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Life cycle cost analysis of tomato production in innovative urban agriculture systems

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ABSTRACT

The construction of innovative urban agriculture systems in cities has increased due to food and environmental concerns. While the environmental performance of urban agriculture has been extensively studied, research on the life cycle costs of urban agriculture systems is still limited, which constraints sustainability-oriented decision-making processes. This paper analyses the economic viability of tomato production cycle in an innovative building with an integrated urban agriculture system in rooftop by applying the life cycle cost methodology. The data was collected from direct measurements and internal and external sources. To calculate labour costs, a customised data collection sheet was created. The results are presented by life cycle stage, cost category and type of cost (fixed & variable). Results indicate that the main cost drivers for tomato production are labour (24.7%), the rooftop greenhouse structure (15%), external pest control (12.6%), and rainwater consumption (9.5%), accounting altogether for 61.8% of the total costs. Accordingly, cost reduction solutions are evaluated through the development of sensitivity scenarios (rooftop greenhouse structure design, tap water use and rainwater tank size), including the consideration of another relevant aspect, such as the role of the production level output, as it can greatly influence the economic viability and profitability. Finally, the main environmental and social aspects of these urban production systems are also included.

1. Introduction

The world population is estimated to increase from 7.7 billion in 2019 to 9.7 billion (+26%) in 2050 (UN, 2019). Currently, more than half of the world population lives in urban areas and this tendency is projected to reach 68% in 2050 (UN, 2018). Therefore, population growth and rapid urbanization is putting pressure on global food security due to the increased demand on food (UNCCD, 2017). For instance, it was estimated that 9.2% of the world population (over 700 million people) experienced serious problems regarding food security in 2018 (Egal, 2019). Nowadays, a third of all edible food (1.8 billion tonnes) is wasted (Ellen MacArthur Foundation, 2019), even though there are currently more than 820 million hungry and malnourished people (FAO, IFAD, UNICEF, WFP and WHO, 2019). This is due to existing differences in land and water availability between developed and underdeveloped countries (Ibarrola Rivas and Nonhebel, 2016).

Additionally, agriculture is responsible for 70% of global freshwater use and deforestation, making the agri-food industry the world's second largest emitter of greenhouse gas (GHG) emissions, accounting for 25% of all human-caused emissions (FAO, 2017; Ellen MacArthur Foundation, 2019). Interestingly, the Ellen MacArthur Foundation (EMF) has estimated that from the 7.1 billion tons of food produced globally, approximately 40% is eaten in cities, where 2.8 billion tons of organic waste is produced (Ellen MacArthur Foundation, 2019). Likewise, it is estimated that 80% of all food will be destined for consumption in the cities by 2050 and therefore they have huge potential to influence the way in which food is produced and eaten, and how food waste is managed.

In the context of sustainable city development, the implementation of urban agriculture (UA) can provide relevant opportunities for efficient food production (Pearson et al., 2010; Thomaier et al., 2015), helping achieve the 2030 sustainable development goals (SDGs) (UN, D.

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E.S.A., 2016). UA can likewise increase biodiversity in cities (Van Tuijl et al., 2018) and help to reduce pollutant emissions, facilitating the adaptation and mitigation of the impact of climate change (SDG 13) (Bendt et al., 2013; Lwasa et al., 2014). UA may contribute in at least three ways on a social level: i) it is an important element of food security strategies to 'feed citizens', and to fight chronic hunger (SDG 2) in developing countries, ii) it an also contribute to community development, e.g., through activities to increase social cohesion (SDG 10) between different groups in society to provide work opportunities for unemployed workers, and iii) it can be used for educational purposes (SDG 4) to increase awareness among citizens regarding food production, e.g. by organizing workshops, courses and tours. Finally, it can as well contribute to improving economic sustainability in cities (SDG 8) by (i) generating new income (SDG8) since there are several companies that use UA for commercial purposes (e.g. Lufa Farms in Montreal (Canada), Panasonic Factory Solutions Asia Pacific (Singapore), The Plant in Chicago (USA), (ii) promoting innovation, research, and knowledge (SDG9) through the creation of R&D labs on-site in the urban farms or collaboration with educational institutes (e.g., Science Barge, Sky Green, UrbanFarmers AG); and finally, (iii) offering recreational and tourist activities (e.g. Brooklyn Grange in New York (USA), Xiedao Green Resort in Beijing (China) (Van Tuijl et al., 2018).

UA can be defined as "an industry located within (intra-urban) or on the fringe (peri-urban) of a town, city or metropolis, which grows or raises, processes and distributes a diversity of food and non-food products" (Mougeot, 2000, p.11) and it comprises of a huge variety of different forms such as community gardens, vertical farming, or urban farms among many (Van Tuijl et al., 2018). However, there is a growing interest in the development of Vertical farming (VF) or ZFarming forms of UA such as indoor farms, rooftop greenhouses (RTGs), or rooftop gardens due to the insufficient space available in cities to support traditional ground agriculture and the lack of resources needed for agricultural production, such as water and energy (Specht et al., 2014; Thomaier et al., 2015). Among the VF forms of UA, RTGs are gaining popularity due to the increasing interest in the development of innovative food production spaces and promotion of food self-sufficiency in urban areas (Sanyé-Mengual et al., 2015).

RTGs can have notable environmental, economic and social benefits, such as reduced food miles, improved community food security, and community outputs (Cerón-Palma et al., 2012; Specht et al., 2014). Going one step further, additional benefits could be expected through the construction of integrated roofto greenhouses (i-RTGs). This innovative option has the particularity that resource flow such as rainwater, CO_2 and heat, can be integrated in a bidirectional way building-rooftop greenhouse. This integration will contribute to the reduction of the environmental impact of the building and the food production system overall (Sanyé-Mengual et al., 2015).

The life cycle environmental performance of UA has been extensively analysed in the literature by means of life cycle assessment (LCA), however the use of life cycle cost (LCC) for the evaluation of the economic viability is still very limited (Sanye-Mengual et al., 2017). This was also supported by a previous literature review study based on 20 references analysing the use of LCC in UA over the last two decades (Peña and Rovira-Val, 2020). The results of that study identified problems in the application of LCC methodology in UA such as the frequent not inclusion of essential costs such as operational labour and infrastructure intro the cost calculation. According to Lu et al. (2017), the exclusion of the labour identified as the most significant operation cost (Sanyé-Mengual et al., 2015) and an important production factor (Baumgartner and Belevi, 2001) was the main reason for the incomplete LCC analysis in many UA studies (Lu et al., 2017). Regarding, the infrastructure cost (e.g., greenhouse structure), its inclusion in the LCC is crucial for future development of UA in cities, especially for boost the implementation of innovative environmentally friendly UA systems on a large scale. Moreover, the results of that literature review also releveled that the LCC was frequently integrated with LCA, but they were not applied at same level since the principal analysis was always LCA, while LCC played just a very secondary role. This is an important constraint since although LCA is a relevant tool to analyse environmental impacts, LCA findings are limited for effective decision-making without the integration of complete economic data with LCC (Norris, 2001).

Hence, the overall objective of this paper is *to analyse the economic viability of artisan tomato production to provide recommendations to promote the UA in rooftop greenhouses in cities*. To achieve the main objective, the following specific objectives were established:

(i) To identify main cost drivers and propose reduction alternatives.
(ii) To analyse the potential variability in the results based on changes in main cost drivers.
(iii) To analyse the role of production level output as important variable affecting the economic viability and profitability.

The tomato crop was selected for analysis since (i) tomatoes are the most consumed vegetable worldwide after potatoes (20.8 kg/capita in 2017) (FAO, 2020) and (ii) they are typically used in greenhouse production (Hochmuth and Hochmuth, 2018) because it is relatively easy to grow in comparison to cucumbers and lettuce, and yields can be high. Likewise, tomatoes were the second most sold vegetable in Mercabarna (the food distribution centre of Barcelona) at 87,100 tonnes sold or 14, 31% of the total of sold vegetables in 2019 (MercaBarna, 2019).

As far as the authors are aware, this study is the first to analyse the LCC of tomato production in i-RTGs well made for better decision-making by (i) including infrastructure and labour costs, (ii) classifying fixed and variable costs, and (iii) applying additional break-even point (BEP) analysis to find the optimal level of production to be sold and determinate the maximum level of fixed costs at different selling prices. The study is also complementary to the previous research of Sanjuan-Delmás et al., (2018a) where the LCA was performed to quantify the environmental impacts of tomato production in the same case study.

2. Methodology

This section explains how the LCC was performed to determine the economic viability of artisan i-RTG tomato production. First, the case study is presented. Secondly, the application of the LCC methodology is explained. Primary data was gathered through novel data collection protocols developed for this purpose (e.g., registry of the hours worked on the crop and consumption of materials) and secondary data from internal and external sources.

2.1. Description of the case study

The case study is the integrated rooftop greenhouse of the LEED-Gold certified building that hosts the Institute of Environmental Science and Technology (ICTA) in the main campus of the Universitat Autònoma de Barcelona (UAB) in Barcelona province (Figure B1 in Appendix B). Both, the building, and its greenhouse, are *innovative systems*. On one side, the building's LEED-Gold certificate recognizes its high level of Leadership in Energy and Environmental Design. On the other, the greenhouse in the rooftop is also *innovative* because of the integration of several flows between the building and the greenhouse (rainwater, CO_2 and energy), which optimise the environmental performance of the system (Pou et al., 2015). Complementary information can be seen in *Appendix A- A1. Description of the case study*.

The flow integration of the studied case is limited to the use of rainwater. Two consecutive tomato crops with the same characteristics and production cycles, were studied: years 2018 and 2019. However, only the LCC results for 2019 crop are presented and discussed. This is due to the problem that there was not a device for measuring labour hours, unlike other crop parameters quantified by electronic measurement tools (e.g., water consumption, solar radiation, etc.). This problem was observed in the crop 2018 and consequently in the crop 2019 a standard time for carry out each defined crop production task was established to have an accurate measure of labour time for crop production. Hence, the 2018 crop was considered as a trial version that allowed the development of refined data collection tools with the purpose of get more accurate results for the crop 2019.

The tomato variety cultivated was Coeur-de-boeuf (Lycopersicon esculentum var. Arawak) which stands out for the size of its pieces, which can reach up to 500g and it is mainly used for fresh salads. This variety is highly appreciated for its size and flavour, with an average price of 2,92 €/kg (OCU, 2018).

The tomato was cultivated in a hydroponic system, a soilless system that uses perlite volcanic stones as a substrate (Fig B2 from Appendix B), containing 171 plants in total. The productive area (substrate area) was 84.3 m^2 from the total extension of the i-RTG (122.1 m^2) and the period of study was the crop cycle: 7 months, from January to July.

2.2. Life cycle cost (LCC)

LCC is an economic evaluation technique that aims to quantify all costs and cash flows that emerge during the entire life cycle of a product, service, and project (Ammar et al., 2013). The LCC of artisan tomato production followed the guidelines provided by Hunkeler et al., (2008), Swarr et al., (2011) and ISO (2008), as described below.

2.2.1. Goals, scope, and functional unit

The aim of the applied LCC was to quantify the total cost of artisan i-RTG tomato production, with the following specific objectives:

(i) To present the costs of tomato production by life cycle stage, by cost category and by fixed and variables.
(ii) To identify the main cost drivers and propose reduction alternatives
(iii) To analyse the costs variation considering different sensitivity scenarios

Regarding total costs, they are presented in terms of variable and fixed costs because both are relevant to make decisions regarding the economic viability of any business (Walther and Skousen, 2009). Fixed costs were calculated as a proportional part of the economic amortization of assets during the analysed period (7 months), while variable costs were quantified based on the unitary cost of consumable resources.

