Environmental assessment of an integrated rooftop greenhouse

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Abstract

Vertical farming is emerging as an effective measure to grow food in buildings and can increase food production in urban areas in a more sustainable manner. This study presents a comprehensive environmental assessment of food production in an integrated rooftop greenhouse (i-RTG) – an innovative vertical farm consisting of a rooftop greenhouse connected to a building – and considers rainwater, residual heat (energy), residual air (CO_2) and food from an industrial ecology perspective. This synergistic connection preserves resources and improves conditions in the greenhouse and the building. The goal of the study is to show the feasibility of the system and to calculate the environmental impacts from its whole life cycle, from infrastructure to end of life, by comparing these impacts with those of conventional production. The results show that the system is feasible and produced 30.2 kg/m^2 of tomato over 15.5 months. The synergy with the building allows the cultivation of winter-fall crops without supplying heating and maintained an average temperature 8 °C higher than that outdoors. Moreover, rainwater was used to irrigate the crops, reducing consumption from the water supply network by 80-90%. The environmental assessment showed that the operation of the i-RTG has more impacts than the infrastructure due to the use of fertilisers, which account for 25% of the impacts in four of the six impact categories studied. Regarding the infrastructure, the greenhouse structure and rainwater harvesting system of the building have substantial environmental impacts (over 30% in four of the six impact categories). Comparison with a conventional greenhouse demonstrates that the i-RTG has a better environmental performance, showing between 50 and 75% lower impacts in five of the six impact categories (for instance, 0.58 kg of CO_2 equivalent per kg of tomato vs. 1.7 kg), mainly due to the reduced packaging and transport requirements. From this study, it was concluded that optimisation of the amount of infrastructure material and management of the operation could lead to even better environmental performance in future i-RTG projects.

Keywords: food security, urban agriculture, vertical farming, LCA, water-energy-food nexus, industrial ecology

1. Introduction

Ensuring food security is a major concern worldwide (FAO et al. 2015). Providing enough nutritious food will likely become increasingly difficult due to the increasing world population and its concentration in cities (United Nations 2013). Innovative solutions are needed to address this problem.

In this context, urban agriculture is a growing trend that consists of growing food in and around cities and can contribute to food security in both developed and developing countries (Orsini et al. 2013; Mok et al. 2014). Additionally, urban agriculture has unique advantages, such as social education, the creation of local employment (reducing commuting), reduced food transportation distances and the development of local economies (Altieri et al. 1999; Bon et al. 2010; Kortright and Wakefield 2011; Nadal 2015).

An advanced type of urban agriculture is vertical farming, which is based on the production of food in buildings (Besthorn 2013; Thomaier et al. 2015). Similar concepts have been defined in previous literature, such as Z-Farming or Skyfarming (Despommier 2010; Specht et al. 2013). Vertical farms are classified depending on the level of integration with the building, for example, by the placement (rooftop, facade), exposure (exposed, enclosed, closed), growth medium (aeroponic, hydroponic, aquaponic) and production purpose (educational, research, commercial) (Association for Vertical Farming 2016).

The concepts of highly technological systems for food production in buildings, completely isolated from nature, and establishing synergy between buildings and crops have been discussed by several authors (Hessel and Bar-On 2002; Fischetti 2008; Despommier 2010, 2011; Germer et al. 2011). Nevertheless, pilot implementations of this technology in a research context are required to prove its feasibility, elucidate and resolve potential problems and assess its performance. Indeed, previous studies detected the need for scientific articles assessing vertical farming systems, highlighting the necessity of adopting a life cycle perspective in the analysis (Specht et al. 2013; Mok et al. 2014; Sanyé-Mengual et al. 2016).

In vertical farming, rooftop greenhouses (RTGs) are greenhouses located on top of buildings and can be either isolated from the building or integrated at several levels, in regard to water, energy and CO_2 flow (Pons et al. 2015). Occupying unused rooftops for agriculture has great potential for widescale implementation in urban areas, including major cities (Rodriguez 2009; Astee and Kishnani 2010). For instance, a city such as Bologna (Italy) could fulfil 77% of its vegetable requirements with rooftop farms with productivities of 15 kg/m^2 (Orsini et al. 2014). The short-term implementation of RTGs on available rooftops in a logistic park in Barcelona with 13 ha of suitable rooftop area could produce 2,000 tonnes of tomato annually, which would fulfil the demand of 150,000 people (Sanyé-Mengual et al. 2015a).

The concept of an integrated rooftop greenhouse (i-RTG) was proposed and discussed in previous literature (Caplow 2009; Cerón-Palma et al. 2012). i-RTGs share resources with the building and have the potential to increase both the productivity and the efficiency of crops using these synergies. This connection allows for optimisation of the energy behaviour of the building, reduction of CO_2 emitted by the building, increased crop yield and minimisation or elimination of external water use. Several rooftop greenhouse experiments have been reported worldwide (Wilson 2002; Engelhard 2010). Nevertheless, to the best of our knowledge, no experimental case studies have been conducted integrating the greenhouse and the building. In addition to the advantages stated above, an i-RTG could potentially reduce the environmental impacts of vegetable production. Quantifying these environmental burdens of the pilot i-RTG is of interest to examine the potential for reducing the environmental impacts of food production (Sanyé-Mengual et al. 2012, 2015b).

The main objective of the study is to determine the feasibility of producing food in i-RTGs and examine possible problems. This study also aims to evaluate the environmental performance of the system and to analyse both the crop and its synergy with the building with respect to rainwater, residual heat (energy), residual air (CO_2) and food from an industrial ecology perspective.

The specific goals of the study are as follows:

- To assess an i-RTG with food production (tomato crops) over an extended period (more than a year) in a Mediterranean climate.
- To quantify the environmental impacts of the life cycle of the system and to detect environmental hotspots using the life cycle assessment (LCA) methodology.
- To compare the impacts of tomato consumption with respect to production in the i-RTG and a conventional greenhouse with similar theoretical conditions.
- To evaluate the feasibility of i-RTGs as food production systems and propose measures for optimisation in terms of resource efficiency and productivity.

2. Methodology

2.1. Description of the integrated rooftop greenhouse (i-RTG)

The ICTA-ICP building on the Universitat Autònoma de Barcelona campus (Spain) is a research centre designed with high standards of sustainability. The building is 7,500 m^2 (six floors) and contains a covered rooftop with four areas that can be used for vertical farming (Figure 1). This study analyses the food production in one of these four areas (marked in Figure 1) as a pilot i-RTG case study. As stated in the previous section, the main innovation of the i-RTG is that it is connected with the building from an industrial ecology perspective, as shown in the diagram of Figure 1.

