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

Israel Torres Pineda 1, Jeong Hwa Cho 2,3, Dongkeun Lee 1, Sang Min Lee 1, Sangseok Yu 2 and Young Duk Lee 1,*

1 Environmental Systems Research Division, Korea Institute of Machinery & Materials, Daejeon 34103, Korea; israeltp@kimm.re.kr (I.T.P.); keun5832@kimm.re.kr (D.L.); victlee@kimm.re.kr (S.M.L.)
2 School of Mechanical Engineering, Chungnam National University, Daejeon 34134, Korea; jh.cho@snu.ac.kr (J.H.C.); sangseok@cnu.ac.kr (S.Y.)
3 Department of Rural Systems Engineering, Seoul National University, Seoul 08826, Korea
* Correspondence: ydlee@kimm.re.kr; Tel.: +82-42-868-7945
† This paper is an improved version of the conference paper published in the ECOS 2020 proceedings.

Received: 7 October 2020; Accepted: 27 October 2020; Published: 30 October 2020

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 CO₂ 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 CO₂. 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.
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 m² and volume of 7815 m³. 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 in the 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 m³ 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.

![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).](image1)

**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).

![Annual heating (January to April and September to December) and cooling (May to August) load simulation in a conventional greenhouse.](image2)

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

![Annual heating (January to April and September to December) and cooling (May to August) load simulation in a rooftop greenhouse.](image3)

**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.

| Impact Category | Acronym | Unit       |
|-----------------|---------|------------|
| Abiotic depletion | AD      | kg Sb eq   |
| Global warming (GWP100a) | GWP | kg CO₂ eq   |
| Photochemical oxidation | PO | kg C₂H₄ eq  |
| Acidification    | AP      | kg SO₂ eq  |
| Eutrophication   | EU      | kg PO₄ 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 CO₂ 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 0.1025/0.0851 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\(_2\)H\(_4\) 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 CO₂ eq| 1.0 × 10⁰ | 1.8 × 10⁻¹| 6.2 × 10⁻²| 7.5 × 10⁻¹| 5.1 × 10⁻³  |
| PO     | kg C₂H₄ eq| 1.6 × 10⁻⁴| 7.2 × 10⁻⁵| 1.2 × 10⁻⁵| 7.8 × 10⁻⁵| 9.6 × 10⁻⁷  |
| AP     | kg SO₂ eq| 2.6 × 10⁻³| 1.1 × 10⁻³| 4.0 × 10⁻⁴| 1.0 × 10⁻³| 1.9 × 10⁻⁵  |
| EU     | kg PO₄ 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 × 10¹  | 1.9 × 10⁰  | 4.8 × 10⁻¹| 1.1 × 10¹  | 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](image_url)

**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](image_url)

**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 CO₂ 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.](image)

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.

Author Contributions: Conceptualization, Y.D.L.; Data curation, D.L. and S.Y.; Formal analysis, I.T.P. and J.H.C.; Funding acquisition, S.M.L.; Methodology, Y.D.L.; Project administration, S.M.L.; Software, I.T.P., J.H.C., and S.Y.; Supervision, Y.D.L.; Validation, S.Y.; Writing—original draft, I.T.P. and D.L.; Writing—review & editing, Y.D.L. All authors have read and agreed to the published version of the manuscript.

Funding: This study was financially supported by the Korea Institute of Machinery & Materials (KIMM), a government-funded research institution in South Korea.

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

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 m² per year.

| Infrastructure per m² 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 × 10⁻³ |
| 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                       | m³       | 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 × 10⁹   |
| Gas motor, 206 kW                                          | p        | 6.2 × 10⁻¹⁰ | 3.1 × 10⁹   |
Table A1. em Cont.

