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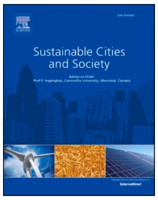

Assessment of the food-water-energy nexus suitability of rooftops. A methodological remote sensing approach in an urban Mediterranean area

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ABSTRACT

This work established a framework to identify and analyze the technical feasibility of roofs for integrating urban agriculture, rainwater harvesting, and photovoltaic systems using various remote sensing. The framework was applied to a region north of Barcelona. Three levels of solar access requirements for tomatoes, leafy crops, strawberries, and microgreens were established. The case study included compact and disperse urban forms, residential and nonresidential building uses and various building typologies. It was identified that 8% of the roof area is feasible for tomato and lettuce production, and production could satisfy the 210% of average intake of tomatoes and the 21% average yearly consumption of lettuce. Rainwater harvesting systems could supply 94.26% of the water requirements for lettuce growing in an open-air system; in contrast, 53% of irrigation could be satisfied for tomato production in rooftop greenhouse systems. The results showed a potential for 80% of roof area to be used for rainwater harvesting systems, representing the average yearly water consumption of 44% of citizens for laundry, showering, toilet flushing, cleaning and irrigation uses. Finally, 50% of the roofs are suitable for photovoltaic panels, representing an average energy consumption of 18% of citizens.

1. Introduction

Cities cover about 1% of the surface area on the planet and house about 55% of the world's population (almost 75% in Europe). With increased urbanization, the proportion of the world's population living in cities is predicted to rise to 70% globally by 2050, and up to 85% in Europe (European Investment Bank, 2018). Urban areas that are functional as centers of production, consumption, and human settlement contain a variety of vital driving forces for social, economic, and environmental stability and sustainability (Chang et al., 2020). Cities consume about 70% of global resources and emit 70% of all greenhouse gases (European Investment Bank, 2018) which generates environmental, social and economic consequences. Food, water, and energy security have become pressing concerns, to supply these essential needs, cities must depend on their hinterlands (McGranahan & Satterthwaite, 2003), rendering cities unsustainable. Food, water, and energy demand are expected to increase by more than 50% in 2050 (International Renewable Energy Agency, 2015). In this context, cities must improve resource management through sustainable urban planning strategies (Bibri & Krogstie, 2017) considering the food-water-energy (FWE) nexus.

1.1. The nexus between FWE and land in cities

Food production requires energy (and water) in many stages of the food system. Energy is necessary in irrigation systems, farm machinery,

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Table 1
Characterization of rooftops using remote sensing and geographic information systems (GIS) to integrate UA, RWH, or PV.

Resource production	Scale of study case	Data collection and GIS technique used	Software	Building use							Roof data acquired with remote sensors						Reference
				C	I	R	E	I	Re	W	A	S	SR	M	BF	BH	
F	N	Building footprint solar map from LiDAR	ArcGIS	•	•						•	•	•		•		Berger (2013)
F	Ci	Land use map Google Earth	ArcMap		•						•						Haberman et al. (2014)
F	Ci	DSM from LiDAR	ArcMap	•	•	•					•					•	Saha & Eckelman (2017)
F	Co	DSM from LiDAR; spectral signatures from LWIR data	QGIS		•						•	•	•	•			Nadal et al. (2017)
W	Co	Aerial imagery LiDAR data	Esri	•	•	•					•						Grant et al. (2017)
W	Ci	Satellite image DEM from LiDAR	QGIS			•				•	•						Lupia et al. (2017)
W	N	Building footprint from satellite imagery	ArcGIS	•		•	•				•			•			Radzali et al. (2018)
E	Ci	DSM from LiDAR	ArcGIS	•	•	•		•	•		•		•				Bayrakci Boz et al. (2015)
E	Ci	DSM from LiDAR	ArcGIS			•	•	•			•		•				Brito et al. (2012)
E	N	Google Earth satellite imagery	ENVI EX	•		•		•			•		•				Khan & Arsalan (2016)
E	Co	Building footprint from LiDAR	Not specify	•		•					•		•				Kodysh et al. (2013)
E	Ci	Aerial imagery	ArcGIS			•					•		•				Wiginton et al. (2010)

Resource production: food (F), water (W), and energy (E). Scale of the studies: city (Ci), county (Co), and neighborhood (N). Building use: commercial (C), industrial (I), residential (R), educational (E), institutional (I), recreational (Re), and warehouse (W). Roof data acquired with remote sensors: area (A), slope (S), solar radiation (SR), material (M), building floors (BF), and building height (BH).

fertilizer production, greenhouse heating and cooling, packing, transportation and distribution (FAO, 2015; Midgley et al., 2019). Energy is required to extract, pump, lift, collect, transport and treat water. The agri-food sector consumes 30% of the world's energy (FAO, 2016). According to projections, by 2050, the demand for energy will double globally (International Renewable Energy Agency, 2015). Energy inputs into the food supply chain are likely to increase in the coming decades, leading to increased energy production necessities (FAO, 2016; International Renewable Energy Agency, 2015).

Nowadays, 24% of total freshwater consumption exceeds the regional capacities (Motoshita et al., 2020), producing consequences such as water resource overexploitation, stress, and scarcity (Campisano & Modica, 2015; Gosling & Arnell, 2016). In addition, climate change has negative repercussions for water cycles (Arnell & Gosling, 2016; Gosling & Arnell, 2016). Water is also needed during the production processes of energy required for water abstraction, distribution, and treatment, as well as food production and distribution processes. In addition, indirect water plays an important role on farm machinery, fertilizer production, packing, transportation processes.

Agriculture consumes 70% of water worldwide (International Renewable Energy Agency, 2015). As the largest consumer of freshwater resources globally, agricultural practices have substantial impacts on water security. Agricultural contamination remains a major source of water pollution. Different agricultural activities, such as fertilization, manure spreading and irrigation, have impacts on surface water and groundwater; for example, approximately 70% of the water pollution in China comes from agriculture in the form of runoff from fertilizers, pesticides and animal waste (International Renewable Energy Agency, 2015).

Land is also an important resource concerning the FWE nexus and is a finite resource needed for food production and some forms of energy (e.g., wind and solar farms) and water (e.g., catchment areas, water supply infrastructure and ecosystem services) (FAO, 2015; Midgley et al., 2019). Agriculture already uses 12% of the world's land surface for crop production (FAO, 2011). Moreover, the use of some of these areas for the agriculture sector would compromise valuable ecosystem services and biodiversity (FAO, 2011).

The production of local resources in cities is a key strategy to ensure the resilience of and accessibility to food, water, and energy. The European Investment Bank (2018) emphasizes that, energy systems should be built around renewable energy sources and local generation (European Investment Bank, 2018). In the case of food systems, urban agriculture (UA) is an approach to increase local food production satisfying food demand in cities (Hume et al., 2021), and may contribute to food insecurity. UA has advantages in different fields, such as social (e.g., social inclusion), environmental (e.g., transport emissions reductions) and economic impacts (Lupia et al., 2017; Mok et al., 2014; Parece et al., 2016; Thomaier et al., 2015). In addition, rainwater harvesting systems (RWHSs) are strategies for managing water resources, providing sustainable water cycles and minimizing water tap demand (Jha et al., 2014; Sojka et al., 2016). Regarding the energy sector, bioenergy, solar photovoltaic (PV) or solar thermal panels can satisfy a relevant part of energy demands (Corcelli et al., 2019; Midgley et al., 2019).

In urban areas, land is an increasingly scarce resource, and the high price and competition for residential buildings, industrial growth or infrastructure construction represent some of the main threats to the local production of food, water, and energy (Benis et al., 2018a; Midgley et al., 2019). In this sense, since rooftops cover half of the impermeable surfaces in cities (Farreny et al., 2011), there are many areas that could be potential spaces for producing food (e.g., through the installation of open-air agriculture or rooftop greenhouses (RTGs)), water collection (e.g., rainwater harvesting systems) and energy (e.g., solar photovoltaic or solar thermal panels).

1.2. Rooftops as productive spaces

Rooftops have the potential to improve urban metabolism by producing resources (for instance, food, water, and energy) (Corcelli et al., 2019). In the case of promoting local food production, the environmental benefits are mainly related to a reduction in transportation requirements and the consequent environmental impacts (Cerón-Palma et al., 2012; Sanyé-Mengual et al., 2013). The transformation of rooftops into productive spaces is becoming a common practice in many cities worldwide (Gundula Proksch, 2016) (see Appendix 1 for cities examples).

Different criteria must be considered to assess the feasibility of integrating FWE systems. Climatic conditions are crucial to determining the potential integration of FWE systems. For food production, sunlight access is the main climate parameter for determining the suitability of rooftop urban agriculture (RUA), based on the requirements of the selected horticultural crop (FAO, 2013). Regarding the integration of RWHS, it is necessary to consider the rainwater potential, which refers to the entire amount of rainfall in the area under consideration (Worm & van Hattum, 2006). Solar energy, as in the case of RUA, requires solar radiation on rooftops, and shadows from the built environment play an important role in identifying potential areas.

Roof characteristics, such as their geometry, area, slope, solar radiation and materials, also need to be considered. In the following section, the literature concerning roof characterization using remote sensing (RS) to assess the potential integration of FWE systems is described.

1.3. Remote sensing data to assess rooftops for FWE production

Remote sensing has been utilized to assess the feasibility of roofs to implement FWE systems. Roof data acquired using light detection and ranging (LiDAR) sensors have been applied to assess the UA, RWHS, or PV potential of roofs. LiDAR systems allow us to obtain geometric data and to compute solar access to roofs. Table 1 illustrates a summary of works assessing UA, RWH, and PV potential on roofs using remote sensing data.

Previous works using remote sensing for data acquisition focused on a single vector food, water or energy (Table 1). Toboso-Chavero et al. (2018) assessed the potential integration of the FWE nexus on residential buildings. Architectural and urban requirements were based on the method adapted by Nadal et al. (2017). However, roof data acquisition was conducted by means of architectural layouts, implying difficulties for the application at larger scales, such as counties or cities. The method proposed by Nadal et al. (2017) uses GIS and RS to obtain and manage information to identify suitable roof areas on industrial roofs for commercial purposes. In this sense, there is a need to assess the viability and potential roofs for the assessment FWE production from an integrated framework, based on the acquisition of urban and architectural data using remote sensing technology. Most of the studies considered residential, industrial, and commercial buildings to integrate UA, RWHS or PV systems. Especially for RUA integration, industrial followed by commercial buildings have a greater presence in previous studies. To a lesser extent, studies have been carried out for self-consumption purposes considering smaller roof areas and educational and housing roofs (Nadal et al., 2018, 2019; Saha & Eckelman, 2017). Non-profit UA spaces can provide educational and self of belonging functions. However, no methodological framework has been found that meets both commercial and self-consumption purposes. Roof material criteria is rarely considered to assess the potential of UA, RWHS or PV systems (Table 1). The knowledge of roof materials is valuable as an indicator of the construction systems and their load-bearing capacity to support the weight of FWE systems (Nadal et al., 2017; Sanyé-Mengual, Cerón-Palma, Oliver-Solà, Montero, & Rieradevall, 2015). Besides, the quality and quantity of rainwater harvested from roofs are significantly affected by roofing materials (Farreny et al., 2011). However, the process of acquiring rooftop data is complex, laborious, and time-consuming since a detailed database to analyze is needed (Nadal et al., 2017). In addition, data collection through site visits or visual interpretation may limit the scale to be analyzed. Hyperspectral imaging data acquired using Long Wave Infrared (LWIR) remote sensor has resulted fast, automated and digital tool for identifying roofs characteristics (Nadal et al., 2017). However, it has been suggested that the use of two or more sensors operated simultaneously with different spectral ranges, can improve discrimination of materials in urban contexts (Roberts et al., 2012) see Appendix 2 for more information about this section.

1.4. Sunlight access for rooftop urban agriculture

Another important aspect refers to sunlight access which has received little consideration in the literature, referring to the assessment of UA on rooftops. This criterion is critical for growing food. Solar radiation is a fundamental energy source for photosynthesis which ultimately affects crop yields. However, current methods to identify potential roofs for UA areas normally define a target daily light integral (DLI) value between 20 – 25 mol/m^2/day (originally expressed in MJ/day, Nadal et al., 2017; Sanyé-Mengual, Cerón-Palma, Oliver-Solà, Montero, & Rieradevall, 2015). Another study assumed that roof area suitable for PV is also suitable for UA (Berger, 2013).

DLI target usually satisfies light requirements for single species, usually tomato crops (Benis et al., 2017b; Nadal et al., 2017; Sanyé-Mengual, Cerón-Palma, Oliver-Solà, Montero, & Rieradevall, 2015). Compared to the optimal DLI crop requirements (see Appendix Table A3), this is a high threshold that results in over-energy lighting needs in the majority of crops (Benis et al., 2017b), leading to high environmental costs derived from LED systems. Thus, high DLI targets also underestimate the urban potential area that could grow low and medium-DLI crop types.

In this context, the novelties of this approach are the integration of additional urban and architectural requirements to existent methods, the consideration of FWE systems, the use of two hyperspectral remote sensors with a high spatial resolution (as a basis for data acquisition), and the classification of optimal daylight needs for crops in both RTGs and open-air systems.

1.5. Objectives

The main objective of this study is to assess the feasibility of roof areas to integrate food production, rainwater collection, and solar energy systems in cities using remote sensing technologies. In this regard, the specific objectives are 1) to establish a framework for evaluating the potential integration and self-sufficiency of FWE systems for commercial and nonprofit purposes; and 2) to apply the procedure in a Mediterranean area.

2. Materials and methods

2.1. Case study

The case study is located in a Mediterranean region in the El Vallès Occidental, north of the Spanish city of Barcelona. The Vallés Occidental is composed of 23 municipalities, and some of them are part of the Metropolitan Area of Barcelona. This area was chosen due to its sunny weather predominance, which offers a strong potential to integrate both RTGs, open-air rooftop agriculture and solar energy systems. This climatic area can also offer winter crop production without requiring any active system to heat greenhouses. There are recent initiatives from the city council to promote productive roofs and institutional and citizen awareness of UA. Additionally, the case study area includes a pilot RTG at the Institute of Environmental Science and Technology (ICTA) and the Catalan Institute of Paleontology (ICP) building, where different types of crops have been produced since 2015 by the Fertilecity project team (Fertilecity, 2018). Regarding rainwater, several municipalities started to approve water-saving regulations (Domènech & Saurí, 2011), including RWHS, since the amount of precipitation makes the integration of these systems in this area suitable.

2.2. Criteria to integrate FWE systems for commercial and nonprofit purposes

The work developed by Nadal et al. (2017) and Toboso-Chavero et al. (2018) was used as a basis for developing the methods of this work and adding other aspects specially climatic, urban, and architectural.