The scope of the study was from cradle to gate, covering two main stages: (i) *infrastructure* and (ii) *production*. The *infrastructure* stage includes initial investment costs of assets (tangible and intangible) needed for production, all of them are fixed cost. The *production* stage includes input item costs and waste costs (classified as outputs), these costs are mainly variable and those specific items that are not variable by unit were calculated as a proportional part during the analysis period. Fig. 1 illustrates the scope of the study, whereas Table 1 provides detailed information of all considered costs.

Costs related to the maintenance activities stage were not considered due to the following reasons: (i) no reparation or replacement activities took place during the analysed period and (ii) if maintenance operations were to be required, the costs are negligible (e.g., change of small spare parts such as ball valves, PVC elbow, etc.). Thus, the exclusion of maintenance costs is not considered to affect the results. Finally, costs at the end-of-life (EoL) stage, the costs related to decommissioning of the greenhouse structure, the production system and the recycling of materials were not included due to the uncertainty in waste management practices after the long lifespan of the infrastructure, which for buildings is typically considered 50 years.

The functional unit (FU) used in the calculations was defined as "1 kg of tomatoes grown and harvested in a i-RTG over a 7-month production cycle in the Metropolitan Area of Barcelona (Spain)". This is the typical FU (1 kg of product) considered in most UA studies (Peña and Rovira-Val, 2020).

2.2.2. Life cycle cost calculation

The total LCC cost of the 2019 crop was calculated as described in Equation (1)

$$LCC\ (€/kg) = C_I + C_P \quad (1)$$

Where C_I = infrastructure costs and C_P = production costs.

For the infrastructure costs, initial capital investments needed for production (greenhouse structure and other asset categories (i.e., the

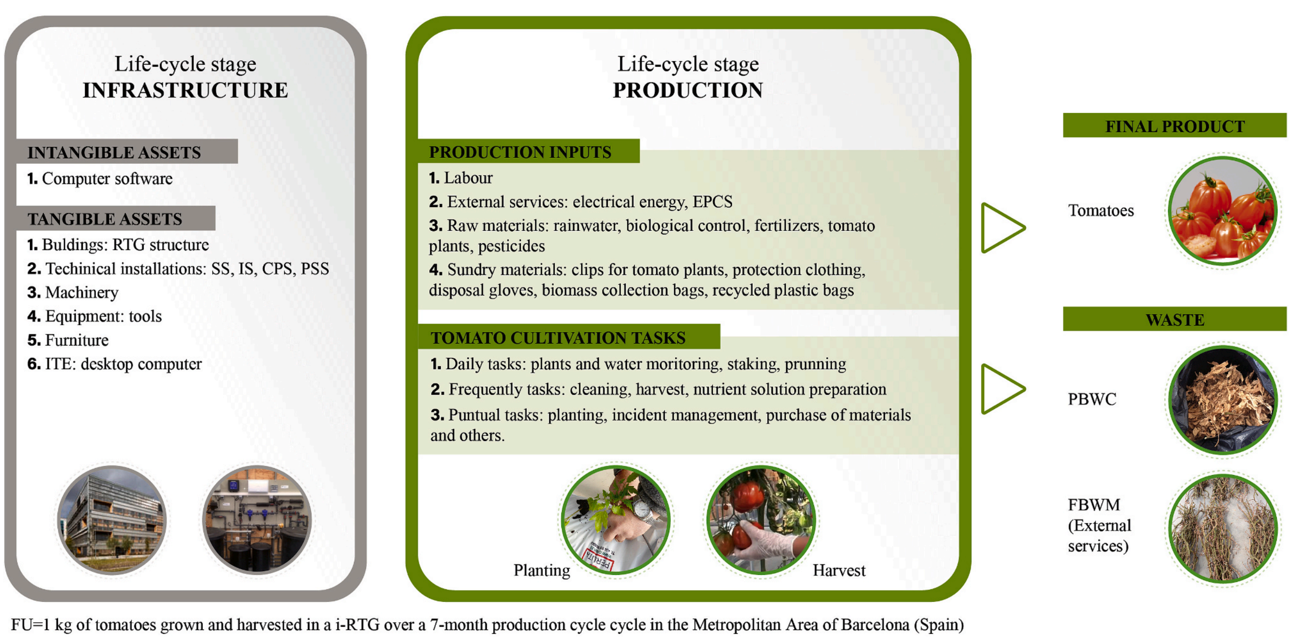

Fig. 1. Scope of the study. Acronyms: RTG structure = Rooftop greenhouse structure; SS=System of sensors; IS=Irrigation system; CPS= Curtains and partitions system; PSS= Production supporting system; ITE: Information technology equipment; EPCS = External pest control specialist; PBWC= Pruning biomass waste collection; FBWC=Final biomass waste collection.

Table 1
Life cycle cost inventory of i-RTG tomato production in 2019.

Life cycle Stage	Costs group	Cost category	Fixed or Variable Cost	Cost item	Lifespan (years)	Quantity		Cost (€) [b]	
						Cycle [a] (1,068 kg)	1 kg	Cycle [a] (1,068 kg)	1 kg
INFRASTRUCTURE	***INTANGIBLE ASSETS***	***Computer software***	***Fixed***	Computer software for sensors data	10	5.83E-02	5.46E-05	35.9	0.03
				Subtotal Computer software				***35.9***	***0.03***
	TANGIBLE ASSETS	***Buildings***	***Fixed***	Rooftop greenhouse structure (122.14 m^2)	50	1.17E-02	1.09E-05	813.3	0.76
				Subtotal Buildings				***813.3***	***0.76***
		Technical installations (Auxiliary facilities)	***Fixed***	System of sensors	10	5.83E-02	5.46E-05	260.7	0.24
				Irrigation system	10	5.83E-02	5.46E-05	236.6	0.22
				Curtains and partitions system	10	5.83E-02	5.46E-05	139.9	0.131
				Production supporting system	3	1.94E-01	1.82E-04	45.1	0.04
				Subtotal Technical installations				***682.3***	***0.6***
		Machinery	***Fixed***	Balance; maximum: 6.5 kg	5	1.17E-01	1.09E- 04	28.6	0.027
				Balance; maximum: 60 kg	5	1.17E-01	1.09E- 04	77.8	0.073
				Conductivity tester	5	1.17E-01	1.09E- 04	8.8	0.008
				Ph tester	5	1.17E-01	1.09E- 04	8.8	0.008
				Backpack Sprayer, capacity 12L	5	1.17E-01	1.09E- 04	5.5	0.005
				Backpack Sprayer, capacity 1L	5	1.17E-01	1.09E- 04	1.3	0.001
				High pressure cleaner	5	1.17E-01	1.09E- 04	9.6	0.009
				Hand pallet truck up to 300 kg	5	1.17E-01	1.09E- 04	47.5	0.044
				Security camera	5	1.17E-01	1.09E- 04	135.2	0.127
				Subtotal Machinery				***323.1***	***0.3***
		Equipment	***Fixed***	Hose,25 m	5	1.17E-01	1.09E-04	5.12 €	0.0048
				Hose holder	5	1.17E-01	1.09E-04	6.45 €	0.0060
				Broom	5	2.33E-01	2.18E-04	0.39 €	0.0004
				Dustpan	5	1.17E-01	1.09E-04	1.47 €	0.0014
				Nylon working gloves	5	4.67E-01	4.37E-04	0.40 €	0.0004
				Goatskin working gloves	5	1.17E-01	1.09E-04	0.92 €	0.0009
				Pruning scissors	5	3.50E-01	3.28E-04	6.37 €	0.0060
				Belt (pruning scissors)	5	1.17E-01	1.09E-04	0.73 €	0.0007
				Cover for pruning scissor	5	2.33E-01	2.18E-04	0.62 €	0.0006
				Drill, 710W	5	1.17E-01	1.09E-04	6.56 €	0.0061
				Protective glasses	5	1.17E-01	1.09E-04	1.39 €	0.0013
				Protective mask	5	1.17E-01	1.09E-04	3.93 €	0.0037
				Tool case	5	1.17E-01	1.09E-04	4.25 €	0.0040
				Pliers	5	3.50E-01	3.28E-04	9.06 €	0.0085
				Blade cutter	5	1.17E-01	1.09E-04	0.57 €	0.0005
				Screwdriver	5	4.67E-01	4.37E-04	1.62 €	0.0015
				Flexometer, 5m	5	1.17E-01	1.09E-04	0.57 €	0.0005
				Wrenches	5	2.33E-01	2.18E-04	4.33 €	0.0041
				Hammer	5	1.17E-01	1.09E-04	1.40 €	0.0013
				Handsaw	5	1.17E-01	1.09E-04	0.75 €	0.0007
				Flange tension gun	5	1.17E-01	1.09E-04	1.75 €	0.0016
				Polyethylene shovels,	5	4.67E-01	4.37E-04	0.66 €	0.0006
				Electrician scissors	5	1.17E-01	1.09E-04	0.92 €	0.0009
				Subtotal Equipment				***60.2***	***0.056***
		Furniture	***Fixed***	Wooden wardrobe	5	1.17E-01	1.09E-04	4.8	0.0045
				Wooden table	5	1.17E-01	1.09E-04	4.8	0.0045
				Aluminium ladder,	5	1.17E-01	1.09E-04	8.7	0.0081
				PVC rolling stool	5	1.17E-01	1.09E-04	2.8	0.0026
				Plastic bin	5	1.17E-01	1.09E-04	3.6	0.0034
				Subtotal Furniture				***24.6***	***0.023***
		Information technology equipment	***Fixed***	Desktop computer	10	5.83E-02	5.46E-05	20.9	0.020
				Subtotal Infor. technology equipment				***20.9***	***0.020***
				Total Infrastructure stage (I)				**1,960.3**	**1.8**
PRODUCTION PRODUCTION	***INPUTS & OUTPUTS***	***Direct labour***	***Variable***	Labour (hrs)		239	2,21E-01	1,339.7	1.3
				Subtotal Direct labour				***1,339.7***	***1.3***
		External services	***Fixed***	External pest control specialist (€)		cycle proportion [c]		682.2	0.6
				Pruning biomass waste collection (unit)		1	9.36E-04	142.8	0.13
			Variable	Electrical energy (kWh)		1,903	1.78E+00	189.3	0.18

(continued on next page)

Table 1 (*continued*)

Life cycle Stage	Costs group	Cost category	Fixed or Variable Cost	Cost item	Lifespan (years)	Quantity		Cost (€) [b]	
						Cycle [a] (1,068 kg)	1 kg	Cycle [a] (1,068 kg)	1 kg
				Final biomass waste management (unit)		1	9.36E-04	169.4	0.20
				Subtotal External services				***1,183.7***	***1.1***
		Raw materials	***Variable***	Rainwater [d]		59.5	5.57E-02	517.4	0.5
				Biological control		0.7	6.6E-04	167.3	0.16
				Fertilizers [e]		89.5	8.4E-02	92.2	0.09
				Tomatoes plants		171	1.60E-01	68.2	0.064
				Pesticides [f]		0.932	4.7E-04	27.2	0.0254
				Subtotal Raw materials				***872.3***	***0.84***
		Sundry materials	***Variable***	Clips for tomato plants		2,565	2.40E+00	27.2	0.025
				Protection clothing		16	1.50E-02	23.2	0.022
				Disposable gloves		50	4.68E-02	3.2	0.003
				Biomass collection bags		30	2.81E-02	11.2	0.010
				Recyclable plastic bags		4	3.75E-03	1.0	0.001
				Subtotal Sundry materials				***65.8***	***0.062***
				Total Production stage (II)				**3,461.5**	**3.3**
				TOTAL FIXED COST (TFC)				***2,785.3***	***2.6***
				TOTAL VARIABLE COST (TVC)				***2,636.5***	***2.5***
				TOTAL COST (I+II)				**5,421.8**	**5.1**

[a] Based on 7-month crop consumption in physical units.
[b] VAT % excluded.
[c] Calculated as 2/3 of the total invoice of annual service contract for pest control monitoring.
[d] Rainwater cost was calculated as 7-month amortization of the available Rainwater harvest system.
[e] KH_2PO_4, KNO_3, $CaCl_2$, Mg $(NO_3)_2$, K_2SO_4, Ca $(NO_3)_2$, Sequestrene (Fe), Hortrilon (Fe, Mn, Zn, Cu, B, Mo).
[f] Pesticides included: Sulfur (S), Heliosufre (sulfur 72%), Insecticidal soap and Neemazal (natural insecticide).

assets that last more than one crop cycle), the economic depreciation cost (also named amortization) of such assets was calculated applying the 2nd Accounting Standard Property, plant, and equipment of the Spanish general accounting plan (ICAC, 2007). Specifically, section 2. Subsequent measurement, 2.1. Depreciation, which provides the depreciation definition:

Property, plant, and equipment shall be depreciated on a systematic and rational basis over the useful life of the assets, considering their residual value and based on impairment normally incurred due to operational wear and tear, and considering potential technical or commercial obsolescence.

