS**, CHRISTOS STABOULIS***

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Abstract

While agriculture's role in carbon emissions has been studied broadly, there is a notable lack of disaggregated studies that focus on the carbon footprint of specific products, such as tomatoes. This is further exacerbated by the fact that tomatoes are a staple food in many countries, and the carbon emissions associated with their production could vary significantly across different cultivation methods, regions, and supply chains. This literature gap limits our understanding of where emissions originate and where they can be mitigated. In this context, the aim of the present paper is to provide a comprehensive evaluation of the equivalent carbon footprint in greenhouse tomato production in Greece by means of a Life Cycle Assessment. Results indicate that the energy required to produce the tomato is the factor that has the greatest impact on the environmental impact. The fertilizers and the materials used to package the product also affect significantly the overall environmental impact. Tomatoes are an essential component of global food systems. Thus, even marginal improvements in the carbon efficiency of tomato production could yield significant environmental benefits, and a detailed carbon footprint analysis could influence policy and practice.

Keywords: *Carbon footprint, Life Cycle Assessment (LCA), Sustainable tomato production, Optimization process, Agricultural policy.*

1. Introduction

Agriculture is a major contributor to the global carbon footprint, with its activities accounting for roughly a quarter of global greenhouse gas emissions (Poore and Nemecek, 2018; Lynch *et al*., 2021). The sector plays a pivotal role in shaping environmental sustainability. Among many different agricultural crops, tomato (*Solanum lycopersicum L.*) holds a place of significant importance, ranking as one of the most cultivated and consumed vegetables worldwide, second only to the potato in terms of production volume (Padmanabhan *et al*., 2016).

* Department of Chemistry, Democritus University of Thrace, Kavala, Greece.
** Department of Forestry and Natural Environment, Democritus University of Thrace, Drama, Greece.
*** Department of Agricultural Economics, Aristotle University of Thessaloniki, Thessaloniki, Greece.
Corresponding author: cstamp@agro.auth.gr

Tomatoes, a staple food in global diets and one of the most widely cultivated crops worldwide, are grown in over 180 countries and account for around 182 million tons of production annually (FAOSTAT, 2022). In 2022, the European Union produced a significant quantity of tomatoes, with Italy being the largest producer, accounting for 40% of the total EU production. Spain and Portugal followed, producing 24% and 9%, respectively. Overall, the EU harvested around 15.4 million tons of tomatoes in 2022 (European Commission, 2022).

In Greece, tomato production is a significant agricultural industry, with the country consistently ranking among the top 20 tomato producers worldwide. Within Europe, Greece often ranks among the top five tomato-producing nations, depending on the year (FAOSTAT, 2022. Greece is also a significant producer of tomatoes within the Mediterranean region, particularly known for its greenhouse cultivation methods. In terms of production volume, Greece consistently produces over 900,000 tons of tomatoes annually (FAOSTAT, 2022).

While precise statistics on tomato production's standalone carbon footprint are not always available, since its carbon emissions could vary significantly across different cultivation methods, regions, and supply chains, it is evident that reducing emissions in such high-produced crops could have a meaningful impact on global efforts to decarbonize agriculture. Decarbonizing major agricultural industries, such as the tomato industry, is key to tackling climate change (Ardakani *et al*., 2019; Migliore *et al*., 2019; Sovacool *et al*., 2021), but to do so we need reliable ways to measure the carbon footprint of goods produced in this industry. Carbon footprint assessments help identify the most significant sources of emissions within production processes, allowing for targeted mitigation strategies.

The production of tomatoes involves a variety of processes, including land preparation, cultivation, irrigation, fertilization, harvest, post-harvest processing, packaging, and transportation (Khoshnevisan *et al*., 2014). These stages contribute to carbon emissions through energy use, material inputs (such as fertilizers, pesticides, and packaging), and waste generation. Given the complexity of production systems and the broad scope of the topic, there is a pressing need to study the environmental impact of tomato production at various stages of the production process. Such understanding is essential for developing more eco-friendly agricultural practices and informed policies that mitigate carbon emissions effectively. Without a clear understanding of where environmental issues in tomato production stem from, it becomes impossible to implement the right strategies for mitigation. As tomatoes are a staple food in numerous countries and a key element in global food systems, even marginal improvements in the carbon efficiency of their production could yield substantial environmental benefits.