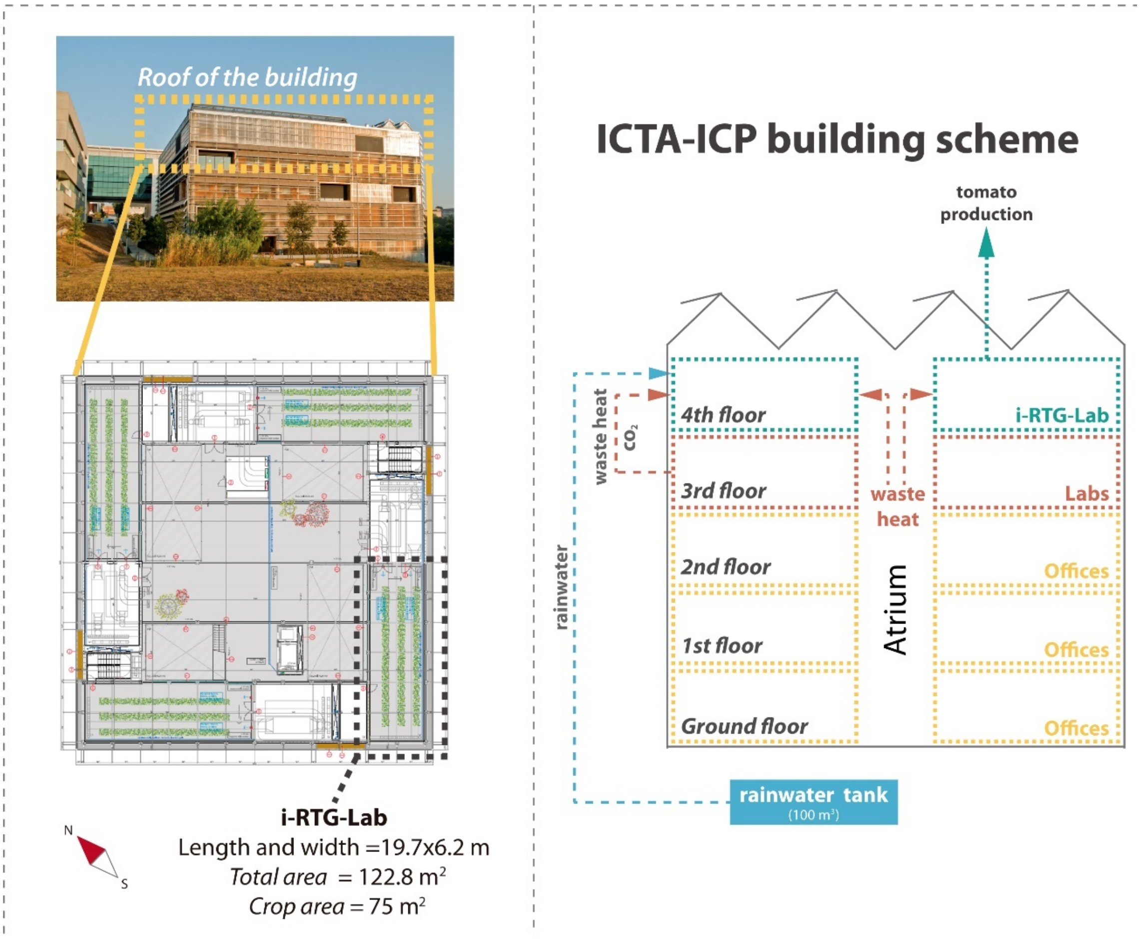

Figure 1. Diagram of the water, waste heat and CO_2 flows in the ICTA-ICP building and blueprint of the rooftop with the i-RTG.

The external structure of the ICTA-ICP building is composed of a metal frame with corrugated polycarbonate sheets that can be opened or closed to provide ventilation (Figure 2). This structure comprises the walls and the roof of the building and the i-RTG. The opening and closing of the sheets is automatic depending on the temperature and is controlled with specially designed software, following a protocol that can adapt to different external conditions. The greenhouse also contains internal polyethylene film curtains that can be rolled up or down to connect the greenhouse to the building or to isolate it. It should be highlighted that the i-RTG and the building were independently designed, and the greenhouse was adapted to the existing conditions on the rooftop. Residual air from temperature-controlled areas in the building (always between 20 and 24 °C) is injected into the i-RTG. This air flow improves the temperature of the greenhouse, cooling in summer and warming in winter, and provides higher CO_2 concentrations, which benefit the plants. The shared air not only benefits the i-RTG but also contributes to controlling the temperature of the building (synergistic conditions).

The building also contains a rainwater harvesting system that integrates water collected from the roof of the ICTA-ICP building and the roof of the nearest building (Eureka). Water passes through a primary filter to remove solids and is collected in a 100 m^3 water storage tank. This untreated rainwater is used in the i-RTG to irrigate the crops and water ornamental plants in the building, reducing the demand for potable water from the conventional distribution network. In total, the building has a harvesting surface of 900 m^2.

Figure 2. i-RTG with a crop of two weeks (top left), i-RTG with a crop of four months (top right), i-RTG from the atrium (bottom left), and polycarbonate sheets in the wall of the greenhouse (bottom right).

2.2. Plant materials and growth conditions

The pilot i-RTG has a total area of 122.8 m^2 (Figure 1) and a cropping area of 84.34 m^2. In total, 171 tomato plants were grown, 47 of which were perimeter plants with non-standard conditions.

A hydroponic system was used for irrigation to supply a nutrient solution (water plus fertilisers, also called fertigation) to plants located on an inert substrate. More specifically, the crop has an open hydroponic system, and thus, the leachates (excess nutrient solution) are disposed of. Two 300 litre tanks were installed for water storage in the greenhouse to avoid interruption in case of water supply failure. A pump propels water from the tanks, which replenish constantly, and the nutrients are injected from a concentrated nutrient solution to the water flow. Finally, water is applied to the plants through drippers with a flow of 2 L/h.

The substrate of the crop is composed of 57 perlite bags distributed in rows with a distance of 1.2 m between them. Each of these bags measures 1 m long, contains 40 L of perlite and provides a substrate for three plants.

The crops were beef tomato varieties (*Lycopersicon esculentum*, *Arawak* for spring crops and *Tomawak* for winter crops). Seedlings grown in peat for 4 to 6 weeks (at a local garden centre) were transplanted to the perlite bags in the greenhouse. Three crops were grown from February 2015 to July 2016. Table 1 shows the specific cultivation periods. The third crop was interrupted due to a critical condition (affected by plagues). Produce was harvested when there was a significant amount of ripe fruits (daily during the peak of production). A follow-up of the state of the plants was carried out by agronomy experts twice per month to prevent or treat possible plagues and plant diseases.

Table 1. Characteristics of tomato cultivation

Cultivation	Season	Starts	Harvest starts	Finishes	Days (n)
S1	Spring-summer	10/02/2015	20/04/2015	23/07/2015	164
W	Fall-winter	15/09/2015	17/12/2015	04/03/2016	169
S2	Spring-summer	08/03/2016	23/05/2016	20/07/2016	133

S=spring crop, W=winter crop

2.3. Experimental analyses

The concentration of nutrients was measured periodically to ensure adequate nutrient supply. Samples were collected once per week from the nutrient solution and three times per week from the leachates (during S2, both were collected daily). The concentrations of Cl^-, NO_2^-, NO_3^-, PO_4^{3-}, SO_4^{2-}, Ca^{2+}, K^+ and Mg^{2+} were measured using ionic chromatography. Additionally, the pH and EC were measured daily for both the nutrient solution and the leachates. According to the results of these analyses, adjustments were made to tailor the nutrient solution to the requirements of the crops.

A protocol was defined to evaluate the quality of the tomatoes produced by the W and S2 crops. This assessment considered the size, weight and sugar content of the tomatoes. Three rows of plants were selected, and ten representative tomatoes were collected, excluding perimeter plants and exceptionally large or small fruits. The diameter and weight were measured for all the tomatoes collected. For each of the rows, the degrees Brix (sugar content) was measured for six of the ten tomatoes. For each crop, the average values of all implemented protocols were considered.

2.4. Life cycle assessment (LCA)

The LCA methodology was used to quantify the environmental impacts of the system following ISO 14040 and 14044 (ISO 2006a, b).

2.4.1. Goal and scope

The whole system was considered for the LCA, from the materials to the end of life of the i-RTG, including all elements. Figure 3 shows the diagram of the i-RTG life cycle, distinguishing between the infrastructure (when the lifespan of the element is more than five years) and operation (the lifespan is less than five years).