No residual value was considered feasible for any of the assets. Regarding their useful life, this was defined as years of operational use and the depreciation period associated to each asset element (see complete list in Table 1) was estimated according to the greenhouse technicians' opinion:

- Computer software (for sensors data): 10 years.
- Building or construction cost is separated from Land cost. According to financial accounting standards, depreciation is only applied to the construction cost. For building, the usual criterion was applied: 50 years.
- Technical installations: 10 years, except for the Production supporting system (bags of substrate: perlite volcanic stones) that need to be renewed every 3 years.
- Machinery: 5 years.
- Equipment: 5 years. This estimation could be 3 or 5 years. The last was selected because we estimated that these small tools could be used during more time than just one single research project (in Spain 3 years).

After estimating the years of lifespan, the proportional amortization cost for one tomato crop period (7 months) was calculated using the following equation:

$$Amortisation\ cost\ = \frac{Initial\ cost}{Lifespan\ (years)} \times \frac{7\ month}{12} \tag{2}$$

Regarding the production cost, consumed items (consumables), in the 7-month production cycle, these were calculated as in Equation (3)

$$Cost\ (consumable\ item) = Consumption \times unit\ cost\ €) \tag{3}$$

2.2.3. Life cycle inventory

Table 1 presents the life cycle inventory of all considered costs of artisan i-RTG tomato production. The costs are presented by (i) *Life cycle stage*; (ii) *Cost group*. The Spanish general accounting plan (ICAC, 2007) was used to classify the infrastructure items into (a) intangible assets: computer software and (b) tangible assets: buildings, technical installations, machinery, equipment, furniture, and information technology equipment; (iii) *Cost category*. In this regard, four technical installations were identified: (i) system of sensors; (ii) irrigation system; (iii) curtains and partitions system and (iv) production supporting system. Detailed information about the composing elements of each technical installation can be found in the Appendix B (Table B1) and (iv) *Cost item*.

It is worth mentioning that labour and transport costs were included in all costs at the infrastructure stage. This was because the elements of this stage, such as rooftop greenhouse structure and building installations, were part of the ICTA-UAB building constructed in 2014 and detailed information about the number of working hours spent on construction and transportation was not available. As was the case with the cost of machinery and tools. At the production stage, transport costs were also integrated in the cost of all items since the transportation cost was unknown because they were not specified in the invoices of raw and consumable materials.

2.2.4. Data collection and monetarization

This section explains how consumption and monetarization data was collected and calculated. The information is presented following the two stages included in the case study: infrastructure and production. The percentage of the VAT was not included in costs due to the research-oriented nature of the building of the case study.

2.2.4.1. Infrastructure costs. The costs of the infrastructure stage are presented in Table 1 and Fig. 2 (in the Results section). Secondary data such as invoices and other similar documents provided mainly by the internal accounting system was used. When the data was not complete, external sources were consulted such as suppliers, online shops, and experts. In the case that a cost element was no longer available on the market, similar products were used to obtain the approximated cost.

It was not possible to separate the specific structure cost of the rooftop greenhouse from the total building cost. For that reason the structure cost was calculated as un average cost based on (i) the real construction cost for 1 m^2 of the building, which is high since it includes all technical installations, materials and elements used for the different activities of all floors; (ii) the cost for 1 m^2 of rooftop based on a budget, excluding electrical installations; and (iii) the cost for 1 m^2 of the rooftop greenhouse structure estimated in Sanyé-Mengual et al., (2015) without considering electrical installations as well.

Finally, to estimate the lifespan needed for the calculation of economic amortization of the intangible and tangible assets, experts (architects, civil engineers, and agricultural engineers) and references in the literature (e.g., Sanjuan-Delmás et al., 2018a) were consulted.

2.2.4.2. Production costs. The cost of the production stage (see Table 1 and Fig. 2) includes the costs of all inputs items as well as two outputs (biomass waste). They were classified in four cost categories: direct labour, external services, raw materials, and sundry materials.

Regarding direct labour, this cost category involved the labour of people who directly participated in the tomato production process. Unlike other crop parameters measured using technical devices (e.g., water consumption, solar radiation, etc.), a device to quantify for working hours was not available. A daily register of working hours of cultivation tasks was designed and implemented (e.g., plant monitoring, water monitoring, nutrient solution preparation, pruning, staking, harvesting). The template used for this purpose can be seen in the Appendix B (Table B2). A tested standard time for each task was established to secure an accurate measurement of labour time consumed. The unitary cost per working hour for a basic agriculture worker was obtained from the database of the Ministry of Agriculture, Livestock, Fisheries and Food of the Government of Catalonia (Goverment of Catalonia, 2016).

The next group, external services, included the following four costs items: external pest control specialist (EPCS), electrical energy, prunning biomass waste collection (PBWC) and final biomass waste management (FBWM). The cost of the EPCS was calculated based on the annual service contract for monitoring the crops for signs of insects, rodents, and other pests. It was estimated that the service for the tomato production was 2/3 of the total invoice. For electrical energy cost, units consumed were taken from a previously created register (Excel file) and the energy price was provided by an expert involved in the project. Regarding PBWC cost, the service of urban waste collection was used (municipality of Cerdanyola del Vallès) and its cost was gathered from the Barcelona Metropolitan area's website. Finally, the cost of the FBWM was estimated based on a carrier budget and included the recollection of the final biomass waste and its transportation to the treatment plant in the nearest municipality.

Raw material costs included five cost items: rainwater, biological control, fertilizers, tomato plants and pesticides. The rainwater consumed came from the rainwater harvest system (RWHS) which is part of the ICTA-UAB building and supplies rainwater to the toilets of the building, ornamental plants, and all crops. Hence, only the proportional amount of the amortization cost of the RWHS parts was included. Data about consumed biological control, fertilizers, tomato plants and pesticides were obtained from the daily register of the research group Sostenipra running the Fertilecity project, while their unitary prices were collected from invoices or delivery notes.

Finally, data about consumed sundry consumable materials (e.g., clips for tomato plants, protection clothing, disposable gloves) was gathered from the afore mentioned Excel file, while unitary prices were collected from invoices and websites (online shops, products databases).

3. Results and discussion

In this section the results and discussion are presented in four parts. The first part presents the LCC results of artisan i-RTG tomato production as follows: (i) contribution by life cycle stage and cost category; (ii) variable and fixed costs; (iii) the four main cost items (cost drivers) responsible for 61.8% of the total cost are discussed: labour, rooftop greenhouse structure, EPCS, and rainwater. The second part presents the results of the sensitivity assessment to determine the potential variability in the results according to changes in: rooftop greenhouse structure and rainwater. The sensitivity assessment was omitted from labour cost since no significant difference between the working hours spent on tomato production in the studied case and conventional greenhouses was found. Sensitivity scenarios were not established for the EPCS either due to uncertainty about the time spent (hrs) on tomato production. In the third part, the role of the production level output as an important element affecting the economic viability and profitability is presented. Moreover, environmental, and social aspects of the i-RTGs are addressed.

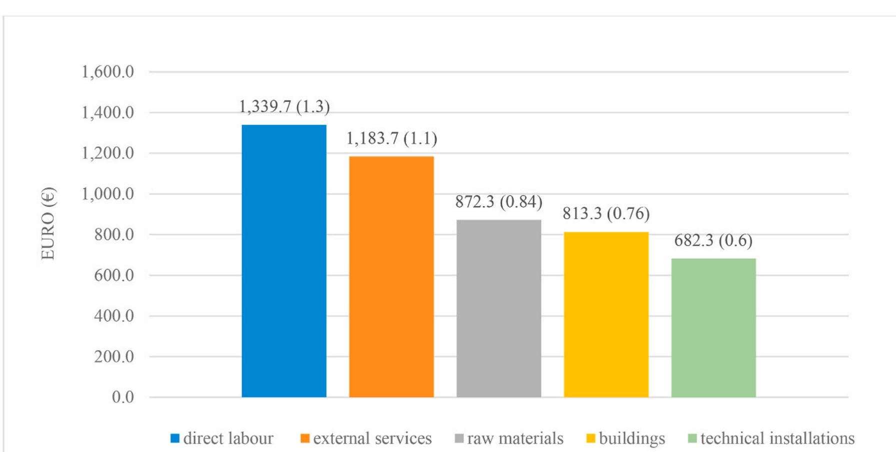

Fig. 2. Five main cost categories responsible for 90.2% of the total cost. Presented in €/cycle and €/kg (in parentheses).

3.1. LCC of artisan i-RTG tomato production

3.1.1. Contribution by life cycle stage and cost category

Total tomato production in 2019 was 1,068 kg at a total cost of 5,421.8 € (VAT % excluded), which is equivalent to 5.1 €/kg (see Table 1). The production stage had the largest contribution with 63.8%, followed by the infrastructure stage with 36.2%.

By cost category, the following five are responsible for 90.2% of the total cost as follows: (i) direct labour with 24.7%, (ii) external services with 21.8%, (iii) raw materials with 16.1%, (iv) buildings with 15.0% and (v) technical installations with 12.6% (Fig. 2).

From these five cost categories, the four main cost items (cost drivers), responsible for 61.8% of the total cost, are discussed later: labour from direct labour, i-RTG structure from buildings, EPCS from external services, and rainwater from raw materials.

3.1.2. Variable and fixed costs

As mentioned in section *2.2.1.*, by life cycle stage all infrastructure stage costs are fixed and in the production stage almost all costs are variable with exception of two specific items: (i) the EPCS, and (ii) the PBWC. In this regard, the total fixed cost (TFC) accounts for 51.4% (2,785.3 €/2.6 €/kg) and the total variable cost (TVC) for 48.6% (2,636.5 €; 2.5 €/kg).

From the production stage the EPCS is a fixed cost because it is a fixed annual amount for the service contract for pest control monitoring on several crops and the proportion for tomato crop was estimated at 2/3 of the total invoice. The PBWC cost is a similar case since it is the amount of the annual fee for the urban waste collection service in Cerdanyola del Vallès municipality. Nevertheless, these costs would be avoided in the future if other options were available, that is: (i) if their own staff had pest control expertise and (ii) if the pruning waste were used for compost.

Regarding the fixed costs, the following six cost items are identified as having important contributions (81.7%) to the TFC: (i) i-RTG structure with 29.2%; (ii) EPCS with 24.5%; (iii) system of sensors (SS) with 9.4%; (iv) irrigation system (IS) with 8.5%, (v) PBWC with 5.1%, (vi) curtains and partitions system (CPS) with 5% (Fig. 3).