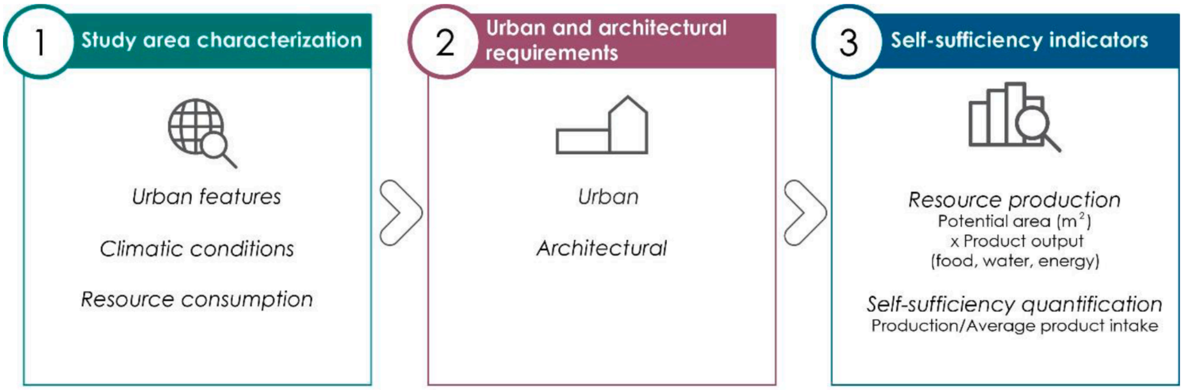

Figure 1. Phases to evaluate the feasibility of roof areas to integrate food production, rainwater collection, and solar energy systems in cities based on Toboso-Chavero et al. (2018) and Nadal et al. (2017).

The previous authors considered in their methods the short-term potential implementation of the systems on industrial and residential rooftops. For this reason, a literature review was performed to detect and establish the needed criteria to broaden the focus of the framework for this work Figure 1 summarizes the phases of the method used for this work: phase 1 study area characterization was based on the work developed by Toboso-Chavero et al. (2018) and enhanced with a literature review. Phase 2 urban and architectural requirements, and phase 3 self-sufficiency indicators were based on Nadal et al. (2017) and extended with a literature review and own developed work for determine crops day light requirements (see Appendix 3 and 44).

3. Development of the Framework

Figure 2 illustrates the framework developed to identify feasible roof areas to integrate food, water, and energy systems in cities. It is divided into three phases: study area characterization (Phase 1), urban and architectural requirements (Phase 2), and self-sufficiency indicators (Phase 3). Figure 2 also shows the methods for data acquisition for each criterion, mainly based on RS. Each of the phases is described below.

Phase 1 Study area characterization. In this phase, the characteristics of the study area are obtained. Phase 1 is divided into the following three steps:

a) Urban features. GIS is used to define the boundaries and to conduct a spatial analysis. Data about population density, at the county, city, or neighborhood level, depending on the scale of the study area. Urban form, building use, and building typology are needed to conduct a spatial analysis. Population density was acquired at municipality level from a public dataset. Roof area, land use, use and typology of buildings is acquired using GIS. Urban form is acquired using a literature review, and GIS information. To identify land use and building typologies, two vector layers were used: (1) The Urban Planning Map of Catalonia (UPMC), downloaded free from the Department of Territory and Sustainability (2019), and (2) roof polygons obtained from a previous work developed by the authors. Data from these two layers were integrated using the tool *join attributes by localization* from QGIS software.
b) Climatic conditions. Since climatic conditions play an important role regarding the potential of FWE systems, a minimum solar radiation of 800 MJ/m^2/year is needed for food production (microgreens) in open-air systems and a minimum of 300 mm/year of rainfall. To obtain this information, datasets from public websites are used. The rainfall dataset was obtained from a weather station (Rural Cat, 2019) over a period of 21 years (from 1996 to 2017). The average annual solar radiation was obtained from an atlas of solar radiation in Spain (Sancho et al., 2012).
c) Resource consumption. Food, water, and energy consumption are needed to determine the resource quantity required, these data are also used in *Phase 3*. Both datasets and a literature review are used to obtain resource consumption information.

Food, water, and energy demand was acquired from regional and local public reports (Ajuntament de Barcelona Medi Ambient i Serveis Urbans, 2016; Departament d'Agricultura Ramaderia Pesca i Alimentació, 2017; Medi Ambient i Serveis Urbans-Ecologia Urbana Agència d'Energia de Barcelona, 2019)

Phase 2 Urban and architectural requirements. This phase is divided into two steps and various criteria by each step. For the architectural step, Figure 2 shows the minimum requirements needed to integrate FWE systems.

a) Urban requirements. Building laws and land uses must be considered to ensure that the new infrastructures meet legal requirements. Limitations and regulations regarding urban aesthetics for the implementation of the infrastructure must be reviewed. These data are obtained using a literature review of urban and architectural codes of the city. It is important to know the building use to establish the purpose of the infrastructure. Two purposes are proposed: commercial and nonprofit (for self-consumption and including educational and social objectives). Retail and industrial buildings are more suitable options for commercial purposes, while residential buildings, schools, and public services buildings are desirable for nonprofit goals. To address legal requirements, Barcelona Metropolitan General Plan regulations and building codes (Metropolitan area of Barcelona, 2018) were consulted. Building uses were identified from the layers explained previously in section a) of *Phase 1: Study area characterization*.
b) Architectural requirements. This step considers four criteria: area, slope, solar access, and roof material. The first three (geometric characteristics) were acquired using a LiDAR sensor, and the last one was acquired using hyperspectral remote sensing. Each of the criteria is described below.

Roof area. A minimum roof area is needed for food and energy purposes. For commercial energy infrastructures, a minimum of 100 m^2 is needed, and in the case of food production, a minimum of 500 m^2 is required. With respect to nonprofit goals, energy systems require a minimum of 24 m^2, and food systems require a minimum of 13 m^2.

Roof slope. This criterion is divided into two: if the roof is flat with a maximum slope of 10%, food production systems can be integrated; if the roof slope is greater than 10%, energy and rainwater harvesting systems can be implemented.

Solar access. This criterion is divided into four groups, one for energy systems, in which a minimum of 1,900 MJ/m^2/year is needed, and three

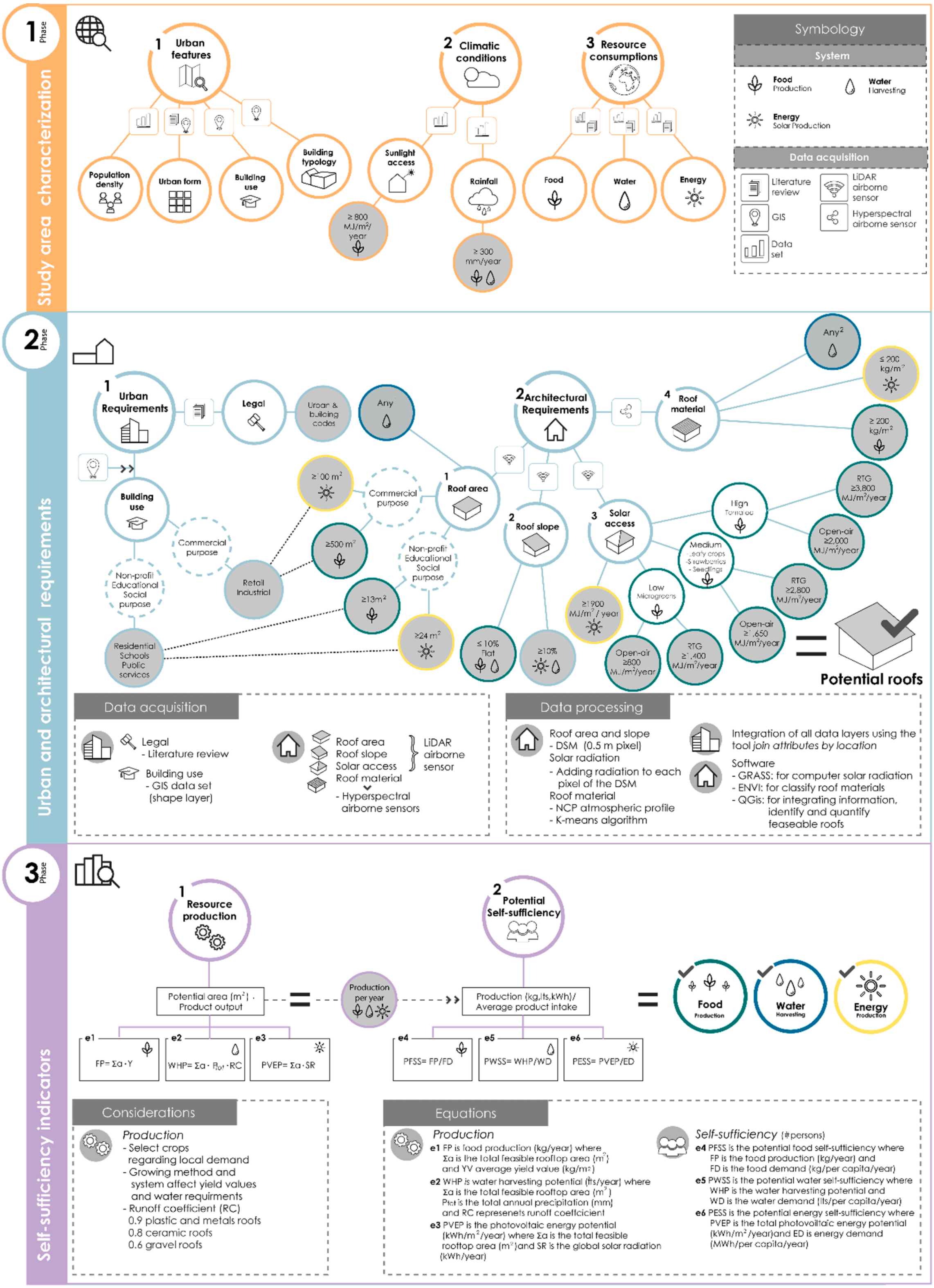

Figure 2. Workflow proposed to identify feasible roof areas to integrate urban agriculture, rainwater harvesting, and photovoltaic energy systems. The sunlight access criterion of the phase 1 study area characterization refers to the minimum energy radiation for producing microgreens.

for food production, according to the crop and food production system. The three levels are high, medium, and low for tomatoes; leafy vegetables, strawberries, and seedlings; and microgreen crops, respectively. Each level of solar access is divided into two corresponding food production systems: RTGs or open-air. Therefore, the minimum requirements of solar access for food systems are as follows: tomatoes growing in RTGs at 3,800 MJ/m^2/year and those growing in open-air at 2,000 MJ/m^2/year; leafy vegetables, strawberries, and seedlings cultivated using RTGs at 2,800 MJ/m^2/year and those using open-air at 1,650 MJ/m^2/year; and microgreens produced in RTGs at 1,400 MJ/

m^2/year and those produced in open-air at 800 MJ/m^2/year (see Appendix 4). In this work, priority was given to roofs with high radiation levels for the integration of greenhouses. These infrastructures have the advantage of greater climate control in addition to a higher production of the crop. When the integration of urban agriculture was possible, solar energy was not considered because current panels diminish light for crops. It was demonstrated that transparent photovoltaic (TPV) panels are not yet developed for commercialization (Lee et al., 2020).

Roof material. The load-bearing capacity to support the weight of the system is essential, and a minimum load-bearing capacity of 200 kg/m^2 is required for crops. A lower capacity can be suitable for energy systems. The load capacity of the roof does not condition rainwater collection in this sense, and any material has potential for water systems with special attention paid to health risks according to roof materials and the future use of water resources. It is necessary to consider the part of the building in which the storage tank will be located. If the tank is placed on the roof, load-bearing must be considered. This framework does not consider water location, size, and weight tank.

- Geometric and solar radiation characterization. LiDAR remote sensing technology was used to characterize the geometric properties of roofs. Then, solar irradiation on surfaces was computed with GRASS software, version 7.4. This process considered all of the shadow effects in the surrounding area. The airborne sensor Leica ALS50-II (LiDAR) was used on a flight conducted in 2013. Based on high density of points (4 points/m^2), a digital surface model (DSM) with a spatial resolution of 0.5 m pixels was obtained. This model contained all of the geometric characteristics of the terrain and buildings, such as area and slope. The model also included objects on rooftops (e.g., air conditioning installations) and objects that can produce shadows over roofs. The point cloud was classified as ground, vegetation, buildings, and other objects that were not rooftops. Then, points that were considered noisy, such as powerline wires, points with low intensities, and points in the air, were excluded (Kodysh et al., 2013; Suomalainen et al., 2017). The average annual solar irradiation was computed considering climatic conditions with the r.sun library in GRASS software, version 7.4, by adding direct and global radiation received at each pixel of the DSM every hour for one day of each week over the whole year. In this calculation, all the shadows generated by buildings, vegetation, topographies, etc., were considered.
- Roof material characterization. Previous work developed by the authors on rooftop classification was used, the work included hyperspectral data acquired during a day flight in 2018 with two imager spectrometers: an Airborne Imaging System for Different Applications (AISA) Eagle II and a Thermal Airborne Spectrographic Imager 600 (TASI-600). Data obtained by remote sensors were processed using a cluster algorithm (K-means) to classify roof material data. In the present work, two classes of roofs were totally excluded to integrate FWE systems. Fiber cement roofs were excluded because of their low load-bearing capacity to support RTGs, open-air UA, and PV panels, as well as health risks for collecting rainwater; additionally, green roofs were excluded considering that these roofs already have a use that contributes to more sustainable cities. It should be noted that the location and weight of the water tank for RWHS were not considered in this work.

Data layers with geometric characteristics (area and slope) and nongeometric characteristics (solar radiation, roof materials, use and typology of buildings) were integrated into a single GIS layer with QGIS software using the *joint attributes by location* tool. Once all of the data were integrated into a single layer, potential roofs were identified using *select by expression*. With this tool, roof requirements for each system (food, water, and energy) were filtered and then extracted into a new layer of roof polygons that fully fit the established criteria. In this work, potential areas for food production were prioritized with respect to energy production.