The inventory for the LCA was elaborated by collecting data during the construction of the rainwater harvesting system and the auxiliary equipment and the operation (inputs-outputs) of the i-RTG during the experiment. Additionally, the inventory for the greenhouse structure was compiled using data from Sanye-Mengual et al. (2015).

The functional unit selected for assessment is 1 kg of tomato delivered for consumption. To calculate the impacts of the functional unit, all edible produce was considered, only excluding tomatoes affected by blossom or plagues (which represent less than 2% of the total produce). All the environmental impacts reported in the study refer to this functional unit.

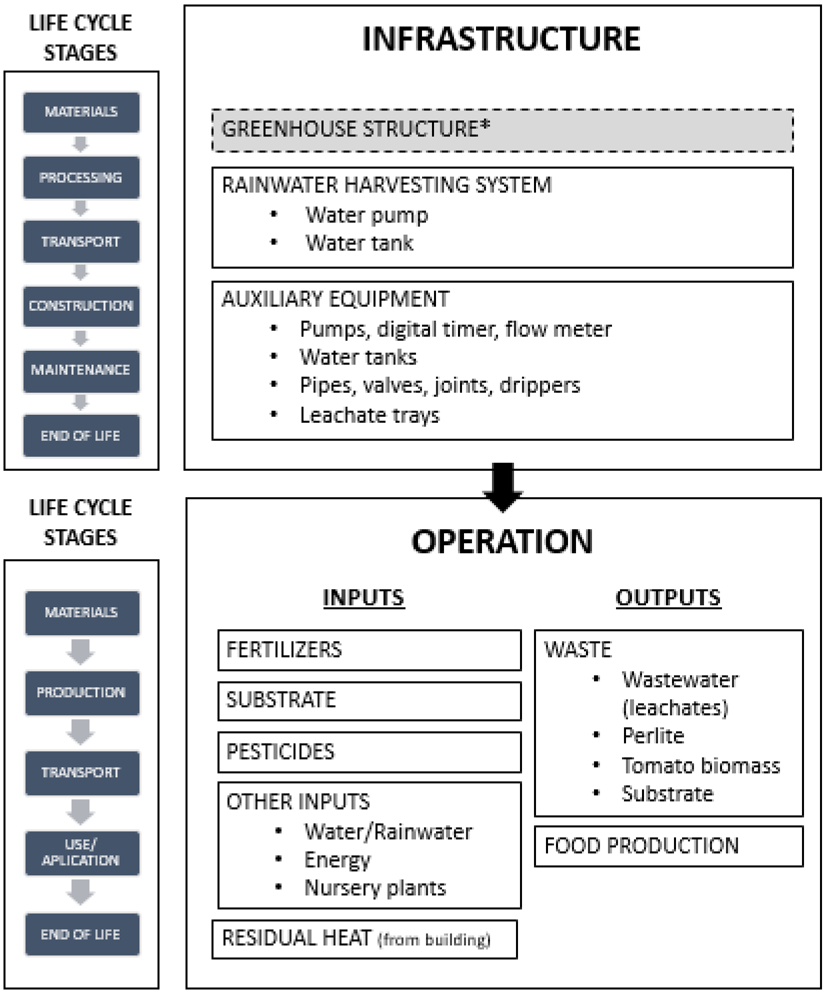

Figure 3. Diagram of the i-RTG and system boundaries of the assessment.
*Data for the inventory of the greenhouse structure was obtained from Sanye-Mengual et al. (2015).

The environmental impacts of tomato production in the i-RTG were compared with those of conventional production in a standard multi-tunnel greenhouse. For this, a scenario for conventional food production was defined, considering the same system boundaries. Table 2 gives the scientific articles used as data sources for the LCA, all of which were published by the Sostenipra research group.

Table 2. Summary of the data sources considered for the life cycle inventory

	i-RTG	Conventional greenhouse	Environmental information
Greenhouse infrastructure			Ecoinvent 3
Greenhouse structure	BL (a)	BL (b)	
Auxiliary equipment	OD	BL (b)	
Rainwater harvesting system	OD	-	
Management of the greenhouse			
Use of water and fertilisers	OD	BL (c,d)	
General management	OD	BL (b)	
Agricultural data			
Crop yield	OD	BL (c)	
Water consumption	OD	BL (c)	
Compost biomass	BL (e)	BL (f)	
Packaging and distribution			
Packaging of the product	-	BL (a)	
Distribution distances and losses	-	BL (a)	

(a) Sanye-Mengual et al. (2015), (b) Martínez-Blanco et al. (2011), (c) Muñoz et al. (2015), (d) Muñoz et al. (2008), (e) Martínez-Blanco et al. (2010) (f) (Colón et al. 2012). OD=own data, BL=based on the literature.

2.4.2. Life cycle inventory of the i-RTG

This section presents the relevant assumptions and data sources considered for the inventory of the i-RTG LCA.

Infrastructure

The corresponding impacts of the rainwater harvesting system were allocated to the i-RTG according to its consumption. For the allocation, the lifespan and the rainwater supplied to the system were used to calculate the impacts per cubic metre of rainwater.

According to the expertise of the authors and similar to previous studies, a 50 year lifespan was assumed for the rainwater harvesting system (Vargas-Parra et al. 2013; Sanjuan-Delmás et al. 2015) and the greenhouse structure (Sanye-Mengual et al. 2015), and a ten year lifespan was assumed for the auxiliary equipment (Hoffman et al. 2007).

The detailed inventory for the infrastructure and its description can be found in section 3.2 and **Supplementary Information A**.

Operation

The assessment of the fertilisers and pesticides used in this work includes impacts of the emissions to air generated during application, which were estimated in accordance with Montero et al. (2011). The impacts derived from the generation of leachates, which were discharged to the sewer network, were considered emissions to water (into nature) provided there was no guarantee that these contaminants were removed in the municipal wastewater treatment plant. Furthermore, the waste biomass was composted in the greenhouse, and the impacts were calculated according to Martínez-Blanco et al. (2010).

The electricity required for opening and closing the walls and roof was estimated using data from the building software, and the electricity consumed by water pumps was estimated considering the characteristics of the pumps and the amount of water pumped. The Spanish 2015 electricity mix (Red eléctrica de España 2015) was used.

Transport

The database used to acquire environmental information included transport to markets based on average values. Additionally, transportation from the market to the i-RTG was included. This distance was 35 km for fertilisers, pesticides and auxiliary equipment; 60 km for rainwater harvesting construction materials; and 850 km for substrate bags (the bags were not available locally and had to be imported from Almeria). All distances covered during transport were doubled because the vehicle was empty on the trip back.

End of life

For the end of life assessment, the impacts of materials that were disposed of were included, but possible impacts of recycling were considered to be charged to the subsequent systems. Auxiliary equipment was assumed to go to the landfill, while all pumps and tanks (including the rainwater tank) were assumed to be recycled. A distance of 30 km was assumed for travel from the i-RTG to the landfill or the recycling station.

Comparison with the reference scenario

In the reference scenario, the packaging and distribution required to reach the consumer's home and the product loss (17%) were determined according to Sanye-Mengual et al. (2015). None of these elements were found in the i-RTG, where the produce was taken by the users of the building using their own bags and without extra transport. Details of the inventory for the definition of this scenario can be found in **Supplementary Information B**.

Unlike this study, previous studies did not include the impacts of the residual nutrient solution used for irrigating the soil-based crops. To maintain the same system boundaries, the impact of these leachates was not included in the comparison between i-RTGs and conventional greenhouses.

