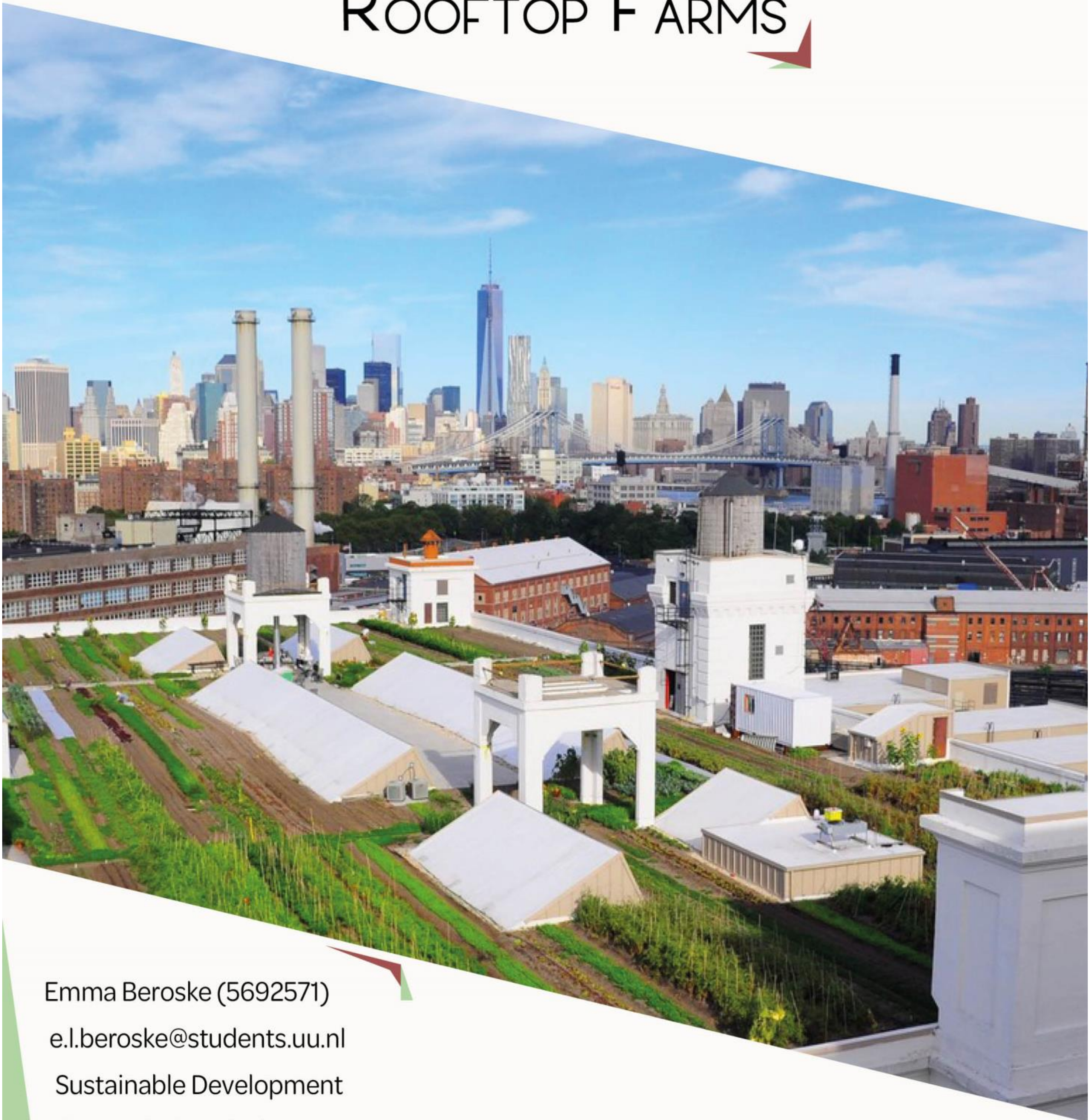
THE SUSTAINABILITY OF URBAN ROOFTOP FARMS



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Summary

Population is predicted to reach 9 billion by 2050 with a majority living in urban areas. With the effects of climate change and a growing number of mouths to feed, urban rooftop farming initiatives have emerged as an interesting solution to solving the myriad of challenges facing cities. The production of food on rooftops has been linked to a wide range of sustainability aspects as it can contribute to improving food security, heat island effect mitigation, biodiversity increase, job creation, storm water management and social cohesion. Rooftop farm initiatives have been gaining momentum over the past decades. A growing body of literature has been developed, reviewing the current trends, sustainability aspects and performance of rooftop farms compared to that of conventional production.

However, to achieve the full sustainability potential of urban rooftop farms, understanding the critical aspects that contribute to their impact considering the environmental, economic, and social perspectives is essential. This research focuses on understanding the classification of different types of rooftop farming initiatives by compiling ongoing urban rooftop farms (URFs) worldwide. A review of the current literature on the different sustainability aspects of rooftop agriculture is then conducted. Moreover, the study analyzes the environmental and economic performance of URFs by examining the life cycle assessment and costings to determine the key benefits, impacts and areas of improvement. The sustainability assessment then formed the basis for recommendations on the design of sustainable URFs. Results show that the typology, farming methods and function of URFs can vary widely in turn influencing their sustainability impact. At present, the metrics being used to evaluate the performance of URF do not evaluate the full range of sustainability benefits. Future research should focus on developing new metrics to provide a complete picture of the sustainability impact of rooftop farms.

Preface

The following thesis is presented "The Sustainability of Urban Rooftop Farms". This thesis project has been composed to fulfill the graduation requirements of the Sustainable Development (MSc) program at Utrecht University. In an increasingly urbanized world, retrofitting farms onto every potential roof appears to be an interesting solution. Examining the sustainability of food production within cities and the factors that influence it can inform future urban rooftop farming practitioners and urban planning.

I would like to thank prof. dr. Ernst Worrell for his helpful guidance and valuable feedback during the research process. It was a pleasure to be under his supervision. I would also like to reserve a special mention to my friends and family for their continuous support throughout the project.

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1. Introduction

1.1 Societal background

World population is projected to reach the 9 billion mark by 2050, almost two thirds of which is predicted to live in cities (Specht et al., 2014; UN, 2019). Although cities only occupy 2% of the Earth's surface, they consume 75% of its resources (Thomaier et al., 2015). Cities are known to have a considerable footprint on the natural environment and human well-being which extends beyond their political borders due to the extensive consumption of resources and production of waste (Harada & Whitlow, 2020). In addition, by virtue of their larger shares of both population and wealth, cities consume the most part of global food, the production of which is a major cause of multiple forms of environmental degradation (Goldstein et al., 2016). Against the background of increased urbanization and growing population, another mega-trend is threatening the ability to meet the rising demand for food namely the decrease in productive agricultural land (Specht et al., 2014). Agriculture occupies 40% of the planet's land surface and accounts for 25% to 33% of greenhouse gas (GHG) emissions, responsible for more than 70% of freshwater depletion, driving biodiversity loss due to deforestation and habitat fragmentation (Clark & Tilman, 2017). Large-scale industrial agriculture is also resource intensive and largely relies on fossil fuel laden chemicals and minerals that pollute aquatic and terrestrial ecosystems (Clark & Tilman, 2017; Goldstein et al., 2016). Besides the fact that productive land is becoming scarcer, food crops are competing for land, water, and other resources as well as other types of land uses such as bioenergy or nature conservation (Specht et al., 2014). In parallel, climate change poses an increasing threat on agricultural productivity and global food security. The changing nature of climate variability and extremes is estimated to reduce major crop yields by 3.1% to 7.4% and thus negatively affect food security (Molotoks, Smith & Dawson, 2021).

Furthermore, in an increasingly globalized and urbanized world, food supply chains cover longer transportation distances (Buehler & Junge, 2016). The geographical and psychological decoupling between the production location and location where the products are consumed is also a source of concern. In the United States, food travels an average of 1500 miles thus resulting in considerable associated environmental impacts (Saha & Eckelman, 2017). With an increased awareness on increasing food miles as a result of growing international food trade, environmental advocates have called on the localization of global food supply networks (Weber & Matthews, 2008). The geographical disconnect between farm and fork is further reflected in the alienation of consumers in cities from the food production, nature, and the basic values of rural life (Jansma & Visser, 2011).

Additionally, cities are facing increasing challenges. Urban areas are seen to produce warmer temperature than rural spaces resulting in an urban heat island effect phenomenon (Li et al., 2018). Simultaneously, the combustion of fossil fuel from factories and transportation means emits considerable numbers of pollution particles in the atmosphere of the built environment

(Li et al., 2018). Nevertheless, cities can play an important role in the creation of more resilient societies and are ideal breeding grounds for innovation. As increasing urbanization is unavoidable, there is an urge to mitigate the negative impacts of urban development on the natural environment (Specht et al., 2014; Thomaier et al., 2015). A sustainable city is a city where the needs of the present are met without compromising the ability of future generations to meet their own needs. A sustainable urban environment can thus be organized in such a way that it reduces its dependence on the surrounding countryside and becomes more self-reliant. There is thus a drive to reimagine cities with the least possible ecological footprint and minimal pollution, that efficiently use land, recycle materials, promote compost, and thus curtail the contribution of the urban environment towards climate change (Safayet et al., 2017). A major cultural shift is needed in cities in which maximized design quality and livability, cultural diversity and social prosperity are at its core. Authors have put a strong emphasis on the reintegration of food in cities to address these challenges (Thomaier et al., 2015).

With resources becoming scarcer and an increasing number of mouths to feed, urban agriculture (UA) arose as one of the solutions that can contribute to solving the myriad of challenges cities are facing. UA is defined as "an industry located within or on the fringe of a town, a city or a metropolis, which grows or raises, processes and distributes a diversity of food and non-food products, (re-)using largely human and material resources, products and services found in and around that urban area, and in turn supplying human and material resources, products, and services largely to that urban area" (Grard et al., 2018). Nevertheless, the concept of growing food in cities is not new and can be traced back to ancient civilization (Pons et al., 2015). However, nowadays, the limited land availability and competitive real-estate markets in cities are definite obstacles for the implementation of in-ground agriculture projects. Instead, retrofitting food production onto facades or rooftops of commercial or residential buildings is seen as an attractive alternative to occupy otherwise unused space in the built environment (Appolloni et al., 2021; Harada & Whitlow, 2020). These new types of urban farming initiatives fall under the term zero-acreage farming (ZFarming) which describes all types of UA characterized by the non-use of farmland or open-spaces (Specht et al., 2015). Different types of ZFarming practices exist globally, and their goal and purpose can vary (Buehler & Junge, 2016). Besides growing food, the goal of these green infrastructure projects can include stormwater management, air pollution abatement, biodiversity restoration, energy savings or recycling of food waste through composting (Harada & Whitlow, 2020). Rooftop agriculture (RA) is a form of ZFarming, consisting in the cultivation of plants and crops on the rooftops of urban buildings and has been recognized as a promising solution to enhance food security for an increasing urban population (Appolloni et al., 2021; Sanjuan-Delmás et al., 2018). RA is also considered to be a form of building-integrated agriculture (BIA) and can include both rooftop greenhouses (RTGs) and open-air rooftop farms (Appolloni et al., 2021). Urban rooftop farming is a field of growing interest and emerged as an effective measure to increase resilience to climate change while contributing to social and economic inclusion of marginal populations and those experiencing gender inequality (Appolloni et al., 2021). Urban rooftop farming projects are arising worldwide and are a source of new opportunities regarding resource efficiency, specific implementation processes and networks, new farming technologies, and new patterns of food supply and urban spaces (Thomaier et al., 2015).

1.2 Scientific background and previous studies

With UA rising as a popular countermovement to the fragility of the current food system, a growing body of scientific literature on urban rooftop agriculture has emerged (Buehler & Junge, 2016). Rooftop farming projects have surfaced globally, and studies have been reviewing the current status of the trend and their spatial distribution (Buehler & Junge, 2016; Appolloni et al., 2021; Thomaier et al., 2015). A study by Buehler and Junge (2016) investigates the current practices in large commercial urban rooftop farms (URFs) which they categorize into either hydroponic systems in greenhouses or soil-based open-air farms. After examining 57 case studies, they identify that further research is needed to improve the operation of hydroponic farms, deepen the technical and economic aspects of URF, and render them a widespread sustainable solution (Buehler & Junge, 2016). A study by Thomaier and colleagues (2015) investigated different ZFarming activities. They first analyzed the present practices of 73 existing ZFarms and described them in terms of strategic orientation, spaces used, farming method, farming products and market orientation. They then discussed the contribution that ZFarms can have to sustainable UA. Aspects such as resource efficiency, opportunities for new farming methods and new pattern in food supply networks were included (Thomaier et al., 2015).

Besides examining the different typology of UA, studies have also assessed the environmental aspect of these projects. Research has found that depending on certain factors, such as the structure of the farm, the type of substrate or the use of fertilizer, URFs can have a positive environmental performance (Sanyé-Mengual et al., 2015; Grard et al., 2018). Moreover, the operation of URF has been linked to various other sustainability aspects including development of local economy, social cohesion, and reduced energy use (Specht et al., 2014). A study by Specht and colleagues (2014) used a sustainability framework to illustrate the role of ZFarming in future urban food production. Dividing aspects of ZFarming into a social, economic, and environmental dimension, they reviewed the major benefits and limitation of these projects. Environmental advantages include reducing food miles and environmental impact of architecture. Social benefits encompass linking consumer to food production and improving community food security while commodity outputs are listed as economic advantages (Specht et al., 2014).

1.3 Knowledge gap

Research has found that urban agricultural activities in rooftop farming settings can be as unsustainable as conventional agribusiness if not managed properly (Specht et al., 2014). In addition, in northern climates, a study showed that UA may not be as environmentally beneficial as once presumed as it does not necessarily lead to reduced land use and carbon sequestration (Goldstein et al., 2016). Instead, solar cells were found to be a more advantageous option to mitigate climate change. However, when assessing their performance research tends to omit the social implications and the other sustainability aspects of urban rooftop farming projects such as their effect on biodiversity, food security, job creation, heat island effect reduction or community building. A full review of all the different sustainability aspect associated with URF is thus necessary to grasp their potential. Currently, research has largely focused on the environmental and economic dimensions of URF while the social dimension is generally not sufficiently addressed. In addition, many studies investigate the environmental and economic performance of URFs by conducting life cycle assessment (LCA) and seldom include life cycle costings (LCC) of these projects. However, a comparison of the different results has yet to be done. As urban rooftop farming presents a multitude of benefits, the implementation of URF projects on a larger scale remains an interesting regenerative solution that contributes to the development of sustainable cities. In order to render urban rooftop farming projects successful, operators need to use positive potentials meaningfully by focusing on local resources and energy efficient production while including the social dimension (Specht et al., 2014). A knowledge gap exists as to how urban rooftop farming projects can be made successful and as sustainable as possible while considering all three sustainability aspects.

