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Environmental Impact of Fresh Tomato Production in an Urban Rooftop Greenhouse in a Humid Continental Climate in South Korea †

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Abstract: In this work, we used life cycle assessment (LCA) to determine the environmental impact of fresh tomato production using a conventional greenhouse (GH) located in a rural area versus a rooftop greenhouse (RTG) located in an urban area in South Korea. The heating and cooling loads were modeled for a period of 12 months using the simulation software TRNSYS. The comparative LCA was then performed for the GH and RTG using these data. It was found that 19% less energy is required for heating an RTG and 38% more energy is used for cooling compared with a GH. Nevertheless, the total energy load reduction for the RTG is 13%. This decreased energy consumption is due to smaller heat losses of the RTG during the colder months. The decreased energy load, combined with the elimination of transportation, storage, and handling losses during the distribution stage, resulted in 43% less global warming potential, 45% less cumulative energy demand and abiotic depletion, 37% less photochemical oxidation and acidification, and 27% less eutrophication for the RTG. Further studies with seasonal yield data, energy sources, and integrated energy flows are expected to provide a better understanding of the advantages of urban farming in this region.

Keywords: LCA; environmental impacts; agriculture; heating; energy consumption

1. Introduction

In view of the sheer expansion of the population and increasing living standards across the planet, our food systems are facing intensification across the entire supply chain [1–3]. One of the most intensified food systems is the agricultural sector. This sector is experiencing several changes that are leading to unintended consequences such as forest loss, increase in greenhouse gas emissions, soil degradation, groundwater depletion, and eutrophication, among others [4]. These environmental impacts, linked to the intensified production of food, have been the focus of numerous studies in recent decades. Therefore, a few methodologies have been developed in order to assess the environmental impact that we have on the environment. One of the most successful and widely used in recent years is the life cycle assessment (LCA). A life cycle assessment is defined as a "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product throughout its lifecycle" by the International Organization for Standardization [5]. An LCA has four stages: (a) definition of goal and scope, (b) inventory analysis, (c) impact assessment, and (d) interpretation of the results obtained from each stage. The original application of the LCA methodology was in the industrial

sector. However, its use has become widespread in the food and agricultural areas [6]. With the LCA methodology, it is possible to find the activities or processes that have a higher impact on the environment. In general, energy intensive activities have a higher impact on the environment, and few agricultural activities are as highly energy intensive as cultivation in greenhouses in colder regions of the world. This is because of the necessity of climate control to provide produce all year round. Besides climate control, highly technological greenhouses also have a CO_2 supply and artificial lighting to promote product growth. In addition, they have several controls for maintaining the appropriate climate conditions and the optimum doses of macro- and micronutrients.

The typical greenhouse is also evolving and experiencing several changes that might help mitigate the impacts of large-scale food production. For instance, urban rooftop greenhouses (RTGs) might help bring the food supply chain closer to the consumer, thus reducing the need for long-distance transportation from rural areas into cities. Moreover, they are integrated into the building in order to exchange energy flows, such as hot or cold air for heating and cooling, and CO_2. RTGs are expected to improve the sustainability of urban areas as a result of the economic, social, and environmental benefits that they bring [7]. Such benefits include reduced transportation [8], diminished burden on fertile agricultural areas [9], and increased availability of urban fresh produce [7]. Other benefits include thermal insulation for buildings and, therefore, reduced energy consumption for climate control purposes in the case of isolated RTGs [7]. Hence, in terms of energy consumption, rooftop greenhouses are expected to outperform their rural counterparts in terms of environmental performance. This could benefit large cities such as Seoul, in South Korea, where tomato is mainly produced in greenhouses [10].

The humid continental climate of South Korea is characterized by four distinct seasons, and the contrast between the winter and summer is large and plays an important role in reducing the demand for both heating and cooling energy [11]. Summers are hot and humid, with monsoons occurring from June to September. August has the hottest daily average temperatures, which oscillate between 22 and 30 °C. The winters are colder and drier than for other places of similar latitude. In January, the daily average temperature ranges from −7 to 1 °C [12]. The large variations in temperature and humidity of summers and winters represent a challenge for the production of tomato in an RTG in terms of energy consumption and environmental impact. Therefore, in this study, we compared the environmental impacts of two systems, a conventional greenhouse (GH) and a rooftop greenhouse (RTG). The energy loads were obtained through simulation of building energy. Given the big differences between the two systems, the energy data were added into a model for the production of fresh tomato to examine all the benefits associated with rooftop greenhouse production.

2. Methodology Details

Using LCA, it is possible to evaluate and compare the environmental impact of a product or system. In this case, the relative intensity of the energy demand, resources, consumption, and pollutants of the two systems were evaluated. This section outlines the tomato production process, the details of the building energy simulation, and the LCA methodology details.

2.1. Fresh Tomato Production Process Details

Fresh tomato production takes place mostly in greenhouses in soilless culture because of the high yield compared with open field production in soil [13]. In this LCA, tomato is produced in greenhouses using different covering materials. For the RTG system, the covering is glass, while double ethylene vinyl acetate (EVA) copolymer sheet is used as the covering material in the GH system. The heating system considered for both systems is a gas boiler system. The modeled production system and its boundary are shown in Figure 1. The production system is divided into infrastructure (greenhouse structure, irrigation, and climate control), production (seedlings, fertilizers, pesticides, water, and transport), energy (heating and cooling), and distribution (packaging, distribution, and losses). Both systems are considered soilless and use rockwool as growing media.