2.4.3. Environmental information and calculation method

The Simapro 8.2 software was used along with the ReCiPe method (Hierarchist; H) to calculate the environmental impacts. The environmental information was acquired from the Ecoinvent 3 attributional database.

According to the expertise of the authors and previous literature (Brentrup et al. 2004), the following impact categories from the ReCiPe method (H) were selected as indicators: climate change (CC), ecotoxicity (ET), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME) and fossil fuel depletion (FD). For ET, the addition of three ReCiPe impact categories (terrestrial, freshwater and marine ecotoxicity) was considered.

3. Results and discussion

3.1. i-RTG: a new urban food production system

The system produced 30.1 kg of tomato per square metre over 15.5 months, providing a total of 2,540 kg of food (Table 3). For reference, the system could grow approximately 1,660 kg of tomatoes per year, whereas the annual consumption in Spain is 13.5 kg of tomatoes per capita (Ministerio de Agricultura 2016), which means that the i-RTG could supply tomatoes to 110 people. This figure proves that the i-RTG has the potential to produce a significant amount of food throughout the year.

The productivity was found to be on average three times higher for the spring crops (S1/S2) than for the winter crop (W). Moreover, tomatoes grown in winter are smaller and have a slightly lower sugar content (Table 3). This difference in productivity is a result of the relatively lower solar radiation and temperature during winter. Although in absolute terms the consumption of resources (water, fertilisers) is lower due to the reduced evapotranspiration, the decrease in the productivity makes winter crops less efficient. However, tomatoes hold a significant added value in winter, because winter is not their natural growing season in the Mediterranean region.

The i-RTG makes cultivation easier during the winter because the system takes advantage of warm air from the building, affording milder temperatures (on average, between 5 and 8° higher than that outdoors; Table 3), which improves the growing conditions considerably and avoids the necessity for heating. Nadal et al. (2017) estimated that to achieve these temperatures in a similar greenhouse located on the ground would require 341.9 kWh of thermal energy/m^2/year, generating between 5.5 and 113.8 kg CO_2 eq/m^2/year (depending on the heating system and type of fuel). This heating would increase the carbon footprint of production by several times its current value.

Table 3. Agronomic data for spring and winter crops in the integrated rooftop greenhouse (i-RTG)

		Units	S1	S2	W
Food	Total yield	kg of tomato/m^2	15.3	10.5	4.4
	Tomato average diameter	mm	-	78.3	57.9
	Tomato average weight	g	176	188	119
	Degrees Brix	ºBx	-	5.1	4.7
Water	Water use efficiency	L/kg of tomato	63.8	47.3	103.8
	Percentage of rainwater used	%	82	90	88
Energy	Average temperature i-RTG	ºC	21.3	21.2	19.5
	Average temperature outside	ºC	16.2	16.1	11.8
	Maximum temperature i-RTG	ºC	34.6	29.2	26.0
	Minimum temperature i-RTG	ºC	11.8	13.9	14.6

S1=spring crop 1, S2=spring crop 2, W=fall/winter crop.

It is important to highlight that shading from some elements of the building structure (ventilation conduit, inner wall; Figure 4) diminished productivity in the i-RTG. This shading is a common problem affecting vertical farming systems because the systems are usually adapted to existing structural conditions. As is well known in agriculture, the productivity of a greenhouse is strongly influenced by the total solar radiation reaching the crop. For tomato, between 2 and 2.65 kg per of produce square metre is accumulated for every 100 additional MJ/m^2 of solar radiation incident on the crop (Papadopoulos and Pararajasingham 1997). Thus, minimising the influence of shading elements on solar radiation can help significantly improve the crop yield.

Figure 4. i-RTG with a two-week crop and the ventilation conduit (top left), inner wall of the i-RTG (top right), tomatoes on the crop (bottom left) and tomatoes produced in the i-RTG (bottom right).

The water use efficiency (WUE), i.e., the water consumed for irrigation per unit produce, was better for the spring crops, which was more than double that of the winter crop. The lower productivity of W compared with S1 and S2 implies higher water consumption per unit produce. The WUE values reported for beef tomato crops in standard greenhouses are lower, 33.3 and 63.5 L/kg of tomato for the spring and winter crops, respectively (Muñoz et al. 2015). This higher efficiency is due to the lack of optimisation in the management of crops grown in the i-RTG. Moreover, a more efficient mechanism to evacuate heat in the summer would reduce temperature and hence diminish evapotranspiration. However, it should be highlighted that most of the water consumed in the i-RTG was rainwater collected from the building (80-90%). The remaining 10 to 20% was tap water, which was on average approximately 1.6 m^3 per month during the cropping period. Thus, the final external demand of water for the i-RTG is even lower than that for conventional greenhouses due to its high self-sufficiency. Moreover, the implementation of improvements for the optimisation of the system in future crops might also significantly reduce the WUE.

3.2. Life cycle inventory of the i-RTG crops

Table 4 shows the inventory of the operation phase for the spring (S1, S2) and winter (W) crops grown in the i-RTG. The data are given as per kg of tomato produced and per square metre of cultivation area. The inventory of the i-RTG infrastructure can be found in **Supplementary information A**.

Table 4. Inventory of the operation life cycle phase for the spring (S1, S2) and winter (W) crops grown in the i-RTG.

Element	Material	Units	S1		W			S2		
			per crop	per kg tomato	per crop	per kg tomato	Ratio W/S1	per crop	per kg tomato	Ratio S2/S1
Substrate*	Perlite	kg	71.8	5.6E-02	74.0	2.0E-01	3.6	58.2	6.6E-02	1.2
	HDPE	kg	1.9	1.5E-03	1.9	5.3E-03	3.6	1.5	1.7E-03	1.2
Fertilisers	KNO_3	kg	18.6	1.4E-02	11.6	3.1E-02	1.6	12.7	1.4E-02	0.7
	KPO_4H_2	kg	11.2	8.7E-03	5.2	1.4E-02	2.2	5.7	6.4E-03	1.0
	K_2SO_4	kg	26.9	2.1E-02	10.0	2.7E-02	1.3	10.9	1.2E-02	0.6
	$Ca(NO_3)_2$	kg	34.6	2.7E-02	12.5	3.4E-02	1.3	13.7	1.6E-02	0.6
	$CaCl_2$	kg	10.9	8.4E-03	4.2	1.2E-02	1.4	4.6	5.3E-03	0.6
	$Mg(NO_3)_2$	kg	22.9	1.8E-02	8.5	2.3E-02	1.3	9.3	1.1E-02	0.6
	Hortilon / Tradecorp	kg	0.8	6.4E-04	0.4	1.0E-03	1.6	0.4	4.7E-04	0.7
	Sequestrene	kg	0.8	6.4E-04	0.4	1.0E-03	1.6	0.4	4.7E-04	0.7
Pesticides	Potassium soap	kg	1.2	9.3E-04	2.4	6.5E-03	7.0	1.2	1.4E-03	1.5
	Wettable sulphur	kg	0.2	1.2E-04	0.8	2.0E-03	17.5	1.5	1.7E-03	14.6
	Costar (80% bacillus thuringiensis)	kg	0.0	0.0E+00	0.1	1.6E-04	-	0.2	2.4E-04	-
	MeemAzal (10 g/L $C_{35}H_{44}O_{16}$)	kg	0.0	0.0E+00	0.0	4.9E-05	-	0.1	8.2E-05	-
Water	Tap water	m^3	14.9	1.2E-02	4.2	1.1E-02	1.0	5.2	5.9E-03	0.5
	Rainwater (infrastructure)	m^3	67.2	5.2E-02	38.1	1.0E-01	2.0	36.6	4.1E-02	0.8
Processes										
HDPE	Extrusion, plastic film	kg	1.9	1.5E-03	1.9	5.3E-03	3.6	1.5	1.7E-03	1.2
Energy - opening/closing slabs	Electricity, Spanish mix 2015	kWh	4.7	3.7E-03	4.4	1.2E-02	3.3	4.0	4.5E-03	1.2