To this end, the overarching scope of the present study is to evaluate the carbon footprint associated with tomato production in Greece, with a focus on the equivalent carbon dioxide (CO_2) emissions resulting from both the materials and processes involved in cultivation and the management of waste post-production. Specifically, the study quantifies the total CO_2 emissions of tomatoes by means of a Life Cycle Assessment (LCA), considering key factors such as energy use, fertilizers, packaging, and waste management practices. By identifying major contributors to the carbon footprint and exploring strategies for mitigation, this research seeks to provide valuable insights into how the tomato production process can be made more sustainable.

The subsequent sections are organized as follows: The next section briefly outlines the relevant literature. The third section describes the LCA methodology and the utilized data inventory. The fourth section presents the results and discusses the findings. The last section concludes and also examines the implications of these results for practice and policymaking.

2. Literature Review

The environmental impacts of agricultural practices have garnered significant attention in recent years (Springmann *et al*., 2018). Several studies have focused on evaluating the carbon footprint associated with these practices, emphasizing the need for sustainable production methods to mitigate greenhouse gas (GHG) emissions (González-García *et al*., 2018; Poore and Nemecek, 2018; Castillo-González *et al*., 2024). And if, as alleged, agriculture's role in carbon emissions has been studied broadly, there is a notable lack of detailed research specifically addressing the carbon footprint of tomato production (Bosona and Gebresenbet, 2018; Canaj *et al*., 2019).

A comprehensive study by Solimene *et al*. (2023) explores the carbon footprint of tomato cultivation using Life Cycle Assessment (LCA). The article discusses the various methodologies employed to assess the carbon footprint and highlights the role of innovative farming techniques, such as precision agriculture, in minimizing environmental impacts. Interestingly, their findings indicate that the largest contribution to climate-changing gases comes from the use of fertilizers. The authors advocate for policies that encourage sustainable agricultural practices to ensure long-term environmental health and food security (Solimene *et al*., 2023).

Pedala *et al*. (2023) present a detailed evaluation of the environmental impacts of agriponic systems, with a specific focus on tomatoes. Their findings suggest that the carbon footprint of tomato production varies significantly depending on regional practices and technologies employed. The study emphasizes the interconnectedness of food production systems and their contribution to climate change, advocating for a holistic approach to sustainability that includes reducing emissions throughout the supply chain. The authors call for further research to explore alternative materials used for seed pods, fertilizer bottles, and greenhouse components, in order to reduce the reliance on plastic, concluding that utilizing materials that have lower environmental impacts, or are made from recycled plastics can be beneficial. This study advocates comprehensive strategies addressing both primary production and supporting materials, suggesting the potential of locally tailored approaches in regions where traditional and modern agricultural practices coexist. Common pattern in Mediterranean countries.

The research conducted by Bosona and Gebresenbet (2018) highlights the importance of using lifecycle approaches to mitigate the environmental impact of tomato production. Particularly, their empirical effort attempts to assess the environmental burdens of organic tomato produced and distributed in Sweden. The study reveals that even though the drying process consumes additional energy, it can be traded off by reduction of product volume and packaging material, which in turn reduces transport fuel and post-harvest product loss, especially in the case of transporting over long distances. Moreover, in the detailed study of Del Borghi *et al*. (2014), the results of a Life Cycle Assessment (LCA) performed on 13 tomato-based products produced in Italy are presented and discussed. Findings indicate that the agricultural phase and packaging production are the life-cycle stages with the highest impact in all the categories considered. The authors conclude that the identified improvement options related to the packaging subsystem are the reduction of weight and the switch to different packaging materials. These studies underscore the need to evaluate both packaging and transport in carbon footprint assessments for tomatoes, which could be particularly relevant in Greece, where exports and long-distance transport are common.

A recent study conducted by Naseer *et al*. (2022) explores the environmental impact of tomato production, focusing on quantifying and mitigating the carbon footprint across different production systems. The study identifies energy-efficient practices and optimized resource use as critical strategies for reducing emissions. Findings underscore the need for adopting renewable energy sources and precision agriculture techniques, especially in greenhouse systems, to lower the carbon footprint in tomato cultivation sustainably. These findings align with the need for region-specific solutions in Mediterranean climates, where solar energy and optimized irrigation may offer viable alternatives to more energy-intensive systems.