Concerning variable costs, five cost items contribute to 90.4% of the TVC: (i) labour with 50.8%, (ii) rainwater with 19.6%, (iii) electrical energy with 7.2%, (iv) FBWM with 6.4% and (v) biological control with 6.3%. The amount as €/cycle and €/kg can be seen in Fig. 3.

3.1.3. Characterization of main cost drivers

The following four cost items have a key role in the total cost (TC): (i) labour; (ii) rooftop greenhouse structure; (iii) EPCS; and (iv) rainwater. Each one contributes over 9% to the TC, while their sum contribution accounts for 61.8% (Fig. 4). Therefore, the reduction of these costs is essential in achieving economic viability since they are the main drivers of the TC. The next sections analyse each of them in-depth and propose alternatives for cost reduction.

3.1.3.1. Labour cost. Labour was the core cost driver, accounting for 50.8% of the TVC and 24.7% of the total cost. Previous research on the topic demonstrated that labour contributed to 30–45% of the total

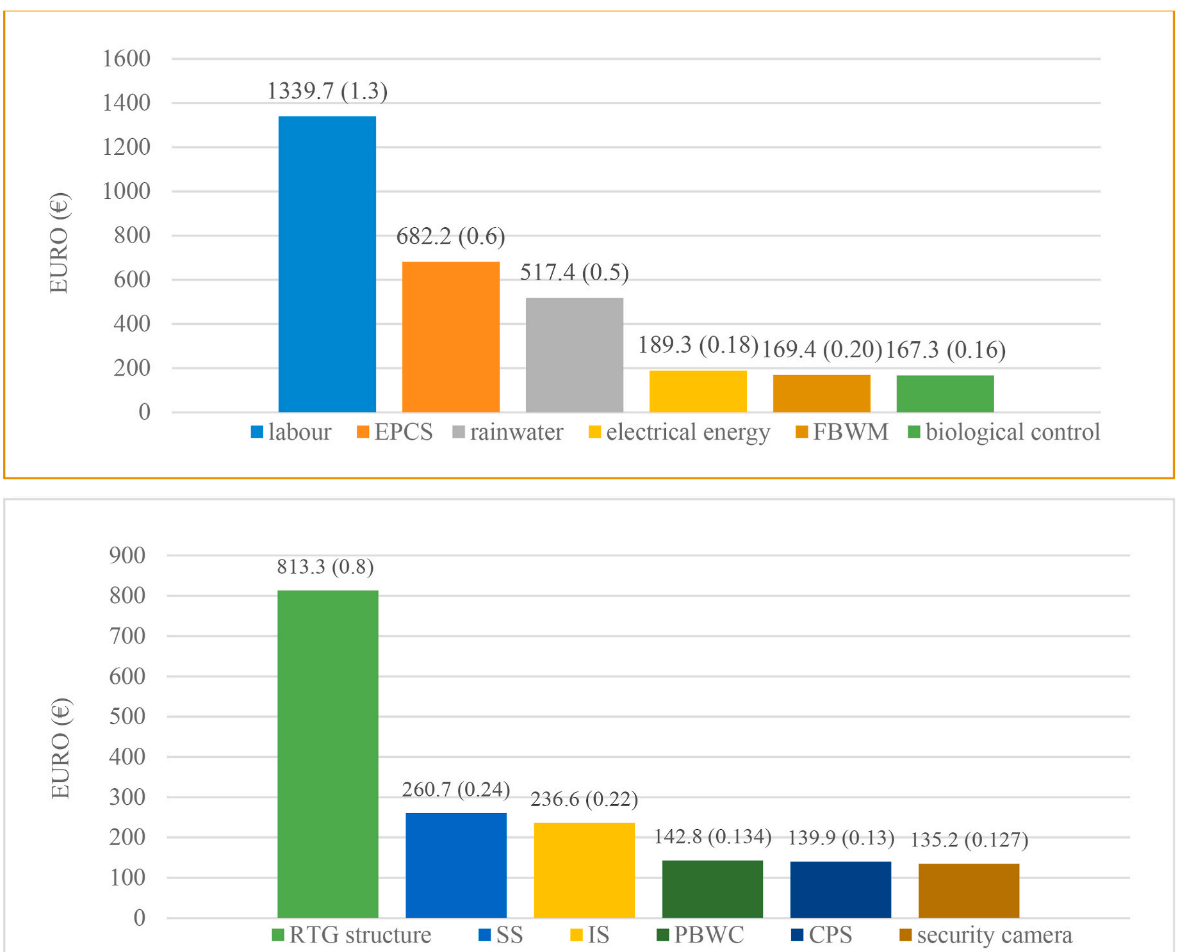

Fig. 3. Main variable (above) and fixed (below) cost items presented in €/cycle and €/kg (in parentheses). Acronyms: RTG (rooftop greenhouse), SS (system of sensors), IS (irrigation system), PBWC (pruning biomass waste collection), CPS (curtains and partitions system), EPCS (external pest control specialist).

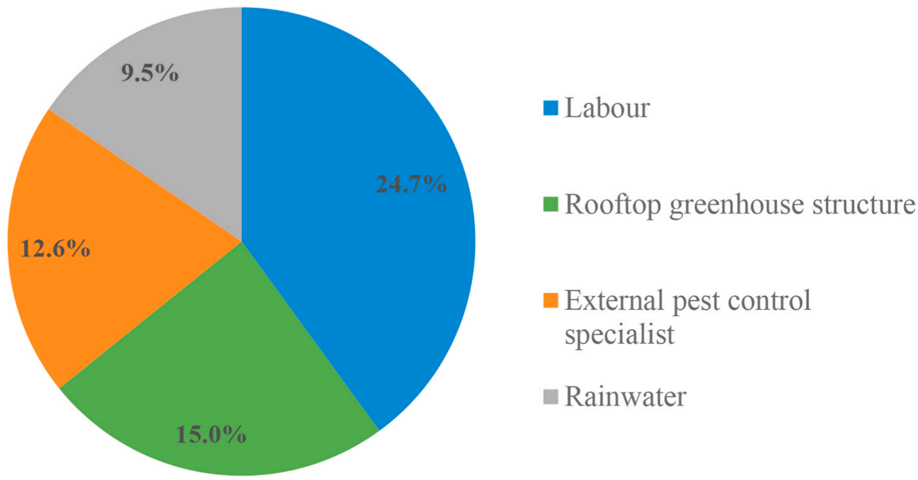

Fig. 4. Contribution of the four cost drivers to 61.8% of the total cost.

tomato production cost.

In the case studied, it was difficult to calculate the working hours as it was necessary to separate the time spent on production from the time devoted to other experimental tasks with the same tomato crop, such as nutrients recovering in Rufí-Salís et al. (2020 a,b).

The results, are consistent with other studies in the literature highlighting that labour is the main cost driver in tomato production (Çetin and Vardar, 2008; Keskin et al., 2010; Barrett et al., 2012; Taki et al., 2013; Testa et al., 2014; Sanyé-Mengual et al., 2015; Albaladejo-García et al., 2018; Cáceres Hernández et al., 2018). The reason is that tomatoes are one of the highest labour demanding crops since it is mainly harvested by hand, probably due to the availability of cheap labour (Çetin and Vardar, 2008). This happens, for instance, in Turkey, China, and India who are among the top 10-tomato producers worldwide (Çetin and Vardar, 2008) and also applies in Spain and The Netherland, the biggest European tomato producers (Ibarrola-Rivas et al., 2020).

On the other hand, the labour cost strongly depends on the working hours required. In this regard, the working hours spent per m^2 for tomato cultivation in conventional greenhouses for industrial production in Almeria is 2.83 h/m^2 per crop (based on 1840 working hours and 650 m^2) (Cámara-Zapata et al., 2019), which is the same efficiency ratio as the artisan tomato production in the i-RTG (based on 239 working hours and 84.3 m^2). This is an important finding that makes a valuable contribution of this study to the literature on innovative rooftop greenhouse tomato production. It demonstrates that the efficiency level is the same (i) in two different tomato production systems (industrial conventional greenhouses versus innovative i-RTG) and (ii) in two different sized productions (large versus small).

There are several examples in the literature about labour reduction costs by using non-paid working hours. For instance, the use of volunteer work is one of the most commonly applied in UA projects (Lui, 2015). Another way is through the "self-pick" strategy. This strategy also called "you-pick"/"pick-your-own" is a direct marketing approach where customers do the harvest task themselves and this is a way to decrease the labour cost since harvesting consumes many working hours. (Ernst and Woods, 2014; Liu, 2015).

3.1.3.2. Rooftop greenhouse structure. The rooftop greenhouse structure was the second most important cost driver for artisan tomato production, contributing to 29.2% of the TFC and 15.0% of the TC. In the case studied, the i-RTG structure is an integral part of the building (Sanjuan-Delmás et al., 2018b) which is high-tech and composed of steel (0.836 kg/m^2), concrete (0.212 kg/m^2), polycarbonate (0.032 kg/m^2), low-density polyethylene (0.006 kg/m^2), polyester (0.0008 kg/m^2) and aluminium (0.0008 kg/m^2) (Sanyé-Mengual et al., 2015).

Estimating the usual 50-year lifespan for economic amortization of buildings, its cost was calculated to be 11.4 €/m^2/year, which was 22.6% higher than the average cost for a high-tech RTG of 9.3 €/m^2/year (calculated with the average of 329 €/m^2 and 600 €/m^2) (Ackerman, 2012 Milford et al., 2019). The higher cost in the case studied is because information on the specific rooftop greenhouse structure cost was not available, and its cost was calculated as an average cost (see 2.2.4.1). However, this cost could have been reduced if a study for optimization of construction materials had been carried out during the building design phase (Sanjuan-Delmás et al., 2018b). Moreover, the size of the studied case structure is small (artisan) with a production area of only 84.3 m^2, therefore there is a need for designing medium and large size i-RTGs to facilitate the RTG expansion in cities in the future.

Based on these considerations, future research should optimise the rooftop greenhouse structure (prototype, materials, and cost) by considering different sizes (e.g., small, medium, and large) helping to make decisions for implementing these innovative UA systems on a larger scale. Sanyé-Mengual et al., (2015) discussed that this is a crucial condition since the rooftop greenhouse structure cost could be a possible barrier for future development.

3.1.3.3. External pest control specialist. The EPCS was the third main cost driver, contributing to 24.5% of the TFC and 12.6% of the TC. It was the service provided from an external specialist for monitoring the crops for signs of insects, rodents, and other pests. As mentioned in *2.2.4.2.*, this is an annual service contract with a closed price, classified as a fixed cost, and the cost assigned to the tomato crop was calculated as 2/3 of the total invoice.

This significant cost could be reduced or avoided in the future by providing specialized training on sustainable pest prevention and control to the personnel responsible for the tomato production.

3.1.3.4. Rainwater cost. Rainwater was the fourth largest cost, accounting for 19.6% of the TVC and 9.5% of the total cost of the crop in 2019, where 59.5 m^3 of rainwater was consumed, that is 0.056 m^3/kg (56 litres/kg). As mentioned in *2.2.4.2.*, this cost was calculated as the economic amortization of the RWHS (pipes, water tank, materials). For the crop period of 7 months, it was 517.4 €, i.e., 1 m^3 of rainwater costs 8.7€. This cost is more than three-times higher than the cost of tap water, estimated at 2.5 €/m^3 based on 150.9€/cycle (Aigües de Barcelona, 2020). This large cost is due to the great capacity of the RWHS (water tank, materials used) which was designed to supply rainwater to the toilets, ornamental plants of the building and all crops in the rooftop greenhouses (Sanjuan-Delmás et al., 2018b).