Energy - rainwater pump	Electricity, Spanish mix 2015	kWh	1.5	1.1E-03	0.8	2.1E-03	1.8	0.8	8.5E-04	0.7
Energy - nutrient solution Pump	Electricity, Spanish mix 2015	kWh	16.8	1.3E-02	9.5	2.6E-02	2.0	9.1	1.0E-02	0.8
Nursery plants**	Diesel	kWh	0.0	2.3E-05	0.0	7.9E-05	3.5	0.0	3.3E-05	1.5
	Electricity, Spanish mix 2015	kWh	0.2	1.5E-04	0.2	5.3E-04	3.5	0.2	2.2E-04	1.5
	Transport, passenger car	km	14.0	1.1E-02	14.0	3.8E-02	3.5	14.0	1.6E-02	1.5
Leachates (emission to water)	Cl^-	kg	5.7	4.4E-03	2.6	7.2E-03	1.6	0.5	5.6E-04	0.1
	NO_3^-	kg	23.7	1.8E-02	4.9	1.3E-02	0.7	7.3	8.3E-03	0.5
	PO_4^{3-}	kg	2.2	1.7E-03	0.8	2.1E-03	1.2	1.0	1.1E-03	0.7
	SO_4^{2-}	kg	11.0	8.6E-03	3.4	9.3E-03	1.1	4.2	4.8E-03	0.6
	K^+	kg	13.1	1.0E-02	4.1	1.1E-02	1.1	4.9	5.5E-03	0.5
	Mg^{2+}	kg	1.4	1.1E-03	0.6	1.7E-03	1.6	0.6	6.4E-04	0.6
	Ca^{2+}	kg	7.0	5.4E-03	2.1	5.7E-03	1.1	2.5	2.8E-03	0.5
Waste – biomass	Biomass	kg	383.2	3.0E-01	345.6	9.4E-01	3.2	300.3	3.4E-01	1.1
Waste – substrate*	Sanitary landfill	kg	73.7	5.7E-02	75.9	2.1E-01	3.6	59.8	6.8E-02	1.2
Transport fertilisers	Transport, van	tkm	8.9	6.9E-03	3.7	1.0E-02	1.5	4.0	4.6E-03	0.7
Transport pesticides	Transport, van	tkm	0.1	7.3E-05	0.2	6.2E-04	8.4	0.2	2.4E-04	3.2
Transport perlite*	Transport, lorry	tkm	125.3	9.7E-02	129.1	3.5E-01	3.6	101.6	1.2E-01	1.2

HDPE=high density polyethylene, *Allocated according to the duration of the crops, **Retrieved from Antón (2004)

As seen in Table 4, water and fertilisers are the largest material inputs in the i-RTG. This consumption is linked to the WUE because both water and fertilisers are supplied through the fertigation system. In this sense, the spring crops were more efficient than the winter crop, as mentioned above. The use of pesticides is a sensitive issue in vertical farming due to the proximity to people's living or work places. For this reason, only small quantities were used when necessary, always selecting the mildest available option for environmental and health reasons.

The substrate for cultivation and waste biomass from the crop are also significant elements of the i-RTG operation. Substrate bags lead to materials and waste that must be landfilled and imply transport at the beginning and end of the life cycle. Biomass from the crop plants was composted in the greenhouse, avoiding transport and landfilling, although certain materials were required for the installation of the composter, and emissions were generated during the composting process.

3.3. Environmental performance of the i-RTG

The environmental impacts of tomato production in the i-RTG are shown in Table 5. The complete results obtained from the LCA can be found in **Supplementary Information C**.

The spring crops showed better environmental performance than the winter one, where S2 had the least impact with between 50 and 60% lower environmental impacts than W. These impacts are clearly affected by key factors such as the WUE, the season and the productivity. A higher WUE not only implies a larger water demand but also a larger quantity of fertilisers, which have significant influences on the environmental impacts. Moreover, S2 showed better environmental performance than S1, with 30 and 40% less impact by freshwater and marine eutrophication, respectively. The higher impact of S1 is also derived from a greater consumption of water due to the occurrence of exceptionally high temperatures that spring and summer. Another reason that must be highlighted is the lack of experience of the staff running the system during S1, which improved during the crop cycle and in the following cycles (W, S2).

Table 5. Total environmental impacts per kg of tomato crops grown in the i-RTG

		CC	ET	TA	FE	ME	FD
		kg CO_2 eq	kg 1,4-DB eq	kg SO_2 eq	kg P eq	kg N eq	kg oil eq
S1	Spring crop 1	6.10E-01	1.37E-02	3.11E-03	6.65E-04	6.52E-03	1.50E-01
W	Winter crop	1.41E+00	3.01E-02	7.29E-03	3.05E-03	1.20E-02	3.78E-01
	Ratio W/S1	2.31	2.20	2.34	1.36	1.10	2.52
S2	Spring crop 2	5.60E-01	1.22E-02	2.93E-03	4.60E-04	3.75E-03	1.52E-01
	Ratio S2/S1	0.92	0.89	0.94	0.69	0.58	1.01

CC=climate change, ET=ecotoxicity, TA=terrestrial acidification, FE=freshwater eutrophication, ME=marine eutrophication, FD=fossil fuel depletion.

The contribution of each element in the i-RTG to the total environmental impacts is shown in Figure 5. The results show that most of the environmental impacts are generated during the operation of the i-RTG, especially for freshwater and marine eutrophication (FE, ME), in which operation contributed over 90% to these impact categories. In contrast, infrastructure has a larger impact on fossil fuel depletion (FD), contributing between 55 and 60% of the impact.

During the operation of the greenhouse, the use of fertilisers has the most impact, accounting for more than 25% in four of the six impact categories considered. The impacts of fertilisers are higher in S1 due to the higher WUE (mentioned above) and account for more than 30% in five of the six impact categories. The environmental impacts of fertilisers are generated during their production due to the high quantities of chemicals, such as sulphuric acid and nitric acid, and the large amounts of energy (heat and electricity) required in the process. Prior studies assessing the life cycle of conventional greenhouses have concluded that the use of fertilisers was critical from an environmental perspective (Muñoz et al. 2008, 2015).