1.4 Research aim

To reach the full sustainability potential of URF, their inputs should be carefully selected, and their operation should be optimized. This study aims to investigate which factors are most important when aiming to achieve sustainable urban rooftop farming projects. Sustainability is pertaining to a wide range of areas as reflected by the 17 Sustainable Development Goals (SDG) put forward by the United Nations. Several of the SDG encompass the notion of a sustainable and secure food supply within a resilient and low carbon infrastructure. In the context of URF, the sustainability impact of rooftop farming initiatives can be related to a wide variety of aspects including heat island effect mitigation, food security, energy efficiency or biodiversity improvements.

The research solely focused on rooftop farming initiatives onto which edible foods are grown including vegetables as well as livestock and honey production. All green roofs or non-food producing projects were thus not considered. In addition, the other indoor farming projects or in ground farms were excluded as this study solely aims to examine projects that are located on rooftops of building. Furthermore, this research seeks to understand the available evidence of the different sustainability impacts driving the implementation of URFs taking into accounts the environmental, economic, and social dimensions. Moreover, using life cycle assessment and life cycle costing studies, the research compares different elements of URF such as infrastructure and operation and examines their impact considering the three pillars of sustainability. A critical review of existing life cycle assessments and costings studies of URF is thus conducted. Finally, this research attempts to contribute to the existing body of literature by deepening the understanding of the sustainability impact of URFs. Recommendations for key design criteria for sustainable URFs can then be put forward to inform further urban planning and URF practitioners.

1.5 Research question

To attain the research aim, the following main research question was established:

> What are the critical factors that influence the sustainability of urban rooftop farms?

To answer this main research question, several research sub-questions were formulated, namely:

- How can existing urban rooftop farming projects be classified?
- What are the key sustainability aspects driving the implementation of URF?
- What is the environmental and economic performance of the different types of urban rooftop farms?
- Based on the sustainability assessment, what are the key design criteria for sustainable URFs?

1.6 Scientific and societal relevance

In increasingly densifying urban area, there is a dire need to layer the levels of cities and integrate food production on a more local scale to sustain growing population while doing it in a sustainable manner. Although urban rooftop farming projects are sprawling across many major cities around the globe, their implementation on a larger scale has yet to be achieved. In a world where urban farms would be retrofitted onto every possible rooftop, understanding their main benefits and tradeoffs is of paramount importance to reach their full sustainability potential. To render urban rooftop farming projects successful, there is a need to integrate environmental, economic, and social aspects of urban agriculture. Moreover, knowledge on the extent to which cities would reach a more sustainable environment is important to then provide rough recommendation on how they can be implemented.

2. Theory

In this chapter the different concepts used in the research and common food production methods used in urban rooftop farming projects are explored.

2.1 Urban agriculture

Although UA is not a novel concept, it has gained considerable momentum over the past decades. In 2000, a study estimated that 200 million city dwellers produce food for the urban market corresponding to 15 to 20% of the world's food supply (Dieleman, 2017). Since then, the amount has significantly grown as UA related activities have spread across cities in both developed and developing countries (Dieleman, 2017). Nowadays, UA is practiced in most parts of the world. In Ghana's capital city, Accra, up to around 90% of all fresh vegetables consumed originate from urban production while in Hanoi, Vietnam, 80% of vegetables are produced in urban and peri urban settings (Dieleman, 2017). Nevertheless, UA remains a complementary activity to the dominant agricultural production system taking place in rural areas, yet it still increases the overall efficiency of the food system (Orsini et al., 2020). UA can contribute to the production of certain crops such as cereals, roots and vegetables, fruits, and herbs, as well as livestock and other animal-based products including eggs, meat, and milk. Nonetheless, horticultural crops such as vegetables and aromatic herbs growing in small fields and gardens are dominating a vast part of UA projects (Orsini et al., 2020).

When considering UA in its different forms, one of its most crucial distinguishing features is its integration into the ecological, economic and social urban system. However, such level of integration firstly relies on the use of resources including land, water, labor, and organic wastes (Dieleman, 2017). On the other hand, it also depends on the extent to which UA projects produce for urban inhabitants and impact the city in terms of ecology, economy, food security, social cohesion, health, poverty alleviation and cultural meaning (Dieleman, 2017).

2.2 Urban rooftop farming

As one part of the many ways in which UA exists, the integration of food production in and on buildings, also called building-integrated agriculture (BIA), is considered one of the new approaches to food production. This practice offers the possibility to take advantage of otherwise unutilized space without impeding on the city's many uses for available land (Astee & Kishnani, 2010). BIA can take on many forms and can be categorized into sky farming, edible walls, and balconies, indoor farming and rooftop farming as illustrated in Figure 1. RA can be taken on by a wide range of stakeholders and can present an array of production systems and technologies for a variety of reasons and purposes (Dubbeling, 2017). Rooftop farming is instrumental in specific urban planning and development goals particularly pertaining to the optimization of city space and when attempting to address the impacts caused by climate change (Dubbeling, 2017). One of the most recent trends is the creation of rooftop gardens and vertical gardens in highly urbanized and densely built spaces presenting limited amounts of open space. These developments have mainly been a response to the need to invest in ecological infrastructure to meet demands for sustainability and resilience (Dieleman, 2017).

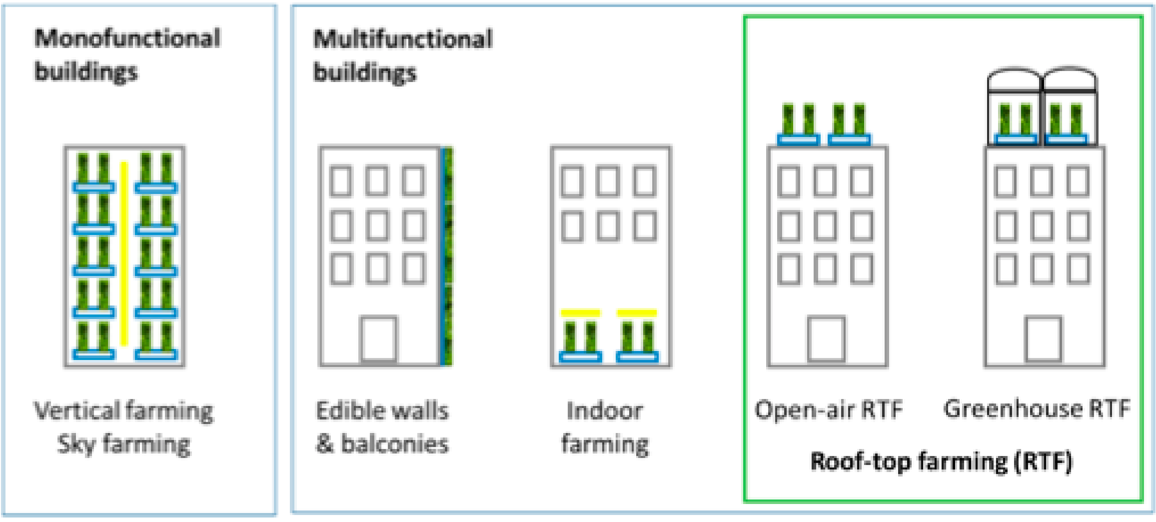

Figure 1: Typologies of the different forms of building-integrated agriculture (Buehler & Junge, 2016).

2.3 Typology of urban rooftop farms

As previously mentioned, URFs exist in many different forms and their farming methods can vary depending on the project. One of the most common types is represented by open-air rooftop farms or gardens which utilize low-tech systems such as growing containers or raised beds filled with soil (Orsini et al., 2020). The substrate used in soil-based systems is often translated soils and / or organic ones allowing for the cultivation of a wide range of crops with a high intensity level (Rodríguez-Delfín et al., 2017).

Another type of URF is rooftop greenhouses which are commonly associated with more complex technological systems used to increase both production capacity and resource efficiency (Orsini et al., 2020). These indoor systems often use growing systems without soil in situ referred to as soilless cultures. Soilless systems include plants grown either on solid rooting medium called substrate or directly in a nutrient-rich solution without any solid component called hydroponic systems or directly in contact with the atmosphere and recurringly sprayed with a nutrient solution in so-called aeroponic systems (Rodríguez-Delfín et al., 2017). Depending on the management of the drain solution or leachate, soilless systems are either open or closed loop. In open-loop systems, any excess leachate goes to waste and is not recycled while closed-loop systems allow for the captured drainage to be recycled (Rodríguez-Delfín et al., 2017).

2.4 Hydroponic system

Hydroponic systems utilize engineering techniques allowing for the optimization of crop production, quality, and yield (Gould & Caplow, 2012). In recirculating hydroponic systems, the roots of the growing plants are submerged in a nutrient-rich water containing all the essential minerals needed for a plant to grow thus removing the need for soil (Figure 2). Such recirculating system is considered one of the most modern and environmentally sustainable method as it reuses the same nutrient solution and water until all useful elements are depleted (Gould & Caplow, 2012). Nowadays, hydroponics is one of the most intensive methods for horticultural production. However, it necessitates high levels of technology and investment.

Different types of hydroponic techniques exist, and the Nutrient Film Technique (NFT) and floating hydroponics are two of the most employed systems. NFT is a water-based system consisting of a continuous flow of nutrient solution through the channels in which the plant roots grow and develop. The floating technique is a simpler system where the plant roots are grown on polystyrene trays that are floating in containers filled with nutrient solution (Rodríguez-Delfín et al., 2017). One of the main advantages of these systems is the reduction of soil-borne pathogens along with an improved control of nutrient and water supplies. This in turn fosters higher crop yield of high quality and nutritive value outperforming productions in traditional soil-based systems. In addition, in the case of closed-loop systems, better environmental protection can be assured as no leachate is leaked into the surroundings (Rodríguez-Delfín et al., 2017).

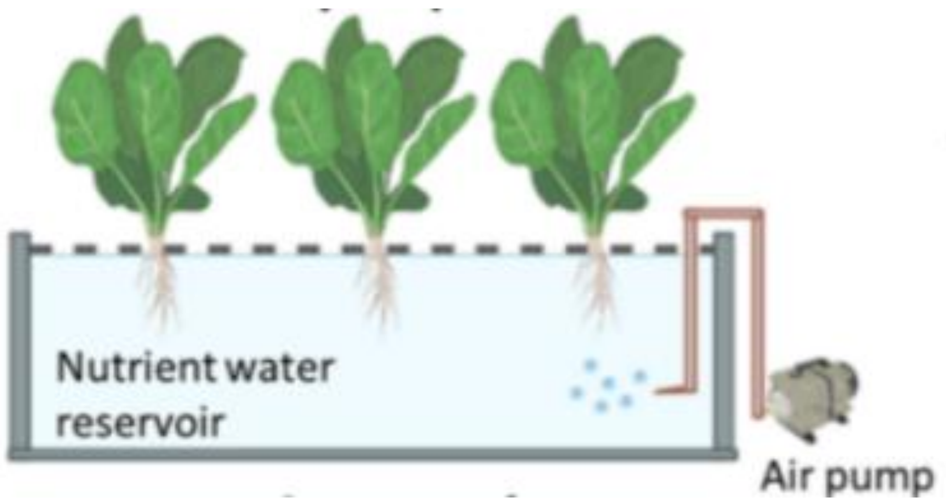

Figure 2: Diagram of a hydroponic system (from Maluin et al., 2021).

2.5 Aeroponic system

Like the hydroponic system, aeroponics is another type of soilless cultivation technique consisting in the production of plants suspended in the air and growing in a humid environment without a growing medium (Figure 3) (Reyes et al., 2011). In this air-water growing system, the lower portion of the plant is hung inside a growth chamber that is under complete darkness while the upper portion of the plant extends outside the growth chamber (Lakhiar et al., 2020). Due to the lightness of the system, the plant containers can be mounted on top of one another in a vertical column allowing for space optimization and high-level production per unit area. Nutrients are directly supplied periodically onto the roots of the plants through different atomization nozzles in a closed circuit and trickle down through the growth column (Lakhiar et al., 2020; Ziegler, 2005). As the plant consumption is limited to the absorption of the necessary amount of nutrient, a significant amount of water savings can be achieved (Ziegler, 2005). Similarly to the hydroponic system, this efficient growing technique allows for a high yield under specific controlled conditions including nutrient concentration, pH, temperature, spraying time and intervals and oxygen availability (Lakhiar et al., 2020).

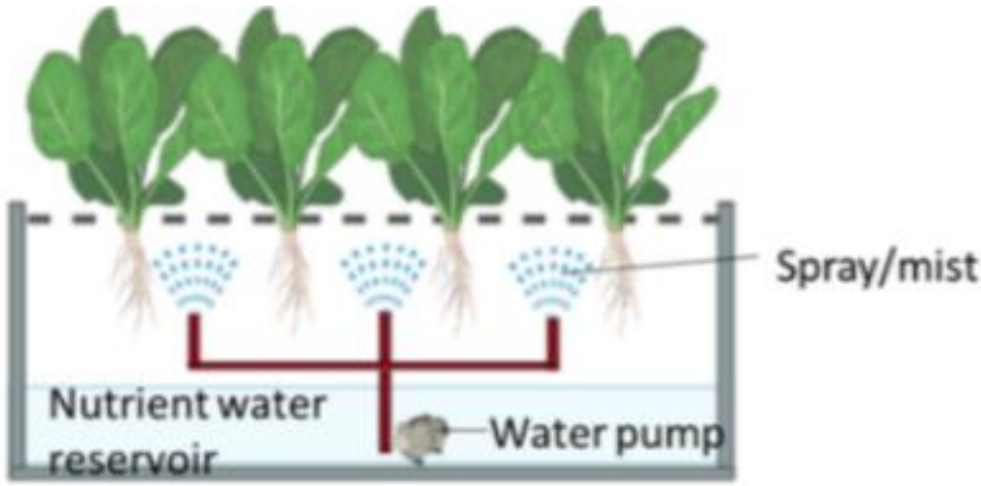

Figure 3: Diagram of an aeroponic system (from Maluin et al., 2021).