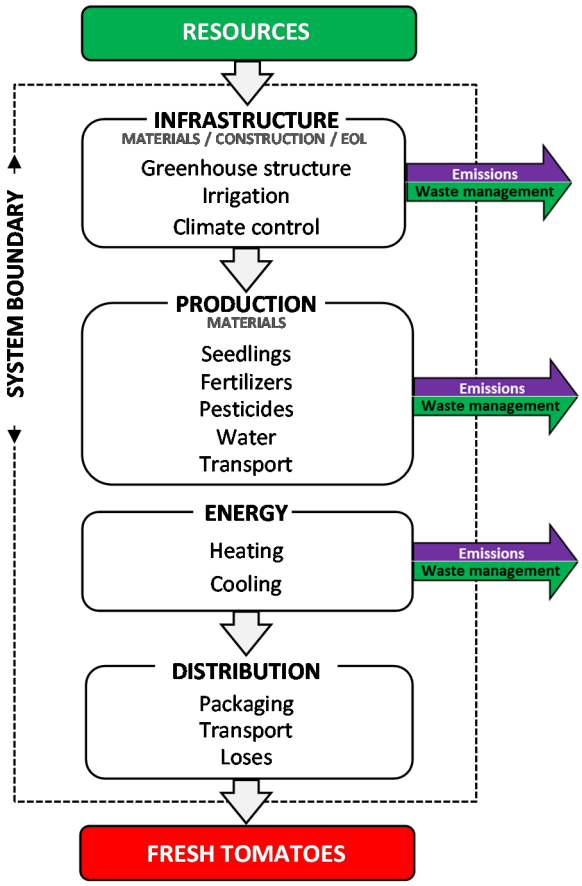

Figure 1. Schematic representation of the processes and system boundary of the life cycle assessment (LCA) study.

2.2. Building Energy Simulation: Load Calculation Details.

A building load simulation was performed for both the GH and RTG. The simulation was modeled using TRNSYS [14], which is a transient system simulation program. Both greenhouses are Venlo type with a total area of 1690 m^2 and volume of 7815 m^3. However, the GH covering is made of EVA copolymer (U-value = 5.62 W m^{-2} K^{-1}), while the covering for the RTG is made of 16 mm double wall tempered glass (U-value = 3.25 W m^{-2} K^{-1}). Another difference is the floor layer; in the case of the GH, the ground floor has a U-value of 0.378 W m^{-2} K^{-1}, while the in RTG, the U-value of the floor (or in this case, the adjacent ceiling) is 0.261 W m^{-2} K^{-1}. The model contains other data regarding the orientation of the structures, materials, ground temperature, convective coefficients, window frame factor, local weather data, and initial values. Utilizing the typical reference year (TRY), we generated monthly data of 12 specific years and integrated them into the hourly data in this model. The optimal growing temperature for tomatoes ranges from 20 to 25 °C, with a minimum of 5 °C and maximum of 32 °C. Therefore, the following heating temperature program was implemented: during daytime: 22–25 °C, during nighttime: 12 to 15 °C. Cooling was operated as follows: during daytime: 27–30 °C, during nighttime: 24 to 27 °C. Thermal curtains and shading curtains were closed when the global solar radiation was below 5 W m^{-2} and above 800 W m^{-2}, respectively. Forced ventilation is activated when the internal temperature is above 26 °C during intense solar radiation (09:00 to 20:00). In the case of the RTG, the simulation does not consider the exchange of energy flows and only considers the initial temperature of the floor at the rooftop. The rated thermal power of the heater was selected as 95 kW. The maximum air flow rate of the blower in the heater was 225 m^3 min^{-1}, and the boiler efficiency was assumed to be 80%. An energy balance based on this model results in both the heating and cooling loads. These results were validated with climate data from an existing conventional greenhouse located

in a rural area of northeast South Korea (37°76′ N, 126°77′ E) and the RTG results with a recently built RTG at the Korea Institute of Machinery and Materials (36°23′ N, 127°21′ E) (Figure 2a,b). The details of the simulation and validation of the results can be found in [15]. The building load analysis results are shown in Figures 3 and 4.

(**a**) (**b**)

Figure 2. Picture of the rooftop greenhouse (RTG) located at Korea Institute of Machinery and Materials in Daejeon, a middle part of South Korea (**a**), and the conventional greenhouse (GH) located in the southeastern part of South Korea (**b**).