Phase 3 Self-sufficiency indicators. This phase is divided into two steps: resource production and self-sufficiency potential. Food production consists of a variety of systems and methods for growing crops that affect growing values and water requirements for irrigation; in the case of RWH, the quantity of rainwater harvested from roofs is affected by roofing materials; and for photovoltaic systems, solar radiation influences the amount of energy produced. Thus, the first step uses different equations, in which the total roof area that fulfills the criteria for *Phase 2* identified as potential and other parameters are used to obtain the production per year of food, water or energy. In the second step, self-sufficiency potential uses results derived from the first step and consumption of resource data to obtain how many people can be supported by the food, water, or energy supplied.

a) Resource production. Tomatoes and lettuce were considered suitable crops due to the amount of household consumption data in the region of the case study. Tomatoes were chosen because they are the second most consumed vegetable in Barcelona, after potatoes (Departament d'Agricultura Ramaderia, Pesca i Alimentació, 2017), which cannot be produced in hydroponic RTG systems. Lettuce represents the most consumed leafy vegetable (Departament d'Agricultura Ramaderia, Pesca i Alimentació, 2017). Soil-less systems for both open-air and RTG conditions were considered. Food-crop yield was obtained for RTGs and open-air studies from Barcelona. Average yield values are listed in the Appendices Table A1. To calculate the rainwater harvesting potential, runoff coefficients of 0.80 (ceramic), 0.90 (metals), and 0.60 (gravel) were considered (Farreny et al., 2011) according to roof materials in the study case. Multicrystalline silicon (multi-Si) technology was chosen for PV because it is the most common in the market (Paiano, 2015) for estimating energy production, and a PV panel efficiency (new) of 26% was considered (Lee et al., 2020).

To determine the potential production of food, water, and energy, the total feasible rooftop area (m^2) obtained from the application of the framework using remote sensing technology (Phase 2) was used in the following equations:

- To quantify food production, Equation 1 was used, where ***FP*** is the yearly food production (kg), $\sum \boldsymbol{a}$ is the total feasible rooftop area (m^2), and ***YV*** is the average yield value (kg/m^2).

$$FP = \sum a \times \mathrm{YV} \tag{1}$$

- To determine the water harvesting potential, Equation 2 was used, where *WHP* is the yearly amount of rainwater harvested from rooftops (L), $\sum \boldsymbol{a}$ is the total feasible rooftop area (m^2), P_{tot} is the total annual precipitation (mm), and *RC* is the runoff coefficient (harvesting efficiency of the system, depending on roof material; see above).

$$WHP = \sum a \times P_{tot} \times RC \tag{2}$$

- To determine solar energy production, Equation 3 was used, where *PVEP* is the yearly amount of photovoltaic energy production (kWh/m2/year), $\sum \boldsymbol{a}$ is the total feasible rooftop area (m^2), and *SR* is the global solar radiation potential (kWh/year).

$$PVEP = \sum a \times SR \tag{3}$$

b) Self-sufficiency. Fresh tomato and lettuce consumption of 14.9 and 4.4 kg/per capita/year, respectively, was considered (Departament d'Agricultura Ramaderia Pesca i Alimentació, 2017). Water consumption of tomatoes and lettuce production in Barcelona in open-air and RTG systems and the soil-less method were considered for calculations

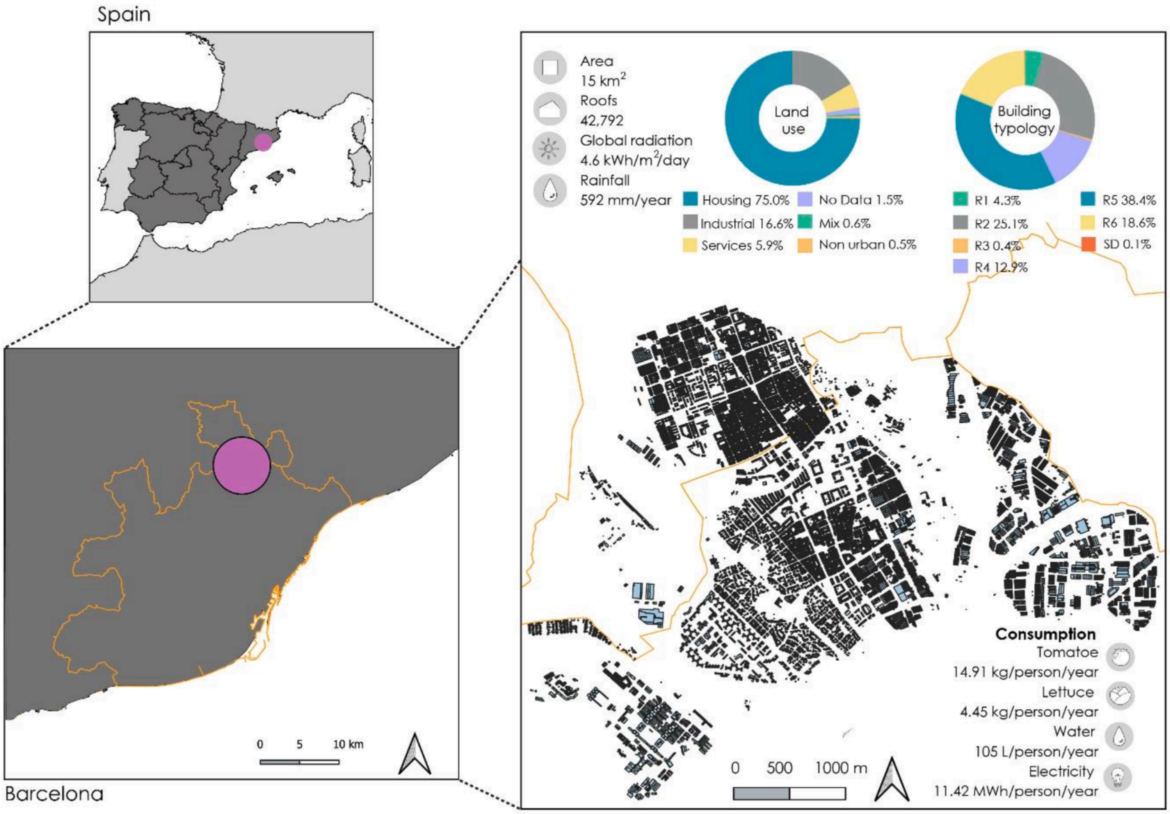

Figure 3. Location and study area characterization. Building typologies of housing in the study area included low rise buildings in nuclei and center populations (R1), compact and open building blocks (R2), blocks with interior patios (R3), isolated blocks or towers (R4), detached houses (R5), terraced houses (R6), and building blocks for public equipment housing (SD).

of water self-sufficiency for irrigation crops (see Appendices Table A2). In addition, the water demand for domestic use was acquired from the *El consum d'aigua a Barcelona L'aprofitament i els usos dels recursos hídrics* (water consumption in Barcelona The use of water resources) report, considering an average of 105 L/household/day, including laundry, showering, toilet flushing, cleaning and irrigation (Ajuntament de Barcelona Medi Ambient i Serveis Urbans, 2016). The average yearly energy consumption over a period of 19 years was estimated from data obtained from the *Balanç d'energia amb efecte d'hivernacle i emissions de gasos de Barcelona 2017* (Energy Balance and Greenhouse Gas Emissions of Barcelona 2017) report (Medi Ambient i Serveis Urbans-Ecologia Urbana Agència d'Energia de Barcelona, 2019).

To determine the potential of self-sufficiency (# persons), the following equations were used.

- To quantify potential food self-sufficiency, Equation (4) was used, where *PFSS* is the self-sufficiency of total food production, FP is the food production (obtained from Equation 1), and FD is the average food demand (kg/per capita/year).

$$PFSS = \mathrm{FP}/\mathrm{FD} \tag{4}$$

- To quantify potential water harvesting self-sufficiency, Equation (5) was used, where *PWSS* is the self-sufficiency of the total water collection of roofs, WHP is the water harvesting potential (obtained from Equation 2), and WD is the average water demand (L/per capita/year).

$$PWSS = \mathrm{WHP}/\mathrm{WD} \tag{5}$$

- To quantify potential solar energy self-sufficiency, Equation (6) was used, where *PESS* is the self-sufficiency of total PV energy production, PVEP is the total photovoltaic energy production (obtained from Equation 3), and ED is the average energy demand (MWh/per capita/year).

$$PESS = \mathrm{PVEP}/\mathrm{ED} \tag{6}$$

4. Results

4.1. Study area characterization

Figure 3 illustrates the study area location in the Valles Occidental region north of Barcelona, Spain, and its main characteristics. The study area has approximately 67,000 inhabitants and compromises 15 km^2 with compact and diffuse urban forms and a total of 3 km^2 of roofs ranging from 0.25 m^2 to 13,480.5 m^2. Roofs were in different land uses: housing (75.0%), industrial (16.6%), services (5.9%), mix (0.6%), and non-urban (0.5%). Some roofs were not identified with respect to the land use location (1.5%). Different building typologies of housing were found: 4.3% corresponded to low rise buildings in the founding nuclei and centers populations (R1); 25.1% to compact and open building blocks, corresponding to historical growth of a structure before 1950 (R2); 0.4% to multifamily blocks with interior patios, corresponding to modern extension (R3); 12.9% to blocks or towers configured from an isolated multifamily building (R4); 38.4% to detached houses for single families (R5); 18.6% to terraced houses for single families (R6); and 0.1% to building blocks for public equipment housing (SD). The average global radiation was 4.6 kWh/m^2/day, and the average annual rainfall over the study area was 592 mm.

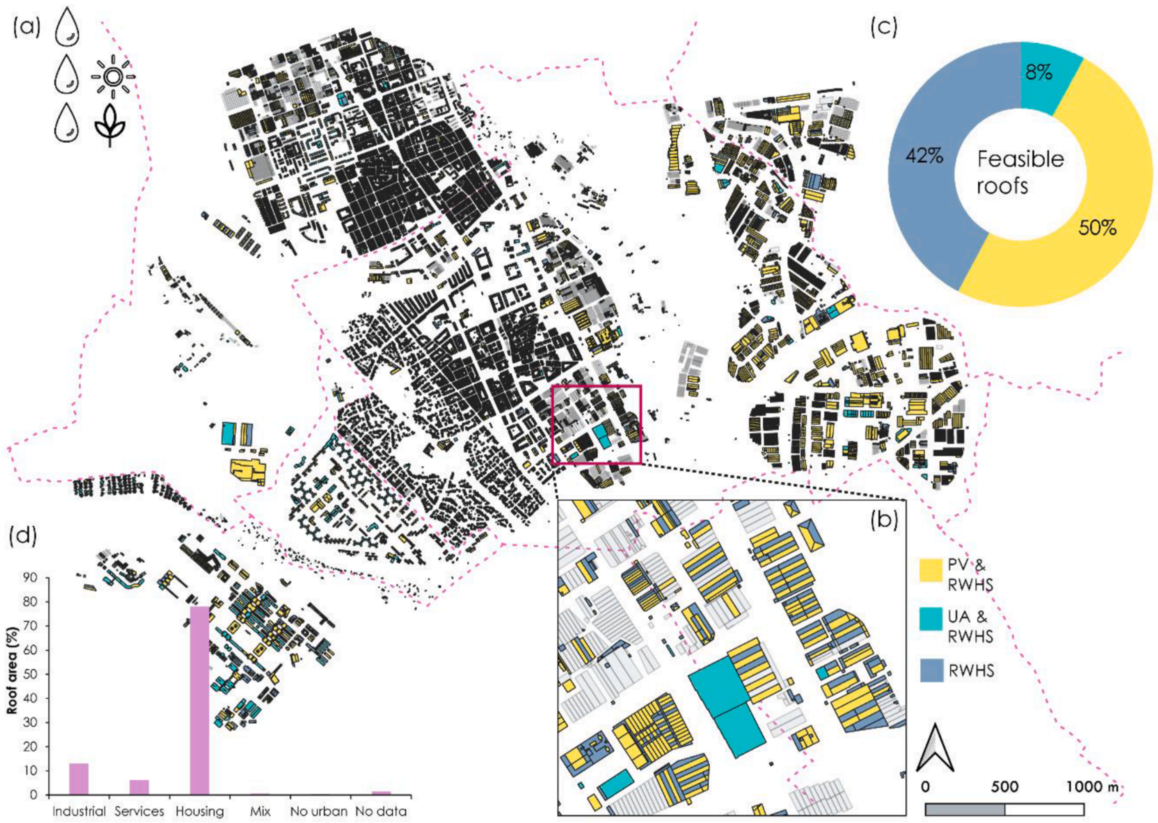

Figure 4. (a) Potential roofs over the study area. (b) Details of identified potential roofs on industrial and services buildings. (c) Proportion of potential roofs for PV and RWHS, UA & RWHS and RWHS.

Food production is allowed for self-consumption. Land use types do not include agriculture use. For this reason, UA for commercial purposes is not permitted. On some rooftops, RTGs were not permitted due to the maximum height and volume restrictions. In this sense, a case-by-case review by local technicians is required. To integrate RWHS and PV systems on rooftops, no restrictions were found. According to the Spanish Technical Building Code, it is mandatory to include minimums for electricity and sanitary hot water self-sufficiency in new buildings and developed building extensions (except for residential buildings) when the constructed area exceeds or is increased by more than 3,000 m^2.

4.2. Analysis and quantification of potential roofs for integrating FWE systems

After applying the proposed framework, potential roofs were obtained. In this section, the results are presented in layers according to the systems studied. A total of 38,575 roofs (2.6 km^2) representing 87% of the total roof area were identified for integrating UA, RWHS, and PV (Figure 4a). These results were identified by different colors according to the systems, as shown in detail in Figure 4b. Result showed that 8% (0.2 km^2) of total roofs identified as potential could integrate both UA systems (commercial and self-consume) and RWHS. The 50% (1.3 km^2) of potential areas could integrate PV and RWHS systems. The 42% (1.1 km^2) of feasible roofs were potential for integrating RWHS (Figure 4c). It can be observed that 78% of potential rooftops were residential housing, 13% industrial, 6% services buildings, mix (0.5%) and nonurban (0.3%) were recognized in similar proportion, and 1.4% of roofs did not have data about building use (Figure 4d). A total of 92 green roofs were detected, of which 7 roofs were identified as potential for tomatoes crop using open-air system and 9 for solar energy. These potential areas represent 0.013% for RUA and 0.016% for PV of the total roof area. As indicated in section 3 Development of the Framework, rooftops classified as *green roofs* were discarded from the analysis of potential, production and self-sufficiency.

A total of 823 roofs and 0.2 km^2 were identified for integrating UA and RWHS (Figure 5a). The results of potential areas were identified by different colors according to the growing system and crop type, as shown in detail in Figure 5b. The distribution of potential roofs for UA was as follows: RTGs for tomato production 100,610.5 m^2 (49.0%); RTGs for lettuce crops 7,410.2 m^2 (3.6%); open-air for growing tomatoes 97,043.25 m^2 (47.3%); and open-air for lettuce production 89 m^2 (0.04%) (see Figure 5c).