2.6 Aquaponic system

Aquaponics is a modern farming technique which combines the production of horticultural products in a hydroponic system with a water-based production system rearing aquatic organisms (Figure 4) (Alsanius, Khalil & Morgenstern, 2017). This advanced food production technique recycles the nutrient-rich wastewater from the fish tank through the hydroponic unit subsequently fertilizing the plants. The closed-loop system thus avoids the discharge of phosphorus and nitrogen laden water into the environment (Lakhiar et al., 2020). In addition, the synergetic interaction between fish, microorganisms and plants minimizes the need for nutrient and for mineral fertilizer input and the output of waste thus reducing the environmental impact of both fish and plant production (Goddek et al., 2015).

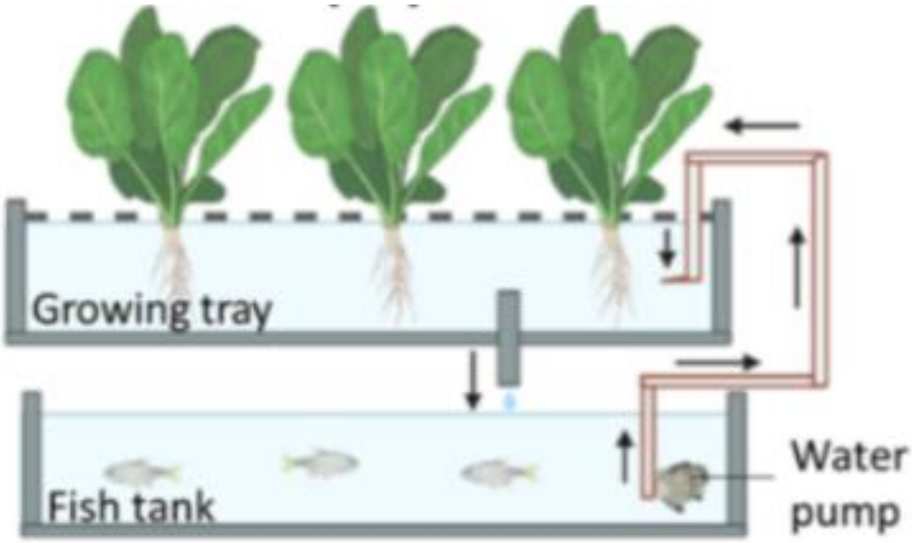

Figure 4: Diagram of an aquaponic system (from Maluin et al., 2021).

3. Methods

The methodological approach used in this research is described in the following section (Figure 5). To answer the main research question, a classification of existing URF projects was first conducted. Thereafter, a literature review compiling the different sustainability aspects driving the implementation of URF was performed. Another literature to investigate the environmental and economic performance of different types of URF initiatives was then presented. Based on the sustainability assessment, recommendations on key design criteria can be put forward to reach sustainable URF.

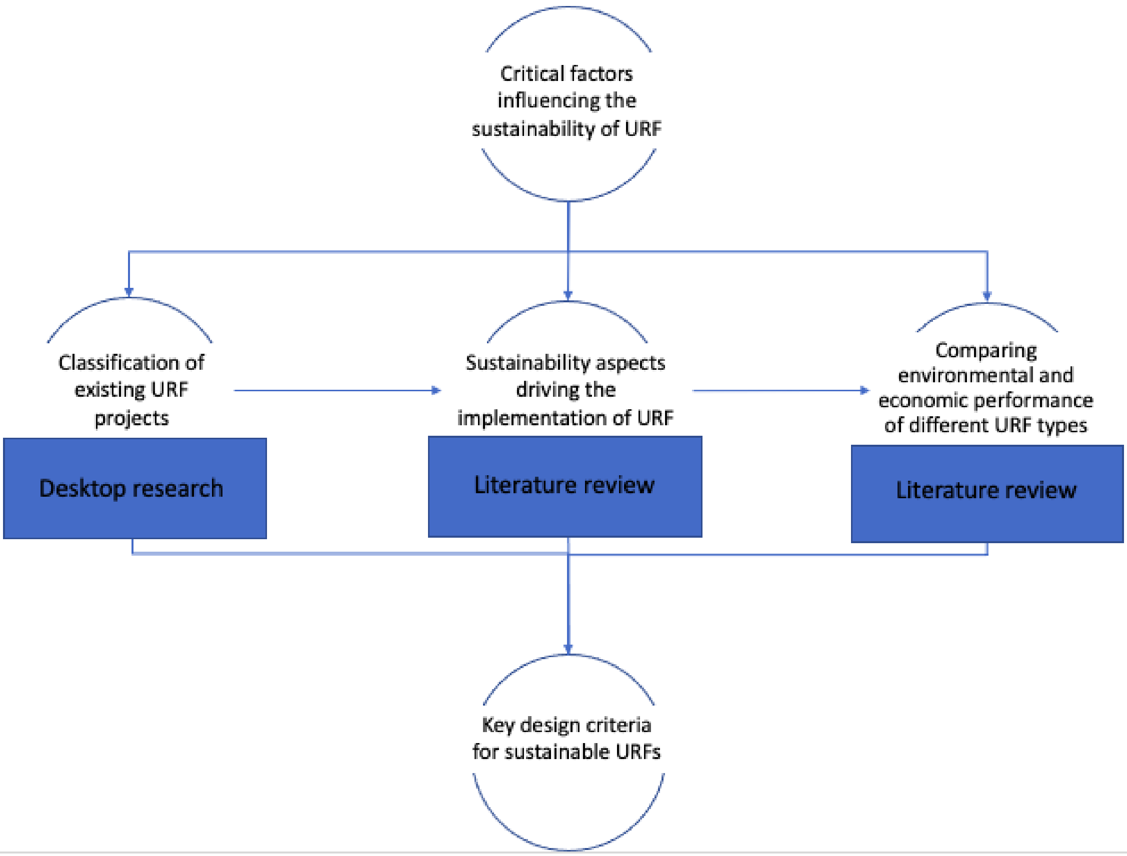

Figure 5: Methodological approach used for this research.

3.1 Classification of urban rooftop farms

3.1.1 Search and selection criteria

To understand the different elements that constitute existing urban rooftop farming projects and their purpose, extensive research was carried out to create a comprehensive list of ongoing URF projects. A database was built upon previously established classifications of URFs found in the literature and complimented by conducting additional desktop research. Non-scientific articles, grey literature and other urban agriculture websites were examined in the search of previously unidentified projects. The methodological approach used in this research was based on the methods used in studies by Buehler and Junge (2016) and Thomaier and colleagues (2015) which investigated the global trend and present practices of rooftop farming and ZFraming projects. With the help of search engines such as Google and Google Scholar, a variety of scientific articles, news articles, websites, reports, and blog posts were collected from which different urban rooftop farming projects were found. In addition, websites of URF companies and urban farming news portal were used to identify more case studies. The search for different projects across the globe was carried out by using the key words “urban rooftop farm” combined with a country or city name. The methodological approach consisted of searching for the presence of existing URF projects by continents and different counties.

Once the URF project found, the following parameters were recorded namely its name, location, size, year of commissioning, type of farming method divided into open-air and indoors (i.e., greenhouse) and further specified into hydroponics, in soil, raised beds, aquaponics or aeroponics system. The type of building the project is set up on, the type of food grown, and its primary function divided into commercial, life quality, educational or social and research were also recorded. If applicable, the secondary function of a project was also noted. The parameters are further depicted in Table 1 and were used to evaluate each URF project. The function description is based on the methods of the study by Buehler and Junge (2016). A detailed description of each function can be found in Table 2.

Furthermore, the inventory only included projects for which all relevant information could be found namely, the surface area, the year of commissioning, type of rooftop farming and its function. Once a suitable project found, complementary desktop research was carried out to collect relevant information. A Google Maps search was also done to identify whether a green rooftop can be observed from above. To obtain additional information, the search was complemented by social media platforms of the projects, explaining the nature and background of the initiative. While the inventory of existing URF is by no means exhaustive and statistically representative, it does serve the purpose of providing a broad overview of current initiatives of urban rooftop farming projects worldwide.

Table 1: Description of the different parameters used to categorize urban rooftop farming projects.

Parameter	Description
Location	Name City / Country / Continent
Commissioning	Year
Surface area	Area in m^2
Farming method	Open-air, indoor greenhouse, in soil, aquaponics, hydroponics, aeroponics
Building type	Office building, residential, industrial, hospital, school, warehouse, shopping center, supermarket, other
Function	Commercial, life-quality, educational / social, research
Type of food	Vegetables, fruits, aromatic herbs, edible flowers, chicken, fish, bees

Table 2: Description of the different functions of urban rooftop farming projects.

Function	Description
Commercial	- Main objective is to sell produce to costumers - Farm is mainly run by paid workers
Life-quality	- Main objectives are social activities and education - Farm is mostly run by volunteers - Products are sold and consumed by the operators / volunteers
Educational / social	- Farm is built on an institution: school, hospital, community center - Objectives: food production, recreation, and education
Research	- Research into URF or other scientific field of agriculture

3.1.2 Data processing

Once the URFs recorded, the compiled data was processed using Excel to calculate and visualize the most frequent trends. Firstly, the geographical location of the URF was examined to find in which cities, countries and continents URF projects were most prevalent. Moreover, the year of the projects' commissioning was examined to understand when they first started being developed and gaining momentum. The surface of the cultivated rooftop area was also examined to establish which size is most common. Thereafter, the types of farming system used were assessed to establish which cultivation methods are most used. Additionally, the types of building onto which rooftop farms are being installed was investigated to determine which types are most frequent. As certain projects can have more than one function, the primary function was first examined followed by a secondary function when applicable and their absolute frequency was determined. Finally, the absolute frequency of the types of food being produced was investigated to see which are the most recurrent.

3.2 Sustainability aspects driving the implementation of urban rooftop farms

A literature review was conducted to assess the state-of-the-art of the sustainability aspects related to URFs taking into account the three sustainability dimensions. This part of the research seeks to understand they key sustainability aspects driving the implementation of URFs and in what ways their operation is related to sustainability. Moreover, it aims to examine which important factors are most frequently included in URF studies. A more specific focus was put on the environmental, economic, and social dimensions mentioned in scientific literature of urban rooftop farming projects. Using search engines including Google Scholar, Scopus, and Web of Science, a range of scientific articles was selected based on relevance of the study. A combination of a several key words such as environmental, economic, and social sustainability, urban rooftop farms and integrated rooftop agriculture were used to find suitable literature. Only relevant scientific articles that specifically focused on rooftop agriculture and investigated any sustainability aspects of URF were selected. Therefore, articles which more generally addressed the concept of urban agriculture and not rooftop farming were not considered. A snowball sampling method was utilized to uncover relevant articles using a key document as a starting point from which new articles could be retrieved from the bibliography. The selected studies and articles specifically addressed environmental, economic, and social potential and limitations of URF. The most frequent aspects of sustainability associated with URF mentioned in the literature were then compiled.

3.3 Comparing the sustainability performance of urban rooftop farms

In this part of the study, LCA and LCC studies on URFs are investigated to compare the environmental and economic performances of rooftop farming projects depending on how they are set up.

3.3.1 Life cycle assessment

LCA is a methodology used to quantify the environmental impact of a system or product over its whole life cycle (Sanjuan-Delmás et al., 2018; Hauschild, Rosenbaum & Olsen, 2018). The quantitative nature of the method allows to compare the environmental impacts of different processes and can be used to point to the processes that are the most environmentally impactful (Hauschild et al., 2018). LCA can cover a broad range of environmental issues which include climate change, land occupation and transformation, freshwater use, aquatic eutrophication, toxic impacts on human health, depletion of non-renewable resources and eco-toxic effects from metals and synthetic organic chemicals (Hauschild et al., 2018). The method has been standardized in ISO 14040 (2006a) - 14044 (ISO 2006b) and according to these standards, an LCA should be conducted in a four-stage process consisting of the goal and scope definition, inventory analysis, impact assessment and finally the interpretation (Sanyé Mengual, 2015).

The goal and scope definition are intended to establish the purpose of the study and application. The context of the study is set by the goal definition which then forms the basis for the scope definition (Hauschild et al., 2018). It is also in this phase that a functional unit is determined which is a quantitative representation of the function or service for which the assessment is performed (Hauschild et al., 2018). The geographical and temporal boundaries of the study must also be selected to clearly separate the system from the environment (Hauschild et al., 2018). Following the definition of the goal and scope, the inventory analysis compiles information regarding physical flows in terms of input of resources, materials, semi-products, and products along with the output of emissions, waste, and other valuable products of the system (Hauschild et al., 2018). Thereafter, the life cycle impact assessment stage transforms the physical flows from the inventory results into their environmental impact (Sanyé Mengual, 2015). Finally, the interpretation stage considers the results of both the inventory analysis and impact assessment to reach a main conclusion and provide recommendation to support potential decision-making process (Sanyé Mengual, 2015).

3.3.2 Life cycle costing

Although LCA has mainly been used to determine the environmental impact of a system, social and economic impact can also be included (Hauschild et al., 2018). LCC is another technique which aims to quantify the costs associated with the life cycle of a product (Hauschild et al., 2018). Conducting an LCC can have several purposes as it can be used as a planning or optimization tool or it can be part of a life cycle sustainability assessment or to evaluate investment decisions (Hauschild et al., 2018). Following a similar approach to the LCA, LCC consists of a four-phase method that follows the ISO 14040 standards (Sanyé-Mengual, 2015). However, the impact assessment stage that is used in LCA is converted to an aggregation step in LCC where costs are grouped by categories (Sanyé-Mengual, 2015). If the LCC is conducted in parallel to an LCA, the functional unit and system boundaries must be identical. Moreover, costs must be quantified in one currency and should be based on a common year when performing the inventory analysis (Hauschild et al., 2018).

3.3.3 Search and selection criteria

A literature review to retrieve relevant LCA and LCC studies investigating the environmental and economic sustainability of URF was first conducted. As economic and environmental aspects of URF are more easily quantifiable than their social impacts, a focus on these two dimensions has been chosen. To gather the scientific literature, search engines such as Google Scholar, Scopus, and Web of Science, were used with a combination of key words including sustainability, life cycle assessment, life cycle costing, environmental impact, and urban rooftop farm. To be included in the review, the article had to specifically conduct either an LCC or and LCA or both. Once the relevant studies selected, the LCA and LCC findings of different urban rooftop farming projects were assessed and compared. To ensure a fair comparison, the system boundaries and functional unit used for each LCA and LCC were also considered. Lessons on the most sustainable practices were then drawn from the different LCA and LCC results, and recommendations on the design of sustainable URFs were put forward.

4. Results

In this section, the results of the study are shown. First the classification of the existing URF initiatives is presented. Thereafter, the different drivers for the implementation of URF and the sustainability aspects they are associated with is put forward. Finally, the assessment of the LCA and LCC studies of URF is described.