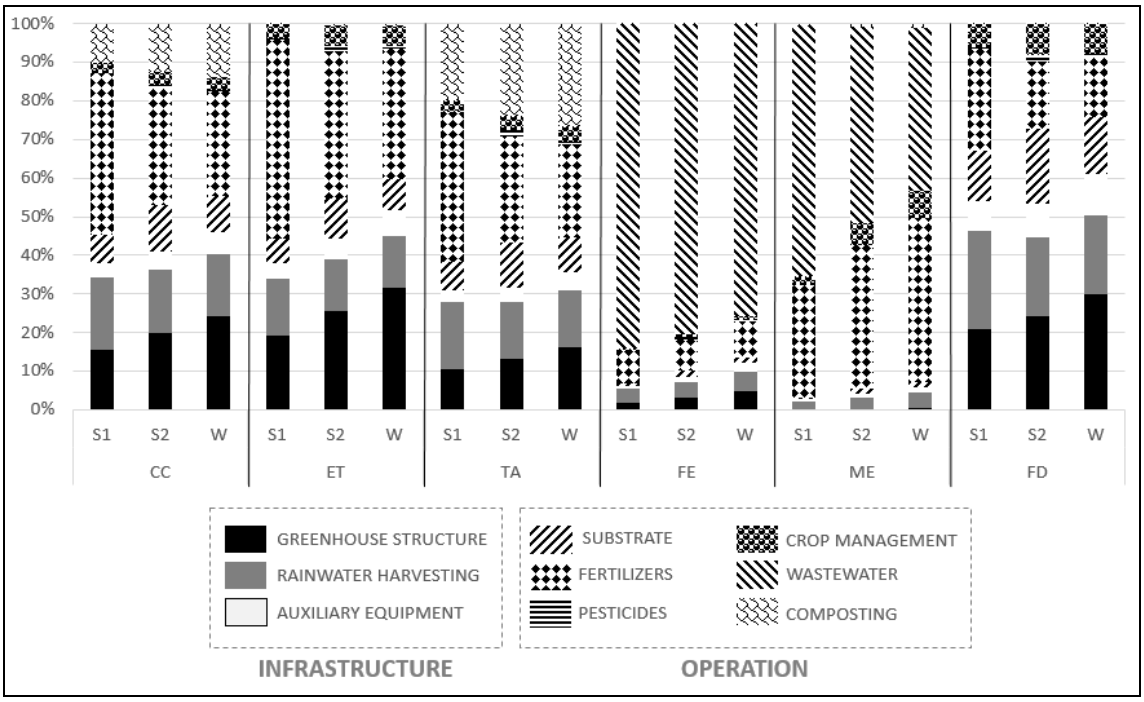

Figure 5. Contribution of system elements to the total environmental impacts of the spring (S1/S2) and winter (W) crops. CC=climate change, ET=ecotoxicity, TA=terrestrial acidification, FE=freshwater eutrophication, ME=marine eutrophication, FD=fossil fuel depletion.

Wastewater (leachates from the crop) sent to the sewer contributes between 40 and 85% of the environmental impacts of freshwater and marine eutrophication (FE, ME). These impacts are caused by the nitrates and phosphates contained in the leachates of the crops, which are discharged into the sewer network and sent to a wastewater treatment plant. Nevertheless, as stated in the methodology section, the most extreme case was considered in the assessment, assuming that all nitrates and phosphates discharged into the sewer remained after treatment in the wastewater treatment plant and eventually arrived in the environment. For instance, if the treatment plant included a denitrification process, the amount of nitrates discharged into the environment would be lower, although other impacts would result from the denitrification processes. The reuse of leachates for watering ornamental plants in the building would significantly reduce the environmental impacts and at the same time increases the overall efficiency of the building (reducing the amount of water and fertilisers used for ornamental plants). Another option would be to use the leachates to irrigate ground-based crops, reducing the impacts and utilising the nutrients. All these are options to be considered for implementation in future crops.

Composting biomass is another environmental hotspot of i-RTGs. Composting generates between 20 and 30% of the impact on terrestrial acidification (TA) and 10 to 15% of the impact on climate change (CC) due to the release of gases during the composting of organic matter. Ammonia (NH_3) emissions have great potential for terrestrial acidification, whereas nitrous oxide (N_2O) affects climate change. To a lesser extent, the substrate bags also generate substantial impacts, accounting for 10 to 20% of fossil fuel depletion (FD) and between 5 and 12% of the other three impact categories. Most of these environmental impacts are generated during the production of the substrate.

Regarding the infrastructure of the i-RTG, the environmental impacts of the greenhouse structure (including the steel framework and the polycarbonate sheets) allocated to each of the crops is the most important contributor. This greenhouse structure produces between 10 and 30% of the impacts in four of the six impact categories. The steel used for construction has the most impact due to the manufacturing processes and the resultant emissions of mercury to air and manganese and arsenic to water. Another important environmental hotspot is the construction of the rainwater harvesting system allocated to the i-RTG, which represents between 10 and 25% of the impact in four of the six categories. These impacts are generated during the manufacture of the 100 m^3 water tank, which requires a significant amount of glass fibre-reinforced polyester.

3.4. i-RTG vs. standard greenhouse

The environmental impacts of tomatoes from the i-RTG and a conventional greenhouse were compared, as shown in Figure 6. It can be observed by comparing spring and winter crops separately that the i-RTG has lower environmental impacts in five of the six impact categories analysed. For instance, spring crops in the i-RTG generate on average 0.58 kg of CO_2 equivalent per kg of tomato, while conventional greenhouses generate 1.7 kg, which is consistent with previous literature (Payen et al. 2015). For the winter crops, the i-RTG generates 1.4 kg of CO_2 equivalent per kg of tomato, whereas conventional production generates 2.0 kg. Packaging and distribution of the produce have the most impact in the conventional system. In this scenario, the produce was assumed to travel 500 km from the south (Almeria) to the north of Spain (Barcelona), but this distance could be larger because fruits are often imported from other countries and continents. Production from the i-RTG does not require packaging or distribution. For this reason, the environmental impacts of conventional production are more than double those of i-RTG in some impact categories (and would be higher if they came from distant regions).

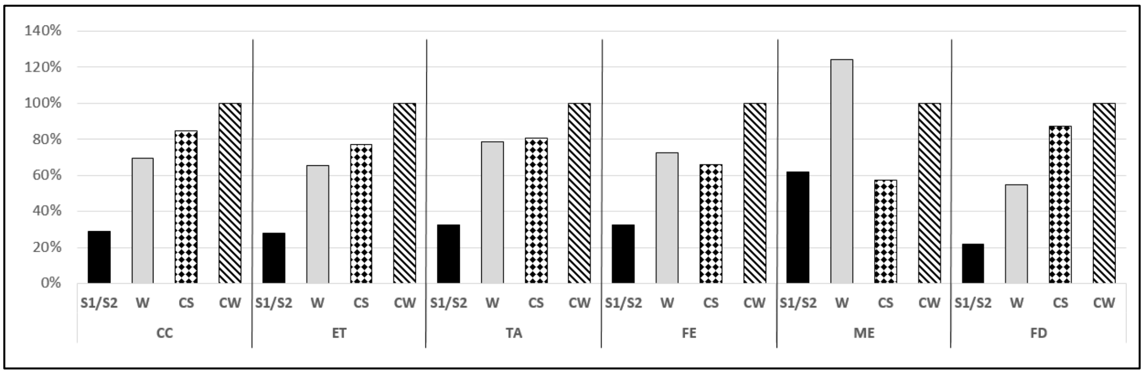

Figure 6. Comparison of the environmental impacts of crops grown in the i-RTG and a conventional greenhouse. S1/S2=average values for spring crops, W=winter crop, CS=spring crop in conventional greenhouse, CW=winter crop in conventional greenhouse, CC=climate change, ET=ecotoxicity, TA=terrestrial acidification, FE=freshwater eutrophication, ME=marine eutrophication, FD=fossil fuel depletion.

Comparison between the performance of the pilot i-RTG and a standard greenhouse with similar conditions is complex. Conventional production systems are expected to be more efficient in the use of resources because they benefit from the economy of scale and because their main purpose is economic benefit. In contrast, research i-RTGs have different priorities and are usually small installations. For instance, they may provide potential positive social impacts if they become educational centres or if they are used for community agriculture, as discussed in the previous literature (Caplow 2009; Sanyé-Mengual 2015). As the case under assessment is a small pilot facility for research purposes and is not optimised regarding management, there is significant potential for improvement, which may increase productivity and reduce environmental impacts.