Lastly, it is well-documented in the relevant literature that LCA studies can capture the environmental impacts of foods, diets, and food production systems (Ruviaro *et al*., 2013; Dias *et al*., 2017; Sala *et al*., 2019; Pazmiño and Ramirez, 2021; Pedala *et al*., 2023; Kumar *et al*., 2024; Lee *et al*., 2024). Life Cycle Assessment (LCA) is a key methodological reference for identifying and addressing the above-mentioned issues. It is widely applied across various sectors, including food production, despite the inherent complexity of such processes (ISO 14040:2006a; ISO 14044:2006b). The principles of LCA allow the assessment of the global extent of the inputs, outputs, and potential environmental impacts throughout the life cycle of a product system. LCA follows the phases of (1) goal and scope, (2) life cycle inventory, (3) life cycle impact assessment, and (4) interpretation (Cucurachi *et al*., 2019).

The relevant literature reveals a clear consensus on the significant environmental impacts of tomato production, particularly concerning carbon emissions. The adoption of sustainable practices, supported by comprehensive assessments and targeted policies, is crucial for reducing the carbon footprint and promoting environmental sustainability in the agricultural sector. However, the aforementioned urge the need for continuous research for national and regional adaptations to enhance the sustainability of tomato production. By analyzing the carbon footprint of tomato production in Greece, we can contribute to the EU's broader agenda on climate change and sustainability. This can also serve as a model for similar studies in other Mediterranean countries and provide benchmarks for other regions in Greece or the EU to assess their own agricultural sustainability initiatives.

3. Methodology and Data

3.1. *Methodological Framework*

The stages of the Life Cycle Assessment (LCA) methodology used for the evaluation of equivalent carbon footprint (CO_2) for the production of tomatoes are briefly described as follows:

a) Goal and scope definition. It is the first stage of the methodology, where certain theoretical parameters that characterize the study are determined. These parameters include the objective of the study, its scope, the definition of the system being studied and the boundaries of that system, as well as the geographical coverage and the functional unit used in the study.
b) The Life Cycle Inventory (LCI) stage requires a detailed recording of all materials (including energy) and processes consumed and performed, respectively, throughout the production of the tomatoes (from the acquisition of the raw materials in the production to the packaging and management of the resulting waste).
c) In the Life Cycle Impact Assessment (LCIA) stage, the results of the assessment of the environmental impacts caused by tomato production in terms of equivalent carbon footprint (CO_2) are obtained.
d) The last stage is the interpretation of results. The results of the environmental impact assessment are summarized and are used to draw conclusions based on the objective of the study that has been determined. The present analysis refers to the environmental aspects of the tomato production process without considering economic or social factors.

3.2. *Goal and Scope Definition*

The objective of the present study is to evaluate the environmental impacts caused by the production of tomatoes by means of the valuation method regarding the equivalent carbon footprint (CO_2) that is produced. The results can be used to shape the environmental profile of the product under consideration for its environmental certification as well as to determine the impact of the materials consumed and the processes followed for its production on the environment.

The boundaries of the system that are examined from "a set of criteria that determine which individual processes are part of the system" (ISO 14040, 2006a). For this study, the boundaries of the system cover the entire production process of the tomato product, from the stage of obtaining the raw materials required, the materials and energy consumed, and the production processes up to the stage of packaging the tomatoes and the management of the resulting waste.

As far as the process of allocation is concerned, it is defined according to ISO 14040 (2006a, b) as "the separation of inputs and outputs referred to a process or system between the system under study and another system or systems". In the frame of the present study, there is only the production of tomatoes, and hence, there is no need for any separation.

According to ISO 14040 (2006a, b), the functional unit describes "the basic operation of a system and provides a reference against where input and output data can be quantified". For the present study, the functional unit used is one kilogram (1 kg) of finished tomato product, while the geographical coverage refers to Greece and the wider European area.