Figure 6a shows potential roofs for UA and their location distribution by land use. It can be observed that most rooftops were located in service land use areas. Regarding each growing system distribution of feasible rooftops according to land use, they were as follows: RTGs for harvesting tomatoes: 56.6% services, 41.5% industrial, 0.7% housing, and 1.2% mix; RTGs for growing lettuce: services 91.1% and 8.9% housing; open-air system for tomatoes: 59.4% housing, 23.4% services, 14.3% industrial, 0.4% mix, and 2.5% without data; and finally, open-air lettuce: services 68.9%, and 31.1% without data. Figure 6b also shows the potential roof distribution by building typology of housing use (60%). Most roofs belonged to typology R4 with 61.1%, followed by R6 with 30.1%, R2 with 6.1%, R5 with 2%, and R3 with the fewest potential roofs with 0.5%; no roofs were identified as typology R1.

Figure 7 shows the results of tomato and lettuce production and self-sufficiency. The total roof area for tomato crops could produce 2,097 tons per year, 73.4% by RTGs and 26.6% by open-air systems. Production could satisfy the average intake for 140,620 persons, representing 210% of the population over the study area (Figure 7a). Regarding lettuce crops, the results showed that a total of 62.3 tons per year could be produced, 99.5% by integrating RTGs and 0.5% by open-air systems. This production could satisfy the consumption of 14,000 inhabitants,

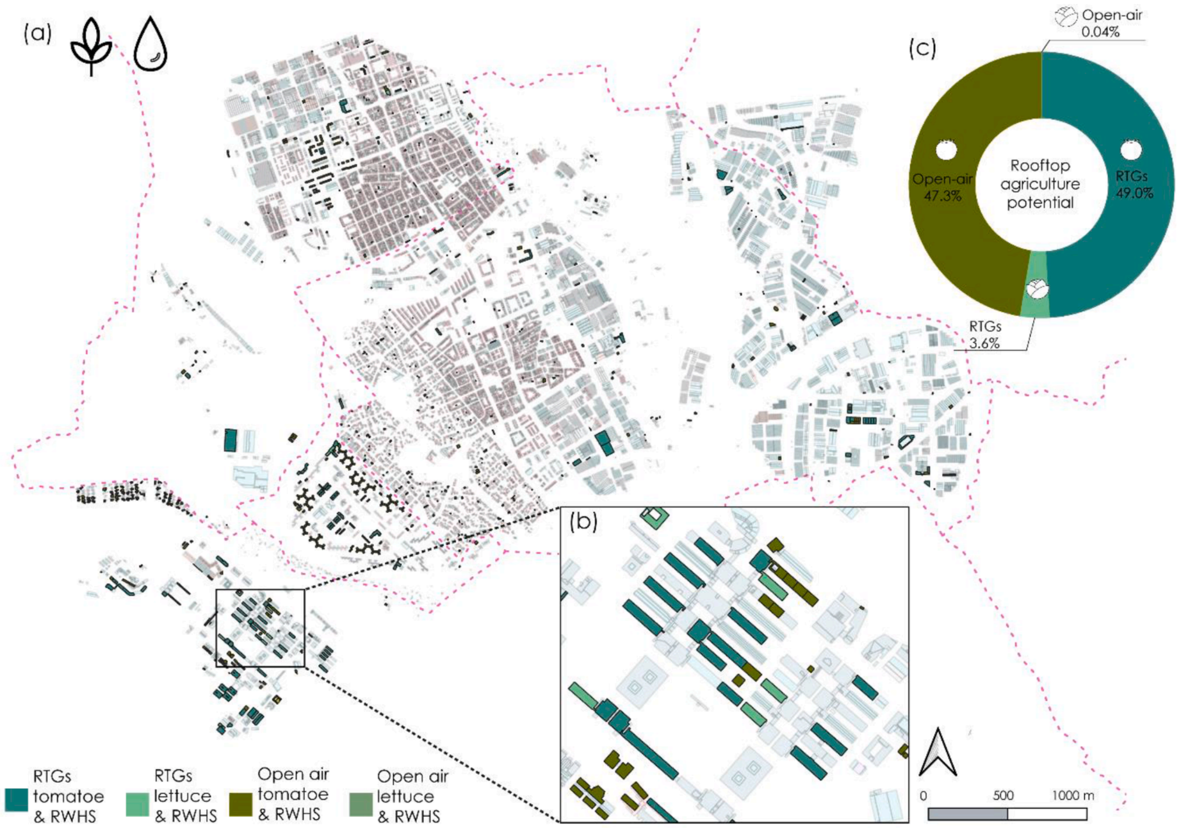

Figure 5. (a) Potential roofs to integrate rooftop agriculture and RWHS over the total study area. (b) Details of identified potential roofs on educational buildings from the Autonomous University of Barcelona. (c) Distribution of potential roofs according to growing system and crop type.

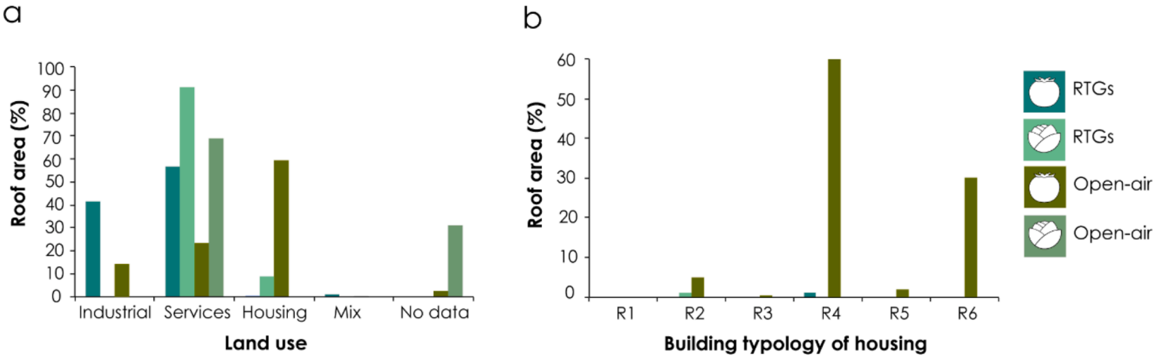

Figure 6. (a) Potential roofs identified to integrate rooftop agriculture and their distribution by land use and (b) by building typology of housing.

representing 21% of citizens in the study area (Figure 7b).

Self-sufficiency analysis for crop irrigation showed that the integration of RWHS could supply 94.3% of the total water requirements for lettuce crops in open-air systems and 82.1% for the same crop in RTGs, as well as 63.2% for tomatoes in open-air and 53.0% for the same crop in RTGs (Figure 7c).

A total of 8,088 roofs (1.3 km^2) were identified to integrate PV panels and RWHS (Figure 8a). Potential roofs were assigned the yellow color. Details of the identified roofs of housing and service buildings are shown in Figure 8b. Feasible roofs were located in different land uses, as shown in Figure 8c. Most of the rooftops belonged to industrial (65.1%); housing roofs represented 20.1%; service rooftops represented 12.6%; polygons without land use information represented 1.3%; and few roofs were mixed and nonurban at 0.6% and 0.4%, respectively.

The results showed that a total of 140,300 MWh/m^2/year could be produced on roofs, representing the average consumption of 18% of the population in the study area (Figure 8d). The results showed that a total of 1,124,000 m^3 of rainwater per year could be collected on roofs (considering potential roofs from figures 8a and 9a) representing the average consumption of 44% of the population in the study area for laundry, showering, toilet flushing, cleaning and irrigation uses (Figure 8d).

A total of 1.1 km^2 of roofs were identified as feasible for integrating RWHS (Figure 9a). These results did not consider potential roofs for agricultural irrigation (shown in Figure 5a) and neither did feasible roofs for RWHS and PV (shown in Figure 8a). The results of potential roofs for integrating RWHS are shown in blue. Details of the identified roofs of housing and service buildings are shown in Figure 9b. It was identified that most rooftops belonged to industrial (43.1%) and housing (40.2%) uses; service rooftops represent 14.1%; some polygons (1.6%) did not show information related to land use; and FWE roofs were mixed and nonurban at 0.7% and 0.4%, respectively (Figure 9c).

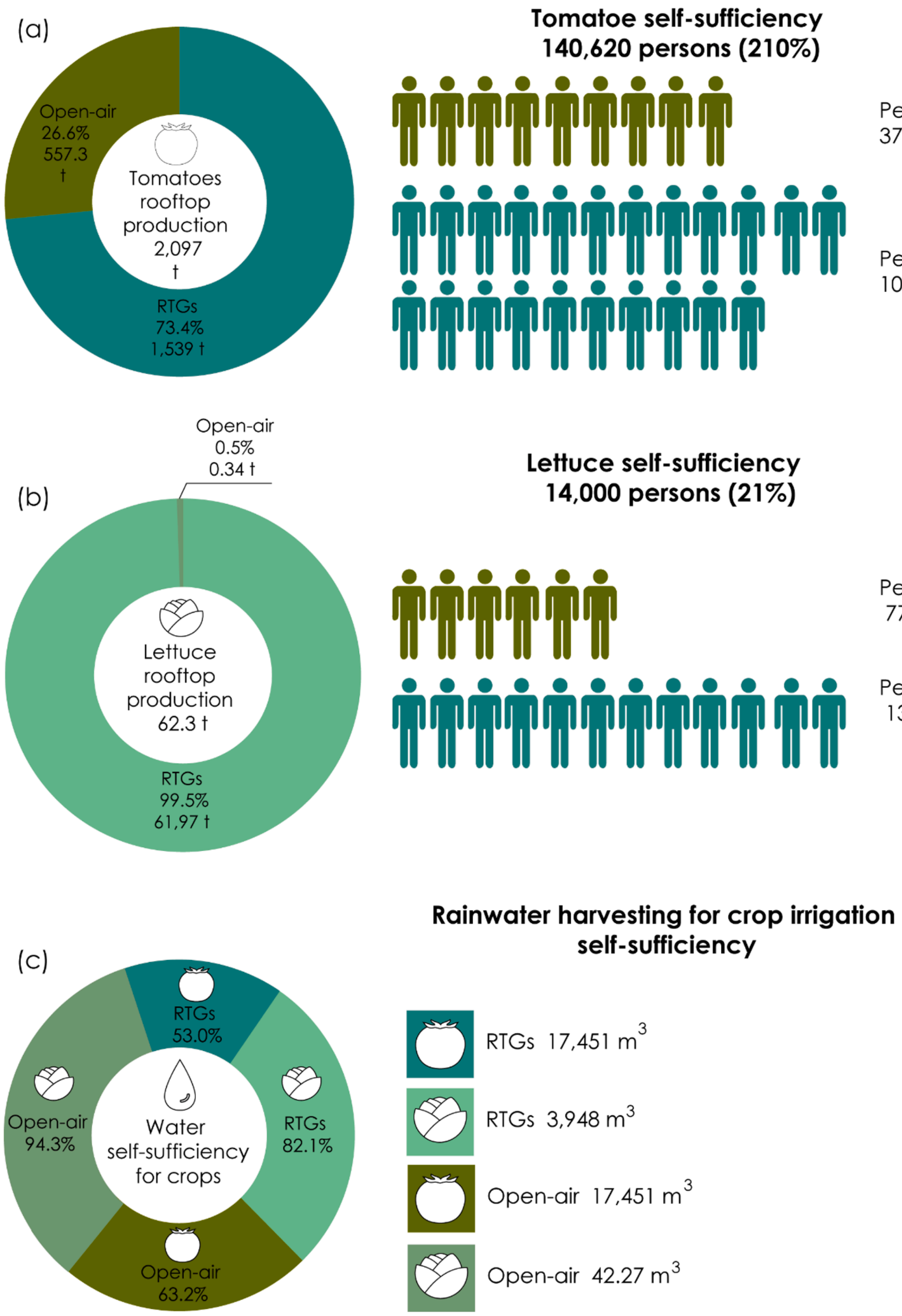

Figure 7. Rooftop urban agriculture production and water self-sufficiency by crop. (a) Tomato production in open-air and RTG systems and self-sufficiency. (b) Lettuce production in open-air and RTG systems and self-sufficiency. (c) Water self-sufficiency for irrigation regarding the type of crop and system. Potential areas for integrating UA were considered for rainwater collection for crop irrigation.

5. Discussion

5.1. Rooftop potential to integrate FWE systems and building use

In relation to feasible roofs for UA and food production, this work found that 8% of roofs in the study area could integrate urban agriculture. This result is similar to those obtained by Sanyé-Mengual, Cerón-Palma, Oliver-Solà, Montero, & Rieradevall, (2015) in a logistic and industrial park area located in Barcelona where a 8% of roofs were found feasible for RTGs representing 13 h. Compared to Sanyé-Mengual, Cerón-Palma, Oliver-Solà, Montero, & Rieradevall, (2015) work the feasible roof area in the present study was 7 ha greater, even so, tomato

Figure 8. (a) Potential rooftops for solar energy production by PV panels and RWHS over the study area. (b) Details of identified potential roofs in housing and service buildings. (c) Potential roofs identified to integrate PV panels and RWHS and their distribution by land use. (d) Energy and water self-sufficiency.

Figure 9. (a) Potential rooftops for integrating RWHS over the study area. (b) Details of identified potential roofs in housing and services buildings. (c) Potential roofs identified to integrate RWHS and their distribution by land use.

production was not significantly higher in our results, this difference could have occurred because 26.6% of roofs were feasible for open-air systems, and the yield production was less than that with RTG systems. Concerning other works, quantitative differences were found. In an industrial area of Barcelona, was found that 3% of roofs were feasible while another study carried out in the same city in retail parks showed great potential 53% (Nadal et al., 2017; Sanyé-Mengual et al., 2016). The difference about potential roofs could be related to the rooftop building materials, roof systems from retail parks tend to be more resistant than in industrial parks (Sanyé-Mengual, Cerón-Palma, Oliver-Solà, Montero, & Rieradevall, 2015).

In this study, services and housing rooftops were the most feasible for integrating RUA, which can be attributed to the structural requirements (for more details on this part of the discussion see the Appendix 5).

It was noted that the R4 building typology showed greater potential than R5, R2, and R6, which had higher representation over the total study area. These typologies showed a large number of shadows and pronounced slopes, especially the R6 housing typology. Blocks or towers configured from an isolated multifamily building were found to be the most promising typology for RUA purposes. The work developed by Toboso-Chavero et al. (2018) already concluded that block-isolated multifamily buildings have the potential to integrate open-air and RTG systems. These results show that building morphology and urban configuration could play an important role in rooftop UA potential. It was found low percentage (1.5%) of roofs without data information about land use, which could be due to the use of airborne datasets provided by different institutions and acquiring data on different dates which could generate some outdated data.