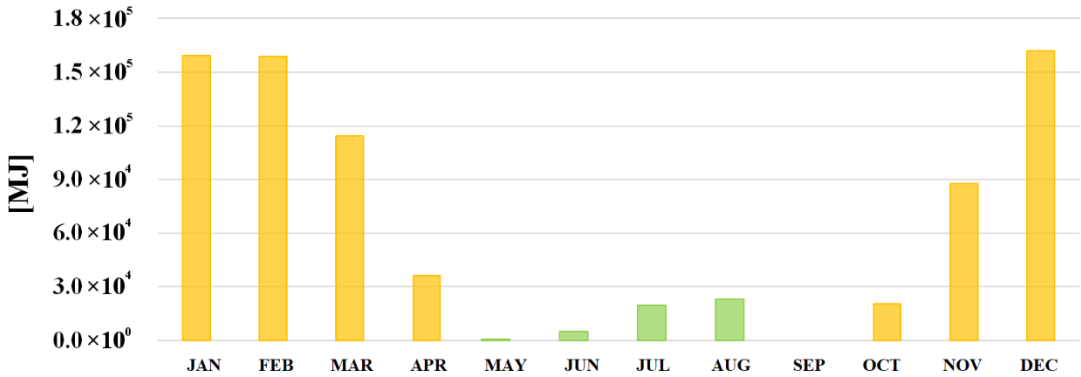

Figure 3. Annual heating (January to April and September to December) and cooling (May to August) load simulation in a conventional greenhouse [7].

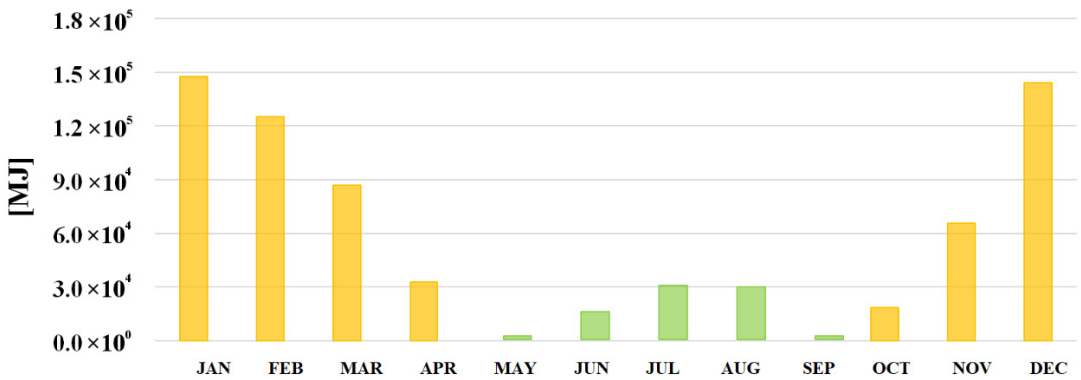

Figure 4. Annual heating (January to April and September to December) and cooling (May to August) load simulation in a rooftop greenhouse [7].

The simulation shows that the annual heating load in the case of the RTG is 19% smaller compared with the GH. This difference is driven by the weather conditions in the respective locations, the covering materials, and the floor insulation. However, the cooling load in the RTG is higher by 38% in comparison. Despite the large increment in cooling load, the absolute values of energy requirements are much higher in the heating operation than in the cooling operation. The total energy load of the RTG is 13% lower than that of the GH.

2.3. LCA Methodology: Goal, Scope, and Functional Unit

In this study, we followed the international organization for standardization (ISO) guidelines for the implementation of LCA [5,16], which consist of four steps: (1) definition of goal and scope, (2) a life cycle inventory (LCI), (3) a life cycle impact assessment (LCIA), and (4) life cycle interpretation. The goal of this study was to compare the environmental performance of two fresh tomato production systems with similar characteristics in a humid continental climate such as that found in South Korea. The first system is a representative conventional greenhouse (GH) of the Venlo type located in a rural area 315 km away from Seoul in South Korea. The second system is a rooftop greenhouse (RTG) located in an urban area, in this case, in Seoul, South Korea. CML-IA baseline V3.05/World 2000 was the chosen impact assessment methodology for this study. CML is a widely used LCIA method in agriculture [17,18] and a recommended method in the International Reference Life Cycle Data System handbook [19]. To compare the two systems, five impact categories were selected. These impact categories are the most commonly used in agriculture and reflect the general environmental performance of the system [20]. The impact categories are abiotic depletion (AD), global warming potential (GWP), photochemical oxidation (PO), acidification (AP), and eutrophication (EU). In addition, the cumulative energy demand (CED V1.10) was also obtained. The list of impact categories and units is shown in Table 1. The functional unit (FU), related to the inputs and assessed impacts, was defined as the production of 1 kg of fresh tomato retailed for consumption at the local market in the case of the GH. Regarding the RTG, it is considered an idealized scenario in which local consumers arrive at the RTG to directly acquire the produce; this removes the need for extra packaging and transportation.

Table 1. Assessed impact categories.

Impact Category	Acronym	Unit
Abiotic depletion	AD	kg Sb eq
Global warming (GWP100a)	GWP	kg CO_2 eq
Photochemical oxidation	PO	kg C_2H_4 eq
Acidification	AP	kg SO_2 eq
Eutrophication	EU	kg PO_4 eq
Cumulative energy demand	CED	MJ

2.4. Details of the Life Cycle Inventory

The data for greenhouse infrastructure, production, and distribution inputs were taken from the ECOINVENT 3.4 database [21]. Energy requirements were obtained from the building energy simulation. The complete inventory list can be found in Appendix A.