4.1 Classification of urban rooftop farms

The search for existing urban rooftop farming projects resulted in the compilation of a total of 144 cases (see Appendix 1). An overview of the spatial diversification of the projects can be found in Table 3. The spatial diversification, type of farming methods and functions of the different URF are illustrated in Figure 6.

Table 3: Spatial diversification summary of urban rooftop farms.

City	N	Country	N	Continent	N
Paris	18	USA	31	Europe	53
New York	16	France	31	North America	42
Hong Kong	15	China	22	Asia	41
Tokyo	7	Canada	11	Africa	4
Chicago	5	Japan	7	Oceania	2
Montreal	5	Belgium	5	South America	1
Shanghai	4	Italy	4	Central America	1
Toronto	3	Singapore	4		
Turin	3	Germany	3		
Dhaka	2	Netherlands	3		
Boston	2	South Africa	3		
Other	60	Other	20		

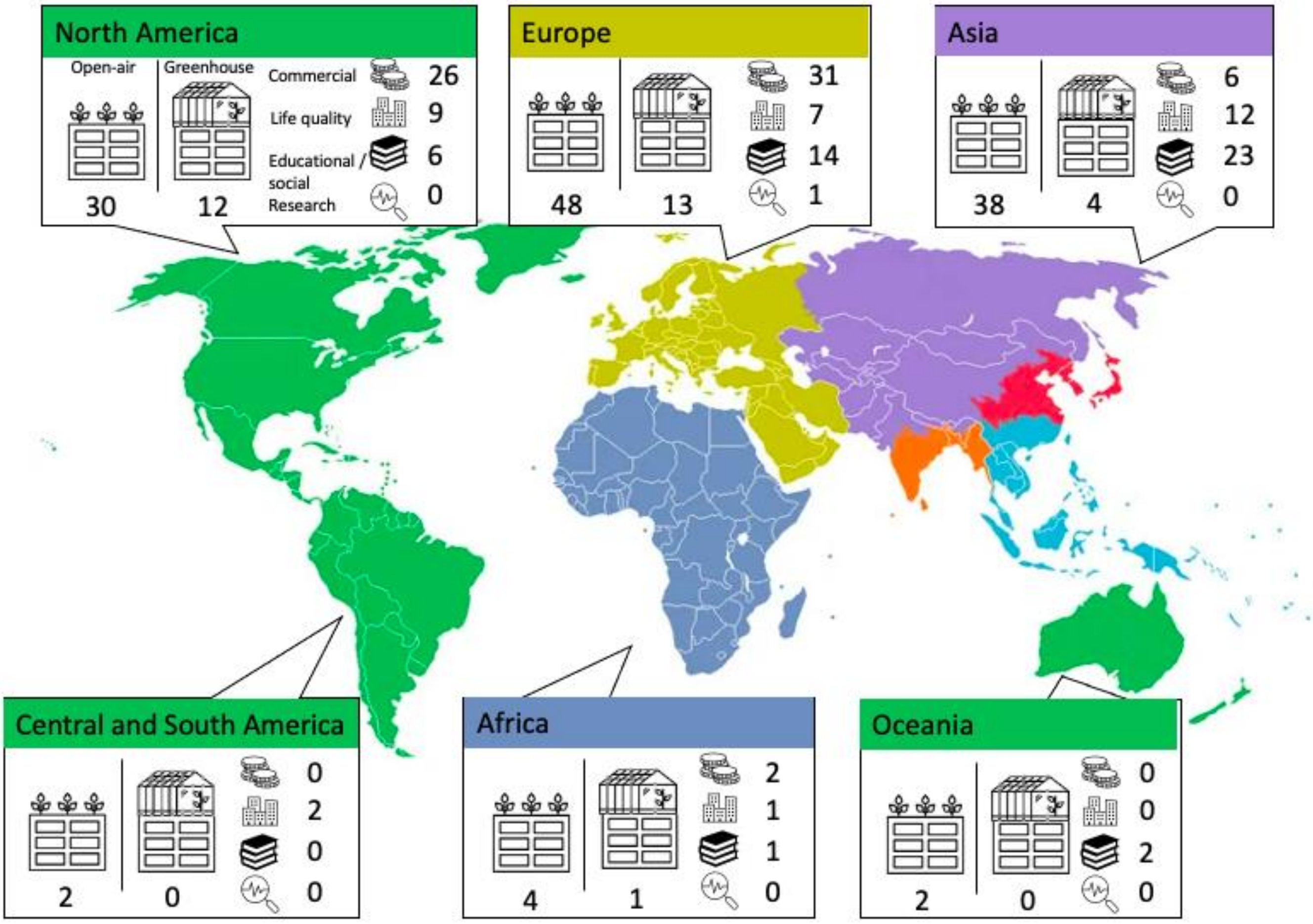

Figure 6: Spatial diversification, type of farming methods and function of URF projects worldwide (adapted from Appolloni et al., 2021).

4.1.1 Spatial diversification of URF projects

Regarding the spatial diversification, the majority of URF projects were found in Europe (N = 53) followed by North America (N = 42) and closely followed by Asia (N = 41). Conversely, fewer projects were found in Africa (N = 4), Oceania (N = 2), and South and Central America (N = 2). For the vast part, rooftop farming initiatives were mostly found in the Northern hemisphere with France (N = 31) and the United States (N = 21) having the most projects. China and Japan also presented a multitude of projects with 22 and 7 projects encountered respectively. At the city level, a large majority of projects was found in Paris (N = 18 with a total rooftop farming area of 3.99 ha) followed by New York (N = 16 with a total rooftop farming area of 3.29 ha) and Hong Kong (N = 15 with a total rooftop farming area of 0.89 ha). However, the most common trend observed is the presence of only one URF project in a city.

4.1.2 Commissioning

In terms of year of commissioning, most projects have started in recent years with an average of projects founded in 2013. A sharp increase in URF can be observed after 2010 (Figure 7). The oldest project found started its operation in 1988. The rooftop farm of the Changi General Hospital is set up in Singapore and was built with the idea to create a more restful and serene environment for patients while producing food for the hospital and absorbing the heat of the roof (Figure 8) (Changi General Hospital, 2021). The most recent project encountered was built in 2021 and is found on the rooftop of an office building on the outskirts of Paris. This project called Farm West Colombes consists of the installation of aeroponic towers producing a variety of vegetables, fruits and aromatic herbs distributed to the employees of the building (Figure 8) (Farm West – Colombes, 2021).

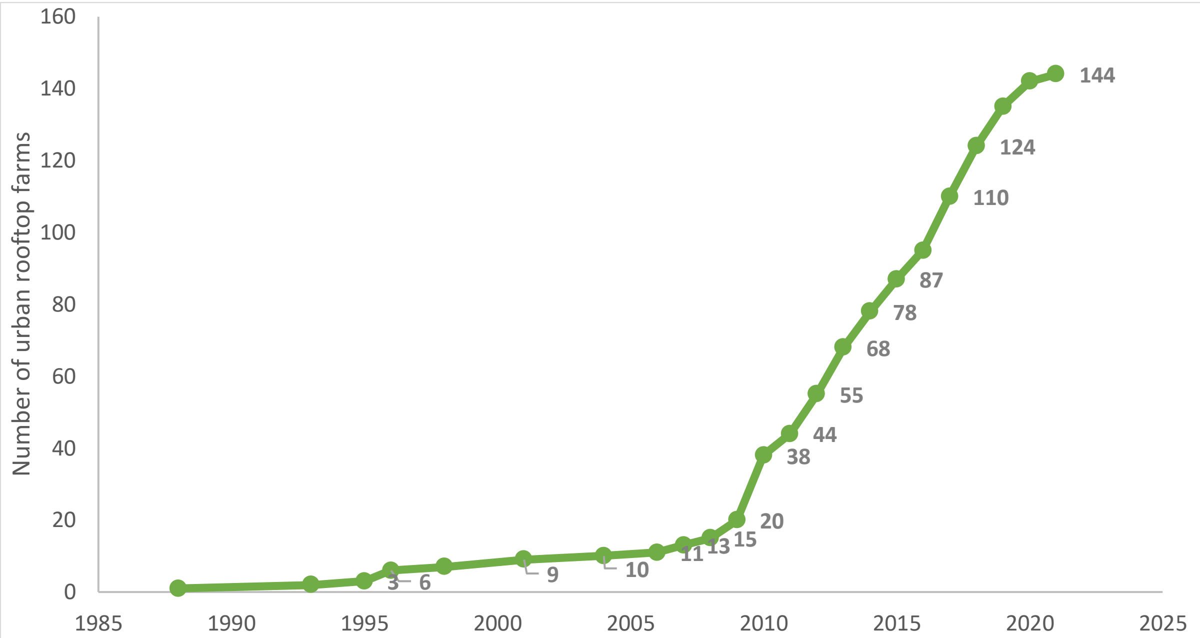

Figure 7: Cumulative frequency of urban rooftop farm commissioning over the years.

Figure 8: Different urban rooftop farming projects. a) Changi General Hospital is the oldest recorded URF. b) Farm West Colombes aeroponic towers. c) Lufa Ville St Laurent is the largest commercial rooftop greenhouse farm, d) Nature Urbaine is the next largest URF project e) the aquaponic REWE Green Farming project is set on top of a supermarket. f) Sky Farm makes use of advanced technology. g) BIGH combines aquaculture with hydroponics. h) Thammasat University mimics the design of rice terraces. i) Dakakker integrates several systems to make their project more efficient.

4.1.3 Surface area

Concerning the surface area of the compiled URFs, most projects were found to be above 500 m^2 with an average of around 1,590 m^2 while the smallest project covered an area of 10 m^2. Overall, larger projects were mostly found in Northern America and Europe. A noticeable trend was that projects of larger sizes were mostly associated with a commercial orientation while smaller projects had a more life quality improvement function. The largest project encountered reaches a total surface area of 15,200 m^2 and was found in Montreal. This commercial farm, Lufa Ville Saint Laurent is currently the biggest rooftop farm in the world and is set as a greenhouse on top of an industrial building (Figure 8) (Our Urban Rooftop Farm, 2021). A project of similar size, reaching 15,000 m^2, called Nature Urbaine has been installed in Paris on top of an exhibition center and was commissioned in 2020 utilizing hydroponics and aeroponics in the open-air as their main farming methods (Figure 8) (Nature Urbaine, 2021).

4.1.4 Types of building used for URF

The types of building used for urban rooftop farming projects varied widely from the rooftops of residential buildings to schools or office buildings (Figure 9). It was generally found that most URF projects were retrofitted on top of shopping centers (N = 21) followed by office buildings (N = 20) and industrial buildings (N = 18). According to Ackerman and colleagues (2014), an explanation for why many projects are found on top of industrial buildings may be due to the fact that they are highly suitable for rooftop farming due to a strong existing transportation network, adequate infrastructure as well as an access to redevelopment capital (Ackerman et al., 2014). In addition, supermarkets were also a common site for rooftop farming activities in recent years. This is for instance the case of the REWE Green Farming in Germany which is a 1000 m^2 indoor greenhouse utilizing an aquaponic system focusing on the production of perch and basil (Figure 8). The installation of rooftop farms on top of supermarkets can be seen as a way to facilitate shorter supply chains. This is also the case for farms found on top of office buildings where the food produced can be used in the kitchens' cafeteria or directly taken by the employees. Moreover, the large-scale buildings in the form of warehouses or industrial buildings often presented commercial functions while rooftop farms retrofitted on the roofs of residential buildings tended to have a life-quality improvement function.

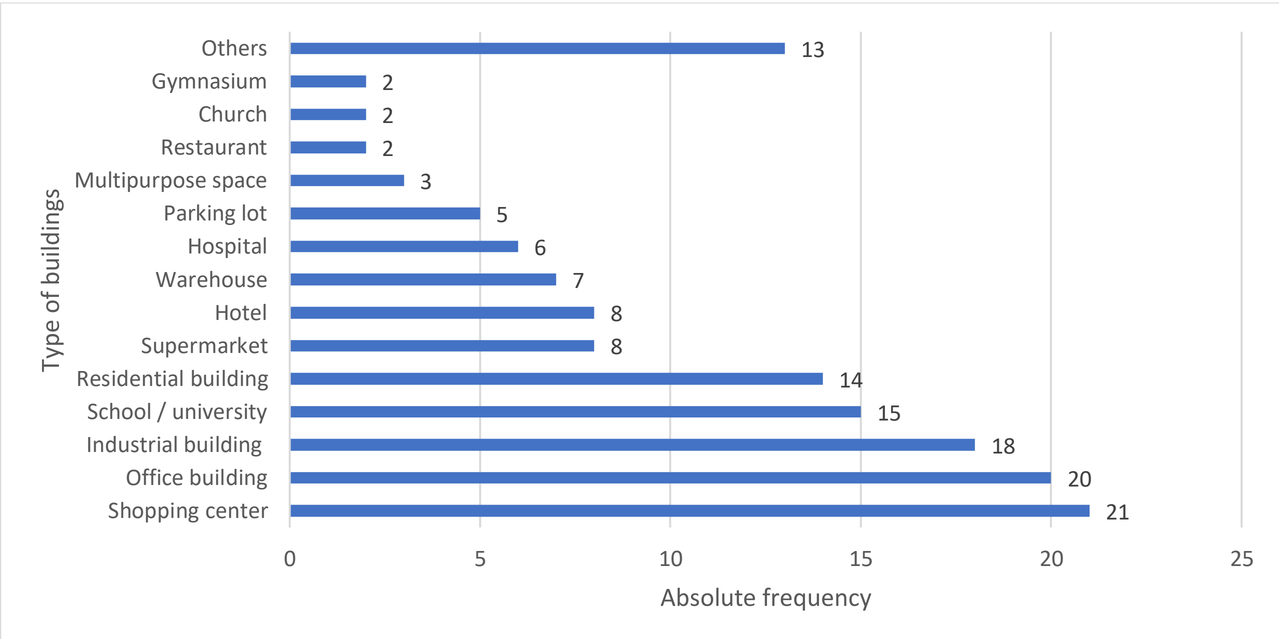

Figure 9: Absolute frequency of the types of building used onto which urban rooftop farming projects are set up.

4.1.5 Farming method

The type of farming methods also varied widely depending on the urban rooftop farming projects (Figure 10). Nevertheless, the most dominant farming method appeared to be under open-air settings (N = 122) whether directly in soil (N = 41) or in the form of filled raised beds or growing containers (N = 72) while indoor greenhouse projects were less frequent (N = 33). Some projects combined the installation of a greenhouse within open-air settings. Many hydroponic systems (N = 22) were encountered as well as aeroponic systems (N = 16) while aquaponics farming system were less prevalent (N = 6). These types of soilless growing systems were most often used in rooftop greenhouses.