| Infrastructure per m² per Year | Unit | GH    | RTG    |
|-------------------------------|------|-------|--------|
| Heat and power co-generation unit, 200 kW electrical | p  | $6.2 \times 10^{-10}$ | $3.1 \times 10^{-10}$ |
| Glass fiber reinforced plastic, polyamide, injection molded | kg | $8.0 \times 10^{-5}$ | n/a |
| Injection molding | kg | $2.1 \times 10^{-2}$ | $1.1 \times 10^{-3}$ |
| Iron scrap, unsorted | kg | $-6.0 \times 10^{-1}$ | $-2.0 \times 10^{-3}$ |
| Oil boiler, 100 kW | p | $1.9 \times 10^{-6}$ | $9.3 \times 10^{-7}$ |
| Polycarbonate | kg | $1.0 \times 10^{-2}$ | n/a |
| Polyester resin, unsaturated | kg | $1.4 \times 10^{-3}$ | n/a |
| Polyethylene, high density, granulate | kg | $4.7 \times 10^{-2}$ | $2.4 \times 10^{-2}$ |
| Polyethylene, linear low density, granulate | kg | $4.8 \times 10^{-2}$ | $2.7 \times 10^{-2}$ |
| Polymer foaming | kg | $4.9 \times 10^{-3}$ | $2.5 \times 10^{-3}$ |
| Polypropylene, granulate | kg | $3.2 \times 10^{-4}$ | n/a |
| Polystyrene, expandable | kg | $4.9 \times 10^{-3}$ | $2.5 \times 10^{-3}$ |
| Polyvinylfluoride | kg | $2.1 \times 10^{-2}$ | $4.9 \times 10^{-4}$ |
| Section bar extrusion, aluminum | kg | $6.4 \times 10^{-3}$ | $1.1 \times 10^{-1}$ |
| Section bar rolling, steel | kg | $2.3 \times 10^{-1}$ | $8.9 \times 10^{-2}$ |
| Sheet rolling, steel | kg | $3.6 \times 10^{-2}$ | $1.8 \times 10^{-2}$ |
| Silicone product | kg | $1.2 \times 10^{-4}$ | n/a |
| Steel, chromium steel 18/8 | kg | $3.4 \times 10^{-2}$ | $1.6 \times 10^{-2}$ |
| Steel, low-alloyed | kg | $5.7 \times 10^{-1}$ | $4.5 \times 10^{0}$ |
| Synthetic rubber | kg | $3.0 \times 10^{-4}$ | $1.5 \times 10^{-4}$ |
| Tractor, four-wheel, agricultural | kg | $1.5 \times 10^{-2}$ | $7.6 \times 10^{-3}$ |
| Wire drawing, copper | kg | $1.8 \times 10^{-3}$ | $1.4 \times 10^{-4}$ |
| Zinc coat, coils | m² | n/a | $9.3 \times 10^{-3}$ |

**Waste management**

| Waste concrete | kg | n/a | $1.0 \times 10^{-4}$ |
| Waste concrete | kg | n/a | $5.0 \times 10^{-1}$ |
| Waste electric and electronic equipment | kg | n/a | $2.0 \times 10^{-3}$ |
| Waste glass | kg | n/a | $4.0 \times 10^{-3}$ |
| Waste glass | kg | n/a | $2.0 \times 10^{-1}$ |
| Waste plastic, mixture | kg | n/a | $3.0 \times 10^{-4}$ |
| Waste plastic, mixture | kg | $1.3 \times 10^{-1}$ | $5.0 \times 10^{-2}$ |
| Waste polyvinylchloride | kg | $2.0 \times 10^{-4}$ | n/a |
| Waste polyvinylchloride | kg | $1.2 \times 10^{-1}$ | n/a |
| Waste rubber, unspecified | kg | $6.9 \times 10^{-6}$ | $3.0 \times 10^{-6}$ |
| Waste rubber, unspecified | kg | $2.9 \times 10^{-4}$ | $1.0 \times 10^{-3}$ |

Table A2. Agricultural inventory inputs per kg per year.