2.4.1. Infrastructure Inventory Inputs

The GH infrastructure data correspond to a double-layer EVA copolymer film greenhouse made of galvanized steel. The structure lifetime is considered to be 25 years. This is a commercial greenhouse that includes heating and cooling systems, a fertigation system, and a CO_2 injection system. The structure contains all the emissions from fabrication to dismantling. It also includes the end-of-life activities such as recycling and disposal of materials. The RTG infrastructure data correspond to a structure of galvanized steel and aluminum covered with glass plates. This dataset was modified with actual data of a recently built rooftop greenhouse in order to reflect the extra materials needed to

support this structure such as concrete, steel, and glass. The expected lifetime of this greenhouse is 50 years.

2.4.2. Production Inventory Inputs

For the agricultural inputs, the same dataset was used in both systems and corresponds to an annual production of 48.3 kg m^{-2}. It also includes fertilization with 0.1025/0/0.0851 kg m^{-2} mineral nitrogen, phosphorus, potassium (NPK) and pesticide usage of kg m^{-2}. Seedlings and rockwool as the growing media as well as transportation and waste management were taken into consideration.

2.4.3. Energy Inventory Inputs

The heating demand based on the simulation corresponds to 437 and 367 MJ per kg of tomato per year for the GH and RTG, respectively. A boiler using natural gas was assumed for both the RTG and the GH. Cooling using electrical energy was considered for both cases. The calculated values for energy per kg per year were 7.95 kWh for the GH and 12.88 kWh for the RTG. This electricity consumption was taken from the electricity mix for South Korea of 2014.

2.4.4. Distribution Inventory Inputs

Finally, in the case of the GH, the distribution stage was modeled considering the use of plastic and cardboard packaging. Because of the location of the GH, transportation from the farm to a distribution center and from the distribution center to retail as well as electricity for cooling during storage at the distribution center were considered. In addition, because of the manipulation of the product at the different transportation stages and at the distribution center, we considered a 10% of loss in the case of the GH system as in [22]. As previously stated, in this study, it was assumed that consumers come directly to the RTG to pick up the produce, eliminating the need for extra packaging, transportation, cooling in a distribution center, transportation to the market, and losses due to product handling during all these stages.

3. Results

3.1. Life Cycle Impact Assessment

Using the software SimaPro (ver. 8.5.2), developed by PRé Sustainability B.V., Amersfoort, The Netherlands [23], all the datasets from ECOINVENT and modeled processes were translated into the chosen environmental impacts defined in Section 2.3. Tables 2 and 3 show the results for the GH and RTG, respectively. These results are the absolute values of the impact categories for each of the system processes: infrastructure, production, energy, and distribution.

Table 2. Life cycle impact assessment (LCIA) results for impact categories (ICs) per functional unit (FU) for tomato production in a conventional greenhouse (GH) in northeastern South Korea.

IC	Unit	Total	Infra	Production	Energy	Distribution
AD	kg Sb eq	5.4×10^{-6}	2.8×10^{-6}	3.6×10^{-7}	3.3×10^{-7}	1.9×10^{-6}
GWP	kg CO_2 eq	1.7×10^{0}	6.3×10^{-2}	6.2×10^{-2}	7.9×10^{-1}	8.3×10^{-1}
PO	kg C_2H_4 eq	2.6×10^{-4}	2.4×10^{-5}	1.2×10^{-5}	8.4×10^{-5}	1.4×10^{-4}
AP	kg SO_2 eq	4.1×10^{-3}	3.5×10^{-4}	4.0×10^{-4}	9.6×10^{-4}	2.4×10^{-3}
EU	kg PO_4 eq	1.5×10^{-3}	1.6×10^{-4}	1.2×10^{-4}	4.6×10^{-4}	8.2×10^{-4}
CED	MJ	2.5×10^{1}	8.9×10^{-1}	4.8×10^{-1}	1.2×10^{1}	1.1×10^{1}

Table 3. LCIA results for impact categories (ICs) per FU for tomato production in a rooftop greenhouse in Seoul, South Korea.

IC	Unit	Total	Infra	Production	Energy	Distribution
AD	kg Sb eq	3.0×10^{-6}	2.2×10^{-6}	3.6×10^{-7}	3.5×10^{-7}	9.4×10^{-9}
GWP	kg CO_2 eq	1.0×10^{0}	1.8×10^{-1}	6.2×10^{-2}	7.5×10^{-1}	5.1×10^{-3}
PO	kg C_2H_4 eq	1.6×10^{-4}	7.2×10^{-5}	1.2×10^{-5}	7.8×10^{-5}	9.6×10^{-7}
AP	kg SO_2 eq	2.6×10^{-3}	1.1×10^{-3}	4.0×10^{-4}	1.0×10^{-3}	1.9×10^{-5}
EU	kg PO_4 eq	1.1×10^{-3}	3.9×10^{-4}	1.2×10^{-4}	6.2×10^{-4}	9.8×10^{-6}
CED	MJ	1.4×10^{1}	1.9×10^{0}	4.8×10^{-1}	1.1×10^{1}	6.1×10^{-2}

For easier visualization, the results are plotted as a percentage of the contribution of each process to the impact categories (Figures 5–7). Here, it is possible to see which system process has more influence over the results in the impact categories. Figure 5 shows a direct comparison of the two systems in each of the impact categories.