The level of complexity of the farming methods was diverse with some projects making use of more technologically advanced systems than others. This was the case of the rooftop project Sky Farm in Shanghai which utilized a vertical farming system with detectors that can activate artificial sunlight and control water levels (Figure 8). Projects using aquaponic farming systems were also more high-tech. This is for instance seen in the aquaponic rooftop project BIGH in Brussels that utilized sustainable technology capturing the energy loss of the building and using rainwater harvesting and recycling systems along with renewable solar energy to run its operation (Figure 8) (BIGH: Brussels Aquaponic Farm, 2021). Other projects utilized more low-input systems or even used designs inspired by nature. This was the case of the rooftop farm at Thammasat University near Bangkok which mimicked the design of rice terraces and utilized traditional agricultural practices as model for their food production (Figure 8) (Thammasat University Urban Rooftop Farm, 2021). Furthermore, the project Dakakker in Rotterdam has a worm compost system that transforms organic waste into fertilizer which can be applied on the roof (Figure 8). In addition, a smart water collection system is currently being tested on the roof. Using a smart flow control based on weather forecast, the smart roof can increase its water storage capacity and ensures a slow drainage of rainwater in periods of heavy rainfall (Dakakker, 2021).

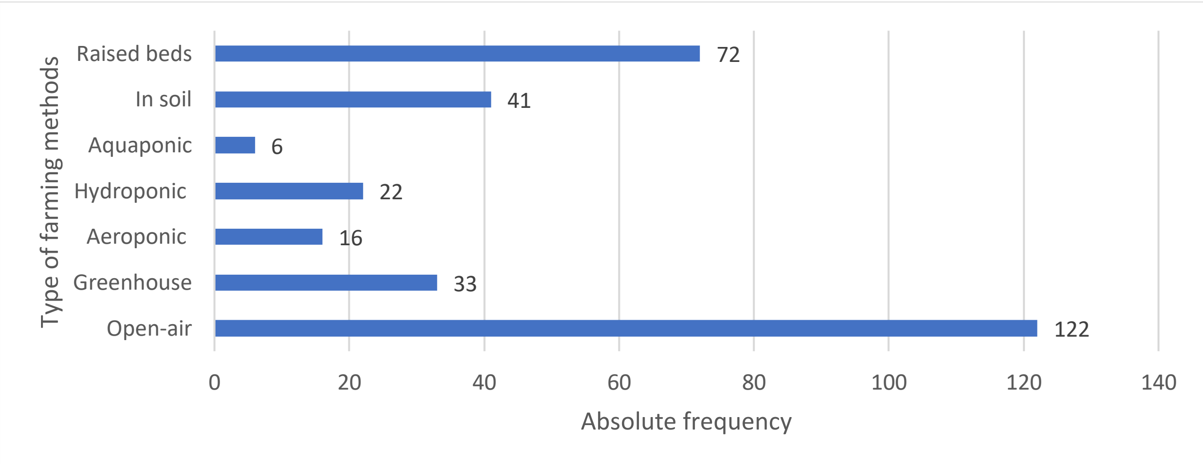

Figure 10: Absolute frequency of the types of farming methods used in the identified urban rooftop farms.

4.1.6 Function

The primary function of the existing URF often appeared to be commercial (N = 66) where the food produced was either directly sold to consumers or to restaurants nearby or linked to a restaurant within the same building (Figure 11). This model guarantees the delivery of extremely fresh produce and short travel distances. In certain cases, commercial projects also included a secondary function such as an educational or life-quality improvement dimension for instance when their activity was combined with workshops and other events that promote learning about sustainable food production. Furthermore, several projects had a more life-quality improvement (N = 45) or educational or social orientation (N = 31) as their primary function where the produce being grown were mainly meant for local consumption and awareness raising on sustainable food productions. Life quality improvement is mostly meant in the sense of educating people on fresh, local, and seasonal foods and strengthening the connection between farm to fork. In addition, many projects also offered the possibility of renting available plots within the rooftop fields for individuals to grow their own foods. Altogether, these socially oriented projects tend to foster community building and knowledge exchange. Only a few projects (N = 4) focused on research as a primary or secondary function.

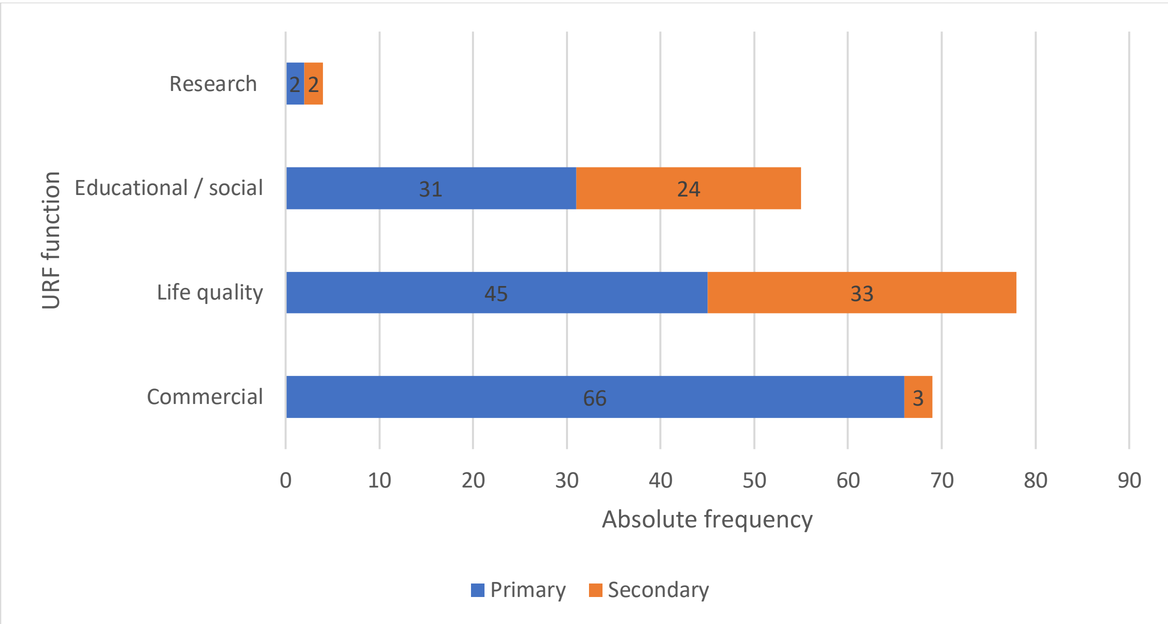

Figure 11: Absolute frequency of the primary and secondary functions of urban rooftop farms.

4.1.7 Type of food produced

For the vast majority, almost every project focused on the production of vegetables (N = 136) accompanied by production of aromatic herbs (N = 106) while fruits (N = 51) are less frequently produced (Figure 12). In certain cases, projects had opted to solely focus on the production of one or two types of foods thus restricting the number of crop types while other diversified their production and incorporated edible flowers (N = 22) or the installation of beehives (N = 24). A recurrent trend seen across many projects was the fact that food was grown organically, without the use of any pesticides or antibiotics when animals were involved.

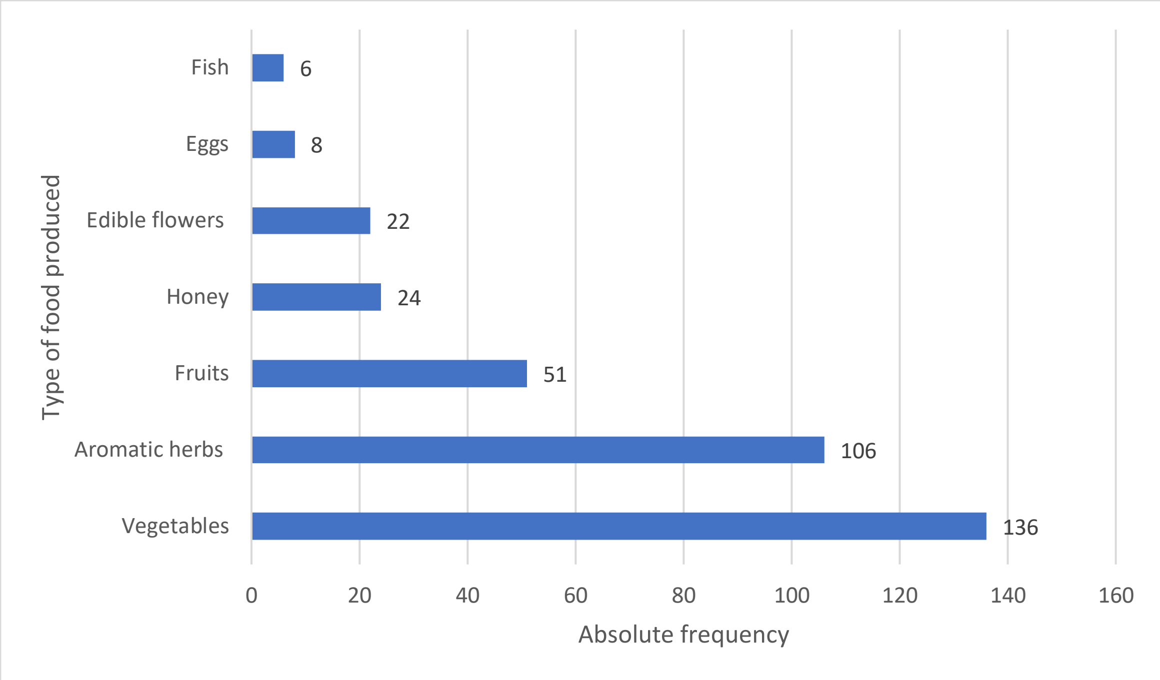

Figure 12: Absolute frequency of the type of food produced on urban rooftop farms.

4.2 Sustainability aspects driving the implementation of urban rooftop farms

A total of 23 studies were analyzed to determine the most recurrent sustainability themes mentioned in the literature that drive the implementation and operation of URF. Out of the studies, an emphasis was placed on the investigating of environmental impacts of URF such as urban heat island mitigation, energy savings or the creation of habitat for biodiversity improvements. Additionally, as URF projects tend to be multifunctional, their environmental, economic, and social sustainability benefits may overlap at times as an interrelation exists between the dimensions (Table 4). For instance, an improvement in energy efficiency and water management can not only have a positive environmental impact but also an economic one as in the long run such impacts may also prevent other direct and indirect costs related to infrastructure or health for instance. Similarly, providing nutritious food to urban dwellers not only has a positive health impact and thus a social dimension but also has an economic impact as healthy diets benefits the economy by placing a lower burden on the health care sector. Yet many of these effects may be difficult to quantify.

Table 4: The different drivers for URF implementation and the interconnectedness of their sustainability aspects.

Sustainability impact	Environment	Economic	Social
Water retention	x	x	
Energy savings	x	x	
Heat island effect	x	x	
Climate change	x	x	x
Ecological footprint and food miles	x	x	x
Land use	x	x	
Biodiversity	x		
Urban air quality	x	x	x
Waste reduction	x	x	x
Employment		x	
Food affordability		x	x
Food provision and food security		x	x
Access to healthy food			x
Health and wellbeing		x	x
Education			x
Linking consumer to producer			x
Community building and resilience	x	x	x

4.2.1 Water management and water savings

Managing water runoff is a crucial aspect of urban planning. Urban vegetation, and more specifically URFs, can significantly improve stormwater management and decrease the impact of heavy rainfall on urban surfaces while providing runoff regulation (Orsini et al., 2020). In fact, UA related activities increase water retention and reduce the peak flow allowing to prevent overloading city sewage infrastructure which is usually one of the causes of urban flooding. URFs increase the water retention capacity of cities. A study estimated that green roofs can reduce runoff through water interception and evapotranspiration with an average precipitation retention of 56% (Lucertini & Giustino, 2021). Another study by Grard and colleagues (2018) investigated the potential of URF in terms of mitigation of runoff water and found that most of the rainfall was retained by the cropping units. The topsoil layer used as substrate for plant growth on rooftops was found to retain 74–84% of the incoming rainfall water (Grard et al., 2018). In addition to the environmental impact of URF on water runoff mitigation, storm water retention from rooftop farming can also save significant costs to the municipality and thus present considerable economic benefits such as avoided costs associated with flooding events (Safayet et al., 2017). Although URFs are known to retain precipitation and reduce the amount of stormwater runoff, there is a lack of clarity on the impact of rooftop farms on the quality of water runoff. Increased quality of runoff water may not be achieved as URF can release low concentrations of fertilizer (Ackerman et al., 2014).

Water savings can also be achieved with URF. Theoretical scenarios of implementing RTGs on retail parks in several world cities estimated that rainwater harvesting from the greenhouse roof could satisfy the crop water requirements (Orsini et al., 2020). For rooftop farms using hydroponic systems, a study described the use of four times less water than conventional farming for the same yield of vegetables (Astee & Kishnani, 2010). Moreover, a study found that each hectare of a re-circulating hydroponic greenhouse has the potential to replace 10 hectares of rural land and save up to 75,000 tons of fresh water per year (Caplow, 2009). To achieve this, recycling water transpiring from crops could be implemented. Such system consists of cooling traps allowing the evaporated water in the greenhouse atmosphere to be fed back into the system. Another solution consists in the conversion of gray water into irrigation water with appropriate conditioning (Specht et al., 2014).

4.2.2 Energy savings and energy efficiency

Urban rooftop agriculture can contribute to reduce the carbon footprint of the built environment through energy savings and efficient management of building resources (Begum et al., 2021). Installing URFs can result in potential annual energy savings up to 15% of a building's annual energy consumption thanks to the additional thermal insulation provided by the green cover (Specht et al., 2014). The addition of a green roof acts as an insulation layer which reduces the rooftop's surface temperature in the summer and thus the energy requirements to keep the indoor air cool (Lucertini & Giustino, 2021). The air temperature under green roofs has been observed to be at least 3°C to 4°C cooler than under bare roofs. In the city of Toronto, a study found that a residential building with a green roof experienced a 25% cooling effect, while the floor under the green roof had a 60% cooling effect (Begum et al., 2021). In the winter, the green layer minimizes heat losses and thus the need for more heating (Lucertini & Giustino, 2021). In turn, URF can reduce the expenses of heating and cooling (Orsini et al., 2014).