| Agricultural Inputs per kg per Year | Unit | GH    | RTG    |
|-------------------------------------|------|-------|--------|
| Ammonia, liquid | kg | $9.5 \times 10^{-5}$ | $9.5 \times 10^{-5}$ |
| Ammonium nitrate, as N | kg | $2.9 \times 10^{-5}$ | $2.9 \times 10^{-5}$ |
| Ammonium sulfate, as N | kg | $3.4 \times 10^{-5}$ | $3.4 \times 10^{-5}$ |
| Application of plant protection product, by field sprayer | ha | $6.2 \times 10^{-6}$ | $6.2 \times 10^{-6}$ |
| Irrigation | m³ | $1.4 \times 10^{-2}$ | $1.4 \times 10^{-2}$ |
| Nitrogen fertilizer, as N | kg | $1.9 \times 10^{-3}$ | $1.9 \times 10^{-3}$ |
| Potassium chloride, as K₂O | kg | $8.7 \times 10^{-4}$ | $8.7 \times 10^{-4}$ |
| Potassium fertilizer, as K₂O | kg | $6.8 \times 10^{-4}$ | $6.8 \times 10^{-4}$ |
| Potassium sulfate, as K₂O | kg | $2.1 \times 10^{-4}$ | $2.1 \times 10^{-4}$ |
| Packaging, for fertilizers or pesticides | kg | $8.0 \times 10^{-3}$ | $8.0 \times 10^{-3}$ |
| Pesticide, unspecified | kg | $9.5 \times 10^{-5}$ | $9.5 \times 10^{-5}$ |
| Planting | ha | $2.1 \times 10^{-6}$ | $2.1 \times 10^{-6}$ |
| Stone wool | kg | $9.2 \times 10^{-3}$ | $9.2 \times 10^{-3}$ |
| Tomato seedling, for planting | p | $5.8 \times 10^{-2}$ | $5.8 \times 10^{-2}$ |
| Transport, tractor, and trailer, agricultural | tkm | $6.3 \times 10^{-4}$ | $6.3 \times 10^{-4}$ |
| Urea, as N | kg | $5.5 \times 10^{-5}$ | $5.5 \times 10^{-5}$ |
Table A3. Energy inventory inputs per m² per year.

| Energy Inventory | Unit | GH | RTG |
|------------------|------|----|-----|
| Heat, central or small-scale, natural gas | MJ | $4.4 \times 10^2$ | $4.0 \times 10^2$ |
| Cooling, electricity, low voltage | kWh | $8.0 \times 10^0$ | $1.3 \times 10^1$ |

Table A4. Distribution inventory inputs per kg per year.

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

References

1. Foley, J.A.; Ramankutty, N.; Brauman, K.A.; Cassidy, E.S.; Gerber, J.S.; Johnston, M.; Mueller, N.D.; O’Connell, C.; Ray, D.K.; West, P.C.; et al. Solutions for a cultivated planet. *Nature* 2011, 478, 337–342. [CrossRef] [PubMed]

2. Godfray, H.C.J.; Beddington, J.R.; Crute, I.R.; Haddad, L.; Lawrence, D.; Muir, J.F.; Pretty, J.; Robinson, S.; Thomas, S.M.; Toulmin, C. Food Security: The Challenge of Feeding 9 Billion People. *Science* 2010, 327, 812–818. [CrossRef] [PubMed]

3. Tilman, D.; Balzer, C.; Hill, J.; Befort, B.L. Global food demand and the sustainable intensification of agriculture. *Proc. Natl. Acad. Sci. USA* 2011, 108, 20260–20264. [CrossRef] [PubMed]

4. Ramankutty, N.; Mehrabi, Z.; Waha, K.; Jarvis, L.; Kremen, C.; Herrero, M.; Rieseberg, L.H. Trends in Global Agricultural Land Use: Implications for Environmental Health and Food Security. *Annu. Rev. Plant Biol.* 2018, 69, 789–815. [CrossRef]

5. International Organization for Standardization. Environmental Management—Life Cycle Assessment—Principles and Framework (ISO 14040:2006). Available online: https://www.iso.org/standard/37456.html (accessed on 30 October 2020).