3.3. *Life Cycle Inventory*

This section outlines the materials and products consumed during tomato production, along with the procedures followed throughout the process. It also records all waste materials generated after production and their respective management methods. The data for greenhouse tomato production were obtained from a typical greenhouse production company in Northern Greece, and particularly, from the region of Eastern Macedonia and Thrace (NUTSII). The area is dominated by heated greenhouses for tomato production. This reliance of the area on greenhouse-based production provides an opportunity to analyze energy consumption and greenhouse gas emissions associated with controlled-environment agriculture. The production takes place annually, from March to November, yielding a total of 7,500 tons (t) of tomatoes per growing season. The quantities mentioned below correspond to one full growing season and are subsequently adjusted to the functional unit of this study, which is 1 kilogram (kg) of the final tomato product. Particularly:

I. Energy

The amount of energy consumed during tomato production is recorded. This energy concerns the electricity consumed during production, which comes from the public electricity supply network in Greece. At the same time, the company uses a high efficiency cogeneration (CHP) of electricity and heat systems with generators of electricity-heat-CO_2 with a total capacity of 8 Mw, which consume natural gas. The thermal energy and carbon dioxide (CO_2) emissions produced by the cogeneration system are used during the tomato production process, avoiding the use of an additional source of thermal energy and carbon dioxide (CO_2) supply for the enrichment of the crop with carbon dioxide. According to the data provided by the company, a total of 216,000,000 m^3 CO_2 (= 395,712,000 kg CO_2) is produced annually from the cogeneration system, of which 170,000,000 m^3 CO_2 (= 311,440,000 kg CO_2 are released into the greenhouses, while the remaining 46,000 m^3 CO_2 (= 84,272 kg CO_2) are released into the air. The electricity produced by the cogeneration system is not used during tomato production but is sold. According to the company's data, the total operating hours of the 4 cogeneration machines are 5,000 per year, i.e., producing a total of 8MW*5,000 h= 40,000 MWh of electricity per year. Therefore, it is considered that the production (consumption) of an equal

Table 1 - Data used in the calculation of the energy required for the tomato production.

Record	*Description*	*Measurement unit*	*Quantity*
Electricity consumed	The amount of electricity consumed by the public electricity supply network	kWh	6,800,000
Electricity produced	The amount of electricity produced by the cogeneration system and is sold	MWh	40,000
Natural gas	The amount of natural gas that is consumed by the cogeneration system	MWh	150,000 *(= 540,000.000 MJ = 540 TJ)*
Lubricants	Lubricants of cogeneration system machines	kg	11,000
Carbon dioxide (CO_2)	Amount of CO_2 produced by the cogeneration system and released into the air	kg	84,272

Source: Authors' own work based on data provided.

amount of electricity from the public electricity supply network is avoided. Table 1 gives the data considered in the calculation of the energy required for the tomato production.

II. Water

The amount of water used during the tomato production process is recorded in Table 2.

III. Fertilizers

The quantity and the type of fertilizers used for the tomato production process are recorded in Table 3.

IV. Insecticides

The quantity and the type of Insecticides used for the tomato production process are recorded in Table 4.

V. Other materials

The quantity and type of other materials, such as tomato seeds, used in the production process and materials used as a substrate for planting are recorded. It is noted that the quantity and type of seeds used are not taken into account in the calculation due to a lack of suitable environmental data in the existing LCI libraries (Table 5).

VI. Final product packaging

The quantity of materials used to pack the tomatoes is recorded in Table 6.

VII. Maintenance of greenhouses

The greenhouses used by the company for tomato production are constructed of load-bearing frame and glass and are permanent structures with a useful life of more than 30 years. Therefore, in the context of the present study, the construction of greenhouses is not included for the evaluation of carbon footprint, but only their maintenance. Specifically, the quantity of mate-

Table 2 - Water used for the tomato production.

Record	*Description*	*Measurement unit*	*Quantity*
Water	Non potable water derived from drillings	m^3	120,000 *(= 120,000,000 kg)*

Source: Authors' own work based on data provided.

Table 3 - The quantity and the type of fertilizers used for the tomatoes production.

Record	*Measurement unit*	*Quantity*
Monopotassium hydrogen phosphate as a source of phosphorus (P)	kg	30,340.0
Calcium nitrate as a source of nitrogen (N)	kg	82,835.0
Potassium nitrate as a source of nitrogen (N) and potassium (K)	kg	78,507.0
Ammonia nitrate as a source of nitrogen (N)	kg	1,040.0
Urea for CHP (nitrogen compound)	kg	34,000.0

Source: Authors' own work based on data provided.

Table 4 - The quantity and the type of Insecticides used for the tomato production.

Record	*Description*	*Measurement unit*	*Quantity*
Insecticides	1. Insecticides with the active compound pyriproxyfen (pyridinyl derivatives). 2. Insecticides with the active compound spiromesifen (tetronic acid derivatives).	lt	250 (*262 kg)*

Source: Authors' own work based on data provided.