In this regard, previous studies that analysed the economic performance of the rainwater harvesting installations concluded to be financially non-viable (Christian Amos et al., 2016; Gao et al., 2017; Ishida et al., 2011; Roebuck et al., 2011, 2012). However negative financial viability does not necessarily mean negative economic viability since the LCC results give economic measures, not economic decisions (Amos et al., 2018). Therefore, the economic evaluation should include wider considerations such as the definition of need, and indirect benefits shown in improved health through water, sanitation, and hygiene (Alexander et al., 2014), which have a socio-economic impact that is often complex to measure in financial terms. Benefits for the whole society may have more value than simply economic costs (Domènech and Saurí, 2011; Beatty and McLindin, 2012). For instance, these technical installations have a great potential to alleviate the increased water demand caused by urbanization (Barthwal et al., 2014) and improve the water security in urban areas (Amos et al., 2018). Hence, the rainwater capturing, and use may help to reduce both tap water consumption and the energy for water treatment and pumping, which contribute to sustainability.

Unlike tap water with which scarcity is one of the main environmental concerns (European Commission, 2010), rainwater is a relatively clean and abundant renewable resource, especially in the Mediterranean area. For instance, it has been forecasted that on average in 2051, tap water availability for the region of Catalonia will decrease by 17.8% and in Southern Catalonia, the decrease could be higher, 70–75% (Duran et al., 2017). Furthermore, there is an uncertainty with the price of the tap water since a report from the Catalan Water Agency indicated that in the period 2005–2015, the price of water increased by 50% (5% annual) and this tendency will continue in the following years (Vargas-Parra et al., 2019).

A previous case study explained that in a Mediterranean climate with low and variable precipitations, the use of RWHSs covered most of the water need for flushing toilets and 60% of the demand for landscape irrigation (Domènech and Saurí, 2011). Similarly, Fragkou et al., (2016) demonstrated the high potential of the Mediterranean region to supply its water needs from rainwater runoff, taking into account all urbanized areas as collectors, where the water self-sufficiency potential varies from 8% to 500% with an overall average above 100% for the regional system.

Based on the expected contribution of rainwater to improve the water security in urban areas, the RWHS should be optimized in future research in terms of design, materials, and cost. This recommendation is also supported by Sanjuan-Delmás et al., (2018b) where the authors explained that both the rooftop greenhouse structure and the RWHS were exaggerated in size, and the material used for its construction could have been reduced if a study of its optimization had been completed during the building design.

3.2. Sensitivity assessment

3.2.1. Rooftop greenhouse structure

The potential variability in the results was analysed by comparing the structure of the case studied to three structural systems suitable to be placed on the roof (RF structure hereafter): (i) intensive green roof for open-air farming (Benis et al., 2018), (ii) medium-tech RTG (Proksch, 2017), and (ii) high-tech RTG (Proksch, 2017; Milford et al., 2019).

The intensive green roof is an uncovered structure for open-air agricultural production. The building cost per m^2 is around 130 euro/m^2 over a lifespan of 40 years or 3.3 euro/m^2/year, including (i) a waterproofing membrane and a root barrier that divide the wet layers from the underlying building rooftop; (ii) a drainage layer that facilitates the removal of excess water; (iii) a filter fabric that avoids the drainage layer from clogging; and (iv) other layers: water retention, substrate and vegetation (Benis et al., 2018). The main difference between the medium-tech and high-tech RTGs is in the construction materials (Proksch, 2017). For instance, the medium-tech greenhouse support structure has a steel frame, and the covering materials are double polyethene plastic (PE) or rigid plastic. While the high-tech support structure has a steel or aluminium frame and the covering materials are more durable such glass and polycarbonate, which is the case of the studied case.

The cost of a conventional medium-tech greenhouse varies from 26 to 88 €/m^2 ($30–100) depending on the used materials and the cost of high-tech greenhouses, both on the ground, are from 126 to 252 ($150–300) depending on materials, climate control, ventilation (Proksch, 2017). But placed on the roof, their costs can increase up to three times (Milford et al., 2019). Hence, the average cost of building medium-tech RTGs varies from 171€/m^2 to 378€/m^2, while for high-tech RTGs from 329 to 426 €/m^2 ($375–485). However, in 2019, it was estimated that a high-tech RTG covered by glass could reach 600 €/m^2. The lifespan was considered to be 50 years by Sanyé-Mengual et al., (2015) and Benis et al., (2018) due to the concrete structure. Since the cost of greenhouse structures can vary across countries (Harada and Whitlow, 2020; Proksch, 2017), in the sensitivity analysis the average cost for a high-tech structure of 465 euro/m^2 or 9.3 €/m^2/year from a cost rank of 329 €/m^2 to 600 €/m^2 was used. In comparison, the cost of the studied i-RTG structure was 570 €/m^2. The cost of each mentioned rooftop farming structure can be seen in Table B3 from the Appendix B and in Table 2 (here in €/m^2/year).

Table 2 presents the results of the sensitivity analysis from replacing the studied case structure cost (Scenario 0) with the cost of (i) an intensive roof for open-air cultivation (Scenario 1); (ii) a medium-tech RTG (Scenario 2) and (iii) an average high-tech RTG (Scenario 3). For Scenario 1 and Scenario 2, a lifespan of 40 years was considered since this structure is made of less resistant materials than the high-tech RTG.

The results revealed that the most notable cost reductions in the total tomato cost and the tomato cost per kg were very similar for the two simplest structures with 11.9% in Scenario 1 (reduction of 578.2 €/cycle; 0.54 €/kg) and 10.9% (reduction of 506.9 €/cycle; 0.47 €/kg) in Scenario 2. While by comparing the case studied structure cost (Scenario 0) with the average cost of the same high-tech structure in Scenario 3, only a small decrease of 2.9% (150.7€/cycle; 0.14 €/kg) in the total cost and the cost per kg was noticed. Hence, the sensitivity analysis supported that the structure of the case studied is high-tech RTG and supports the recommendation of Sanjuan-Delmás et al., (2018b) that the structure cost could be reduced in future research if a optimization study of construction materials were carried out during the building design phase.

3.2.2. Rainwater

As has been mentioned in *3.1.3.4.,* this cost was calculated as the economic amortization of the RWHS (ICTA-UAB). The rainwater tank had a considerable capacity of 100 m^3, used to supply toilets, ornamental plants and all rooftop crops in the building (Sanjuan-Delmás et al., 2018b). The rainwater tank cost was 6.800€ which disproportionately increased the RWHS (ICTA-UAB) cost. Nevertheless, it was estimated that a 20 m^3 tank (this is a fifth part) would be enough for 90% of rainwater needed for the crop irrigation (Sanjuan-Delmás et al., 2018b).

Therefore, here the sensibility assessment (Table 3) was carried out to estimate the costs variations (total cost and cost per kg) by replacing: (i) the use of rainwater with tap water and (ii) the rainwater tank capacity with a smaller one, i.e., 20 m^3 instead of 100 m^3 as Sanjuan-Delmás et al., (2018b) proposed.

Cost data from the Barcelona water supplier website (Aigües de Barcelona, 2020) and online supplier were used to estimate the tap water cost and the cost of the 20 m^3 water tank.

If tap water was used for irrigation, the cost would be 150.9 € or 70.8% less than using rainwater (517.4 €), while the reduction in the total tomato production cost is 366.5 € or 6.8% (Scenario 1). However, although the cost of consuming rainwater is higher in comparison to tap water, the use of rainwater can bring significant environmental, economic, and social benefits. Environmentally, rainwater harvesting on

Table 2
Life cycle cost variation by using alternative types of RF structure.

Scenario	Lifespan	RF structure cost (€/m²/year)	Tomato total cost (€/cycle)	Tomato cost per kg (€/kg)	Variation (Scenario $_{1,2,3}$ - Scenario $_0$)		
					Tomato total cost (€/cycle)	Tomato cost per kg (€/kg)	%
Scenario 1: *Intensive roof for open-air cultivation*	40	3.3	4,843.6 €	4.5	−578.2	−0.54	−11.9
Scenario 2: *Medium-tech RTG*	40	4.3	4,914.8 €	4.6	−506.9	−0.47	−10.9
Scenario 3: *High-tech RTG*	50	9.3	5,271.1 €	4.9	−150.7	−0.14	−2.9
Scenario 0: *Baseline*	50	11.4	5,421.8 €	5.1			

Table 3
Life cycle cost variation by using tap water and 20 m^3 water tank.

	Variation (Scenario $_{1,\ 2}$ - Scenario 0)				
	Tomato total cost (€/cycle)	Tomato cost per Kg (€/kg)	Tomato total cost (€/cycle)	Tomato cost per Kg (€/kg)	%
Scenario 1: Tap water	5,055.3	4.7	−366.5	−0.3	−6.8
Scenario 2: Small rainwater tank (20 m^3)	5,372.0	5.0	−49.8	−0.1	−0.9
Scenario 0: Baseline rainwater & big water tank (100 m^3)	5,421.8	5.1			

the roof can reduce the impact of storm water runoff in the area, which can otherwise damage creeks and other diversity of species. Additionally, it was demonstrated that the construction of RWHS combined with food production is associated with low environmental impacts (Toboso-Chavero et al., 2019). Economically, rainwater use can contribute to saving money on water bills by storing water in an economic way. For instance, in some areas, local councils have introduced cash-back refund plans for those who install a rainwater tank. In this regard, rainwater use for irrigation could be beneficial in the following years due to the uncertainty of the future price of supply water (Amos et al., 2018). Finally, there are expected social benefits related to health issues and personal preferences. For example, some people prefer to consume rainwater since there are no added chemicals that are used to treat mains water supply. Moreover, rainwater is a suitable option in some areas where water is salty and scarce, contains heavy metals or has an unpleasant odour (Rain Harvesting, 2021).

Regarding the size of the rainwater tank, if 20 m^3 were used, the cost of the rainwater tank would be reduced from 6,800 € (100 m^3) to 2,530 € (20 m^3) or 62.8% less which supposes a decrease of 49.8 € in the total tomato production cost or 0.9%. Therefore, the substitution with a smaller rainwater tank could be a viable option.

3.3. Production level output

The production level output is an important aspect affecting the economic viability and profitability of any economic activity. For this reason, has been calculated for the tomatoes production of the studied case by adding an additional BEP analysis. The BEP is the level of production to be sold that completely covers the TFC. At this level the company has no losses. From this level, every additional unit sold contributes to generate profit. The BEP is very useful in knowing the number of units to be sold so as not to have losses from the production activity (Gutierrez and Dalsted, 2012). A BEP analysis is performed in this section (Equation (4)).

$$Break\ even\ point\ (in\ units) = \frac{(Fixed\ costs)}{(SP - VC)} \quad (4)$$

where SP = selling price per unit, VC = variable cost per unit.

The current average market price is between 3.0 €-4.0 € for 1 kg of tomatoes Coeur de boeuf with VAT included (4% in Spain). The analysis assumes that 1 kg consists of 5 tomatoes (number of physical units) which was the average for two consecutive crops (2018 and 2019) and that all produced tomatoes would be commercialized without discriminating their size.

The complete table of results of the BEP analysis can be seen in Table B4 from the Appendix B. Prices between 3.0 € and 5.0 € are not suitable for the studied case because the BEP is above the i-RTG productive capacity (the production average was 5,415 units in 2018 and 2019 crops). Hence, price range to be used it 5.1 € to 5.5 € for the productive area of 84.3 m^2 with a total fixed cost of 2,785.3 € and variable cost per unit of 0.49 €. But in the authors' opinion, this range of prices would be too high for the local market. The reasons for the high selling prices of 1 kg of tomatoes are the elevated fixed costs (rooftop greenhouse structure) and the small cultivation area (84.3 m^2) which limits the productive capacity.