6. Perrin, A.; Basset-Mens, C.; Gabrielle, B. Life cycle assessment of vegetable products: A review focusing on cropping systems diversity and the estimation of field emissions. *Int. J. Life Cycle Assess.* 2014, 19, 1247–1263. [CrossRef]

7. Cerón-Palma, I.; Sanyé-Mengual, E.; Oliver-Solà, J.; Montero, J.I.; Rieradevall, J. Barriers and Opportunities Regarding the Implementation of Rooftop Eco.Greenhouses (RTEG) in Mediterranean Cities of Europe. *J. Urban Technol.* 2012, 19, 87–103. [CrossRef]

8. Sanyé, E.; Cer, I.; Oliver-sol, J. Environmental analysis of the logistics of agricultural products from roof top greenhouses in Mediterranean urban areas. *J. Sci. Food Agric.* 2013, 100–109. [CrossRef] [PubMed]

9. Droegge, P. 100 Percent Renewable: Energy Autonomy in Action; Earthscan: London, UK, 2009; ISBN 978-1-84407-718-2.

10. Heuvelink, E. *Tomatoes*; Heuvelink, E., Ed.; CABI: Wallingford, NY, USA, 2018; ISBN 9781780641935.

11. Chung, M.H.; Park, J.C.; Ko, M.J. Effect of the solar radiative properties of existing building roof materials on the energy use in humid continental climates. *Energy Build.* 2015, 102, 172–180. [CrossRef]

12. Bae, C.; Chun, C. Research on seasonal indoor thermal environment and residents’ control behavior of cooling and heating systems in Korea. *Build. Environ.* 2009, 44, 2300–2307. [CrossRef]

13. Selina, P.; Bledsoe, M.E. U.S. Greenhouse: Hothouse Hydroponic Tomato Timeline. Available online: https://ipmdata.ipmcenters.org/documents/timelines/USgreenhousetomato.PDF (accessed on 27 October 2020).
14. University of Wisconsin-Madison. Solar Energy Laboratory. In TRNSYS, a Transient Simulation Program; The Laboratory: Madison, WI, USA, 1975.

15. Cho, J. The Feasibility Analysis of Economic and Environmental Impact of Air-Conditioning System for Greenhouse Using Dynamic Energy Simulation. Master’s Thesis, Chungnam National University, Daejeon, Korea, 2020.

16. International Organization for Standardization. Environmental Management—Life Cycle Assessment—Requirements and Guidelines (ISO 14044: 2006). Available online: https://www.iso.org/standard/38498.html (accessed on 30 October 2020).

17. iPoint-Systems Gmbh Life Cycle Impact Assessment—Which Are the LCIA Indicator Sets Most Widely Used by Practitioners? Available online: https://www.i-point-systems.com/blog/lcia-indicator/ (accessed on 24 September 2020).

18. Merchant, A.; Combelles, A. Comparison of Life Cycle Impact Assessment Methods in a Case of Crop in Northern France. In Proceedings of the 4th International Conference on Life Cycle Approaches, Lille, France, 5–6 November 2014; pp. 3–6.

19. Tobergte, D.R.; Curtis, S. ILCD Handbook; CRC Press: Boca Raton, FL, USA, 2013; Volume 53, ISBN 9788578110796.

20. Gómez-López, M.D.; Martínez, S.; Gabarrón Sánchez, M.; Faz Cano, A. Course—Life Cycle Assessment for a Sustainable Agriculture. Course Handout. 2017. Available online: http://www.agri-base.eu/wp-content/uploads/2017/05/LCA.pdf (accessed on 30 October 2020).

21. Wernet, G.; Bauer, C.; Steubing, B.; Reinhard, J.; Moreno-ruiz, E.; Weidema, B. The ecoinvent database version 3 (part I): Overview and methodology. Int. J. Life Cycle Assess. 2016, 3, 1218–1230. [CrossRef]

22. Sanyé-Mengué, E.; Oliver-Solà, J.; Montero, J.L; 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. Int. J. Life Cycle Assess. 2015, 20, 350–366. [CrossRef]

23. Pré Consultants. SimaPro (Release 8.5.2.0). 2017. Available online: https://simapro.com/ (accessed on 30 October 2020).

Publisher’s Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.