Table 5 - The quantity and the type of other materials used for the tomato production.

Record	*Description*	*Measurement unit*	*Quantity*
Seeds	Tomatoes seeds	Items	380,000 *(0.5 kg)*
Substrate for planting	Stone wool planting substrate	m^3	860 *(25 tons)*
Plastic parts	Planting supports made of plastic (polyethylene, PE)	kg	2,000
Metallic Parts	Small, iron parts for machinery, etc.	kg	1,000

Source: Authors' own work based on data provided.

Table 6 - Quantity of packaging materials of the products.

Record	*Description*	*Measurement unit*	*Quantity*
Packaging	Cardboard boxes	Item	1,100,000 *(481,800 kg)*

Source: Authors' own work based on data provided.

Table 7 - Quantity of packaging materials of the tomato products.

Record	*Description*	*Measurement unit*	*Quantity*
Maintenance of greenhouses per production period	Glass panes (glasses) without any special coating	m^2	150 *(1,500 kg)*

Source: Authors' own work based on data provided.

rials used for the maintenance of the greenhouses required during the annual tomato production period is recorded in Table 7.

VIII. Transportation of materials

The transports concern both the raw materials used for the production of the tomatoes that are transported by the various suppliers to the production facilities as well as the materials that arise after the completion of production and are transported to recycling units. According to the information provided by the company, these transportations are implemented with 20-ton payload trucks, according to Table 8. The last column of the table calculates the product of the quantity of materials (in tons) and the kilometer distance covered during transportation, a parameter required to calculate the environmental impact.

IX. Waste Management

Waste generated during the production process of tomato products, along with its management, is documented in Table 9. Regarding the recycling of oils used in the cogeneration system, relevant studies (Udonne, 2011; Pires & Martino, 2013) discuss the methods employed for recycling and analyze their environmental impacts. In the present study, it is assumed that the environmental benefits of recycling 1 kg of lubricant oil are equivalent to the benefits gained by avoiding the production of 0.4 kg of new lubricant oil.

X. Environmental Data

Considering the data regarding the quantities of materials consumed and the processes performed to produce tomatoes as they were

Table 8 - Data concerning the transport of materials to/from the facilities.

Materials	*Quantity (kg)*	*Transport distance to/ from the facilities (km)*	*Quantity * Distance (tn*km)*
Fertilizers	226,722	160	36,275.52
Insecticides	262	40	10.48
Packaging materials (Cardboard boxes)	481,800	160	77,088
Stone wool	25,000	3,000	75,000
Glasses	1,500	40	60
Plantation supports (plastic)	2,000	40	80
Oils of machines	11,000	160	1,760
TOTAL (Materials to the facilities)			190,274 tn*km
Waste for recycling	146,000	40	5,840
Waste to landfill	25,000	4	100
TOTAL (Materials from the facilities)			5,940 tn*km

Source: Authors' own work based on data provided.

Table 9 - Waste management.

Record	*Description*	*Measurement unit*	*Quantity*	*Management*
Natural tissues Leaves / stems	Leaves / stems	kg	120,000	Disposal as livestock products
Plastic components	Plantation supports	kg	2,000	Plantation supports
Lubricants	Machines oils	kg	11,000	Recycling by a specialized unit
Paper	Paper / cardboard packaging	kg	12,000	Recycling by a specialized unit
Metallic Components	Steel	kg	1,000	Recycling by a specialized unit
Stone wool	Planting substrate	kg	25,000	Disposal in a landfill

Source: Authors' own work based on data provided.

described previously, the appropriate environmental data are selected from existing environmental data libraries (LCI libraries, Life Cycle Inventory) (Table 10).

3.4. *Life Cycle Impact Assessment*

To assess the environmental impact of the tomato production process, the Global Warming Potential assessment method (IPCC, 2007, GWP 100a 1.01) is used with climate change coefficients for a 100-year time frame. This method was developed by the International Panel on Climate Change (IPCC, 2007; IPCC, 2021) and refers to the possible changes in the Earth's climate due to the concentration of chemical substances ("greenhouse gases") that trap heat from the reflection of sunlight, while under other conditions would pass outside the atmosphere. It focuses on quantifying the environmental impact on the equivalent amount of carbon dioxide produced. The results are calculated in kilograms of equivalent carbon dioxide (CO_2).