In the present work, were detected a low proportion of green roofs. As mentioned in Development of the Framework section, green roofs were discarded from the analysis of potential roofs. However, discarding these roofs implies a decrease in the potential of roofs for the integration of food, water, and energy systems, especially, in the case of pioneers cities that support the integration of green roofs and those where green roofs are mandatory by law such as London or Toronto (City of Toronto, 2009; Grant & Gedge, 2019). While green roofs provide environmental benefits, roofs with food, water, and/or energy systems provide several functions that may be a valuable support for developing resilient cities. Productive roofs can contribute to several goals of the 2030 Agenda for Sustainable Development, emphasizing the important role they may play in urban sustainability (Cristiano et al., 2021). Therefore, for future works, it is important to consider the possibility of larger areas of green roofs with the potential for food and solar energy systems integration.

5.2. Food, water, and energy self-sufficiency

This work demonstrated food self-sufficiency of 210% (140,620 inhabitants). These results are comparable to those reported in previous work by Sanyé-Mengual, Cerón-Palma, Oliver-Solà, Montero, & Rieradevall, (2015) in Zona Franca Park (Barcelona) where the total feasible area for RTGs can satisfy the average tomato demand of 130,000 inhabitants. Benis et al. (2017b) determined using a simulation that the integration of RTGs in buildings in Lisbon can have an efficiency of a factor of four in the case of tomato production. However, differences were also found concerning other studies developed in industrial and residential areas of Barcelona, in which self-sufficiency was reported from 50% to 69% (Nadal et al., 2017; Toboso-Chavero et al., 2018). These differences can be partially attributed to a smaller feasible production area (67% less).

The low feasibility of roofs to integrate lettuce crops in both RTGS (3.6%) and open-air (0.04%) systems is related to the priority given to roofs with high light levels and consequently the consideration of tomato crops, due their consumption in the region is higher than lettuce. However, the roofs that were found to be feasible for tomatoes are also potential for growing lettuce, either year-round or in combined crops with tomatoes (in the months when tomato production is not considered).

With respect to the RWHS for crop production, the results showed that it could be possible to supply at least 63.2% of the water requirements for lettuce crops using both RTGs and open-air and tomatoes growing in open-air systems. The results of this work are better, especially for lettuce growing in open-air systems, which found 94.3% water self-sufficiency compared with that found for a case study in Rome for horticulture gardens, where 57% of water could be supplied by rainwater collection on rooftops (Lupia et al., 2017) (see Appendix 6 for details). The water supply by rainwater for growing tomatoes using RTG systems was 27% lower than that in previous experimental works performed in Barcelona, the water efficiency for crops can be improved with the use of leached recirculation, including an extension of the crop production season to obtain 80% of the water requirements for tomato crops (Sanjuan-Delmás et al., 2018) which were no considered in this work. With respect to domestic water self-sufficiency, in this study, it was found that the RWHS could meet up to 44% of household demands. This result is lower than those reported in previous works. According to (Domènech & Saurí, 2011) 60% of the water demand for irrigation and laundry can be meet with the implementation of RWHS in detached and multi-family housing buildings (see Appendix 7 for more details).

Annual irrigation water requirements and urban-scale water collection were calculated in the model. However, a downscaled analysis in temporal terms affects the overall self-sufficiency results (analysis results and their discussion can be found in Appendix 8). In future research, the model can be improved, including analysis at smaller temporal and spatial scales and relate to the size and location of the water tank, which play important roles regarding the feasibility of RWHS and environmental impacts (Angrill et al., 2012, 2017; Petit-Boix et al., 2018).

Results showed an energy-sufficiency of 18% which is lower than reported in previous studies (ranging from 30% to 46%) from roofs in different districts of Barcelona (Riyahi Alam et al., 2008; Toboso-Chavero et al., 2018). However, differences were found in the data taken as a reference for energy consumption, while this work considered consumption of 11.42 MWh/inhabitant/year (Medi Ambient i Serveis Urbans-Ecologia Urbana Agència d'Energia de Barcelona, 2019), a previous study considered a lower consumption, 2.96 MWh/inhabitant/year (Riyahi Alam et al., 2008).

5.3. Solar irradiation and daylight requirements

The use of LiDAR technology made it possible to identify the solar radiation needed for solar energy and food production at a building scale in an urban scale extension. The method used included the meteorological characteristics of the site. Previous works has concluded the need to consider climatic data and field measurements (Kodysh et al., 2013; Suomalainen et al., 2017). However, this work has not made a comparison of the results with other methods used to compute roof radiation. This could be future work. Suomalainen et al. (2017) found an underestimation of the annual solar radiation of approximately 5% on the sunniest spots on the roof compared to solar radiation based on measured. The model of this work considered the shading of vegetation, however, in the case of deciduous vegetation, in winter solar radiation could increase in these areas. From the data obtained with LiDAR and the computation of irradiation for solar energy, a calculator which includes economic indicators could be generated for decision making by stakeholders use.

Most of the rooftops identified as potential for urban agriculture can integrate tomato crops (RTGs and open-air) which require high solar access. A small portion was feasible for lettuce crops, categorized with a medium-light requirement. No potential areas were detected for crops such as microgreens (low light requirement). However, in other locations where solar radiation is low, crops with lower light requirements could be integrated. According to the calculations made in this work, a minimum of 3,800 MJ/m^2/year is necessary for tomato crops in RTGs, which differs from the light requirements (1,900 MJ/m^2/year minimum) used in previous studies (Nadal et al., 2017; (Sanyé-Mengual, Cerón-Palma, Oliver-Solà, Montero, & Rieradevall, 2015; Toboso-Chavero et al., 2018). In future research, the analysis and consideration of intercropping and economic issues are recommended. In addition, to develop new tools using BIM design for modeling and integrate FWE infrastructures on buildings (Benis et al., 2017b; Khan et al., 2018).

5.4. Population density building typologies and self-sufficiency

This work considered the characteristics of each building. However, the potential roofs and self-sufficiency at urban scale were analyzed. The population density of each municipality can affect the self-sufficiency potential (for more details of the analysis see Appendix 9. It is important to note that not all municipalities have the same typologies and uses of buildings. This related to population density has implications at the municipal and building scale in the potential and self-sufficiency. For example, service and residential buildings showed higher potential for urban agriculture compared to industrial buildings. In the municipality with the lowest population density was found the largest amount of service building area. In this municipality, is located the Autonomous University of Barcelona representing the largest area of educational services. Contrary, most of the building housing with potential are in the county with the highest population density.

Concerning the integration of two systems: photovoltaic and rainwater harvesting, industrial roofs were found more feasible. Seventy-six percent of the potential industrial area was identified in the municipality of Barbera del Valles, while in the most densely populated municipality, there was no industrial buildings. Therefore, in future research, it is recommended to include analyses on a smaller scale, considering the variables mentioned in the previous paragraph.

5.5. Other considerations for future works

The conflict of prioritizing a roof use solar energy generation vs food production could be solved with the emergence of new technologies such as TPV integrated into RTGs. These new types of panels will allow the coexistence of both energy generation and food production. However, although TPV has been extensively researched as a renewable energy source for urban areas, there are still several challenges that do not seem to be fully covered yet. For commercialization of the TPV some main perspectives should be considered high-power conversion efficiency at the same average visible transmittance, aesthetic factors, and feasibility for real-world applications, including modularization and stability evaluation. In this regard, it has been suggested that a high-performance TPV cannot be realized commercially yet (Lee et al., 2020). However, in future research, it is recommended to integrate them in methos for feasibility and self-sufficiency analysis considering both food and solar energy systems in the same infrastructure.

According to Toboso-Chavero et al. (2018) the combinations with larger CO_2 eq savings showed higher self- sufficiency in electricity and hot water, whereas the combinations with lower environmental impacts displayed higher self-sufficiency in food systems. Benis et al. (2018b) found that food production is more beneficial than energy production for both financial return and local job creation. These important environmental and economic impacts must be taken into account in future studies.

6. Conclusion

This study contributes to defining criteria and procedures for assessing the feasibility of rooftops for integrating urban agriculture, rainwater harvesting systems, and PV panels. Data acquisition from remote sensing technology is the basis of the defined framework. In this sense, the availability of data is important. The identification of roof materials can be estimated through the proposed method and the use of remote sensors in the present study. The lack of this information could be a limitation for determining the potential adequate load capacity for the installation of greenhouses and could constitute an information gap in evaluating the potential integration and self-sufficiency of FWE systems in different cities. A lack of information concerning the consumption of products and production at the local or regional level could restrict or lead to less accurate production and self-sufficiency analyses. In relation to this limitation, experimental research on rooftop agriculture for both RTGs and open-air systems in different regions and considering a diversity of crops and according to their consumption products is needed.

In Mediterranean regions, where high radiation potential should be taken as advantage for crops with high lighting requirements without use of artificial light support.

Urban morphology and its characteristics influence the feasibility of potential production, especially for food and energy. Thus, the relationship between urban morphology and building typologies regarding FWE systems must be performed more deeply. This issue could be addressed by characterizing urban structure types using remote sensing technology due to the potential for efficient derivation of mapping urban land at the city scale.

The results of this work indicate that housing and services buildings could be a better location for RUA than industrial buildings. In addition, RUA could represent social cohesion and educational values more directly. However, in other cities building typologies and uses with the greatest potential may be different.

Regarding water self-sufficiency for crop production, the case study demonstrated good performance for most of the systems studied. However, this performance is variable according to the rainwater amounts of the case study location. Some implications can be improved for future works, for example, considering the recirculation of leachate and the factor of occupied area by crops in the case of open-air systems, special and temporal scales as well as with respect to water tanks, size calculations, and feasibility locations, which could be restrictions for implementing RWHS regarding the tank weight and associated environmental impacts.

It is critical to include social, environmental, and economic indicators to carry out a complete sustainability assessment and to guarantee economic sustainability of the infrastructures.

It is important that information about potential roofs be accessible and easy to identify. In this regard, an interactive map with the location and information of these areas has already been implemented in some cities, for example, the rooftop project maps of Melbourne city (City of Melbourne, 2020). Developing this type of interactive map could represent a valuable contribution to decision making for planning.

This work explored potential rooftops already built, but the integration of FWE systems into new buildings is also important. The expansion of cities continues, and the nexus of FWE systems should be considered a part of new buildings. In this sense, the integration of water and energy flows as well as UA in the phase of project design is an important consideration and easier to integrate if the project is conceived from the beginning with the integration of these technologies in mind. For these reasons, it is crucial that FWE studies also focus on the development of new projects and designs that will strongly depend on the geographic location.

Declaration of Competing Interest

No potential conflicts of interest were reported by the authors.

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Appendix 1. Examples of cities that transformed rooftops into productive spaces

New York, Paris, Vancouver, Toronto, Barcelona and Melbourne are some of the cities that have started to convert roofs into potential productive spaces, integrating food production and solar photovoltaic and solar hot water systems (City of Toronto, 2009; The New York City Council, 2010; Ville de Paris, 2019).

Tables A1 and A2.

Table A1
Average yield values and water recquirmets for selected crops

Growing method	Growing System	Crop type	Crop yield (kg/m^2)	growing season	Reference
RTGs	soil-less	Tomatoe	15.3	Spring-summer	Sanjuan-Delmás et al. (2018)
Open-air	soil-less	Tomatoe	5.8	Spring-summer	Boneta et al. (2019)
RTGs	soil-less	Lettuce	8.36	Spring and autum	Rufí-Salís et al. (2020)
Open-air	soil-less	Lettuce	3.85*	Anually	Boneta et al. (2019)

* Lettuce crop yield value in open air considers a policultive of vegetables production. Production in RTGs considers passive heating.

Table A2
Water requirement for tomatoes and lettuce irrigation according to growing systems.

Growing method	Growing System	Crop type	growing season	Water use (L/kg)	Reference
RTGs	soil-less	Tomatoe	Spring-summer	66	Rufí-Salís et al. (2020)
Open-air	soil-less	Tomatoe	Spring-summer	130.5	Boneta et al. (2019)
RTGs	soil-less	Lettuce	Summer and autumn	77.6	Rufí-Salís et al. (2020)
Open-air	soil-less	Lettuce	Spring-summer	130.5	Boneta et al. (2019)

Appendix 2. Remote sensing data and criteria to assess rooftops for FWE production

Area, slope, and solar radiation have been the principal criteria for assessing UA, RWHS or PV systems (e.g., Berger, 2013; Haberman et al., 2014; Kodysh, 2013; Lupia et al., 2017). In addition to roof geometry, some works have integrated other criteria, such as maximum building floors (Berger, 2013) and building height (Saha & Eckelman, 2017), to identify hospitable heights for plants and logistical safety concerns with rooftop access for people for UA purposes; roof materials (Nadal et al., 2017) and construction year (Berger, 2013) have also been identified.

Large surfaces (minimum 465 and 500 m^2) have been considered for commercial (Berger, 2013; Haberman et al., 2014; Nadal et al., 2017; Salvador et al., 2019; Sanyé-Mengual et al., 2015, 2016).

UA in schools, for example, provides environmental education and social cohesion, and according to the main goal of the Global Education 2030 (Agenda UNESCO), it is necessary to acquire sustainability competencies as a core of Education for Sustainable Development (Leicht et al., 2018).

Appendix 3. Criteria to integrate FWE systems for commercial and nonprofit purpose

Phase 1: Study area characterization

The characterization of the study area is based on the following criteria:

a) Urban features. It is important to know the urban context, such as urban form, population density, use and typology of building.

b) Climatic conditions. Resource potential is crucial to determine the feasibility for integrating food, water, energy (FWE) systems. Sunlight amount is necessary for growing food and determine suitable crops, directly affecting crop yields. Solar radiation reached by plants directly impacts the photosynthetically active radiation (PAR), which describes the generally accepted light wavelengths between 400 and 700 nm useful for photosynthesis. The relationship between solar radiation (normally measured in global horizontal radiation, in W/m^{2}h) and PAR (measured with the Photosynthetic Photon Flux Density, in µmol/m^{2}s) cannot be determined accurately unless values for each individual wavelength are known (Langhans & Tibbitts, 1997). Here, an approximation conversion value is calculated using global broad bandwidth and PAR measurements taken during the 2019-2021 period in the Barcelona area in order to give a more precise on-field data. The resulting average conversion factor from recorded daily solar radiation to PAR values used in this study was 2.21 ± 0.01 (CI 95%) to integrate average annual atmosphere conditions that influence this factor. This factor is in line with the 2.29 and 2.12 theoretically reached in daylight and blue-sky conditions respectively (Thimijan & Heins, 1983), which is normally referred in literature. This allow to calculate the cumulative measurement of total daily photons reached by plants in MJ/m^{2}d (known as day light integral, DLI, normally expressed in µmol/m^{2}s) in order to explain the ideal light requirements that saturate the leaf net photosynthetic rate to maximize plant growth (Kozai et al., 2015).