Moreover, when combined with a greenhouse, more benefits may be achieved when the structure is integrated within the metabolism of the building in terms of energetic fluxes such as water and carbon recirculation (Orsini et al., 2020). Regarding energy savings in terms of heating, the installation of a greenhouse structure on a building was found to save up to 41% in heating compared to standalone greenhouses and buildings. Heat loss reduction can thus be achieved through the use of waste heat from the building to heat the greenhouse (Specht et al., 2014). In a study by Nadal and colleagues (2017) investigating an i-RTG to assess the energy efficiency of rooftop greenhouse they found that their case study recycled 43.78 MWh of thermal energy from the main building. In comparison to a freestanding greenhouse heated with oil, the i-RTG delivered yearly carbon savings of 113.8 kg CO_2 eq / m^2 and economic savings of 19.63€ / m^2 per year. When compared to a conventional greenhouse heated with gas, the i-RTG allows to achieve carbon savings of 82.4 kg CO_2 eq / m^2 and economic savings of 15.88 € / m^2 per year. If compared to a freestanding greenhouse heated with a biomass system, carbon savings of 5.5 kg CO_2 eq / m^2 and 17.33 € / m^2 per year of economic savings are obtained by the i-RTG (Nadal et al., 2017). A general cost reduction can be achieved if the energy fluxes of the building the rooftop farm is situated on are optimized. Greater insulation and thermal exchanges can lower the energy consumption of the building and thus decrease the use costs of the building (Sanyé-Mengual et al., 2014). These findings further demonstrate the potential of URF to contribute to energy savings when thermal coupling is achieved with the rest of the building.

4.2.3 Heat island effect and cooling

Increasing vegetation in urban areas has been known to alter the heat balance of cities allowing to mitigate the urban heat island effect by two phenomena. Firstly, increasing green areas allows solar radiation change. Indeed, shading by vegetation halts and redistributes the incoming radiation and diffuses light reflected from other nearby urban surfaces which would otherwise be reflected or radiated as sensible heat by surfaces of the urban area. Secondly, the evapotranspiration taking place in the greened areas acts as a heat sink and contributes to lower ambient and surface temperatures compared to the areas without vegetation (Ackerman et al., 2014; Lucertini & Giustino, 2021). URF initiatives also reduce local temperatures and if widely implemented on an entire city level, significant cooling of the urban environment could be reached (Ackerman et al., 2014). However, the extent to which the urban heat balance is modified also depends on the specific design of URF such as crops, cultivation technique and surface area, as these aspects determine the evapotranspiration rate (Lucertini & Giustino, 2021).

A study by Begum and colleagues (2021) investigated the effect of URF initiatives on microclimate and the extent to which they can cool the environment. To do so, they studied the temperature difference between agricultural roofs with different percentages of surface cover and bare roofs. It was found that the trend of air temperature around agricultural roofs was consistently cooler than bare roofs throughout the day, even when the roof had a small amount of green coverage. As expected, more coverage led to increasing cooling (Begum et al., 2021). Overall, URF was seen to be an efficient way to reduce peripheral surface temperature and provide thermal shading to buildings. However, the extent to which surface temperature are reduced by URF can vary depending on the solar intensity. Increased solar intensity results in more temperature reduction (Begum et al., 2021). Agricultural rooftops can be an effective strategy to mitigate microclimatic changes in urban areas and the urban heat island effect by reducing the heat trapping gas concentration. This in turn can lead to more thermal comfort on local scales (Begum et al., 2021).

4.2.4 Carbon sequestration and climate change mitigation

Another important sustainability aspect of URF is their ability to mitigate climate change through biological carbon storage. As URF exhibit higher productivity levels of vegetation than the farmland areas they replace, the role that URF can have in carbon storage can be significant (Zhao, Brown & Bergen, 2007). An estimation was made that when converting flat roof surfaces amounting to 82 ha in Bologna, Italy to rooftop garden, a potential annual carbon capture and storage of over 600 t of CO_2 could be attained (Orsini et al., 2014). However, air quality and carbon sequestration benefits are minimal for individual roof gardens. To render these benefits more meaningful, a calculation of numerous URF covering a large portion of a city is recommended (Safayet et al., 2017). Reductions in CO_2 concentrations were also observed when measuring above the rooftop surface of an agricultural roof compared to bare roofs. Rooftop farming can control CO_2 rises with and around roofs and can thus play a key role in microclimatic changes (Begum et al., 2021). Nevertheless, climate change mitigation per square meter of rooftop also depends on the type of URF. Rooftop greenhouses were seen to result in a negative global warming potential mitigation. “High-tech” farms are found to have a higher environmental impact when compared to other productive uses of rooftops attributed to the higher energy requirements of food production in controlled environment. (Benis et al., 2018).

4.2.5 Reduced ecological footprint

One driver for the implementation of URF is their potential to reduce the ecological footprint of fresh produce over their entire life cycle by reducing transport requirements, re-using packaging, and limiting product storage time between harvest and consumption (Orsini et al., 2014). Producing food on local scale minimizes the transport distance and brings a myriad of benefits at the community level. Shorter travel distances imply an increase in food quality and nutritional profile as with long traveling distance the shelf life of produce must be extended (Gould & Caplow, 2012). Avoiding or shortening the distance between the production and consumption point also means a reduction of food miles and thus decreased CO_2 emissions which can be considered a significant climate change mitigation action (Lucertini & Giustino, 2021). Nevertheless, the potential advantages of minimizing food transportation distances and thus emissions differ geographically. The reduced ecological footprint claims attributed to the reduced impact of transport emissions is not as significant in cities surrounded by productive agricultural land with a strong regional food supply chain. A lack of studies linking food miles to GHG emissions, resource efficiency, and other indicators of sustainable development integrating the entire value-added chain of food production exist (Specht et al., 2014). However, URF initiatives are likely to contribute to sustainability improvements in cities by reducing transport distances and thereby decreasing the noxious environmental impact along with costs of transportation (Specht et al., 2014).

4.2.6 Farmland preservation

Rooftop farming is put forward as a way to alleviate the demand for fertile agricultural land thus lessening the pressure put on land and further preventing more land degradation and associated environmental impact (Benis et al., 2018). Nevertheless, a widespread implementation of URF initiatives and other forms of urban agriculture would be required to be able to consider rooftop farming as a means to free up rural agricultural land and significantly reduce the environmental burden (Specht et al., 2014).

4.2.7 Biodiversity

Greening rooftops contributes to increasing biodiversity in the built environment. Studies have highlighted that green rooftops and other greenhouse structures can increase the population of urban fauna and subsequently urban biodiversity (Lucertini & Giustino, 2021; Orsini et al., 2014). The creation of living spaces in cities where none had existed before through the implementation of URFs plays an important role in biodiversity conservation. Such initiatives allow for the formation of microhabitats improving wildlife diversity. Additionally, introducing greater plant diversity promotes habitat creation and supports several types of wildlife such as insects, birds, and mammals (Walters & Stoelzle Midden, 2018). A study investigating different urban agricultural projects across various European countries found that most initiatives were considered to promote biodiversity preservation when they cultivated more than thirty crop types and varieties. Conversely, limited biodiversity improvements were observed within intensive monocultural projects (Orsini et al., 2020).

Another study investigated the role of RTGs as a way to increase biodiversity and promote the formation of green corridor networks (Orsini et al., 2014). URFs can contribute to the restoration, preservation and enhances functional biodiversity while creating green corridors allowing various species, particularly the less mobile ones, to increase their dispersion capacity. This in turn can limit the negative impacts of fragmentation caused by urban development. These green corridors consist of a network of hubs for wildlife and ecological processes to move through; and links that connect the system together. A measure of biodiversity improvements was establishing by calculating the green corridor density of the city used as a case study. Green corridor density is found by determining the ratio between the linear distance covered by green corridors and the city surface area (Orsini et al., 2014). RTGs can thus become a way to increase urban biodiversity by becoming hotspots within a network of other URF initiatives within the same city. Nevertheless, to enhance biodiversity and enable beneficial fauna to make the most of the hub, it is recommended that URFs provide shelter, wildflowers for pollen and nectar as well as plants with alternative prey for predators. The promotion of URFs can thus substantially contribute to ensuring long-term persistence and resilience of urban biodiversity (Orsini et al., 2014).

4.2.8 Air pollution abatement

URFs have also been linked to improving urban air quality. A study by Tong and colleagues (2016) investigated the impact of an URF on air quality. However, as roofs are inevitably above local street traffic, rooftop vegetation is thought to minimally contribute to removing traffic related pollution. Moreover, the removal of particulate air pollution depends on the characteristics of the rooftop, the roughness of its vegetation and the position of the roof in relation to the pollution sources (Tong et al., 2016). Nevertheless, it was found that URF can contribute to reducing the concentration of particulate matter in the air. However, in ground plants would be more successful at removing the pollution load. Indeed, plants grown on roofs are less successful at removing air pollution due to the effect of building elevation (Tong et al., 2016).

4.2.9 Waste reduction

The production of food on local scales in URFs reduces food waste as with longer food miles comes spoilage (Gould & Caplow, 2012). From an environmental perspective, growing fresh food with shorter supply-chains minimizes food waste and has an overall positive environmental impact on the entire life cycle of a food product. The generation of food waste is prevented as the production, distribution and retail of any additional food that is not consumed in the end is avoided. Furthermore, the reduction of food waste leads to less GHG emissions resulting from food waste management (Sanyé-Mengual, Rieradevall & Montero, 2017).

Food waste can also be managed through the recycling of organic waste to further improve the city's environment. A composting system, closing the loop of waste recycling can be integrated in the operation of URFs to minimize pollution. Organic matter can be sourced not only from food waste but also animal waste, plant residues. Several concepts of waste management in the context of URF are found in the literature, the main aspect of which is to optimize and close the nutrient cycle (Specht et al., 2014).

4.2.10 Employment

An economic aspect associated with the implementation of agricultural rooftops found in the literature is its participation in local job creation (Begum et a., 2021). In year-round URF initiatives, there is a need for full time workers. A study found that BIA can lead to the creation of up to five times as many jobs compared to rooftop solar panels (Benis et al., 2018). Overall, the results showed that food production on rooftops is more beneficial than energy generation on a local community level both in terms of financial return and local job creation. When assessed from a holistic perspective, the integration of agriculture into buildings can produce significant yields leading to more profits. Nevertheless, this may be site specific and can vary depending on productivity and overall supply chain (Benis et al., 2018). In addition, commercial farms that are set up for profit may be combined with commercial kitchens allowing to create value-added food products that can be sold to restaurants and at farmers' markets. This is turn leads to the creation of new jobs necessitating various qualifications levels in several service sectors along the food chain (Specht et al., 2014). Generally, the creation of jobs is seen to have additional benefits for communities. For instance, when partnerships are forged between URF and social service organizations, new job training program opportunities arise. Moreover, URF initiatives can facilitate partnerships with local school, providing opportunities for youth to learn about food production and get involved in the facility (Benis et al., 2018).

4.2.11 Food affordability

The implementation of URFs is associated with the production of foods on local scales and allows for less food transport. Shorter distances in turn implies less middlemen subsequently reducing the price of food (Gould & Caplow, 2012). Food costs are also expected to decrease due to lower production and transport costs. Indeed, food production related costs can be reduced with less distribution steps, which also implies a decrease in food losses over the supply chain of horticultural products. However, economic barriers can be expected due to a narrow margin from the sale of URF products (Sanyé-Mengual et al., 2015).

4.2.12 Food provision and food security

One of the main objectives of deploying farms on the roofs of building is to provide edible goods for urban dwellers and thus contribute to food security. Orsini and colleagues (2014) took the city of Bologna, Italy as an example to determine its food provision potential when the surfaces of flat roofs are covered with farms. Specifically, they analyzed the potential yield of fresh vegetables from simple soilless production systems in RTGs and the percentage of self-reliance for food production. It was estimated that if implemented on suitable rooftop areas identified for this purpose, rooftop agriculture could provide annually more than 12,000 tonnes of vegetables and satisfy the vegetable demand up to 77% for the citizens of Bologna (Orsini et al., 2014). In Rio de Janeiro, the use of productive roof surfaces could generate sufficient food to meet the annual demand for fresh vegetables for 39.2% of its inhabitants (Dang & Sampaio, 2020). In Toronto, implementing 650,000 m^2 of green rooftops growing vegetable crops would result in a yield of 4.7 million kg of fresh produce per year (Peck, 2003). In another study, Cleveland, USA was used as a case study to compare different food production systems in urban areas. Results showed that rooftop with greenhouses using hydroponic systems can produce 19.5 kg of fresh food per m^2 on average per year compared to 1.3 kg per m^2 per year in conventional urban gardens. Moreover, the use of 62% of the roofs of commercial and industrial buildings in Cleveland could increase food self-sufficiency by 1.5 times (Grewal & Grewal, 2012). Considering food provision in open-air settings, Grard and colleagues (2018) estimated that the yield ranged from 4.4. to 6.1 kg per m^2. Furthermore, growing food in URF settings has an impact on food security. As the current food system is heavily reliant on scarce and non-renewable resources such as fossil fuels, food prices are subject to high fluctuations. Producing food in the urban environment allows to reduce the reliance on fossil fuels and thus contribute to increasing food security (Gould & Caplow, 2012).

4.2.13 Access to healthy and nutritious food

The presence of rooftop farms in cities increases access to nutritional foods. Fostering a greater access to nutritious and perishable fruits and vegetables essential to healthy diets could reduce risks of diet related diseases such as obesity and diabetes (Gould & Caplow, 2012). Production of food in URF settings is a way to provide fresh, nutritious, and affordable produce directly to neighborhoods where other conventional supermarket chains could not reach (Gould & Caplow, 2012). Additionally, growing food in controlled environments reduces the risks of contamination from pathogens while its transportation over shorter distances decreases the chances of food-borne illnesses due to less handling. A shorter supply chain thus means greater control subsequently limiting the potential health risks associated with food (Gould & Caplow, 2012).

Furthermore, in cities where food quality is low from the addition other chemicals to prevent fresh produce from rotting, URF can ensure the supply of fresh fruits and vegetables, free of pesticides and added chemicals. This is for instance seen in Dhaka, Bangladesh where urban dwellers have grown concerned by the hazardous impact of formalin used to maintain product freshness and other chemicals to increase production. URF initiatives were thus found to be a potential solution for the provision of fresh and hygienic food (Safayet et al., 2017).