The BEP equation can be applied here to determine the maximum level of fixed cost for a specific production area size, which includes the production output, and specific unitary variable cost. In this regard, the maximum level of fixed cost is calculated at selling between 3.0 €-5.0 € to find how much the fixed costs have to decrease in order to establish selling prices below 5.0 €. For the studied case: a productive area of 84.3 m^2 with an average production output of 5,415 units (for two consecutive years), and variable unitary cost of 0.49 €.

The complete table of results can be seen in Table B5 from the Appendix B. Selling prices between 3.00 € and 3.6 € are discarded since their average fixed costs would be 920.6 € meaning that they must decrease by 1,864.7 € or 66.9% comparing with the current fixed cost of 2,785.3 €, which is hard to achieve. At selling prices between 3.7 € - 4.3 €, the average fixed cost would be 1,678.7 €, hence a large reduction of 39.7% on average must be made to achieve it. Finally, at the selling price range from 4.4 € to 5.0 €, the average fixed costs would be 2,436.8 € and must decrease by 12.5% on average, which seems feasible with the optimization of the rooftop greenhouse structure and the technical installations in future research. For instance, this can be possible by using reduced, recycled, or less costly materials.

Lastly, previous studies that analysed the economic potential of the RTGs through LCC demonstrated that for some agriculture practices such as hydroponics, the unitary economic cost strongly depended on the yield size (Sanyé-Mengual et al., 2015; Benis et al., 2018; Weidner et al., 2019). For instance, Sanyé-Mengual et al., (2015) found that local tomatoes grown in small yield RTGs have higher unitary economic costs than those produced via conventional large-scale production. In contrast, tomatoes grown in local RTGs with high crop yield size >25 kg/m^2 have not only a lower unitary economic cost but also at the same time have better environmental characteristics. In this regard, it was estimated that to achieve higher economic and environmental performance, the i-RTGs require an annual tomato crop yield of 55 kg/m^2 (Sanyé-Mengual et al., 2015). While in Benis et al., (2018), the recommended yield size for this purpose was calculated to be approximately 70 kg/m^2. In the case of the 2019 i-RTG tomato crop, the yield was 12.66 kg/m^2, considerably lower than required.

For a specific production size, based on the BEP analysis and the previous research, it could be concluded that it is crucial to optimise fixed costs, otherwise it would be necessary to sell the products at a high price that allows to cover all these costs. For instance, it might be possible by using reduced, recycled, or less costly materials of the rooftop greenhouse structure.

3.4. Environmental and social aspect of i-RTGs

Unlike the non-integrated RTGs and conventional greenhouses on the ground, i-RTGs have demonstrated better environmental (Sanyé-Mengual et al., 2018; Sanjuan-Delmás et al., 2018a). For instance, Sanyé-Mengual et al., (2018) demonstrated that i-RTGs environmental savings were 2.1 times for avoided CO2 emissions and 1.8 for energy consumption by comparing the differences between non-integrated RTGs and i-RTGs in retail parks. In comparison with conventional greenhouses, i-RTGs have between a 50 and 75% lower impact on five of six impact categories. Specifically, the environmental savings of i-RTG artisan tomato production were 0.58 kg of CO_2 equivalent per kg versus 1.7 kg of CO_2 from conventional greenhouses (Sanjuan-Delmás et al., 2018a).

Moreover, the role of i-RTGs to improve energy efficiency in buildings was analysed in Nadal et al., (2017). They found that i-RTGs could recycle 43.78 MWh of thermal energy (or 341.93 kWh/m_2/yr) from buildings and that compared to the conventional greenhouse, heated with oil, gas, or biomass systems, i-RTGs can also achieve greater annual carbon and economic savings as follows: (i) 113.8 kg CO_2(eq)/m^2/yr and 19.63 €/m^2/yr compared to oil heated; (ii) 82.4 kg CO_2(eq)/m^2/yr and 15.88 €/m^2/yr compared to gas heated, and (iii) 5.5 kg CO_2(eq)/m^2/yr and 17.33 €/m^2/yr compared to biomass heated.

Later, Muñoz-Liesa et al., (2020) quantified the bi-directional energy exchange between greenhouses and buildings. Together with Nadal et al., (2017), they demonstrated that 98 kWh/m^2/year of heating energy is passively recovered (84% during night-time) by i-RTGs from building waste heat. As well as that, the energy savings of the building are 35 kWh/m^2/year (equal to 4% of the building's annual electricity needs) thanks to the insulating capacity of i-RTGs. This results in an overall 128 kWh/m^2 of annual net energy savings equivalent to 45.6 kg CO_2 eq/m^2, considering 5 kWh/m^2/year are required to operate the building climate system that enables the bi-directional (greenhouse-building) thermal exchange.

Regarding social sustainability, UA activity has been demonstrated to have positive contributions in different aspects: (i) better food and nutrition security, (ii) health improvement, (iii) establishment of jobs for the urban poor; and (iv) inclusion of disadvantaged people or social (Orsini et al., 2013). However, the construction of building-based UA forms such as rooftop farms (open-air) and rooftop greenhouses can be associated with additional social benefits such as improved customer awareness about the origin of the food (Specht et al., 2016; Sanyé-Mengual et al., 2016), improved community building (Sanyé-Mengual et al., 2016), educational benefits (Kortright and Wakefield, 2010; Specht et al., 2016), transparency and creation of new experimental spaces (Specht et al., 2016).

If integrating greenhouses into buildings for UA would have positive impacts as foment food self-sufficiency policies or energy/water-saving policies in the short term (Cerón-Palma et al., 2012), special attention needs to be devoted to the great opportunity for environmental education of *building-based* UA because of its possible effects in the longer run.

Nowadays the interest in analysing social aspects of UA in rooftop greenhouses, as a necessary component of this activity is growing. In this regard, it is worth to mention the ongoing project GROOF-Greenhouses to reduce CO_2 on rooftops, aimed to define the state of the art of the building integrated greenhouse for a more resilient built environment, which includes the analysis of their social performance, but results are not available yet (GROOF, 2022).

Finally, UA products are mostly associated with positive customer perceptions (Ercilla-Montserrat et al., 2019; Grebitus et al., 2020) but the high price is a big barrier for posterior purchase intentions (Grebitus et al., 2017). Nonetheless, customers tend to pay a premium price for locally grown products (Willis et al., 2016; Boys et al., 2014) since they assume that they are fresher, of higher quality and better tasting. Additionally, local production can also benefit de local community enhancing the local economy and benefit the environment at the same time (McGarry-Wolf et al., 2005; Zepeda and Leviten-Reid, 2004) (See A3. Customer preferences from Appendix A).

4. Conclusions

This paper analysed the economic viability of an artisan tomato production in the rooftop of an innovative building with an integrated urban agriculture system. LCC was applied to quantify its total cost by life cycle stage, by cost category and by fixed and variable cost, identifying the main cost drivers, proposing cost reduction alternatives, using sensitivity scenarios, and including the production level output calculations, as a relevant factor for the economic viability and profitability. As far as the authors are aware, this is the first study analysing the life cycle economic viability of tomato production in i-RTGs including essential costs such as labour and infrastructure, which tend to be missing in research on UA. The results are valuable for public administrations or investors with ability to promote policies or funding for the implementation of economically and environmentally sustainable food production in cities. It also contributes to the UA literature by improving academic knowledge on the economic performance of alternative production systems for further sustainability-oriented research on the topic.

The results indicated that the production stage had a major contribution to the TC and five cost categories (direct labour, external services, raw materials, buildings, and technical installations) account for 90.2% of it. The main cost drivers are labour, rooftop greenhouse structure, EPCS and rainwater, determining nearly 62% of the TC. Thus, the reduction of these costs is an essential requirement to achieve economic viability.

An important finding that makes a valuable contribution to the literature on innovative rooftop greenhouse tomato production is that there was the same efficiency in the main cost driver, labour (hours spent per m^2) both (i) in two different tomato production systems (conventional greenhouses versus innovative i-RTG) and (ii) in two different size productions (large versus small).

The managerial implications derived from findings to facilitate the economic viability and contribute to the implementation of i-RTG production are derived from (i) the reduction strategies of cost drivers and (ii) to stablish the adequate production level output. Respecting the reduction of cost drivers (labour, rooftop greenhouse structure, EPCS and rainwater cost), labour and rooftop greenhouse structure are crucial. As the core cost driver (50.8% of TVC and 24.7% of TC) considered strategies for labour cost reduction were: (i) use of volunteer work and (ii) customers' participation in harvest task. Regarding the second cost driver, the rooftop greenhouse structure, that could be a possible barrier for implementing these innovative UA systems on a large scale (Sanyé-Mengual et al., 2015) it is a key condition to reduce its cost optimising prototypes, materials, and sizes (e.g., small, medium and large) to allow making decisions for this initial investment. Regarding the third and fourth cost drivers, the EPCS could be reduced or avoided if staff training was provided and the rainwater cost could be decreased by optimising the rainwater tank size according to the productive area. Last, the size of production area is relevant for the role of production level output. As break-even point demonstrated, high fixed costs and low yields is a combination that impede the economic viability and profitability of i-RTG artisan production.

This study has several constraints: (i) the costs at EoL stage were not included; (ii) it was carried out in a Mediterranean climatic zone with a mild and hot climate and no abundant rains; and (iii) the economic costs of additional innovative technical installations (e.g., water recycling system), used to reduce environmental impacts, which could increase the total costs were not considered since they were still in construction during the analysed period.

Based on these restrictions, future research should: (i) perform more complete LCC by including costs at the maintenance stage, if they were significant, and at the EoL stage with the cost of decommissioning the greenhouse structure; (ii) optimise the rooftop greenhouse structure and the rainwater harvesting systems (design, materials and cost) for different sizes (e.g., small, medium and large); (iii) consider cold climatic zones for analysis since some costs such as energy for heating to guarantee an adequate temperature for plants could be bigger; and (iv) include the economic costs of innovative technical installations (e.g., water recycling system and other future systems) used to reduce impacts on environment. Furthermore, for a fuller LCC, the external environmental cost should also be considered in future research.

Overall, future research should develop sustainable business models for the rooftop greenhouse food production, boosting the integration between building and rooftop greenhouse which should contribute to economic cost reductions and improved environmental and social impacts. For instance, this could be done by selecting appropriate business models to reduce main cost drivers and environmental impacts by providing complementary services which provide notable social benefits (e.g., recreation events, gastronomy, education, therapeutic services, health care, etc.) and contribute at the same time to obtain additional revenues (See A2. Business models from Appendix A).

Finally, rooftop greenhouse food production could also be analysed from another perspective different from a profitable activity for trade. The promotion of food production in rooftop greenhouses could be convenient for self-sufficiency in urban areas, in line with the promotion that energy production for the self-sufficiency is being strongly encouraged by all levels of public administrations. In this regard, research on the social aspects of UA in rooftop greenhouses could contribute to its development.

CRediT authorship contribution statement

Alexandra Peña: Data curation, Writing – original draft, Formal analysis. **M. Rosa Rovira-Val:** Conceptualization, Supervision, Writing – review & editing, Validation. **Joan Manuel F. Mendoza:** Conceptualization, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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References

Ackerman, K., 2012. The Potential for Urban Agriculture in New York City: Growing Capacity, Food Security, and Green Infrastructure. Urban Design Lab at the Earth Institute Columbia.

Albaladejo-García, J.A., Martínez-Paz, J.M., Colino, J., 2018. Financial evaluation of the feasibility of using desalinated water in the greenhouse agriculture of Campo de Níjar (Almería, Spain). ITEA Inf. Tec. Econ. Agrar. 114, 398–414. https://doi.org/10.12706/itea.2018.024.