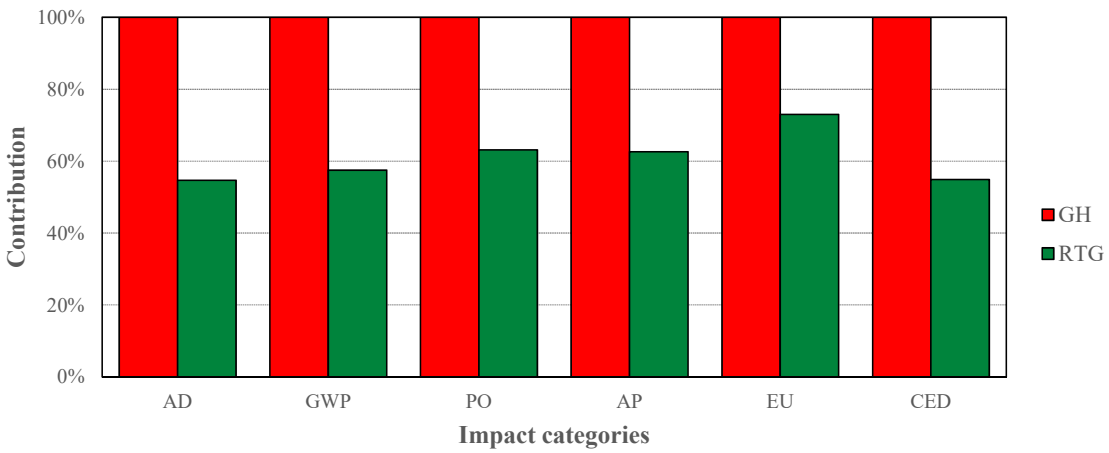

Figure 5. Comparison in five impact categories and cumulative energy demand between the RTG and the GH. Impact categories: AD, abiotic depletion; GWP, global warming potential; PO, photochemical oxidation; AP, acidification potential; EU, eutrophication; CED, cumulative energy demand.

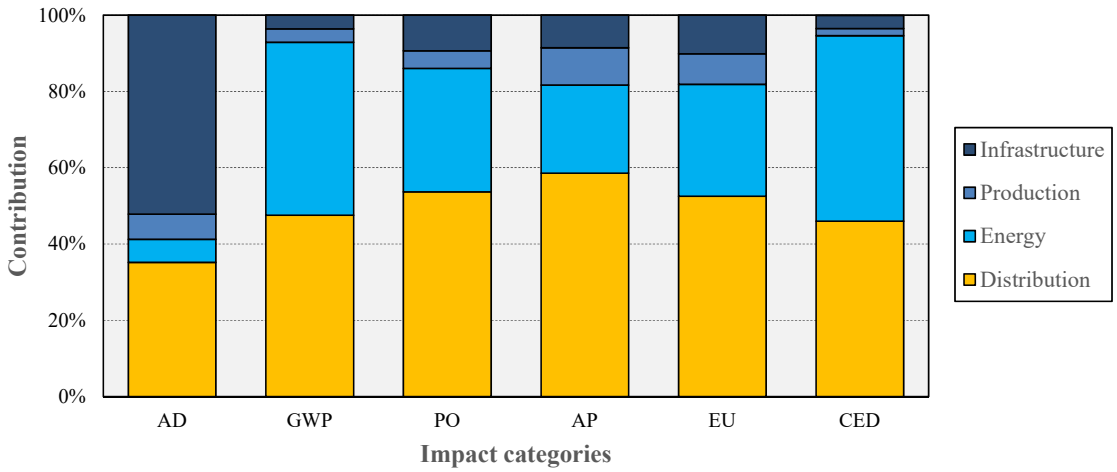

Figure 6. Contribution to the different impact categories for production of tomato in a conventional greenhouse. Impact categories: AD, abiotic depletion; GWP, global warming potential; PO, photochemical oxidation; AP, acidification potential; EU, eutrophication; CED, cumulative energy demand.

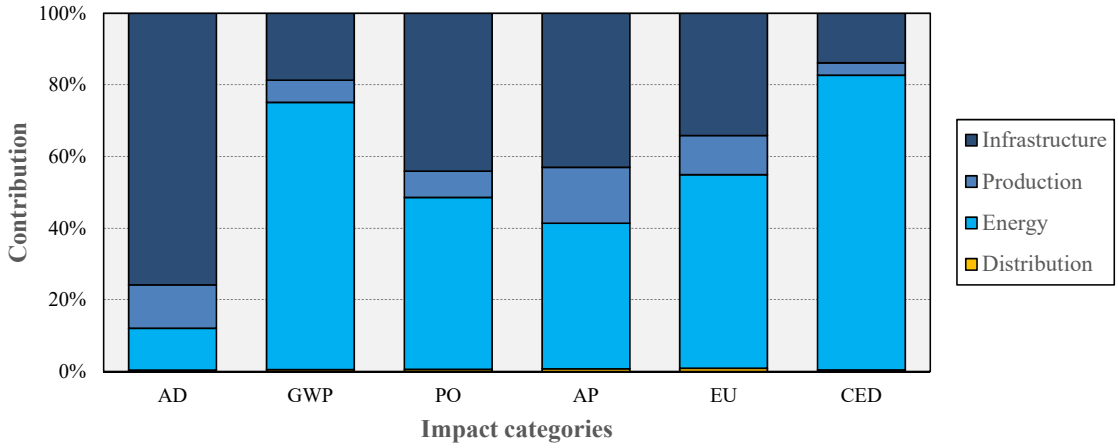

Figure 7. Contribution to the different impact categories for production of tomato in a rooftop greenhouse. Impact categories: AD, abiotic depletion; GWP, global warming potential; PO, photochemical oxidation; AP, acidification potential; EU, eutrophication; CED, cumulative energy demand.