Rainfall over the year plays a key role in determining whether RWHS can compete with other water supply systems, as a general rule, rainfall should be over 50 mm/month for at least half a year or 300 mm/year (FAO, 2014; Worm & van Hattum, 2006).

Phase 2: Urban and architectural requirements

To identify suitable roofs, this phase considers criteria at urban and architectural scales.

a) Urban. Planning and building laws and codes must be considered to ensure that the integration of FWE systems meet legal requirements.

Cities are composed of diverse building types and a variety of uses, such as educational, housing, health, public services, commercial and industrial. Building use is important criterion that can define the purpose of the FWE systems. For example, educational buildings can integrate these systems for educational and self-sufficient purposes (Nadal et al., 2019), commercial and industrial buildings for commercial purposes (Nadal et al., 2017; Sanyé-Mengual et al., 2015, 2016).

Building uses are usually defined in urban planning and local ordinances.

b) Architectural. The characterization of buildings roofs (area, slope, material, radiation and sunlight access) is needed to identify feasibility areas.

- Roof area. A minimum roof area of 500 m^2 is needed for integrating UA for commercial purposes (Nadal et al., 2017). A minimum roof area of 13 m^2 can satisfy the vegetal demand for one person using soil less agriculture systems (Boneta et al., 2019) this was considered for nonprofit purpose.

  Taking into account the energy consumption and the yearly operation and maintenance cost, photovoltaics (PV) suitability requires at least a minimum roof area of 100 m^2 for commercial use and 24 m^2 for residential use (Spertino et al., 2013). The established areas can be geographically sensitive due to major consumption typical at latitudes with less sunlight hours.
- Roof slope. For integrate UA systems, slope of roofs must be flat $\leq$ 10% (Nadal et al., 2017). For rainwater harvesting systems (RWHSs) and PV systems, roof slope was not considering, assuming that PV panels are adjustable.

Solar radiation. Energy systems require solar radiation higher than 13 to 14 MJ/m^2 per day (Nadal et al., 2017). The amount of radiation is essential for growing food, in this work was established three levels of day light requirements for crops. Daily light requirements (measured with DLI) vary depending on the crop and its photoperiod, which range between 6 to 35 mol/m^{2}d. Current methodologies to identify potential urban agriculture areas normally define a target DLI value between 20 – 25 mol/m^{2}d, originally expressed in MJ/day (Benis et al., 2017; Nadal et al., 2017; Sanyé-Mengual et al., 2015).

- Other literature refers to the minimum average solar radiation of 8.5 MJ/m^{2}d defined for Mediterranean crops as reported by Nisen et al. (1998). These DLI targets usually satisfy light requirements for multiple selected crops or single species like tomato plants, which is a reference crop for agriculture studies. However, these are high compared to the optimal DLI requirements for other valuable crops as microgreens (see Table A3), underestimating the urban potential area that could grow low and medium-DLI crop types. Here, three groups of crops are classified according to their optimal daylight needs (i.e., maximum yields), even lower light levels will linearly decrease yields (Kozai et al., 2015) within acceptable crop yields and environmental performance (Rufí-Salís et al., 2020) Grouped DLI requirements are expressed in mol/m^2 and in MJ/m^2 daily and annually in order to facilitate comprehension and applicability of this workflow (see light conversion factor section). Hence, the approach here is to adapt the crop species to the available urban solar radiation, since adapting the light requirements with additional LED lightning would lead into an excess of energy needs with high environmental costs (Benis et al., 2017).
- Roof material. Roof materials are essential data to integrate these systems, if a roof does not have the necessary load-bearing capacity to support the weight of the system, it will not be possible to install a system on it. A minimum load-bearing capacity 200 kg/m^2 is required (Nadal et al., 2017). In the case of RWH, the quality and quantity of rainwater harvested from roofs are significantly affected by roofing materials (Farreny et al. 2011).

Phase 3: Self-sufficiency indicators

Production of FWE systems must be calculated to obtain the production and the self-sufficiency potential. To do this, the following three steps are required: a) Resource production. Potential production is used as indicator to assess the FWE systems integration and to estimate the degree of self-sufficiency. Suitable crops must be identified based on household typical food diet, for this reason, suitable crops can be geographically sensitive. Irrigation water requirements of crops data are needed. Water demand, depend on the type of crops and growing methods an systems, if this information is not available for the selected crop in and the geographic region of the study area, data of evapotranspiration (ETo, mm) is required to calculate (Khangaonkar & Mehaute, 1991). The following considerations should be taken to quantify resource production:

- Food. To quantify crop yield values, growing method (RTGs or open-air) and growing system (soil less or soil-based) must be considered.
- Water. Average rainfall data and runoff coefficient (RC) is required to estimate the potential rainwater harvesting on roofs. RC varies according to roof material from 0.9 to 0.6 (Farreny et al., 2013).
- Energy (PV). The technology for PV for example the most commonly in the market.

c) Self-sufficiency. For this phase, two criteria are necessary: potential production and household consumption. The potential food for self-sufficiency is calculated by dividing the potential production (food, water, energy) by the average consumption of the food

Table A3

Crop classification according to DLI requirements.

Day light requirements (DLI target)	MJ/m^2•year OA / RTG		Crop specie	Optimal DLI (mol/ m^2•day)	Reference
Low	> 6 mol/m^2 > 2.7 MJ/ m^2	**> 800*** **> 1400***	Microgreens	6—12	Kozai et al. (2015); Verlinden (2020)
			Small vegetative crops, green shoots	< 12	Kozai et al. (2015)
			Lettuce	12—17	Albright et al. (2000)
Medium	> 12 mol/m^2	**> 1650***	Leafy crops	12—17	Albright et al. (2000)
	> 5.4 MJ/m^2	**> 2800***	Vegetable seedlings	13	Fan et al. (2013)
			Strawberries	13	Kozai et al. (2015)
			Young / low-wire tomato (e.g. cherry)	13—17.3	Ingestad et al. (1994)
High	> 22 mol/m^2	**> 2000**** **> 3800*****	High-wire tomato	Avg 22—26 Up to 30—35	Spaargaren (2001)
	>10.0 MJ/m^2		High-wire tomato	Avg 22—29 Up to 30—40	Schwarz et al. (2014)

[*] Considering 10 and 12 months of crop season for OA and RTG farming, respectively.

[**] Considering 6 months of crop season equivalent to one short tomato crop.

[***] Considering 8 months of crop season equivalent to one extended tomato crop.

(kg•person•year), water (lts•person•year) and energy (kWh•person•year) in the study area, resulting in the total number of people whose demand is satisfied.

Appendix 4. Light conversion factor and sunlight access for rooftop urban agriculture

The cumulative measurement of total daily photons reached by plants is known as daily light integral (DLI) expressed in mol/m^2/day, and explains the linear relationship between light and plant growth rate needed to saturate the leaf net photosynthetic rate (Kozai et al., 2015). DLI requirements vary depending on the crop and its photoperiod, which range between 6 to 35 mol/m^2/day

Light conversion factor has been studied with on-field measurements in the Urban Agriculture facilities in the Institute of Science and Technology (ICTA-UAB) in the compounds of Universitat Autònoma de Barcelona in the city of Cerdanyola del Vallès, in the Barcelona region. The weather station in this facility is equipped with a global solar radiation (Hukseflux LP02, second class pyranometer) and a PAR Quantum sensor (SKP215 with a ±5% accuracy, typically <±3%) which measures incident quanta between 400 and 700 nm. A CR3000 datalogger from Campbell Scientific measures data every 5sec, recording the averages at hourly intervals during the 2019 to 2021 period.

In order to study the Day Light Integral of crops, the sum of all incident radiation of both sensors has been summed per day and then divided in order to calculate the conversion factor from global radiation (W/m^2) to PAR (PPFD, in µmol/m2s). The obtained values in a box plot are presented in detail in Figure A1. Note that significant differences exist between year quarters, being the second and third quarter greater than the first and fourth. However, as the assessment here is annual based, a unique average value of 2.21 ± 0.01 (CI 95%) for all year has been used.

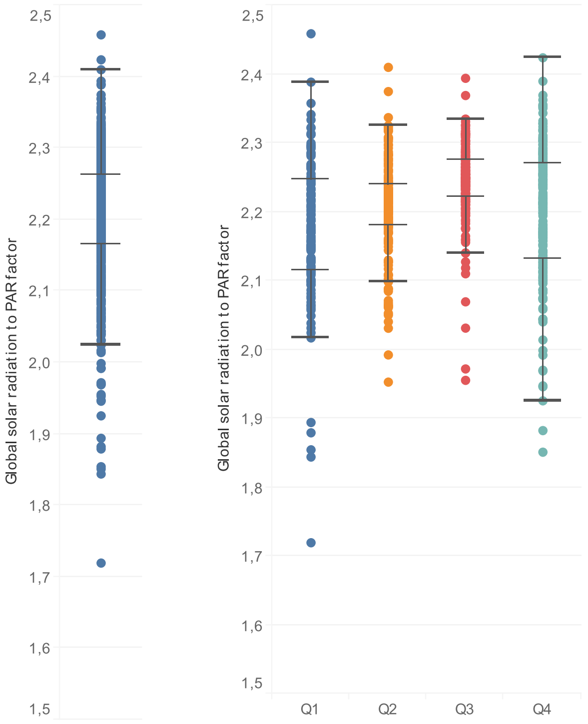

Figure A1. Annual and quarter conversion factor values.

Grouped DLI requirements are expressed in mol/m^2 and in MJ/m^2 daily and annually in order to facilitate comprehension and applicability of this workflow to other solar measurement sites. It is important to note that vegetative crops do not require significant lower DLI during the early stage of the plants development, while fruiting crops like tomatoes require significant lower levels (from 2 to 13-20 mol/m^{2}d) during the vegetative growth stage compared to the fruiting phase up to 40 mol/m^{2}d (Schwarz et al., 2014). Therefore, when calculating the annual light needs for tomato plants in the high DLI group, an average value between 20 and 25 mol/m^{2}d is assumed (i.e., considering that the vegetative phase lasts the same period as the fruiting phase (Philips Lighting Horticulture, unpublished work).

The growing period has been considered according to the average months in the Mediterranean area, excluding the coldest months (December and January) (FAO, 2013).

Similarly, one short tomato crop lasting 6 months has been also considered according to common practices in the Mediterranean climate while an extended tomato crop of 8 months has been considered for rooftop greenhouse farming. Finally, an average solar transmissivity radiation of 70% has been considered, even this could vary according to roof slope and orientation (Castilla, 2005).

Appendix 5. Roof materials and structural discussion

Industrial roofs were present in a larger proportion of the total study area than service roofs. However, a smaller proportion of potential industrial roofs was observed to integrate UA. Generally, this type of roof is characterized by large polygons and a high amount of solar radiation, which makes the integration of RTGs feasible. Even so, most of them have low load-bearing capacity, such as metal decks and light or metal coverings and fiber cement sheets. Low-resistance materials are a barrier to integrating UA systems on roofs in the immediate term, and an adaptation concerning structural reinforcement of the roof is needed for it to be a candidate for UA integration. Similar results were found by Nadal et al. (2017) in an industrial zone of the Metropolitan Area of Barcelona, where roofs met the minimum area and solar radiation but not the load-bearing capacity of the roof material. Service and housing buildings are usually composed of higher load-bearing capacity structures, with non-transitable roof systems composed of concrete and gravel surface finishing or other concrete systems finished with asphalt sheets. These materials meet structural resistance requirements but require a roof finishing adaptation to allow the installation and operation for growing and harvesting food. Regarding housing buildings, roofs were characterized by a variety of the previous roof systems described, in addition to ceramic roofs, which can fulfill the resistance criterion because concrete systems in general are presented in ceramic roof finishing covers. However, some roofs with too much slope could have metal structures that might not fulfill the resistance requirement

Appendix 6. RWHS for crop production

These differences can be related to the following reasons: (1) catchment area, this work considered all roof areas as catchment surfaces; (2) RC value, this work considered a variety of RCs (0.9,0.8, and 0.6) according to roof materials in the area, while a conservative value of 0.6 was considered for all potential areas by Lupia et al. (2017); and (3) water requirements, establishment of water consumption for irrigation plays an important role, and soil-less systems, such as perlite, require less water than soil based systems

Appendix 7. Domestic water self-sufficiency

These differences could be due to the RC values used; previous work considered 0.85 for all roofs (Domènech & Saurí, 2011). The present study incorporates the identification of roofing materials which allowed distinguishing the spatial distribution of them and therefore, considering a variety of RCs from 0.6 to 0.9. Farreny et al. (2013) reported water self-sufficiency ranging from 80% to 90% from water collected from rooftops, in addition to paved covers at ground surface (roads, car park, and paved pedestrian areas) which represented 67% of the catchment area in retail parks from Barcelona. Therefore, considering water harvesting in ground-level areas could increase the potential for water self-sufficiency, however various implications of the system would have to be studied.

Appendix 8. Downscaled analysis water self-sufficiency irrigation

The Figures A2 and A3 show the water self-sufficiency per system and crop per month. For tomato cultivation in greenhouses, self-sufficiency ranges from 28% to 48%; tomato in an outdoor system from 34% to 75%; lettuce in greenhouses from 44% to 100% and lettuce in the open air from 51% to 100%.

A smaller-scale analysis contributes to a better understanding of water tank sizing and its relation to weight (aspects not included in this work). Other studies carried out at a smaller scale (building and neighborhood) found for the city of Callafel (Catalonia, Spain) tank sizes of 4 m^3 for roof area less than 200 m^2 could only meet 20% and 57 m^3 water tank could supply from 76 % to 99% according to roof area from 201 to 1000 m^2 for toilet flushing and laundry (Petit-Boix et al., 2018); in Barcelona city a 7 m^3 cistern size could supply water demands (Toboso-Chavero et al., 2018). It is necessary to evaluate water tank size at the building level on a case-by-case basis or as a whole for those with the same typologies.

Appendix 9. Population density of each municipality and the self-sufficiency potential

Table A4 shows a comparison between the highest and lowest density municipalities in the study area and the differences in self-sufficiency by system. The greatest difference is in the food (total tomato production) and water, exceeded by up to 65 and 13 times, respectively, by the municipality with the lowest density. In addition to population density, other factors can affect the potential, the urban

Table A4
Population density and self-sufficiency by system

Municipality	Population density (inhabitants/km2)	Self-Sufficiency (number of times)			
		Food Tomato	Food Lettuce	Water	Solar Energy
Badia del Vallès	14,426.88	9.7	1.0	2.0	0.9
Cerdanyola del Vallès	1,889.39	74	7.4	15.5	6.5

For self-sufficiency analysis the potential area of the total study area is considered.