Alexander, K.T., Oduor, C., Nyothach, E., Laserson, K.F., Amek, N., Eleveld, A., Mason, L., Rheingans, R., Beynon, C., Mohammed, A., 2014. Water, sanitation and hygiene conditions in Kenyan rural schools: are schools meeting the needs of menstruating girls? Water 6 (5), 1453–1466.

Ammar, M., Zayed, T., Moselhi, O., 2013. Fuzzy-based life-cycle cost model for decision making under subjectivity. J. Constr. Eng. Manag. 139, 556–563. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000576.

Amos, C.C., Rahman, A., Gathenya, J.M., 2018. Economic analysis of rainwater harvesting systems comparing developing and developed countries: a case study of Australia and Kenya. J. Clean. Prod. 172, 196–207. https://doi.org/10.1016/j.jclepro.2017.10.114.

Barrett, C.E., Zhao, X., Hodges, A.W., 2012. Cost benefit analysis of using grafted transplants for root-knot nematode management in organic heirloom tomato production. HortTechnology 22, 252–257. https://doi.org/10.21273/horttech.22.2.252.

Barthwal, S., Chandola-Barthwal, S., Goyal, H., Nirmani, B., Awasthi, B., 2014. Socio-economic acceptance of rooftop rainwater harvestingea case study. Urban Water J. 11 (3), 231–239.

Baumgartner, B., Belevi, H., 2001. A Systematic Overview of Urban Agriculture in Developing Countries. EAWAG/SANDEC, Dübendorf, pp. 1–34.

Beatty, R., McLindin, M., 2012. Rainwater harvesting and urban design in Australia. Proc. Water Environ. Fed 2012 9, 6435–6447.

Bendt, P., Barthel, S., Colding, J., 2013. Civic greening and environmental learning in public-access community gardens in Berlin. Landsc. Urban Plann. 109, 18–30. https://doi.org/10.1016/j.landurbplan.2012.10.003.

Benis, K., Turan, I., Reinhart, C., Ferrão, P., 2018. Putting rooftops to use – a Cost-Benefit Analysis of food production vs. energy generation under Mediterranean climates. Cities 78, 166–179. https://doi.org/10.1016/j.cities.2018.02.011.

Boys, K.A., Willis, D.B., Carpio, C.E., 2014. Consumer willingness to pay for organic and lo- cally grown produce on Dominica: insights into the potential for an "organic island". Environ. Dev. Sustain. 16 (3), 595–617.

Cáceres Hernández, J.J., Godenau, D., González Gómez, J.I., Martín Rodríguez, G., Ramos Henríquez, J.M., 2018. Tomate canario de exportación: una evaluación de costes. Inf. Tec. Econ. Agrar. 114, 280–302. https://doi.org/10.12706/itea.2018.017.

Cámara-Zapata, J.M., Brotons-Martínez, J.M., Simón-Grao, S., Martinez-Nicolás, J.J., García-Sánchez, F., 2019. Cost–benefit analysis of tomato in soilless culture systems with saline water under greenhouse conditions. J. Sci. Food Agric. 99, 5842–5851. https://doi.org/10.1002/jsfa.9857.

Cerón-Palma, I., Sanyé-Mengual, E., Oliver-Solà, J., Montero, J.-I., Rieradevall, J., 2012. Barriers and opportunities regarding the implementation of rooftop Eco.Greenhouses (RTEG) in mediterranean cities of Europe. J. Urban Technol. 19, 87–103. https://doi.org/10.1080/10630732.2012.717685.

Çetin, B., Vardar, A., 2008. An economic analysis of energy requirements and input costs for tomato production in Turkey. Renew. Energy 33, 428–433. https://doi.org/10.1016/j.renene.2007.03.008.

Christian Amos, C., Rahman, A., Mwangi Gathenya, J., 2016. Economic analysis and feasibility of rainwater harvesting systems in urban and peri-urban environments: a review of the global situation with a special focus on Australia and Kenya. Water 8 (4), 149.

de Barcelona, Aigües, 2020. Precios Y Tarifas. http://www.aiguesdebarcelona.cat/facturadelaigua/es/precios-tarifas/. (Accessed 15 July 2020).

Domènech, L., Saurí, D., 2011. A comparative appraisal of the use of rainwater harvesting in single and multi-family buildings of the Metropolitan Area of Barcelona (Spain): social experience, drinking water savings and economic costs. J. Clean. Prod. 19 (67), 598–608.

Duran, X., Picó, M.J., Reales, L., 2017. El Cambio Climático en cataluña. Resumen ejecutivo del Tercer informe sobre el cambio climático en Cataluña. Generalitat de Catalunya.

Egal, F., 2019. Review of the State of Food Security and Nutrition in the World. https://doi.org/10.26596/wn.201910395-97, 2019, World Nutrition.

Ellen MacArthur Foundation (EMF), 2019. Cities and Circular Economy for Food. Ellen MacArthur Found, pp. 1–66.

Ercilla-Montserrat, M., Sanjuan-Delmás, D., Sanyé-Mengual, E., Calvet-Mir, L., Banderas, K., Rieradevall, J., Gabarrell, X., 2019. Analysis of the consumer's perception of urban food products from a soilless system in rooftop greenhouses: a case study from the Mediterranean area of Barcelona (Spain). Agric. Hum. Val. 36, 375–393. https://doi.org/10.1007/s10460-019-09920-7.

Ernst, M., Woods, T., 2014. Pick-your-own (U-Pick) Marketing. University of Kentucky Department of Agriculture Economics, pp. 1–4.