3.2. Life Cycle Interpretation

Comparing the total impact in each category of both systems, it can be observed that the RTG has a favorable position in most categories, except in production, where both systems have the same input values. Considering the total value from all of the processes, the RTG has better performance; for example, there is 43% less GWP and 45% less CED compared with the GH. Abiotic depletion also has a high reduction of 45%. Photochemical oxidation and acidification are both reduced by 37%, and eutrophication decreases by 27%. However, energy consumption is not the only reason for this reduction. Regarding infrastructure, the RTG has a higher impact in most categories. For instance, the RTG has 200% higher GWP and PO compared with the GH. The drivers of this large difference are the use of glass in the case of the RTG, as well as the larger amount of steel needed for its construction. The difference is because stiffer supports and steel bars are needed to safely operate the greenhouse on the rooftop of a building. Despite the 50-year lifespan of the RTG, the humidity and weather conditions will probably result in more frequent and difficult maintenance procedures being required than compared with the GH, which has only a 25-year lifespan. Figure 8 shows the GWP comparison per process.

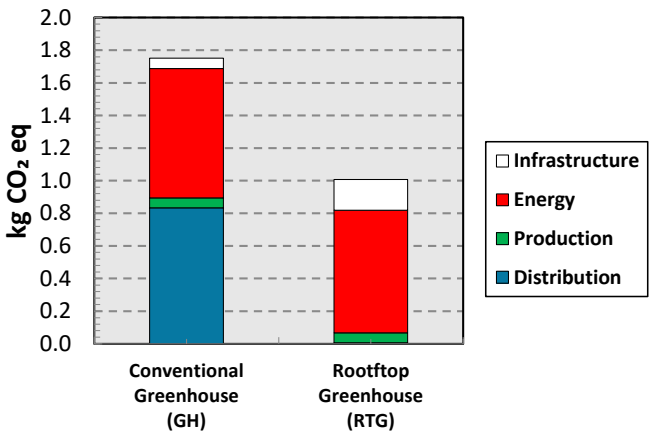

Figure 8. GWP comparison between the RTG and the GH per process in kg CO_2 eq.

From the energy viewpoint, the difference is already substantial between the two systems based on the building energy simulation. The RTG requires 19% less heat compared with the GH, but 38%

more energy for cooling. The total energy is 13% lower for the RTG. This translates into 5% less GWP, 6% less PO, and 7% less CED. The heat losses in the cold months are smaller in the RTG compared with the GH. These favorable environmental conditions could be enhanced in a co-generation scenario or if energy flows are exchanged between the building and the greenhouse.

Distribution represents another area where there is a large reduction in the impacts of the RTG since transportation from the farm to the consumer is no longer needed. In addition, refrigeration and losses occurring during product handling are avoided. Figure 9 shows the contribution of each component of the distribution process to the impact categories. These include packaging, cardboard, loses, transportation, and cooling. Transportation includes the following: farm to warehouse, warehouse to distribution center (DC) and DC to retail. It can be observed that the cardboard utilized for packaging the product represents a major proportion in all categories.