Table 10 - Environmental data libraries (Life Cycle Inventory).

Category	*Dataset*	*LCI Library*	*Geographical coverage*
Energy	Electricity, high voltage, production GR, at grid/GR U	Ecoinvent Unit Processes	Greece
Energy	Natural gas, burned in gas turbine/GLO U	Ecoinvent Unit Processes	International
Energy	Lubricating oil, at plant/RER U (kg)	Ecoinvent Unit Processes	Europe
Water	Water, completely softened, at plant/RER U	Ecoinvent Unit Processes	Europe
Fertilizers	Fertilizer (P_2O_5)	LCA Food DK	Europe
Fertilizers	Fertilizer (K_2O)	LCA Food DK	Europe
Fertilizers	Calcium nitrate, as N, at regional storehouse/RER U	Ecoinvent Unit Processes	Europe
Fertilizers	Potassium nitrate, as K_2O, at regional storehouse/RER U	Ecoinvent Unit Processes	Europe
Fertilizers	Ammonium nitrate, as N, at regional storehouse/RER U	Ecoinvent Unit Processes	Europe
Fertilizers	Urea, as N, at regional storehouse/RER U	Ecoinvent Unit Processes	Europe
Insecticides	Pesticide unspecified, at regional storage/CH U	Ecoinvent Unit Processes	Europe
Packaging	Corrugated board boxes, technology mix, prod. mix, 16,6 % primary fibre, 83,4 % recycled fibre EU-25 S	European Life Cycle Database (ELCD)	Europe
Maintance	Float glass uncoated ETH U	ETH-ESU 96 Unit Processes	Europe
Other	Rock wool, at plant/CH U	Ecoinvent Unit Processes	Europe
Other	Polyethylene, HDPE, granulate, at plant/RER U	Ecoinvent Unit Processes	Europe
Other	Cast iron, at plant/RER U	Ecoinvent Unit Processes	Europe
Recycling	Livestock feed (soy)	LCA Food DK	Europe
Recycling	Recycling PE B250	BUWAL 250	Europe
Recycling	Recycling paper B250	BUWAL 250	Europe
Recycling	Recycling ECCS steel B250	BUWAL 250	Europe
Disposal	Disposal, mineral wool, 0% water, to inert material landfill/CH U	Ecoinvent Unit Processes	Europe
Transport	Transport, lorry, 20-28t, fleet average/CH U	Ecoinvent Unit Processes	Europe

Source: Authors' own work.

4. Results and discussion

4.1. *Results*

Table 11 presents the results of the calculations concerning the equivalent produced carbon dioxide that corresponds to the materials consumed and the processes required to produce tomatoes. The total CO_2 emissions resulting from these activities during a growing season (7,500 tons of tomatoes) amount to 3,779,618.59 kg CO_2 eq. or 0.50395 kg CO_2 eq. per kilogram of tomatoes.

Table 12 presents the results of the calculations concerning the equivalent produced carbon dioxide that corresponds to the management of the waste resulting from the production of tomatoes, both for recycling and disposing in landfills. The total carbon footprint from waste management is -34,783.01 kg CO_2 eq. (or -0.00464 kg CO_2 eq. per kg tomato), indicating that the waste management process actually contributes a net reduction in carbon emissions, mainly due to recycling efforts. This is a key aspect of sustainability in agricultural systems,

Table 11 - Quantity of the equivalent CO_2 to produce tomatoes.

Materials/ Processes	*Equivalent CO_2 produced per growing season (7,500 t) (kg CO_2 eq.)*	*Equivalent CO_2 produced per kg tomato (kg CO_2 eq.)*
Energy		
Electricity consumed	6,894,931.51	0.91932
Electricity produced and sold	-40,558,420.62	-5.40779
Natural gas consumed in the cogeneration system	36,154,335.75	4.82058
Lubricants	11,762.74	0.00157
Carbon dioxide released	84,272	0.01124
Water	3,189.73	0.00043
Fertilizers	551,600.67	0.07355
Insecticides	1,834.09	0.00024
Other materials	41,939.91	0.00559
Packaging	554,737.75	0.07397
Maintenance of greenhouses	1,541.97	0.00021
Transport of Materials to the facilities	36,745.95	0.00490
Transport of Materials from the facilities	1,147.14	0.00015
TOTAL	3,779,618.59	0.50395

Source: Authors' calculations.