4.2.14 Health, life quality improvements and increased wellbeing

Beyond the benefits associated with food production and the natural environment, several benefits associated with increased wellbeing have been observed when individuals partake in community gardening (Orsini et al., 2014). Indeed, enhancing the mental and physical health of community members can also be achieved through URFs. Although few studies exist on the therapeutical benefits of community gardening, it is well known that gardening related activities are found to reduce psychological disorders, enable stress recovery, and foster cardiac rehabilitation. (Orsini et al., 2014). In addition, engaging in gardening activities can improve individuals' diets by increasing their consumption of fruits ang vegetables and providing a wider variety of produce. Gardening can result in mental health improvements by reducing stress levels, enhancing self-confidence, providing therapeutic and green spaces for people facing trauma along with feeding imagination and inspiration. URF can serve as spaces for leisure and physical activities for people of all walks of life (Specht, Reynolds & Sanyé-Mengual, 2017).

Furthermore, the implementation of an URF at the Boston Medical Center has been linked to many benefits including increased wellbeing of patients and employees attributable to interactions with the green space (Musicus et al., 2019). More generally, URF initiatives are seen to increase social bonding and interactions for instance when tenants share fruits and vegetables (Safayet et al., 2017).

4.2.15. Education

When growing up in an urban environment, children often have a limited connection to farming or interaction with outdoor spaces. Therefore, they lack the experience and awareness of how food is produced (Walters & Stoelzle, Midden, 2018). Growing food in URF setting can be a great educational opportunity for children to learn where their food comes from (Gould & Caplow, 2012). URFs provide a unique location to teach people about environmental sustainability, hands-on food production and nutrition while giving them an opportunity to engage with nature. Such initiatives can serve to re-establish a certain respect and understanding of natural processes in the educational system. When URF initiatives offer educational programs or are co-located near schools, children can be empowered to make more educated choices about their impact on the environment (Specht et al., 2014). Additionally, URFs in partnership with universities can led to experimentation, new knowledge generation and training opportunities for students (Sanyé-Mengual et al., 2019).

4.2.16 Linking consumer to food production

Rooftop farming is seen to be an excellent way to create a link between consumers and food production. A recent trend in urban lifestyle in which city inhabitants long to become closer to the production of food again can be met with URFs. Indeed, consumers have been increasingly asking for fresh and local foods with lower carbon footprints, greater transparency, and closer involvement in the food production chain (Specht et al., 2014). URFs provide an opportunity for this. Additionally, URF initiatives are classified as so-called alternative food networks consisting in the formation of new networks that re-spatialize and re-socialize food production, distribution, and consumption. This in turn promote new consumer-producer relations subsequently opening specific learning channels and enhancing consumers' knowledge about food and agricultural production (Sanyé-Mengual et al., 2019). This may be especially relevant for urban residents in underserved areas where URF can be seen as an opportunity for people to directly engage with food production and procurement (Ackerman et al., 2014).

4.2.17 Community building and increased resilience

A rooftop farm is a place where people can come together for mutual benefit that provides a common social and cultural identity for inhabitants of a city. Urban agriculture more generally is often associated with the idea of fostering community empowerment (Ackerman et al., 2014). In addition, certain aspects of city neighborhoods such as crime rate or noise levels are associated with a lack of neighborhood social ties. Community gardening can become an accelerator for community building in urban areas. For example, the development of community garden can lead to the creation of resilient urban neighborhoods as well as improving the recovery of cities when confronted with sudden crisis (Orsini et al., 2014). As the concepts of resilience and diversity are intertwined, they may be well described by URF that group together inhabitants of a same building which will grow different species. Species and people can thus coexist and together foster the resilience of the system through the creation of improved biodiversity (Orsini et al., 2014). URFs can also be considered to promote resilience through a series of social elements such as communication, information sharing, co-learning and produce exchange and ecological phenomena by reducing the environmental impact of food production and promoting self-sufficiency (Orsini et al., 2014). Moreover, URFs as interactive community spaces allows residents to regroup and hence reduce isolation through sharing of gardening knowledge and inputs, while promoting a participatory approach to community development (Orsini et al., 2014).

However, the assumption that URF increases social cohesion and foster community building may not be applicable to every initiative. In some cases, URF projects can generate negative social impacts and create increased disparities. This is seen for instance when elites displace low-income and culturally diverse communities or when (Orsini et al., 2020; Specht et al., 2014). Access to URF can be imbalanced which in turn accentuates social exclusion and injustice amongst communities as opposed to closing the gap between citizens with different economic and cultural backgrounds (Orsini et al., 2020). Local food movements have been seen to locate or distribute in relatively wealthy areas and cater to well-off consumers. This critique of URF initiatives can be applied to projects claiming to tackle issues of food when the products being sold are only accessible to the people that can afford them (Specht et al., 2014).

4.2.18 Key sustainability impact and factors

Based on the literature review of the key sustainability aspects driving the implementation of URFs, a number of factors that contribute to the sustainability impact have been identified (Table 5). It can be noted that the factors contributing to an environmentally sustainable URF such as water management, biodiversity increase or heat island effect are largely related to the design of the URF including the farming methods, type of vegetation and plant diversity. When considering the factors contributing to the social sustainability of URFs, factors such as accessibility of URF, food affordability, quality of educational programs and productivity of the farm play an important role. Generally, these sustainability aspects are also dependent on the size and primary function of the project.

Table 5: Key sustainability aspects of URFS and their main contributing factors.

Sustainability impact	Characteristics	Main design factor contributing to impact
Water management and water savings	Reduce peak flow and flood prevention from water retention of roof and water interception and evapotranspiration from plants Water recirculating systems	Amount and type of plants Thickness of the layer Rainwater harvesting system Farming method
Energy saving and energy efficiency	Heat loss reduction and cooling effect from extra insulation layer Energy exchanges between host building and rooftop farm	Amount and type of plants Integrated fluxes
Heat island effect and cooling	Increased shading by vegetation Redistribution of solar radiation Evapotranspiration	Amount and type of plants
Carbon sequestration and climate change mitigation	Biological carbon storage from plants	Amount and type of plants Type of rooftop farm
Reduced ecological footprint	Reduced transport requirement	Transport distance to retail / consumption point
Farmland preservation	Alleviating the demand for farmland	Yield and type of plants Amount of land that URF
Biodiversity	Creation of living spaces and microhabitats Formation of green corridors	Amount and type of plants Plant diversity
Air pollution abatement	Removal of particulate matter from atmosphere	Amount and type of plants Retention capacity of plant
Waste reduction	Shorter distribution distances Composting system	Type of packaging Use of compost system
Employment	All year-round jobs	Size and primary function of URF
Food affordability	Shorter distribution distances Less middleman Lower production and transportation costs	Yield and type of plants

Food provision and food security	Annual food production Reduce reliance on non-renewable resources	Yield Farming method
Access to healthy food	Provision of nutritious and fresh food Reduced risk of contamination Pesticide free	Accessibility Farming method
Health, life quality improvements and increased wellbeing	Therapeutical effects of community gardening Increased consumption of fruits and vegetables Reducing stress levels Increase social bonding	Primary function of URF
Education	Educational programs for food literacy Partnership with school and universities	Primary function of URF Educational program
Linking consumer to food production	Creation of alternative food system Promoting new producer-consumer relationships	Primary function of URF
Community building and resilience	Development of resilient urban neighborhood	Primary function of URF

4.3 Comparing the sustainability performance of urban rooftop farms

A total of 12 relevant LCA and LCC studies on URF were identified during the review. The summary of the system under study, the functional unit, system boundaries and indicators used can be found Table 6. Most studies were set in the context of a Mediterranean climate with four of the articles using the i-RTG laboratory at the Institute of Environmental Science and Technology (ICTA) and Catalan Institute of Palaeontology (ICP) as a case study (Box 1) (Sanjuan-Delmas et al., 2018; Rufí-Salís et al., 2020; Sanyé-Mengual et al., 2014; Sanyé-Mengual et al., 2015a). All the identified studies focused on the environmental assessment of URF and conducted LCA while three of these studies also focused on analyzing the LCC of URF. When evaluating the economic performance of URF, all the material costs associated with the different elements of URF were examined. However, indirect cost of the sustainability driver of URF such as air pollution mitigation or heat island effect reduction, were not accounted for. Only one of the studies took into account the social dimension of URF associated with the production of substrate (Toboso Chavero et al., 2021).

The main research focus of the studies was most frequently on the overall environmental performance of the implementation of rooftop farms. The growing media or substrate selection was another recuring research topic. The environmental performance of soilless systems, different crop types and the structure of rooftop farms were also investigated. The indicator that was consistently used in all the studies was the global warming potential (GWP) or climate change indicator. GWP offers the possibility to compare global environmental impacts of specific actions using equivalent CO_2 emissions in the atmosphere (Engler & Krarti, 2021). Other indicators such as water consumption or depletion, marine and freshwater eutrophication, terrestrial acidification, ecotoxicity and fossil fuel depletion were also commonly investigated. In terms of methodological approach, studies either collected experimental data over the course of longitudinal studies or utilized of available data on the different processes of the system under study throughout its life cycle. Lastly, a striking aspect is that most studies assessed the environmental performance of RTGs while open-air rooftop farms were less considered.

Considering the functional units used in the studies, 1 kg of food product was mostly utilized while only few cases where an impact was assessed based on the area of an URF (Table 6). Finally, the system boundaries used to investigate the impact of URF differed depending on the research focus. Some studies utilized a using a cradle to grave perspectives which implies taking into account the effects material extraction until the end of life of a project. However, some studies assess the environmental impact of URF from the cradle up until the farm gates. In this case, the impact associated with of distribution and the end of life of an URF are disregarded.

Table 6: Summary of system, functional unit, system boundaries and indicators used in LCA and LCC studies of URF.

Authors	System under study	Functional Unit	System boundaries	Indicators
Toboso Chavero et al., 2021	Analyzing the environmental and social performance of growing media imported to Spain for urban rooftop farms	1 m^3 of a growing medium for URF	Cradle to farm	Global warming Terrestrial acidification Freshwater eutrophication Marine eutrophication Ecotoxicity Land use Fossil resource scarcity Water consumption
Dorr et al., 2017	Assessing different crop and substrates selection on the rooftop farm of AgroParisTech	1 kg of product grown in 1 year	Cradle to grave	Climate change Water depletion Fossil depletion Marine eutrophication Human toxicity
Boneta et al., 2019	Investigating the sustainability and self-sufficiency of soilless systems on rooftops using polyculture rooftop home garden in a Mediterranean city	1 kg of edible fruit and leafy products	Cradle to grave	Climate change Terrestrial acidification Freshwater eutrophication Marine eutrophication Fossil depletion Ecotoxicity
Sanjuan-Delmas et al., 2018	Investigating the environmental impacts of tomato production in a rooftop greenhouse compared to those conventionally produced in a standard multi-tunnel greenhouse using the ICTA_ICP in Barcelona as a case study.	1 kg of tomato produced	Cradle to grave	Climate change Ecotoxicity Terrestrial acidification, Freshwater eutrophication Marine eutrophication Fossil fuel depletion
Rufí-Salís et al., 2020	Comparing a closed loop system and a linear system in terms of environmental impact using the ICTA_ICP in Barcelona as a case study	1 kg of beans produced	Cradle to grave	Global warming Terrestrial acidification Freshwater eutrophication Marine eutrophication Fossil resource scarcity Ecotoxicity
Gasperi et al., n/a	Comparing different types of rooftop farming cultivation technique, crop type and rooftop type in Barcelona and Bologna.	1kg of food product	Cradle to farm gate	Global warming potential

Sanyé-Mengual et al., 2015b	Analyzing the economic and environmental performance of rooftop farms in terms of techniques and crops used in the city of Bologna	1 kg of food product	Cradle to farm gate	Global warming Human toxicity Water depletion Cumulative energy demand
Goldstein et al., 2016	Assessing the environmental impact of six urban farms in Boston and New York City	1 kg of fresh food item delivered to the point of purchase in Boston	Cradle to shelf	Climate change, Freshwater ecotoxicity Marine eutrophication Water resource depletion Land use Mineral, fossil, and renewable resource depletion
Torres Pineda et al., 2020	Assessing the environmental impact of tomato production in a RTG in Seoul	1 kg of fresh tomato	Cradle to shelf	Abiotic depletion Global warming Photochemical oxidation Acidification Eutrophication Cumulative energy demand
Sanyé-Mengual et al., 2014	Analyzing the horticulture structure of RTGs using the ICTA_ICP in Barcelona as a case study	Greenhouse structure $1m^2$ of greenhouse structure for a timeframe of 1 year Tomato production 1 kg of tomato produced in a timeframe of one crop period	Greenhouse structure Cradle to grave Tomato production Cradle to farm gate	Global warming potential Cumulated energy demand
Sanyé-Mengual et al., 2015a	Analyzing the environmental and economic performance of RTGs using the ICTA_ICP in Barcelona as a case study	Greenhouse structure $1m^2$ of greenhouse structure for a timeframe of 1 year Tomato production 1 kg of tomato produced in a timeframe of one crop period Consumption point 1 kg of tomatoes retailed for consumption in Barcelona.	Greenhouse structure Cradle to grave Tomato production Cradle to farm gate Consumption point Cradle to consumer	Global warming potential Cumulative energy demand
Kim et al., 2018	Comparing the environmental and economic sustainability of a rooftop garden and a rooftop	140 m^2 of the roof	Cradle to grave	Ozone depletion Global warming Smog

farm in relation to a bare flat roof in Seoul.	Acidification Eutrophication Carcinogenic Respiratory effects ecotoxicity Fossil fuel depletion

The integrated rooftop greenhouse laboratory (i-RTG-Lab) at the Institute of Environmental Science and Technology (ICTA) and Catalan Institute of Palaeontology (ICP)

In 2014, Barcelona was the first south European city to design and incorporate a fully integrated rooftop greenhouse (i-RTG) into its ICTA-ICP building of the Autonomous University of Barcelona (Figure 13) (Nadal et al., 2017). The RTG-Lab began its operation to demonstrate the feasibility of implementing RTGs in Mediterranean areas and the potentiality for i-RTGs (Pons et al., 2015). The design of the research-oriented greenhouse is an eco-innovative concept aiming to enhance the sustainability of both systems involved while producing high-value crops and maintaining indoor comfort in buildings with lower energy inputs (Sanyé-Mengualet al., 2014). The design integrates the residual heat from the buildings, CO_2 concentration in the residual air used as natural fertilizer and rainwater collected on the rooftop (Nadal et al., 2017).