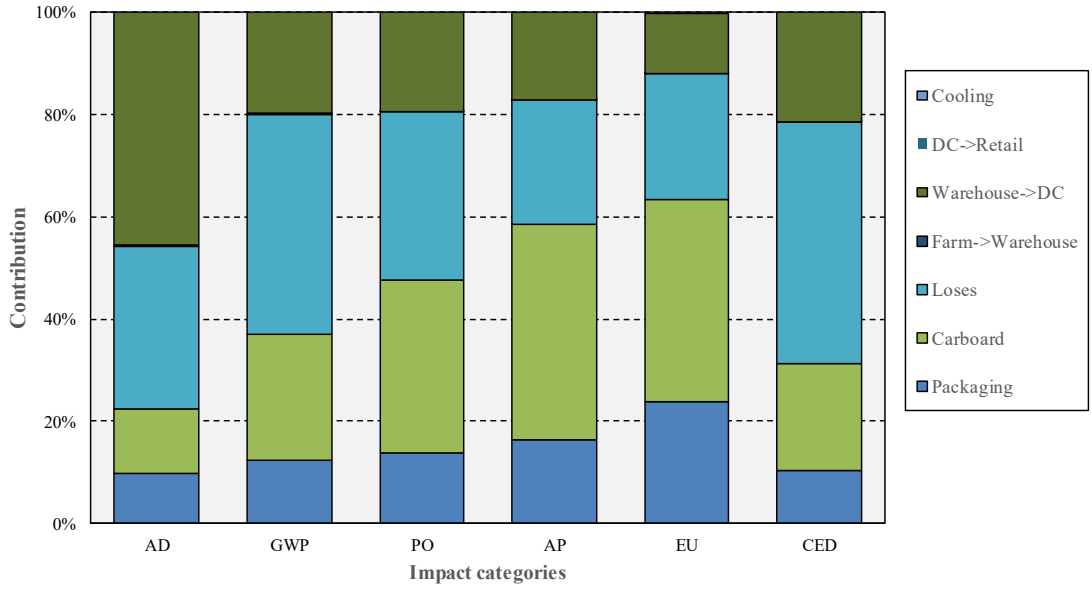

Figure 9. Contribution to the different impact categories for the distribution process in the conventional greenhouse. Impact categories: AD, abiotic depletion; GWP, global warming potential; PO, photochemical oxidation; AP, acidification potential; EU, eutrophication; CED, cumulative energy demand.

4. Further Considerations

Rooftop greenhouses are still in development, and much work is still needed for their integration into the food chain. However, the benefits for large cities are vast in terms of environmental performance. This preliminary study provides a detailed approximation of the environmental impacts of an urban greenhouse focused on the production of fresh tomato. Further studies with seasonal yield data, various heating/cooling systems, and building exchange flow scenarios will help us determine the best possible conditions for urban rooftop farming in the near future.

5. Conclusions

In this work, it was estimated that 19% less energy is required for heating a rooftop greenhouse (RTG) located in an urban area compared with a conventional greenhouse (GH) located in a suburban area. However, 38% more energy is used for cooling. Nevertheless, the total energy load reduction for the RTG is 13%. This decreased energy consumption is due to smaller heat losses of the RTG during the colder months. The obtained savings represent 5% less GWP for the RTG. All other impact categories were also comparatively reduced. For instance, abiotic depletion decreases by 45%, photochemical oxidation and acidification are both reduced by 37%, and eutrophication decreases by 27%. In addition, other inherent advantages of urban farming are all associated with a large reduction

in the environmental impacts. These improvements in the environmental performance are due to a reduction in losses due to product handling, no requirement for transportation from the farm to the consumer, and reduction in packaging. Further analysis using seasonal yield data and scenarios such as different heating systems (co-generation or different fuel sources) as well as the full integration of energy flows between the RTG and the building will be necessary to determine the full range of environmental advantages associated with urban farming.

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Abbreviations

AD	abiotic depletion
AP	acidification potential
CED	cumulative energy demand
GH	conventional greenhouse
EU	eutrophication
FU	functional unit
GWP	global warming potential
LCA	life cycle assessment
LCI	life cycle inventory
LCIA	life cycle impact assessment
NPK	nitrogen, phosphorus, potassium
PO	photochemical oxidation
RTG	rooftop greenhouse

Appendix A

Table A1. Infrastructure inventory inputs per m^2 per year.

Infrastructure per m^2 per Year	Unit	GH	RTG
Acrylic varnish, without water, in 87.5% solution state	kg	1.1×10^{-3}	n/a
Agricultural machinery, unspecified	kg	7.6×10^{-3}	3.0×10^{-4}
Aluminum alloy, AlMg3	kg	n/a	1.1×10^{-1}
Aluminum scrap, post-consumer	kg	-6.0×10^{-3}	-1.0×10^{-1}
Aluminum, cast alloy	kg	6.4×10^{-3}	n/a
Bitumen seal	kg	1.0×10^{-4}	n/a
Blow molding	kg	3.2×10^{-3}	1.6×10^{-3}
Calendering, rigid sheets	kg	1.0×10^{-2}	n/a
Concrete block	kg	1.1×10^{-1}	n/a
Concrete, sole plate, and foundation	m^3	3.8×10^{-4}	7.3×10^{-3}
Copper	kg	6.5×10^{-4}	5.0×10^{-5}
Diesel, burned in building machine	MJ	3.7×10^{-1}	2.3×10^{-1}
Drawing of pipe, steel	kg	3.2×10^{-1}	1.6×10^{-1}
Electricity, low voltage	kWh	6.0×10^{-2}	3.0×10^{-2}
Electronics, for control units	kg	1.6×10^{-5}	1.5×10^{-3}
Ethylene vinyl acetate copolymer	kg	1.2×10^{-1}	n/a
Extrusion, plastic film	kg	1.7×10^{-1}	2.7×10^{-2}
Extrusion, plastic pipes	kg	4.4×10^{-2}	2.2×10^{-2}
Flat glass, uncoated	kg	n/a	6.5×10^{0}
Gas motor, 206 kW	p	6.2×10^{-10}	3.1×10^{0}

Table A1. em Cont.