Table 12 - Quantity of the equivalent CO_2 of waste management after the production of tomatoes.

Waste management	*Equivalent CO_2 produced per growing season (7,500 t) (kg CO_2 eq.)*	*Equivalent CO_2 produced per kg tomato (kg CO_2 eq.)*
Disposal of natural tissue waste as livestock products	-27,140.81	-0.00362
Recycling of plastic parts by a specialized unit	-664.10	-0.00009
Recycling of lubricants by a specialized unit	-4,705.10	-0.00063
Recycling of cardboard packages by a specialized unit	-761.66	-0.00010
Recycling of metallic parts by a specialized unit	-1,688.39	-0.00023
Disposal of stone wool in a landfill	177.04	0.00002
TOTAL	-34,783.01	-0.00464

Source: Authors' calculations.

as it demonstrates that proper waste management can mitigate the overall carbon footprint. Below is an analysis of key contributors:

- Significant reductions in CO_2 emissions come from the recycling of various materials. For instance, the recycling of plasticparts (-664.10 kg CO_2 eq.) and lubricants (-4,705.10 kg CO_2 eq.) offsets the overall carbon impact. This suggests that the adoption of recycling initiatives can play a crucial role in reducing the carbon footprint of tomato production.
- The disposal of natural tissue waste as livestock products results in a negative

Table 13 - Total quantity of the equivalent CO_2 to produce tomatoes.

Environmental Impacts	*Equivalent CO_2 produced per growing season (7,500 t) (kg CO_2 eq.)*	*Equivalent CO_2 produced per kg tomato (kg CO_2 eq.)*
Materials/Processes	3,779,618.59	0.50395
Waste Management	-34,783.01	-0.00464
TOTAL	3,744,835.57	0.49931

Source: Authors' calculations.

Table 14 - Comparison of the equivalent carbon dioxide.

Standard Cultivation	*Production of Equivalent CO_2 ha^{-1} in Florida, USA*	*Production of Equivalent CO_2 ha^{-1} in Greece (greenhouse)*	*Difference*
Fertilizers	1,656 kg CO_2 eq ha^{-1}	1,032 kg CO_2 eq ha^{-1}	-37.68 %
Insecticides	3,268 kg CO_2 eq ha^{-1}	1,834.09 Kg CO_2 eq ha^{-1}	-43.87 %
Water	5,976 kg CO_2 eq ha^{-1}	3,189.73 Kg CO_2 eq ha^{-1}	-46.62 %
TOTAL	52,813 kg CO_2 eq ha^{-1} (0.75 kg CO_2 per kg)	35,226 kg CO_2 eq ha^{-1} (0.49931 kg CO_2 per kg)	-33.3%

Source: Readily available data from Jones et al. (2012). - Authors' calculations.

carbon impact of -27,140.81 kg CO_2 eq., further enhancing the sustainability of the production process. Conversely, the disposal of stone wool in a landfill leads to a very small positive contribution of 177.04 kg CO_2 eq., which minimally impacts the overall carbon footprint.

The sum of the environmental impact caused, on the one hand, by the materials consumed and the processes followed to produce the tomato product and, on the other hand, by waste management, gives the total environmental impact of the final product (tomatoes). These results are presented in Table 13. The overall CO_2 footprint for producing 7,500 tons of tomatoes is 3,744,835.57 kg CO_2 eq. or 0.49931 kg CO_2 eq. per kg of tomatoes.

4.2. *Comparative analysis and discussion*

Although direct comparison of produces from different agricultural areas and different production methods (conventional and organic methods) is difficult, the following table presents a comparison between the LCA results of the current study and results presented in the study of Jones *et al*. (2012). Although the production methods and system boundaries could vary, the comparison enables us to have better understanding on impacts of tomato production under different conditions (greenhouse-based production and open-field based production). Table 14 gives a comparison of the equivalent carbon dioxide produced in a typical crop in Florida, USA, with the corresponding Greek one. The selection of the specific area was made because the climatic data are similar to the Mediterranean climate, which also exists in the area of the unit, but also because, unfortunately, both at the national and European level, there are very few studies related to the production of carbon dioxide during the production of tomatoes. It should be noted that this unit uses drip irrigation.