European Commission (EC), 2010. Water Scarcity and Drought in the European Union. https://ec.europa.eu/environment/pubs/pdf/factsheets/water_scarcity.pdf. (Accessed 11 July 2021).
FAO, 2017. Water for Sustainable Food and Agriculture Water for Sustainable Food and Agriculture. A Report Produced for the G20 Presidency of Germany.
FAO, 2020. FAOSTAT Database [Online]. URL. http://faostat.fao.org/.
FAO, I.F.A.D., UNICEF, W.F.P., WHO, 2019. The State of Food Security and Nutrition in the World 2019. Safeguarding against Economic Slowdowns and Downturns. FAO, Rome.
Fragkou, M.C., Vicent, T., Gabarrell, X., 2016. An ecosystemic approach for assessing the urban water self-sufficiency potential: lessons from the Mediterranean. Urban Water J. 13, 663–675. https://doi.org/10.1080/1573062X.2015.1024686.
Gao, H., Zhou, C., Li, F., Han, B., Li, X., 2017. Economic and environmental analysis of five Chinese rural toilet technologies based on the economic input-output life cycle assessment. J. Clean. Prod. 163, 379e391.
Grebitus, C., Printezis, I., Printezis, A., 2017. Relationship between consumer behavior and success of urban agriculture. Ecol. Econ. 136, 189–200. https://doi.org/10.1016/j.ecolecon.2017.02.010.
Goverment of Catalonia, 2016. Salaries paid by the agricultural entrepreneur. Catalonia 2010-2019. Ministry of Agriculture, Livestock, Fisheries and Food. http://agricultura.gencat.cat/web/.content/de_departament/de02_estadistiques_observatoris/20_observatori_agroalimentari_de_preus/03_preus/07_preus_i_salaris_pagats/fitxers_estatics/Salaris_pagats2010_2019_10.pdf/. (Accessed 20 May 2020).
Grebitus, C., Chenarides, L., Muenich, R., Mahalov, A., 2020. Consumers' perception of urban farming—an Exploratory study. Front. Sustain. Food Syst. 4, 1–13. https://doi.org/10.3389/fsufs.2020.00079.
GROOF, 2022. GROOF - Greenhouses to Reduce CO2 on Roofs. https://www.nweurope.eu/projects/project-search/groof/. (Accessed 22 February 2022).
Gutierrez, P.H., Dalsted, N.L., 2012. Break-Even Method of Investment Analysis. Colorado State University.
Harada, Y., Whitlow, T.H., 2020. Urban rooftop agriculture: challenges to science and practice. Front. Sustain. Food Syst. 4, 1–8. https://doi.org/10.3389/fsufs.2020.00076.
Harvesting, Rain, 2021. Reasons for Using Rainwater: Some of the Benefits of Rain Harvesting. https://rainharvesting.com.au/field-notes/articles/rain-harvesting/reasons-for-using-rainwater-the-benefits-of-rain-harvesting/. (Accessed 10 May 2021).
Hochmuth, G.J., Hochmuth, R.C., 2018. Production of greenhouse tomatoes. Florida greenh. Veg. Prod. Handb. 3, 1–18.
Hunkeler, D., Lichtenvort, K., Rebitzer, G., Ciroth, A., 2008. Environmental Life Cycle Costing. Taylor & Francis. CRC Press, Boca Raton, FL, USA.
Ibarrola Rivas, M.J., Nonhebel, S., 2016. Assessing changes in availability of land and water for food (1960–2050): an analysis linking food demand and available resources. Outlook Agric. 45, 124–131. https://doi.org/10.1177/0030727016650767.
Ibarrola-Rivas, M.-J., Castro, A.J., Kastner, T., Nonhebel, S., Turkelboom, F., 2020. Tele coupling through tomato trade: what consumers do not know about the tomato on their plate. Glob. Sustain. 3 https://doi.org/10.1017/sus.2020.4.
ICAC, 2007. Spanish General Accounting Plan (SGAP). Instituto de Contabilidad y Auditoría de Cuentas. https://www.icac.gob.es/publicaciones/spanish-general-accounting-plan. (Accessed 31 July 2021).
Ishida, C., Grantham, R., Stober, T., Willobee, M., Quigley, M., Reidy, P., 2011. A regional cost-benefit analysis of rainwater harvesting: sustainable economics to justify green technologies. Proc. Water Environ. Fed. 2011 (5), 454–461.
ISO, 2008. ISO 15686-5—buildings and Constructed Assets—Service-Life Planning—Part 5: Life-Cycle Costing. Nederlands Normalisatie- Institut, Delft.
Keskin, G., Tatlidil, F.F., Dellal, I., 2010. An analysis of tomato production cost and labor force productivity in Turkey. Bulg. J. Agric. Sci. 16, 692–699.
Kortright, R., Wakefield, S., 2010. Edible backyards: a qualitative study of household food growing and its contributions to food security. Agric. Hum. Val. 28, 39–53.
Lu, H.R., El Hanandeh, A., Gilbert, B.P., 2017. A comparative life cycle study of alternative materials for Australian multi-storey apartment building frame constructions: environmental and economic perspective. J. Clean. Prod. 166, 458–473. https://doi.org/10.1016/j.jclepro.2017.08.065.
Lui, S., 2015. Business Characteristics and Business Model Classification in Urban Agriculture Business Characteristics and Business Model Classification in Urban Agriculture. MSc diss., Wageningen University.
Lwasa, S., Mugagga, F., Wahab, B., Simon, D., Connors, J., Griffith, C., 2014. Urban and peri-urban agriculture and forestry: transcending poverty alleviation to climate change mitigation and adaptation. Urban Clim. 7, 92–106. https://doi.org/10.1016/j.uclim.2013.10.007.
McGarry-Wolf, M., Spittler, A., Ahern, J., 2005. Apro file offarmers' market consumers and the perceived advantages of produce sold at farmers' markets. J. Food Distrib. Res. 36 (1), 192–20.
MercaBarna, 2019. Mercabarna Stats: Vegetables—Commercialized Tonnes and and Average Prices Euros/Kg 2018-2019. https://www.mercabarna.es/media/upload/pdf/llibre-estadistic-fruita-mercabarna-2019_1585582434.pdf/. (Accessed 15 April 2020).
Milford, A.B., Kårstad, S., Verheul, M., 2019. Exploring the Opportunities for Building a Rooftop Greenhouse.
Mougeot, L.J., 2000. Urban agriculture: definition, presence, potentials and risks, and policy challenges. Cities feeding people series rept 31. https://idl-bnc-idrcdspace directorg/bitstream/handle/10625/26429/117785pdf?sequence=12/. (Accessed 10 April 2020).
Muñoz-Liesa, J., Royapoor, M., López-Capel, E., Cuerva, E., Rufí-Salís, M., Gassó-Domingo, S., Josa, A., 2020. Quantifying energy symbiosis of building-integrated agriculture in a mediterranean rooftop greenhouse. Renew. Energy 156, 696–709. https://doi.org/10.1016/j.renene.2020.04.098.
Nadal, A., Llorach-Massana, P., Cuerva, E., López-Capel, E., Montero, J.I., Josa, A., Rieradevall, J., Royapoor, M., 2017. Building-integrated rooftop greenhouses: an energy and environmental assessment in the mediterranean context. Appl. Energy 187, 338–351. https://doi.org/10.1016/j.apenergy.2016.11.051.
Norris, G.A., 2001. Integrating life cycle cost analysis and LCA. Int. J. Life Cycle Assess. 6, 118–120. https://doi.org/10.1007/BF02977849.
OCU, 2018. Report: Tomatoes, varieties and benefits. Organización de Consumidores y Usuarios. https://www.ocu.org/alimentacion/alimentos/informe/tomates-tipos-y-guia-de-compra /. accessed 10 June 2020.
Orsini, F., Kahane, R., Nono-Womdim, R., Gianquinto, G., 2013. Urban agriculture in the developing world: a review. Agron. Sustain. Dev. 33 (4), 695–720. https://doi.org/10.1007/s13593-013-0143-z.
Pearson, L.J., Pearson, L., Pearson, C.J., 2010. Sustainable urban agriculture: stocktake and opportunities. Int. J. Agric. Sustain. 8, 7–19. https://doi.org/10.3763/ijas.2009.0468.
Peña, A., Rovira-Val, M.R., 2020. A longitudinal literature review of life cycle costing applied to urban agriculture. Int. J. Life Cycle Assess. https://doi.org/10.1007/s11367-020-01768-y.
Pou, M., Sanyé-Mengual, E., Rieradevall, J., 2015. Rooftop greenhouses (i-RTGs) as local production systems in Barcelona: LCA and LCC of lettuce production. Dissertation, UAB.
Proksch, G., 2017. Creating Urban Agricultural Systems: an Integrated Approach to Design. Routletge, Taylor&Francis Group, New York.
Roebuck, R., Oltean-Dumbrava, C., Tait, S., 2011. Whole life cost performance of domestic rainwater harvesting systems in the United Kingdom. Water Environ. J. 25 (3), 355–365. https://doi.org/10.1111/j.1747-6593.2010.00230.x.
Roebuck, R.M., Oltean-Dumbrava, C., Tait, S., 2012. Can simplified design methods for domestic rainwater harvesting systems produce realistic water-saving and financial predictions? Water Environ. J. 26 (3), 352–360. https://doi.org/10.1111/j.1747-6593.2011.00295.x.
Rufí-Salís, M., Calvo, M.J., Petit-Boix, A., Villalba, G., Gabarrell, X., 2020a. Exploring nutrient recovery from hydroponics in urban agriculture: an environmental assessment. Resour. Conserv. Recycl. 155, 104683 https://doi.org/10.1016/j.resconrec.2020.104683.
Rufí-Salís, M., Petit-Boix, A., Villalba, G., Sanjuan-Delmás, D., Parada, F., Ercilla-Montserrat, M., Arcas-Pilz, V., Muñoz-Liesa, J., Rieradevall, J., Gabarrell, X., 2020b. Recirculating water and nutrients in urban agriculture: an opportunity towards environmental sustainability and water use efficiency? J. Clean. Prod. 261 https://doi.org/10.1016/j.jclepro.2020.121213.
Sanjuan-Delmás, D., Llorach-Massana, P., Nadal, A., Ercilla-Montserrat, M., Muñoz, P., Montero, J.I., Josa, A., Gabarrell, X., Rieradevall, J., 2018a. Environmental assessment of an integrated rooftop greenhouse for food production in cities. J. Clean. Prod. 177, 326–337. https://doi.org/10.1016/j.jclepro.2017.12.147.
Sanjuan-Delmás, D., Llorach-Massana, P., Nadal, A., Sanyé-Mengual, E., Petit-Boix, A., Ercilla-Montserrat, M., Cuerva, E., Rovira, M.R., Josa, A., Muñoz, P., Montero, J.I., Gabarrell, X., Rieradevall, J., Pons, O., 2018b. Improving the Metabolism and Sustainability of Buildings and Cities through Integrated Rooftop Greenhouses (I-RTG) 53–72. https://doi.org/10.1007/978-3-319-67017-1_3.
Sanyé-Mengual, E., Oliver-Solà, J., Montero, J.I., 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. https://doi.org/10.1007/s11367-014-0836-9.
Sanyé-Mengual, E., Anguelovski, I., Oliver-Solà, J., Montero, J.I., Rieradevall, J., 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. Hum. Val. 33 (1), 101–120. https://doi.org/10.1007/s10460-015-9594-y.
Sanye-Mengual, E., Oliver-Sola, J., Ignacio Montero, J., Rieradevall, J., 2017. The role of interdisciplinarity in evaluating the sustainability of urban rooftop agriculture. Futur. Food-J. Food Agric. Soc. 5, 46–58.
Sanyé-Mengual, E., Martinez-Blanco, J., Finkbeiner, M., Cerdà, M., Camargo, M., Ometto, A.R., Velásquez, L.S., Villada, G., Niza, S., Pina, A., Ferreira, G., Oliver-Solà, J., Montero, J.I., Rieradevall, J., 2018. Urban horticulture in retail parks: environmental assessment of the potential implementation of rooftop greenhouses in European and South American cities. J. Clean. Prod. 172, 3081–3091. https://doi.org/10.1016/j.jclepro.2017.11.103.
Specht, K., Siebert, R., Hartmann, I., Freisinger, U.B., Sawicka, M., Werner, A., Thomaier, S., Henckel, D., Walk, H., Dierich, A., 2014. Urban agriculture of the future: an overview of sustainability aspects of food production in and on buildings. Agric. Hum. Val. 31, 33–51. https://doi.org/10.1007/s10460-013-9448-4.
Specht, K., Siebert, R., Thomaier, S., 2016. Perception and acceptance of agricultural production in and on urban buildings (ZFarming): a qualitative study from Berlin, Germany. Agric. Hum. Val. 33 (4), 753–769. https://doi.org/10.1007/s10460-015-9658-z.
Swarr, T.E., Hunkeler, D., Kloepffer, W., Pesonen, H.-L., Ciroth, A., Brent, A.C., Pagan, R., 2011. Environmental life-cycle costing: a code of practice. Int. J. Life Cycle Assess. 16, 389–391. https://doi.org/10.1007/s11367-011-0287-5.
Taki, M., Abdi, R., Akbarpour, M., Mobtaker, H.G., 2013. Energy inputs - yield relationship and sensitivity analysis for tomato greenhouse production in Iran. Agric. Eng. Int. CIGR J. 15, 59–67.

Testa, R., di Trapani, A.M., Sgroi, F., Tudisca, S., 2014. Economic sustainability of Italian greenhouse cherry tomato. Sustain. Times 6, 7967–7981. https://doi.org/10.3390/su6117967.

Thomaier, S., Specht, K., Henckel, D., Dierich, A., Siebert, R., Freisinger, U.B., Sawicka, M., 2015. Farming in and on urban buildings: present practice and specific novelties of zero-acreage farming (ZFarming). Renew. Agric. Food Syst. 30, 43–54. https://doi.org/10.1017/S1742170514000143.

Toboso-Chavero, S., Nadal, A., Petit-Boix, A., Pons, O., Villalba, G., Gabarrell, X., Josa, A., Rieradevall, J., 2019. Towards productive cities - environmental assessment of the food-energy-water nexus of the urban Roof Mosaic. J. Ind. Ecol. 23 (4), 767–780. https://doi.org/10.1111/jiec.12829.

UN, D.E.S.A., 2018. United nations department of economic and social affairs, population division. World Population Prospects: The 2018 Revision, Key Facts. New York. https://population.un.org/wup/Publications/Files/WUP2018-KeyFacts.pdf/. (Accessed 5 April 2020).

UN, D.E.S.A., 2019. Department of Economic and Social Affairs, Population Division. World Population Prospects: the 2019 Revision, Highlights. New York. https://population.un.org/wpp/Publications/Files/WPP2019_Highlights.pdf/. (Accessed 5 April 2020).

UN, D.E.S.A., 2016. Transforming Our World: the 2030 Agenda for Sustainable Development. UN General Assembly.

UNCCD, 2017. United nations convention to combat desertification. The Global Land Outlook, 2017, first ed.

Van Tuijl, E., Hospers, G.J., Van Den Berg, L., 2018. Opportunities and challenges of urban agriculture for sustainable city development. Eur. Spatial Res. Pol. 25, 5–22. https://doi.org/10.18778/1231-1952.25.2.01.

Vargas-Parra, M.V., Rovira-Val, M.R., Gabarrell, X., Villalba, G., 2019. Rainwater harvesting systems reduce detergent use. Int. J. Life Cycle Assess. 24, 809–823. https://doi.org/10.1007/s11367-018-1535-8.

Walther, L.M., Skousen, C.J., 2009. M1. Managerial and Cost Accounting. Ventus Publishing ApS, London, United Kingdom.

Weidner, T., Yang, A., Hamm, M.W., 2019. Consolidating the current knowledge on urban agriculture in productive urban food systems: learnings, gaps and outlook. J. Clean. Prod. 209, 1637–1655. https://doi.org/10.1016/j.jclepro.2018.11.004.

Willis, D.B., Carpio, C.E., Boys, K.A., 2016. Supporting local food system development through food price premium donations: a policy proposal. J. Agric. Appl. Econ. 48 (2) https://doi.org/10.1017/aae.2016.10, 192–22.

Zepeda, L., Leviten-Reid, C., 2004. Consumers' views on local food. J. Food Distrib. Res. 35 (3), 1–6. https://doi.org/10.22004/ag.econ.27554.

Glossary

B: Boron
BEP: Break-even point
C_aCl_2: Calcium chloride
Ca $(NO3)_2$: Calcium nitrate
CO_2: Carbon dioxide
CPS: Curtains and partitions system
Cu: Copper
EoL: End-of-life
EPCS: External pest control specialist
FBWM: Final biomass waste management
Fe: Iron
FU: Functional unit
GHG: Greenhouse gas
ICTA: Institute of Environmental Science and Technology
i-RTG: Integrated rooftop greenhouse
IS: Irrigation system
KH_2PO_4: Monopotassium phosphate
KNO_3: Potassium nitrate
LCA: Life cycle assessment
LCC: Life cycle cost
LCCA: Life cycle cost analysis
Mg $(NO_3)_2$: Magnesium nitrate
Mn: Manganese
Mo: Molybdenum
PBWC: Pruning biomass waste collection
PE: Polyethene plastic
PVC: Polyvinyl chloride
RF: Rooftop farming
RTG: Rooftop greenhouse
RWHS: Rainwater harvest system
S: Sulfur
SDG: Sustainable development goal
SS: System of sensors
TC: Total cost
TFC: Total fixed cost
TVC: Total variable cost
UA: Urban agriculture
UAB: Universitat Autònoma de Barcelona
VAT: Value added tax
VF: Vertical Farming
Zn: Zinc