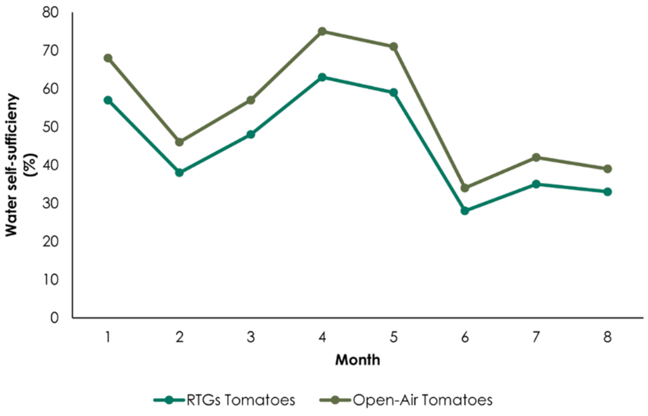

Figure A2. Water self-sufficiency irrigation for tomatoes crop per month.

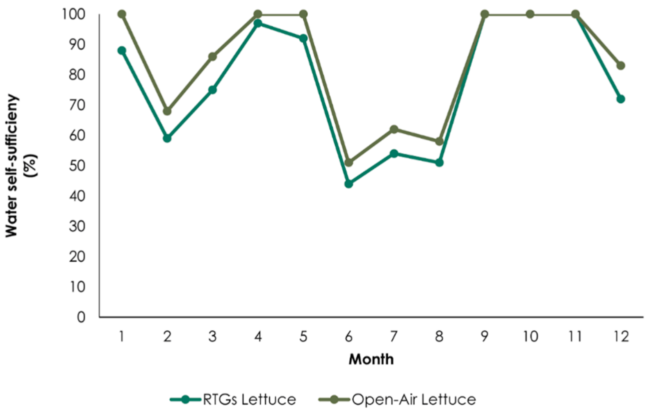

Figure A3. Water self-sufficiency irrigation for lettuce crop per month.

form, the building typology and its characteristics (mentioned above), the number of inhabitants per house, and the consumption differences.

Appendices References

Albright, L. D., Both, A. J., & Chiu, A. J. (2000). Controlling greenhouse light to a consistent daily integral. *Transactions of the American Society of Agricultural Engineers*.

Benis, K., Reinhart, C., & Ferrão, P. (2017). Building-Integrated Agriculture (BIA) In Urban Contexts: Testing A Simulation-Based Decision Support Workflow. *15th IBPSA*, 1798–1807. https://doi.org/10.1016/j.jclepro.2017.01.130

Berger, D. (2013). *A GIS suitability analysis of the potential for rooftop agriculture in New York City* [MSc diss., Columbia University]. https://academiccommons.columbia.edu/catalog/ac:162285

Boneta, A., Rufí-Salís, M., Ercilla-Montserrat, M., Gabarrell, X., & Rieradevall, J. (2019). Agronomic and Environmental Assessment of a Polyculture Rooftop Soilless Urban Home Garden in a Mediterranean City. *Frontiers in Plant Science, 10*, 341. https://doi.org/10.3389/fpls.2019.00341

Castilla, N. (2005). *Invernaderos de plástico: tecnología y manejo*. Mundi-Prensa Libros.

City of Toronto. (2009). *City of Toronto Green Roof Bylaw*. City of Toronto. https://www.toronto.ca/city-government/planning-development/official-plan-guidelines/green-roofs/green-roof-bylaw/

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. *Journal of Cleaner Production, 19* (6–7), 598–608. https://doi.org/10.1016/j.jclepro.2010.11.010

Fan, X. X., Xu, Z. G., Liu, X. Y., Tang, C. M., Wang, L. W., & Han, X. lin. (2013). Effects of light intensity on the growth and leaf development of young tomato plants grown under a combination of red and blue light. *Scientia Horticulturae*. https://doi.org/10.1016/j.scienta.2013.01.017

FAO. (2013). Good Agricultural Practices for greenhouse vegetable crops: Principles for Mediterranean climate areas. In *CRC Press*. https://doi.org/10.1201/b13737-8

FAO. (2014). *Feasibility study of rainwater harvesting for agriculture in the Caribbean subregion*. 74. http://www.fao.org/3/a-bq747e.pdf

Farreny, R., Morales-Pinzón, T., Guisasola, A., Tayà, C., Rieradevall, J., & Gabarrell, X. (2011). Roof selection for rainwater harvesting: Quantity and quality assessments in Spain. *Water Research, 45*(10), 3245–3254. https://doi.org/10.1016/j.watres.2011.03.036

Farreny, R., Rieradevall, J., Barbassa, A. P., Teixeira, B., & Gabarrell, X. (2013). Indicators for commercial urban water management: the cases of retail parks in Spain and Brazil. *Urban Water Journal, 10*(4), 281–290. https://doi.org/10.1080/1573062X.2012.716855

Haberman, D., Gillies, L., Canter, A., Rinner, V., Pancrazi, L., & Martellozzo, F. (2014). The Potential of Urban Agriculture in Montréal: A Quantitative Assessment. *ISPRS International Journal of Geo-Information, 3*(3), 1101–1117. https://doi.org/10.3390/ijgi3031101

Ingestad, T., Hellgren, O., & Lund Ingestad, A.-B. (1994). *SVERIGES LANTBRUKSUNIVERSITET Rapporter Data base for tomato plants at steady-state Methods and performance of tomato plants (Lycopersicon esculentum Mill. cv. Solentos) under non-limiting conditions and under limitation by nitrogen and light*.

Khangaonkar, T., & Mehaute, B. Le. (1991). Original surface disturbances from wave records. *Applied Ocean Research, 13*(3), 110–115. https://doi.org/10.1016/S0141-1187(05)80058-6

Kodysh, J. B., Omitaomu, O. A., Bhaduri, B. L., & Neish, B. S. (2013). Methodology for estimating solar potential on multiple building rooftops for photovoltaic systems. *Sustainable Cities and Society, 8*, 31–41. https://doi.org/10.1016/j.scs.2013.01.002

Kozai, T., Niu, G., & Takagaki, M. (2015). Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production. In *Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production*.

Langhans, R., & Tibbitts, T. (1997). *Plant growth chamber handbook*. Iowa Agricultural and Home Economics Experiment Station.

Leicht, A., Heiss, J., & Byun, W. J. (2018). Issues and trends in education for sustainable development - UNESCO Digital Library. In *UNESCO Publishing*. https://unesdoc.unesco.org/ark:/48223/pf0000261445

Lupia, F., Baiocchi, V., Lelo, K., & Pulighe, G. (2017). Exploring Rooftop Rainwater Harvesting Potential for Food Production in Urban Areas. *Agriculture, 7*(6), 46. https://doi.org/10.3390/agriculture7060046

Nadal, A., Alamús, R., Pipia, L., Ruiz, A., Corbera, J., Cuerva, E., Rieradevall, J., & Josa, A. (2017). Urban planning and agriculture. Methodology for assessing rooftop greenhouse potential of non-residential areas using airborne sensors. *Science of the Total Environment, 601–602*, 493–507. https://doi.org/10.1016/j.scitotenv.2017.03.214

Nadal, A., Rodríguez-Cadena, D., Pons, O., Cuerva, E., Josa, A., & Rieradevall, J. (2019). Feasibility assessment of rooftop greenhouses in Latin America. The case study of a social neighborhood in Quito, Ecuador. *Urban Forestry & Urban Greening, 44*, 126389. https://doi.org/10.1016/J.UFUG.2019.126389

Nisen, A., Grafiadellis, M., Jiménez, R., La Malfa, G., Martínez-García, P. F., Monteiro, A., & Baudoin, W. (1998). Cultures protégées en climat Méditerranéen. *Fao, Rome. Etude Production Végétale et Protection Des Plantes*.

Petit-Boix, A., Devkota, J., Phillips, R., Violeta Vargas-Parra, M., Josa, A., Gabarrell, X., Rieradevall, J., & Apul, D. (2018). Life cycle and hydrologic modeling of rainwater harvesting in urban neighborhoods: Implications of urban form and water demand patterns in the US and Spain. *Science of the Total Environment, 621*, 434–443. https://doi.org/10.1016/j.scitotenv.2017.11.206

Rufí-Salís, M., Petit-Boix, A., Villalba, G., Ercilla-Montserrat, M., Sanjuan-Delmás, D., Parada, F., Arcas, V., Muñoz-Liesa, J., & Gabarrell, X. (2020). Identifying eco-efficient year-round crop combinations for rooftop greenhouse agriculture. *International Journal of Life Cycle Assessment, 25*(3), 564–576. https://doi.org/10.1007/s11367-019-01724-5

Saha, M., & Eckelman, M. J. (2017). Growing fresh fruits and vegetables in an urban landscape: A geospatial assessment of ground level and rooftop urban agriculture potential in Boston, USA. *Landscape and Urban Planning, 165*(August 2016), 130–141. https://doi.org/10.1016/j.landurbplan.2017.04.015

Salvador, D. S., Toboso-Chavero, S., Nadal, A., Gabarrell, X., Rieradevall, J., & da Silva, R. S. (2019). Potential of technology parks to implement Roof Mosaic in Brazil. *Journal of Cleaner Production, 235*, 166–177. https://doi.org/10.1016/j.jclepro.2019.06.214

Sanjuan-Delmás, D., Llorach-Massana, P., Nadal, A., Ercilla-Montserrat, M., Muñoz, P., Montero, J. I., Josa, A., Gabarrell, X., & Rieradevall, J. (2018). Environmental assessment of an integrated rooftop greenhouse for food production in cities. *Journal of Cleaner Production, 177*, 326–337. https://doi.org/10.1016/j.jclepro.2017.12.147

Sanyé-Mengual, E., Cerón-Palma, I., Oliver-Solà, J., Montero, J. I., & Rieradevall, J. (2015). Integrating horticulture into cities: A guide for assessing the implementation potential of rooftop greenhouses (RTGs) in industrial and logistics parks. *Journal of Urban Technology, 22*(1), 87–111. https://doi.org/10.1080/10630732.2014.942095

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. (2016). Urban horticulture in retail parks: Environmental assessment of the potential implementation of rooftop greenhouses in European and South American cities. *Journal of Cleaner Production, 172*, 3081–3091. https://doi.org/10.1016/j.jclepro.2017.11.103

Schwarz, D., Thompson, A. J., & Kläring, H. P. (2014). Guidelines to use tomato in experiments with a controlled environment. *Frontiers in Plant Science*. https://doi.org/10.3389/fpls.2014.00625

Spaargaren, J. J. (2001). Supplemental lighting for greenhouse crops. *Hortilux Schreder B.V. and P.L. Light Systems, Inc, Ontario, Canada*.

Spertino, F., Di Leo, P., & Cocina, V. (2013). Economic analysis of investment in the rooftop photovoltaic systems: A long-term research in the two main markets. *Renewable and Sustainable Energy Reviews, 28*, 531–540. https://doi.org/10.1016/J.RSER.2013.08.024

The New York City Council. (2010). *FoodWorks: A Vision to Improve NYC's food system*. http://growingfoodconnections.org/gfc-policy/foodworks-a-vision-to-improve-nycs-food-system/

Thimijan, R., & Heins, R. (1983). Photometric, radiometric, and quantum light units of measure: a review of procedures for interconversion. *HortScience, 18*(6), 818–822.

Toboso-Chavero, S., Nadal, A., Petit-Boix, A., Pons, O., Villalba, G., Gabarrell, X., Josa, A., & Rieradevall, J. (2018). Towards Productive Cities: Environmental Assessment of the Food-Energy-Water Nexus of the Urban Roof Mosaic. *Journal of Industrial Ecology*. https://doi.org/10.1111/jiec.12829

Verlinden, S. (2020). Microgreens: Definitions, Product Types, and Production Practices. *Horticultural Reviews, 47*, 85–124. https://doi.org/10.1002/9781119625407.ch3

Ville de Paris. (2019). *Les Parisculteurs*. http://www.parisculteurs.paris/fr/

Worm, J., & van Hattum, T. (2006). *Rainwater harvesting for domestic use*. Agromisa Foundation and CTA.

References

Ajuntament de Barcelona Medi Ambient i Serveis Urbans. (2016). *El consum d'aigua a Barcelona L'aprofitament i els usos dels recursos hídrics*. www.bcasa.cat.

Angrill, S., Farreny, R., Gasol, C. M., Gabarrell, X., Viñolas, B., Josa, A., & Rieradevall, J. (2012). Environmental analysis of rainwater harvesting infrastructures in diffuse and compact urban models of Mediterranean climate. *International Journal of Life Cycle Assessment, 17*(1), 25–42. https://doi.org/10.1007/s11367-011-0330-6

Angrill, S., Segura-Castillo, L., Petit-Boix, A., Rieradevall, J., Gabarrell, X., & Josa, A. (2017). Environmental performance of rainwater harvesting strategies in Mediterranean buildings. *International Journal of Life Cycle Assessment, 22*(3), 398–409. https://doi.org/10.1007/s11367-016-1174-x

Arnell, N. W., & Gosling, S. N. (2016). The impacts of climate change on river flood risk at the global scale. *Climatic Change, 134*(3), 387–401. https://doi.org/10.1007/s10584-014-1084-5

Bayrakci Boz, M., Calvert, K., & Brownson, J. R. S. (2015). An automated model for rooftop PV systems assessment in ArcGIS using LIDAR. *AIMS Energy, 3*(3), 401–420. https://doi.org/10.3934/energy.2015.3.401

Benis, K., Reinhart, C., & Ferrão, P. (2017). Development of a simulation-based decision support workflow for the implementation of Building-Integrated Agriculture (BIA) in urban contexts. *Journal of Cleaner Production, 147*, 589–602. https://doi.org/10.1016/J.JCLEPRO.2017.01.130

Benis, K., Turan, I., Reinhart, C., & Ferrão, P. (2018a). 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

Benis, K., Turan, I., Reinhart, C., & Ferrão, P. (2018b). 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

Berger, D. (2013). *A GIS suitability analysis of the potential for rooftop agriculture*. New York City: Columbia University, Article 162285 [MSc diss.] https://academiccommons.columbia.edu/catalog/ac.

Bibri, S. E., & Krogstie, J. (2017). Smart sustainable cities of the future: An extensive interdisciplinary literature review. *Sustainable Cities and Society*, 31, 183–212. https://doi.org/10.1016/j.scs.2017.02.016.