Another complex issue regarding the comparison between i-RTGs and standard greenhouses is the construction of the infrastructure for the i-RTG. Vertical farming systems are usually conditioned by the existing structure of the building, which has drawbacks, such as reduced space for the production area and shading from some building elements. In this specific case study, the roof and walls of the i-RTG belonged to the building structure but were considered in the calculation of the environmental impacts. However, it could be argued that these impacts should not be included because they were not installed for the greenhouse. Excluding this element for the calculation of the i-RTG environmental impacts would significantly improve the environmental performance of the system (see the contribution from the greenhouse structure in Figure 5). In this respect, different assumptions can be considered depending on the situation. For instance, an existing building adapted for a rooftop greenhouse can have different allocation criteria than a building originally designed with a rooftop greenhouse.

3.5. Improving i-RTGs: towards an industrial scale

Future applications of this technology should consider the environmental hotspots detected in this study and the provided recommendations to reduce the environmental impacts of i-RTGs. One of the most significant issues in i-RTGs and hydroponic crops, in general, is the use of fertilisers. The nutrient solution should be adjusted according to the requirements of the plants to avoid the leaching of excess nutrients. Implementing closed hydroponic systems (with recirculation of the leachates) could save significant quantities of water and fertilisers. However, this technology has a more complex mechanism in comparison with open hydroponic systems (without recirculation), requiring devices for filtering and disinfecting the leachates before recirculation, as well as more pumps, pipes and tanks for recirculation. Further studies should assess the payback time of this technology in environmental terms. In other words, it should be assessed whether the savings in fertilisers and water compensate for the extra expenditures in energy and auxiliary equipment.

Another issue that should be considered in the design of an i-RTG is the optimisation of the infrastructure, which can substantially reduce the environmental impacts. The structure of the greenhouse was exaggerated in terms of the size and the quantity of steel to ensure its security. More experience is required in the construction of these structures to provide the same function with a lower use of resources. Reducing the amount of steel or changing the material or global design could be beneficial due to the high environmental burden of steel. Similarly, optimisation of the rainwater harvesting infrastructure can be achieved by reducing the size of the water storage tank, which would significantly reduce the amount of material required for its manufacture. A preliminary assessment to optimise the rainwater tanks was carried out using the software Plugrisost® (Morales-Pinzón et al. 2012; Morales-Pinzón et al. 2015). Applying the software to the case study showed that 90% of the rainwater used for the crops during the assessment period could have been covered with a 20 m^3 tank instead of the current 100 m^3 tank. The reason for this is that the limiting factor in the system is the harvesting surface, not the tank size. Thus, an estimation of the optimum tank size while designing the greenhouse may significantly reduce the environmental impacts.

4. Conclusions

This study has proven the feasibility of utilising i-RTGs for food production in urban areas by taking advantage of synergies between the building and the rooftop greenhouse to produce 19.6 kg of tomato/m^2·year. The synergy with the building afforded significant resource savings, for example, 80 to 90% of the water used for the crop was rainwater collected from the building. These figures mean that to fulfil the average consumption of tomato per person in Spain only 0.7 m^2 of productive area in the i-RTG are required, along with 7.5 m^2 of catchment area to collect rainwater. This system can be an alternative to conventional production and an opportunity to improve food security and self-sufficiency in cities. Moreover, the i-RTG has lower environmental impacts than conventional production in all the impact categories analysed (except marine eutrophication). For instance, a summer crop in the i-RTG generates 0.58 kg of CO_2 equivalent per kg of tomato, while a conventional greenhouse generates 1.7 kg, which proves that i-RTGs can contribute to climate change mitigation.

The ultimate purpose of this study is to foster the application of i-RTGs in urban systems on an larger scale. The industrial application of this technology with larger crops and better conditions would be a crucial step to enhance food production in urban areas. In this context, it is important to provide clear recommendations capturing the lessons learned in this pilot application. For large-scale implementation, improving the management of the system is key to reduce the consumption of fertilisers and generation of leachates. The use of rainwater must be implemented when possible to avoid impacts from transportation and to increase self-sufficiency. Moreover, the infrastructure (greenhouse structure, rainwater storage tanks) should be optimised to reduce the amount of materials used, which can substantially reduce the environmental impacts. Available software and methodologies must be applied to conduct this optimisation.

Future research efforts should focus on improving the efficiency of i-RTGs without increasing the complexity of the system and its management. An example is the implementation of closed hydroponic systems for irrigation, which recirculate water and nutrients in the leachates (open hydroponic systems dispose of the leachates). This technology would allow for substantial quantities of water and nutrients to be saved, but the auxiliary equipment required is more complex and expensive, requiring further knowledge for its operation and additional environmental impact. Moreover, comparison between the i-RTG and conventional production should be expanded to include other perspectives, such as nutritional aspects, reduction of food waste and food security. Food produced in i-RTGs can be more fresh and nutritious due to the proximity to the consumption point and the optimal timing of collection.

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Supplementary Information

Supplementary Information A, B and C can be found in the attached file.

5. References

Altieri MA, Companioni N, Cañizares K, et al (1999) The greening of the "barrios": Urban agriculture for food security in Cuba. Agric Human Values 16:131–140. doi: 10.1023/A:1007545304561

Antón A (2004) Utilización del Análisis del ciclo de vida en la evaluación del impacto ambiental del cultivo bajo invernadero mediterráneo. Universitat Politècnica de Catalunya, Barcelona, Spain

Association for Vertical Farming (2016) Urban Agriculture Integration Typology - Association for Vertical Farming. https://vertical-farming.net/vertical-farming/integration-typology/. Accessed 10 May 2016

Astee LY, Kishnani NT (2010) Building Integrated Agriculture: Utilising Rooftops for Sustainable Food Crop Cultivation in Singapore. J Green Build 5:105–113. doi: 10.3992/jgb.5.2.105

Besthorn FH (2013) Vertical Farming: Social Work and Sustainable Urban Agriculture in an Age of Global Food Crises. Aust Soc Work 66:187–203. doi: 10.1080/0312407X.2012.716448

Bon H, Parrot L, Moustier P (2010) Sustainable urban agriculture in developing countries. A review. Agron Sustain Dev 30:21–32. doi: 10.1051/agro:2008062

Brentrup F, Küsters J, Kuhlmann H, Lammel J (2004) Environmental impact assessment of agricultural production systems using the life cycle assessment methodology. Eur J Agron 20:247–264. doi: 10.1016/S1161-0301(03)00024-8

Caplow T (2009) Building integrated agriculture: Philosophy and practice. Urban Futur 2030 Urban Dev Urban Lifestyles Futur 48–51.

Cerón-Palma I, Sanyé-Mengual E, Oliver-Solà J, et al (2012) Barriers and Opportunities Regarding the Implementation of Rooftop Eco.Greenhouses (RTEG) in Mediterranean Cities of Europe. J Urban Technol 19:87–103. doi: 10.1080/10630732.2012.717685

Colón J, Cadena E, Pognani M, et al (2012) Determination of the energy and environmental burdens associated with the biological treatment of source-separated Municipal Solid Wastes. Energy Environ Sci 5:5731–5741. doi: 10.1039/C2EE01085B

Despommier D (2010) The vertical farm: Feeding the world in the 21stCentury. Thomas Dunne Books., New York

Despommier D (2011) The vertical farm: Controlled environment agriculture carried out in tall buildings would create greater food safety and security for large urban populations. J fur Verbraucherschutz und Leb 6:233–236. doi: 10.1007/s00003-010-0654-3

Engelhard B (2010) Rooftop to Tabletop: Repurposing Urban Roofs for Food Production. University of Washington

FAO, IFAD, WFP (2015) The State of Food Insecurity in the World 2015. Meeting the 2015 international hunger targets: taking stock of uneven progress. Rome, FAO

Fischetti M (2008) Growing Vertical: Skyscraper Farming. Cultivating crops in downtown skyscrapers might save bushels of energy and provide city dwellers with distinctively fresh food. Sci. Am. 18:74–79.