According to Jones *et al*. (2012), the production of equivalent carbon dioxide from the production of tomatoes in open-type crops can reach up to 0.75 kg CO_2 per kg of product produced. The production of tomatoes in the controlled environment of the greenhouse results in a reduction of the emitted carbon dioxide equivalent by 33.3%. A percentage that proves the impressive production possibilities as well as the energy savings realized during the production process. It is also evident that a substantial portion of the carbon dioxide emissions originates from the consumption of electricity and natural gas, while a smaller fraction is generated through the use of water, fertilizers and insecticides.

5. Concluding remarks

5.1. *Conclusions*

The objective of the present study is to calculate the environmental impacts caused by the different stages of the production of tomato products using the valuation method regarding the equivalent carbon dioxide (CO_2) that is produced. The Global Warming Potential valuation method was used to assess the environmental impacts with climate change coefficients over a 100-year time frame, while the results were calculated in kilograms of equivalent carbon dioxide (kg CO_2 eq.). The impacts of the materials consumed and the processes performed during the production process under consideration were calculated to be equal to 0.50395 kg CO_2 eq. per kilo of tomatoes. Accordingly, an environmental benefit resulting from waste management after the completion of the production process was calculated to be equal to 0.00464 kg CO_2 eq. per kilo of tomatoes. This benefit is subtracted from the effects of materials and processes and the total environmental impact caused is obtained equal to 0.49931 kg CO_2 eq. per kilo of tomatoes.

The calculations prove that the energy required to produce the tomato is the factor that has the greatest impact on the environmental impact. The overall effects of this energy depend directly on the amount of electricity produced by the high efficiency cogeneration (CHP) system with natural gas consumption, as well as the amount of electricity consumed for production from the public network. The fertilizers and the materials used to package the product also affect the overall environmental impact. As far as the management of the waste resulting from the production process is concerned, a significant environmental benefit arises from the disposal of natural tissues as livestock products, mainly due to their increased quantity, as well as from the recycling of the lubricating oils used in the machines of the cogeneration system.

5.2. *Policy implications*

On the outcome of policy, the findings of the present study could provide guidance to policymakers and practitioners in developing effective strategies that promote sustainability in tomato production and supply chain while reducing environmental impacts. The results provide important insights into the carbon footprint of tomato production and highlight areas where emissions can be reduced or offset. Particularly:

1. The use of cogeneration systems and the production of surplus electricity to be sold can significantly reduce the carbon footprint, showing a potential path toward more energy-efficient and sustainable tomato production. The positive offset from electricity production is a clear benefit that could be further optimized. Additionally, adopting renewable energy sources (solar, wind, or geothermal) for heating and cooling could significantly reduce the reliance on fossil fuels. Policymakers can incentivize the implementation of such systems and also the use of renewable energy sources through subsidies or tax breaks for energy-efficient technologies.
2. Recycling and the disposal of waste materials in environmentally responsible ways provide opportunities for reducing the overall carbon impact. The recycling of materials like plastic, lubricants, and cardboard can substantially lower emissions, making it a critical area for improving sustainability in tomato production systems. Policymakers can support the development of waste management infrastructure, providing incentives for promoting the adoption of closed-loop systems where waste is reused or repurposed.
3. The emissions from fertilizer use and packaging materials represent significant contributions to the overall carbon footprint. To mitigate this impact, policymakers can promote sustainable agricultural practices such as precision agriculture, which uses technology to apply fertilizers more efficiently, reducing excess and minimizing emissions. The promotion of organic or less energy-intensive alternatives to chemical fertilizers could also be considered. Additionally, encouraging the adoption of biodegradable or recyclable packaging

materials can help lower emissions associated with packaging waste.

By addressing issues such as energy consumption, waste management, and the use of fertilizers and packaging, policymakers can foster a more sustainable agricultural system for the tomato industry at a national or regional level, thereby contributing to the broader EU's agenda on climate change mitigation and sustainable production.

5.3. *Limitations*

A certain limitation of this study is tied to its exclusive focus on the environmental impact of tomato production, specifically the carbon footprint, without incorporating economic considerations. While the environmental aspect is critical for understanding sustainability, economic factors, such as the costs of production, market dynamics, and financial feasibility of emission reduction strategies, are equally important for a holistic assessment. Future research could integrate cost-benefit analyses and economic evaluations to complement the environmental findings and provide a more comprehensive framework for policy formulation.

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