Infrastructure per m^2 per Year	Unit	GH	RTG
Heat and power co-generation unit, 200 kW electrical	p	6.2×10^{-10}	3.1×10^{-10}
Glass fiber reinforced plastic, polyamide, injection molded	kg	8.0×10^{-5}	n/a
Injection molding	kg	2.1×10^{-2}	1.1×10^{-3}
Iron scrap, unsorted	kg	-6.0×10^{-1}	-2.0×10^{-1}
Oil boiler, 100 kW	p	1.9×10^{-6}	9.3×10^{-7}
Polycarbonate	kg	1.0×10^{-2}	n/a
Polyester resin, unsaturated	kg	1.4×10^{-3}	n/a
Polyethylene, high density, granulate	kg	4.7×10^{-2}	2.4×10^{-2}
Polyethylene, linear low density, granulate	kg	4.8×10^{-2}	2.7×10^{-2}
Polymer foaming	kg	4.9×10^{-3}	2.5×10^{-3}
Polypropylene, granulate	kg	3.2×10^{-4}	n/a
Polystyrene, expandable	kg	4.9×10^{-3}	2.5×10^{-3}
Polyvinylfluoride	kg	2.1×10^{-2}	4.9×10^{-4}
Section bar extrusion, aluminum	kg	6.4×10^{-3}	1.1×10^{-1}
Section bar rolling, steel	kg	2.3×10^{-1}	8.9×10^{-2}
Sheet rolling, steel	kg	3.6×10^{-2}	1.8×10^{-2}
Silicone product	kg	1.2×10^{-4}	n/a
Steel, chromium steel 18/8	kg	3.4×10^{-2}	1.6×10^{-2}
Steel, low-alloyed	kg	5.7×10^{-1}	4.5×10^{0}
Synthetic rubber	kg	3.0×10^{-4}	1.5×10^{-4}
Tractor, four-wheel, agricultural	kg	1.5×10^{-2}	7.6×10^{-3}
Wire drawing, copper	kg	1.8×10^{-3}	1.4×10^{-4}
Zinc coat, coils	m^2	n/a	9.3×10^{-3}
Waste management			
Waste concrete	kg	n/a	$1.0E \times 10^{-4}$
Waste concrete	kg	n/a	$5.0E \times 10^{-1}$
Waste electric and electronic equipment	kg	n/a	$2.0E \times 10^{-3}$
Waste glass	kg	n/a	$4.0E \times 10^{-3}$
Waste glass	kg	n/a	$2.0E \times 10^{-1}$
Waste plastic, mixture	kg	n/a	$3.0E \times 10^{-4}$
Waste plastic, mixture	kg	1.3×10^{-1}	$5.0E \times 10^{-2}$
Waste polyvinylchloride	kg	2.0×10^{-4}	n/a
Waste polyvinylchloride	kg	1.2×10^{-1}	n/a
Waste rubber, unspecified	kg	6.9×10^{-6}	$3.0E \times 10^{-6}$
Waste rubber, unspecified	kg	2.9×10^{-4}	$1.0E \times 10^{-4}$

Table A2. Agricultural inventory inputs per kg per year.

Agricultural Inputs per kg per Year	Unit	GH	RTG
Ammonia, liquid	kg	9.5×10^{-5}	9.5×10^{-5}
Ammonium nitrate, as N	kg	2.9×10^{-5}	2.9×10^{-5}
Ammonium sulfate, as N	kg	3.4×10^{-5}	3.4×10^{-5}
Application of plant protection product, by field sprayer	ha	6.2×10^{-6}	6.2×10^{-6}
Irrigation	m^3	1.4×10^{-2}	1.4×10^{-2}
Nitrogen fertilizer, as N	kg	1.9×10^{-3}	1.9×10^{-3}
Potassium chloride, as K_2O	kg	8.7×10^{-4}	8.7×10^{-4}
Potassium fertilizer, as K_2O	kg	6.8×10^{-4}	6.8×10^{-4}
Potassium sulfate, as K_2O	kg	2.1×10^{-4}	2.1×10^{-4}
Packaging, for fertilizers or pesticides	kg	8.0×10^{-3}	8.0×10^{-3}
Pesticide, unspecified	kg	9.5×10^{-5}	9.5×10^{-5}
Planting	ha	2.1×10^{-6}	2.1×10^{-6}
Stone wool	kg	9.2×10^{-3}	9.2×10^{-3}
Tomato seedling, for planting	p	5.8×10^{-2}	5.8×10^{-2}
Transport, tractor, and trailer, agricultural	tkm	6.3×10^{-4}	6.3×10^{-4}
Urea, as N	kg	5.5×10^{-5}	5.5×10^{-5}

Table A3. Energy inventory inputs per m^2 per year.

Energy per m^2 per Year	Unit	GH	RTG
Heat, central or small-scale, natural gas	MJ	4.4×10^2	4.0×10^2
Cooling, electricity, low voltage	kWh	8.0×10^0	1.3×10^1

Table A4. Distribution inventory inputs per kg per year.

Distribution per kg per Year	Unit	GH	RTG
Polyethylene, high density, granulate, recycled	kg	1.2×10^{-1}	1.8×10^{-3}
Folding boxboard/chipboard	kg	1.4×10^{-1}	n/a
Transport, freight, 3.5–7.5 metric ton lorry, EURO6	tkm	2.0×10^{-3}	n/a
Transport, freight, 3.5–7.5 metric ton lorry, EURO6	tkm	3.2×10^{-1}	n/a
Transport, freight, 3.5–7.5 metric ton lorry, EURO6	tkm	7.0×10^{-4}	n/a
Electricity, low voltage	kWh	7.3×10^{-4}	n/a
Losses	p	10%	n/a

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