Brito, M. C., Gomes, N., Santos, T., & Tenedório, J. A. (2012). Photovoltaic potential in a Lisbon suburb using LiDAR data. *Solar Energy, 86*(1), 283–288. https://doi.org/10.1016/J.SOLENER.2011.09.031

Campisano, A., & Modica, C. (2015). Rain water harvesting as source control option to reduce roof runoff peaks to downstream drainage systems. *Journal of Hydroinformatics, di, jh2015133*. https://doi.org/10.2166/hydro.2015.133

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. *Journal of Urban Technology, 19*(4), 87–103. https://doi.org/10.1080/10630732.2012.717685

Chang, N. Bin, Hossain, U., Valencia, A., Qiu, J., & Kapucu, N (2020). The role of food-energy-water nexus analyses in urban growth models for urban sustainability: A review of synergistic framework. *Sustainable Cities and Society, 63*. https://doi.org/10.1016/j.scs.2020.102486

City of Melbourne. (2020). *The rooftop project maps*. https://cityofmelbourne.maps.arcgis.com/apps/MapSeries/index.html?appid=5c6bf1fc3f094e418e55eb1bce03953e.

City of Toronto. (2009). City of Toronto Green Roof Bylaw. *City of Toronto*. https://www.toronto.ca/city-government/planning-development/official-plan-guidelines/green-roofs/green-roof-bylaw/.

Corcelli, F., Fiorentino, G., Petit-Boix, A., Rieradevall, J., & Gabarrell, X. (2019). Transforming rooftops into productive urban spaces in the Mediterranean. An LCA comparison of agri-urban production and photovoltaic energy generation. *Resources, Conservation and Recycling, 144*(January), 321–336. https://doi.org/10.1016/j.resconrec.2019.01.040

Cristiano, E., Deidda, R., & Viola, F. (2021). The role of green roofs in urban Water-Energy-Food-Ecosystem nexus: A review. *Science of the Total Environment, 756*, Article 143876. https://doi.org/10.1016/j.scitotenv.2020.143876

Departament d'Agricultura Ramaderia Pesca i Alimentació. (2017). *Consum alimentari a les llars de Catalunya 2017*. http://agricultura.gencat.cat/web/.content/de_departament/de02_estadistiques_observatoris/09_alimentacio_i_qualitat/dades_consum_catalunya/fitxers_estatics/2017_Consum_Cat.pdf.

Department of Territory and Sustainability. (2019). *Urban Planning Map of Catalonia*. http://territori.gencat.cat/es/06_territori_i_urbanisme/observatori_territori/mapa_urbanistic_de_catalunya/serveis_web_i_dades_obertes/descarrega-de-dades/.

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. *Journal of Cleaner Production, 19*(6–7), 598–608. https://doi.org/10.1016/j.jclepro.2010.11.010

European Investment Bank. (2018). *The 15 circular steps for cities*. www.eib.org/circular-economy.

FAO. (2011). The State of the World's Land and Water Resources for Food and Agriculture – Managing Systems at Risk. *Food and Agriculture Organization of the United Nations, 91*.

FAO. (2013). *Good Agricultural Practices for greenhouse vegetable crops: Principles for Mediterranean climate areas*. CRC Press. https://doi.org/10.1201/b13737-8

FAO. (2015). Statistical Pocketbook 2015. *Food and Agriculture Organization of the United Nations*. https://doi.org/978-92-5-108802-9.

FAO. (2016). Energy, Agriculture and Climate Change Towards energy-smart agriculture. *Food and Agriculture Organization of the United Nations*. https://doi.org/10.1038/2111117a0

Farreny, R., Morales-Pinzón, T., Guisasola, A., Tayà, C., Rieradevall, J., & Gabarrell, X. (2011). Roof selection for rainwater harvesting: Quantity and quality assessments in Spain. *Water Research, 45*(10), 3245–3254. https://doi.org/10.1016/j.watres.2011.03.036

Fertilecity. (2018). *Fertilecity*. http://www.fertilecity.com/.

Gosling, S. N., & Arnell, N. W. (2016). A global assessment of the impact of climate change on water scarcity. *Climatic Change, 134*(3), 371–385. https://doi.org/10.1007/s10584-013-0853-x

Grant, A. T. J., McKinney, N. L., & Ries, R. (2017). An approach to quantifying rainwater harvesting potential using imagery, geographic information systems (GIS) and LiDAR data. *Water Science and Technology: Water Supply, 2012*, Article ws2017026. https://doi.org/10.2166/ws.2017.026

Grant, G., & Gedge, D. (2019). *Living roofs and walls from policy to practice 10 years or urban greening in London and beyond*. www.livingroofs.org.

Proksch, Gundula (2016). *Creating urban agricultural systems: an integrated approach to design*. Taylor francis ltd.

Hume, I. V, Summers, D. M., & Cavagnaro, T. R. (2021). Self-sufficiency through urban agriculture: Nice idea or plausible reality? *Sustainable Cities and Society, 68*. https://doi.org/10.1016/j.scs.2021.102770

International Renewable Energy Agency. (2015). Renewable Energy in the Water Energy & Food Nexus. *International Renewable Energy Agency* (Issue January). http://www.irena.org/publications/2015/Jan/Renewable-Energy-in-the-Water-Energy–Food-Nexus.

Jha, M. K., Chowdary, V. M., Kulkarni, Y., & Mal, B. C. (2014). Rainwater harvesting planning using geospatial techniques and multicriteria decision analysis. *Resources, Conservation and Recycling*, 83, 96–111. https://doi.org/10.1016/j.resconrec.2013.12.003.

Khan, J., & Arsalan, M. H. (2016). Estimation of rooftop solar photovoltaic potential using geo-spatial techniques: A perspective from planned neighborhood of Karachi – Pakistan. *Renewable Energy*, 90, 188–203. https://doi.org/10.1016/J.RENENE.2015.12.058.

Khan, R., Aziz, Z., & Ahmed, V. (2018). Building integrated agriculture information modelling (BIAIM): An integrated approach towards urban agriculture. *Sustainable Cities and Society*, 37, 594–607. https://doi.org/10.1016/j.scs.2017.10.027.

Kodysh, J. B., Omitaomu, O. A., Bhaduri, B. L., & Neish, B. S. (2013). Methodology for estimating solar potential on multiple building rooftops for photovoltaic systems. *Sustainable Cities and Society, 8*, 31–41. https://doi.org/10.1016/j.scs.2013.01.002

Lee, K., Um, H. D., Choi, D., Park, J., Kim, N., Kim, H., & Seo, K. (2020). The Development of Transparent Photovoltaics. *Cell Reports Physical Science*. https://doi.org/10.1016/j.xcrp.2020.100143

Lupia, F., Baiocchi, V., Lelo, K., & Pulighe, G. (2017). Exploring Rooftop Rainwater Harvesting Potential for Food Production in Urban Areas. *Agriculture, 7*(6), 46. https://doi.org/10.3390/agriculture7060046

McGranahan, G., & Satterthwaite, D. (2003). Urban Centers: An Assessment of Sustainability. *Annual Review of Environment and Resources, 28*(1), 243–274. https://doi.org/10.1146/annurev.energy.28.050302.105541

Medi Ambient i Serveis Urbans-Ecologia Urbana Agència d'Energia de Barcelona. (2019). *Balanç d'energia i emissions de gasos amb effecte d'hivernacle de Barcelona* 2017.

Metropolitan area of Barcelona. (2018). *Urban planning and building codes*. https://www.amb.cat/en/web/territori/gestio-i-organitzacio/numamb.

Midgley, S. J. E., New, M., & Methner, N. (2019). Competition for Land, Water and Energy (Nexus) in Food Production. *Food Science Encyclopedia of Food Security and Sustainability*. Elsevier. https://doi.org/10.1016/B978-0-08-100596-5.21993-8 (Vol. 1).

Mok, H. F., Williamson, V. G., Grove, J. R., Burry, K., Barker, S. F., & Hamilton, A. J. (2014). Strawberry fields forever? Urban agriculture in developed countries: A review. *Agronomy for Sustainable Development, 34*(1), 21–43. https://doi.org/10.1007/s13593-013-0156-7

Motoshita, M., Pfister, S., & Finkbeiner, M. (2020). Regional Carrying Capacities of Freshwater Consumption Current Pressure and Its Sources. *Environmental Science and Technology, 54*(14), 9083–9094. https://doi.org/10.1021/acs.est.0c01544

Nadal, A., Alamús, R., Pipia, L., Ruiz, A., Corbera, J., Cuerva, E., Rieradevall, J., & Josa, A. (2017). Urban planning and agriculture. Methodology for assessing rooftop greenhouse potential of non-residential areas using airborne sensors. *Science of the Total Environment, 601–602*, 493–507. https://doi.org/10.1016/j.scitotenv.2017.03.214

Nadal, A., Oriol, P., Cuerva, E., Rieradevall, J., & Josa, A. (2018). Rooftop greenhouses in educational centers: A sustainability assessment of urban agriculture in compact cities. *Science of the Total Environment, 626*, 1319–1331. https://doi.org/10.1016/j.scitotenv.2018.01.191

Nadal, A., Rodríguez-Cadena, D., Pons, O., Cuerva, E., Josa, A., & Rieradevall, J. (2019). Feasibility assessment of rooftop greenhouses in Latin America. The case study of a social neighborhood in Quito, Ecuador. *Urban Forestry & Urban Greening, 44*, Article 126389. https://doi.org/10.1016/J.UFUG.2019.126389

Paiano, A. (2015). Photovoltaic waste assessment in Italy. *Renewable and Sustainable Energy Reviews, 41*, 99–112. https://doi.org/10.1016/j.rser.2014.07.208

Parece, T. E., Lumpkin, M., & Campbell, J. B. (2016). *Irrigating Urban Agriculture with Harvested Rainwater: Case Study in Roanoke, Virginia, USA* (pp. 235–263). Cham: Springer. https://doi.org/10.1007/978-3-319-29337-0_8

Petit-Boix, A., Devkota, J., Phillips, R., Violeta Vargas-Parra, M., Josa, A., Gabarrell, X., Rieradevall, J., & Apul, D (2018). Life cycle and hydrologic modeling of rainwater harvesting in urban neighborhoods: Implications of urban form and water demand patterns in the US and Spain. *Science of the Total Environment, 621*, 434–443. https://doi.org/10.1016/j.scitotenv.2017.11.206

Radzali, N. A. W. M., Shafri, H. Z. M., Norman, M., & Saufi, S. (2018). Roofing assessment for rooftop rainwater harvesting adoption using remote sensing and GIS approach. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives, 42(4/W9)*, 129–132. https://doi.org/10.5194/isprs-archives-XLII-4-W9-129-2018

Riyahi Alam, M. M., Behfar, A., & Shahmoradi, R. (2008). Potential Application of Solar Power Systems for Residential Buildings in High-Density Urban Pattern : The Case of the Eixample District, City of the Barcelona, in Spain. *Recent Researches in Environmental and Geological Sciences Potential*, 342–347. Energy saving; Buildings environment; Sustainable urban development; Solar water-heating system; Photovoltaic system.

Roberts, D. A., Quattrochi, D. A., Hulley, G. C., Hook, S. J., & Green, R. O. (2012). Synergies between VSWIR and TIR data for the urban environment: An evaluation of the potential for the Hyperspectral Infrared Imager (HyspIRI) Decadal Survey mission. *Remote Sensing of Environment, 117*(2012), 83–101. https://doi.org/10.1016/j.rse.2011.07.021

Rural Cat. (2019). *Rural Cat*. https://ruralcat.gencat.cat/web/guest/agrometeo.estacions#.

Saha, M., & Eckelman, M. J. (2017). Growing fresh fruits and vegetables in an urban landscape: A geospatial assessment of ground level and rooftop urban agriculture potential in Boston, USA. *Landscape and Urban Planning, 165*, 130–141. https://doi.org/10.1016/j.landurbplan.2017.04.015 (August 2016).

Sancho, J., Riesco, J., Jiménez, C., Sánchez, C., Montero, J.López, M., … (2012). Atlas de Radiación Solar en España utilizando datos del SAF de Clima de EUMETSAT. *Ministerio de Agricultura*. http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Atlas+de+Radiación+Solar+en+España+utilizando+datos+del+SAF+de+Clima+de+EUMETSAT#0.

Sanjuan-Delmás, D., Llorach-Massana, P., Nadal, A., Ercilla-Montserrat, M., Muñoz, P., Montero, J. I., Josa, A., Gabarrell, X., & Rieradevall, J. (2018). Environmental assessment of an integrated rooftop greenhouse for food production in cities. *Journal of Cleaner Production, 177*, 326–337. https://doi.org/10.1016/j.jclepro.2017.12.147

Sanyé-Mengual, E., Cerón-Palma, I., Oliver-Solá, J., Montero, J. I., & Rieradevall, J. (2013). Environmental analysis of the logistics of agricultural products from roof top greenhouses in mediterranean urban areas. *Journal of the Science of Food and Agriculture, 93*(1), 100–109. https://doi.org/10.1002/jsfa.5736

Sanyé-Mengual, E., Cerón-Palma, I., Oliver-Solà, J., Montero, J. I., & Rieradevall, J. (2015). Integrating horticulture into cities: A guide for assessing the implementation potential of rooftop greenhouses (RTGs) in industrial and logistics parks. *Journal of Urban Technology, 22*(1), 87–111. https://doi.org/10.1080/10630732.2014.942095

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. (2016). Urban horticulture in retail parks: Environmental assessment of the potential implementation of rooftop greenhouses in European and South American cities. *Journal of Cleaner Production, 172*, 3081–3091. https://doi.org/10.1016/j.jclepro.2017.11.103

Sojka, S., Younos, T., & Crawford, D (2016). Sustainable Water Management in Urban Environments. In T. Younos, & T. E. Parece (Eds.), *Sustainable water management in urban environments*. Springer International Publishing. https://doi.org/10.1007/978-3-319-29337-0 (Vol. 47).

Suomalainen, K., Wang, V., & Sharp, B. (2017). Rooftop solar potential based on LiDAR data: Bottom-up assessment at neighbourhood level. *Renewable Energy, 111*, 463–475. https://doi.org/10.1016/J.RENENE.2017.04.025

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). *Renewable Agriculture and Food Systems, 30*(1), 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. (2018). Towards Productive Cities: Environmental Assessment of the Food-Energy-Water Nexus of the Urban Roof Mosaic. *Journal of Industrial Ecology*. https://doi.org/10.1111/jiec.12829

Wiginton, L. K., Nguyen, H. T., & Pearce, J. M. (2010). Quantifying rooftop solar photovoltaic potential for regional renewable energy policy. *Computers, Environment and Urban Systems, 34*(4), 345–357. https://doi.org/10.1016/J.COMPENVURBSYS.2010.01.001

Worm, J., & van Hattum, T. (2006). *Rainwater harvesting for domestic use*. Agromisa Foundation and CTA.