Germer J, Sauerborn J, Asch F, et al (2011) Skyfarming an ecological innovation to enhance global food security. J für Verbraucherschutz und Leb 6:237–251. doi: 10.1007/s00003-011-0691-6

Hessel L, Bar-On D (2002) Self contained fully automated robotic crop production facility.

Hoffman GJ, Evans RG, Jensen ME, et al (2007) Design and operation of farm irrigation systems, 2nd edn. American Society of Agricultural Engineers

ISO (2006a) ISO 14040, Environmental management - Life cycle assessment - Principles and framework. International Organization for Standardization, Geneve

ISO (2006b) ISO 14044:2006 - Environmental management -- Life cycle assessment -- Requirements and guidelines.

Kortright R, Wakefield S (2011) Edible backyards: a qualitative study of household food growing and its contributions to food security. Agric Human Values 28:39–53. doi: 10.1007/S10460-009-9254-1

Martínez-Blanco J, Colón J, Gabarrell X, et al (2010) The use of life cycle assessment for the comparison of biowaste composting at home and full scale. Waste Manag 30:983–994. doi: 10.1016/j.wasman.2010.02.023

Martínez-Blanco J, Muñoz P, Antón A, Rieradevall J (2011) Assessment of tomato Mediterranean production in open-field and standard multi-tunnel greenhouse, with compost or mineral fertilizers, from an agricultural and environmental standpoint. J Clean Prod 19:985–997. doi: 10.1016/j.jclepro.2010.11.018

Ministerio de Agricultura A y MA (2016) La alimentación mes a mes septiembre 2016. Avance de datos provisionales a partir del ultimo censo publicado por el INE.

Mok H-F, Williamson VG, Grove JR, et al (2014) Strawberry fields forever? Urban agriculture in developed countries: a review. Agron Sustain Dev 34:21–43. doi: 10.1007/s13593-013-0156-7

Montero JI, Antón A, Torroellas M, et al (2011) EUPHOROS deliverable 5. Report on environmental and economic profile of present greenhouse production systems in Europe. European Comssion FP7 RDT Project Euphoros (Reducing the need for external inputs in high value protected horticultural and ornament).

Muñoz P, Antón A, Paranjpe A, et al (2008) High decrease in nitrate leaching by lower N input without reducing greenhouse tomato yield. Agron Sustain Dev 28:489–495. doi: 10.1051/agro:2008024

Muñoz P, Flores JS, Antón A, Montero JI (2015) Combination of greenhouse and open-field crop fertigation can increase sustainability of horticultural crops in the Mediterranean region. In: International Symposium on New Technology and Management for Greenhouses. Greensys 2015. Acta Horticulturae (in press). (ed).

Nadal A (2015) Urban Agriculture in the Framework of Sustainable Urbanism. Temes de disseny 0:92–103.

Nadal A, Llorach-Massana P, Cuerva E, et al (2017) Building-integrated rooftop greenhouses: An energy and environmental assessment in the mediterranean context. Appl Energy 187:338–351. doi: 10.1016/j.apenergy.2016.11.051

Orsini F, Gasperi D, Marchetti L, et al (2014) Exploring the production capacity of rooftop gardens (RTGs) in urban agriculture: the potential impact on food and nutrition security, biodiversity and other ecosystem services in the city of Bologna. Food Secur 6:781–792. doi: 10.1007/s12571-014-0389-6

Orsini F, Kahane R, Nono-Womdim R, Gianquinto G (2013) Urban agriculture in the developing world: a review. Agron Sustain Dev 33:695–720.

Papadopoulos AP, Pararajasingham S (1997) The influence of plant spacing on light interception and use in greenhouse tomato (Lycopersicon esculentum Mill.): A review. Sci Hortic (Amsterdam) 69:1–29. doi: 10.1016/S0304-4238(96)00983-1

Payen S, Basset-Mens C, Perret S (2015) LCA of local and imported tomato: an energy and water trade-off. J Clean Prod 87:139–148. doi: 10.1016/j.jclepro.2014.10.007

Pons O, Nadal A, Sanyé-Mengual E, et al (2015) Roofs of the Future: Rooftop Greenhouses to Improve Buildings Metabolism. Procedia Eng 123:441–448. doi: 10.1016/j.proeng.2015.10.084

Red eléctrica de España (2015) El sistema eléctrico español - Avance 2015.

Rodriguez O (2009) London Rooftop Agriculture : A Preliminary Estimate of London's Productive Potential.

Sanjuan-Delmás D, Hernando-Canovas E, Pujadas P, et al (2015) Environmental and geometric optimisation of cylindrical drinking water storage tanks. Int J Life Cycle Assess 20:1612–1624. doi: 10.1007/s11367-015-0963-y

Sanyé-Mengual E (2015) Sustainability assessment of urban rooftop farming using an interdisciplinary approach. Universitat Autònoma de Barcelona

Sanyé-Mengual E, Anguelovski I, Oliver-Solà J, et al (2016) Resolving differing stakeholder perceptions of urban rooftop farming in Mediterranean cities: promoting food production as a driver for innovative forms of urban agriculture. Agric Human Values 33:101–120. doi: 10.1007/s10460-015-9594-y

Sanyé-Mengual E, Cerón-Palma I, Oliver-Solà J, et al (2015a) Integrating horticulture into cities: A guide for assessing the implementation potential of Rooftop Greenhouses (RTGs) in industrial and logistics parks. J Urban Technol 22:87–111.

Sanyé-Mengual E, Cerón-Palma I, Oliver-Solà J, et al (2012) Environmental analysis of the logistics of agricultural products from roof top greenhouses in Mediterranean urban areas. J Sci Food Agric 100–109.

Sanye-Mengual E, Oliver-Sola J, Montero JI, Rieradevall J (2015) 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 20:350–366. doi: 10.1007/s11367-014-0836-9

Sanyé-Mengual E, Oliver-Solà J, Montero JI, Rieradevall J (2015b) 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. doi: 10.1007/s11367-014-0836-9

Specht K, Siebert R, Hartmann I, et al (2013) Urban agriculture of the future: an overview of sustainability aspects of food production in and on buildings. Agric Human Values 31:33–51.

Thomaier S, Specht K, Henckel D, et al (2015) Farming in and on urban buildings: Present practice and specific novelties of Zero-Acreage Farming (ZFarming). Renew Agric Food Syst 30:43–54. doi: 10.1017/S1742170514000143

United Nations (2013) STATE OF THE WORLD'S CITIES 2012/2013 Prosperity of Cities.

Vargas-Parra MV, Villalba G, Gabarrell X (2013) Applying exergy analysis to rainwater harvesting systems to assess resource. Resour Conserv Recycl 72:50–59.

Wilson G (2002) Can Urban Rooftop Microfarms be profitable?

Woolf D, Amonette JE, Street-Perrott FA, et al (2010) Sustainable biochar to mitigate global climate change. Nat Commun 1:1–9. doi: 10.1038/ncomms1053