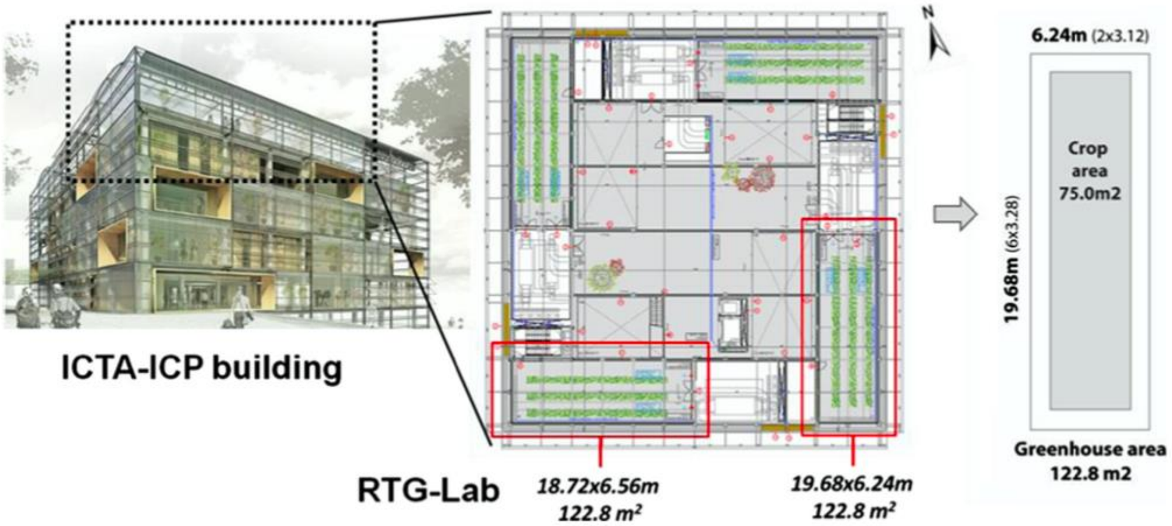

Figure 13: Layout of the RTG-Lab (Sanyé-Mengualet al., 2015a).

4.3.1 Types of rooftop farm and farming technique

In the study by Gasperi and colleagues (n/a) investigating sustainability improvements of rooftop agriculture, tomato production was examined under different types of farming systems. Their results demonstrated that both rooftop agriculture in the form of greenhouse and community rooftop garden led to lower environmental impact in terms of GWP compared to conventional production (Gasperi et al., n/a). Moreover, the production of food in soil may be favored over soilless production methods in order to achieve higher levels of eco-efficiency. Indeed, the production of vegetables in soil results in lower economic costs and environmental burden in terms of GWP than hydroponic systems (Sanyé-Mengual et al., 2015b).

When comparing different growing techniques, Gasperi and colleagues (n/a) uncovered that lettuce production in soil or using a floating technique (e.g., hydroponic systems) resulted in the most environmentally friendly technique with the least environmental impacts with regards to GWP. These two techniques were compared to Nutrient Film Technique (NFT) and was found to be the most environmentally impactful option due to its high energy consumption (Gasperi et al., n/a).

These results are similar to the ones of Sanyé-Mengual and colleagues (2015b) that compared NFT, floating hydroponics and the use of soil as cultivation methods. Tomato production in the open-air rooftop farm in Bologna had a global warming impact 3 times lower than those produced in an RTG in Barcelona from a cradle to farm gate approach. Higher levels of eco-efficiency were generally observed under soil techniques especially for fruits and vegetables production. However, floating techniques for summer crops of leafy greens was recommended in water scarce areas as it is the most water efficient option. Generally, NFT was the most impactful technique, and its use is only recommended if energy-efficient equipment is applied (Sanyé-Mengual et al., 2015b). From an economic perspective, the price of food cultivation ranged between 0.13 and 1.95 € / kg. Production costs varied depending on the type of crops. Overall, production in soil systems was seen to be cheaper than in soilless systems (Sanyé-Mengual et al., 2015b).

When comparing the environmental sustainability of an open-air rooftop farm using a soil system or green roofs to that of a bare flat roof in Seoul, Kim and colleagues (2018) found that the most environmental impactful element of the URF was the installation and the replenishment of lightweight soil which contributed to 42% to 79% of the total adverse environmental impact. The relative contribution of each component in the lightweight soil was characterized and demonstrated that zeolite, used for its sorbent properties, had the highest impact for all categories ranging from 49% to 99% although it constitutes a small fraction of the soil. Overall, as the authors compared the environmental impact of URF to that of a flat roof, the LCA findings demonstrated that the URF has a higher environmental impact than the flat roof. However, it is important to note that the energy cost reduction and air pollution mitigation benefits were not considered in the results of study. Furthermore, major costs were associated with the operation and maintenance stages. The spraying of fertilizer, replenishing of lightweights every year accounting for 61% of the life-cycle costs and the supplying of water for vegetation were the highest contributions. To improve the sustainability of the URF, there is a need to increase the performance of the dominant contributing components. Biochar has been put forward as a potential alternative to improve water retention in soil and reduce the media weight. Additionally, biochar minimizes the release of organic carbon in stormwater runoff from roofs. Future research on developing environmentally friendly and more economic lightweight soil was recommend by the authors (Kim et al., 2018).

4.3.2 Rooftop greenhouse structure

Out of the selected studies, three dove into the environmental impact of the structure of urban RTGs. Sanyé-Mengual and colleagues (2014) investigated the environmental performance of urban horticultural structures using the i-RTG of the ICTA_ICP as a case study. Considering the different materials involved in the construction of the greenhouse, their results estimated that the GWP of the RTG structure was 2.5 kg of CO_2 eq., while the cumulative energy demand was 46.4 MJ / m^2. These results are similar to the ones found in another study by Sanyé-Mengual and colleagues (2015a) where the environmental impact of the structure of the i-RTG-Lab was found to have a GWP of 2.42 kg of CO_2 eq. and an energy demand of 44.0 MJ. The greatest impact was associated with the material stages including material extraction, processing, and transportation accounting for 99% of the GWP. In comparison, the construction of the structure and its transportation to waste disposal facilities had the least impact when considering the entire life cycle on the structure. When considering the different types of materials used in the greenhouse structure, polycarbonate had the largest contribution share to the GWP due to its energy demanding extraction and material processing along with its transportation and maintenance requirements. Although heavier than the low-density polyethylene (LDPE) used in conventional greenhouses, polycarbonate is chosen for its resistance and is used as the cover of the RTG. Steel held the second largest share of the GWP accounting for 29% although it had a bigger presence in the structure in terms of weight. The cumulative energy demand of the system followed a similar pattern of distribution as the GWP over the entire life cycle of the greenhouse.

Regarding the comparison of RTG and a conventional industrial system, the GWP of the RTG structure was found to be 81% more impactful than a multi-tunnel greenhouse. In addition, the cumulative energy demand was 53% higher. The toxicity categories scored the highest in the material stage attaining 58 to 95% because of the steel manufacturing processes and associated air emissions of mercury and manganese and arsenic emissions to water (Sanyé-Mengual et al., 2015c). The higher environmental impact of the RTG is mostly due to the fact that the structure must comply to stricter legal requirements in the urban context and must thus utilize more materials (Sanyé-Mengual et al., 2014). Indeed, the structure of the RTG-Lab need to comply with the Spanish Technical Code of Edification and fire safety law. To ensure resistance and security the structure had to be reinforced (Sanyé-Mengual et al., 2015c). In this case, the RTG-Lab had a 5 times higher steel requirement per square meters than a multi-tunnel house (Sanyé-Mengual et al., 2014). The study by Torres Pineda and colleagues (2020) also found that the structure of an RTG in South Korea had a higher impact in most assessed categories than the infrastructure conventional greenhouse. The RTG was estimated to have a GWP 200% higher than that of conventional greenhouse. These large differences were attributed to the use of a greater amount of steel along with glass for covering while double ethylene vinyl acetate (EVA) copolymer sheet was used in the conventional greenhouse (Torres Pineda et al., 2020).

To render the construction of RTGs more environmentally friendly, the authors suggest changes in legislative requirements that for instance limit the weight of greenhouse structures (Sanyé-Mengual et al., 2015c). The need for more experience in the construction of these structures is also mentioned to lower the use of resources while providing the same function. From an economic perspective, the greenhouse structure of the RTG had a cost 2.8 times higher than a multi-tunnel greenhouse. The total costs of the greenhouse structure reached 11.9€ / m^2 per year while the multi-tunnel greenhouse costs 4.26 € / m^2 per year. Materials used to build and maintain the structure contributed the most to the total cost of the RTG, with steel being the most expensive material representing 63% of the costs (Sanyé-Mengual et al., 2015a). Reducing the amount of steel or changing the type of material or design would be recommended to lower both the environmental burden and economic costs of RTGs (Sanjuan-Delmás et al., 2018).

4.3.3 Substrate selection

The choice of substrate is also important to consider when aiming to achieve an URF with the least environmental impact. In a study by Dorr and colleagues (2017), three different types of substrate mixtures; compost and wood chips; compost, wood chips, and earthworms; and conventional potting soil were assessed in an open-air rooftop garden of AgroParisTech University in Paris. Mixtures containing compost were found to have lower impacts than those using potting soil for all the investigated impact categories. Although the compost production with the necessary auxiliary materials such as clay balls and wood, was the stage with the highest contribution to climate change and marine eutrophication, the overall system still had a lower environmental impact than conventional potting soil. This is mainly due to the higher yields of the systems using compost mixtures which in turn significantly dilute the environmental burden of URFs. Moreover, substrate inoculated with earthworms was seen to have a lower environmental impact than without due to higher yields. The agronomic benefits associated with their addition contribute to increased rate of substrate loss, resulting in more addition of compost to the system and thus increased yield leading to overall lower impacts. The authors suggested that strict regulation of composting practices could reduce the environmental burden of compost production. Nevertheless, as using compost for substrate is a more environmentally favorable choice than potting soil, the authors advised that rooftop farming practitioners incorporate it in their substrate along with applying earthworms or other similar soil macro-organisms (Dorr et al., 2017).

Different growing media for urban rooftop farming were also investigated in a study by Toboso-Chavero and colleagues (2021). Their research focused on assessing the environmental and social performance of the most extensively used growing media namely perlite, peat and coir that are produced in different countries and then transported to Spain.

The production and transport of the growing media was investigated using a life cycle perspective from cradle to farm. Their results showed that the use of coir led to the lowest environmental burden in 5 out of the 8 investigated impact categories since it is a coconut trees by-product. Peat also presented relatively low environmental impacts except for global warming, land occupation and fossil resource scarcity. Contrastingly, perlite had a 44 to 99% higher environmental impact than that of peat and coir. Indeed, perlite is extracted from open-pit mines which consumes large amounts of energy and requires long transportation distances by lorry from Turkey. Perlite was thus considered to be the least favorable option as growing medium. The authors concluded that the use of coir despite its long traveling routes by ship had the best environmental performances compared to the other two growing medium but not in terms of social performance due to its production in the Philippines. Instead, the use of peat appears to be a good alternative from a social perspective, but its availability is aimed to disappear in countries like Germany in favor of peatland preservation. Therefore, there is new market niche for the development of locally grown media that perform well environmentally and socially (Toboso-Chavero et al., 2021).

4.3.4 Types of crops

The types of crops that are grown on URF also influences the environmental performance. In addition to studying substrate selection, Dorr and colleagues (2017) investigated the impact of crop production systems on the overall environmental impact of URFs. The two factors that most strongly affecting the performance of crops are biomass yield and cultivation length. When comparing the production of tomatoes and lettuce, they found that tomatoes had a higher environmental impact than lettuce largely due to their longer growing season and lower yields. Nevertheless, due to longer growing cycles, tomatoes were found to sequester more carbon than lettuce per kg. During crop selection, rooftop agriculture practitioners should thus opt for higher yielding crops with shorter cultivation times (Dorr et al., 2017).

Similar conclusions were reached in the study by Sanyé-Mengual and colleagues (2015b) as they found that lower crop yield and longer crop periods led to higher environmental impact. In their environmental and economic assessment of crop selection in an experimental set up of a rooftop garden in Bologna, they tested the performance of growing lettuce, leafy vegetables, tomato, chili peppers, eggplant, melon, and watermelon in soil. Their results revealed that eggplants and tomatoes obtained the lowest environmental impact in GWP with about 74 g of CO_2 /kg, human toxicity attaining 27g 1-4DBeq /kg and energy consumption attaining 1.20 MJ/kg. Moreover, lettuce cultivation was best performed in soil rather than using a NFT in the wintertime as this would lead to 85 to 95% less environmental impact per kilogram compared to NFT (Sanyé-Mengual et al., 2015b).

These results were comparable to the ones put forward in the study by Gasperi and colleagues (n/a) where the production of different types of crops in organic soil were compared in the Mediterranean area. It was found that eggplants and tomatoes had the largest crop yield with the smallest environmental impact in terms of GWP. In contrast, for melons, watermelons and chili peppers GWP doubled compared to that of eggplants and tomatoes. They thus put forward the production of mixed crops including leafy greens and fruit vegetables as recommendations for sustainability improvements (Gasperi et al., n/a).

4.3.5 Performance of rooftop farming system

When assessing the overall performance of URF initiatives compared to conventional production systems, a reduced environmental impact is often observed attributable to decrease land use, energy or water savings (Sanyé-Mengual et al., 2015a). Regarding the environmental performance of 1 kg of tomato produced in an RTG at the production point, Sanyé-Mengual and colleagues (2015a) found that RTG tomato had a lower environmental impact (10–19 %) than the ones from a multi-tunnel system using a cradle to farm gate perspective.

In addition, the comparison of different types of UA practices using a cradle to shelf perspective performed by Goldstein and colleagues (2016) revealed that the system's environmental performance was directly influenced by the efficient use of agricultural inputs. Rooftop farming did not necessarily provide superior performance to conventional farming for all indicators although URF did present lower impact potential in most of the assessed categories. URF initiatives proved to perform higher regarding freshwater and marine water eutrophication due to a lower use of inorganic fertilizers and pesticides than in conventional production. However, URF scored high in the mineral, fossil, and renewable resource depletion category due to its use of natural gas during its operation stage (Goldstein et al., 2016).

The noxious effects of fertilizer were also noted in the study by Boneta and colleagues (2019). Using a cradle to grave system boundary, the results showed that most of the environmental impact was generated during the operation phase of the open-air rooftop farm including the use of water, substrate, and fertilizers. The fertilizer and associated leachates had the greatest impacts on climate change, terrestrial acidification and ecotoxicity. Authors recommended optimizing fertilizers use by applying them according to crop specificity using irrigation sectors. Leachate treatment should also be optimized by promoting nutrient recirculation within the same system (Boneta et al., 2019). The environmental assessment of the i-RTG by Sanjuan-Delmas and colleagues (2018) also demonstrated that the operation of the project presented the largest impact due to the use of fertilizers accounting for 25% of the impact in four of the studied impact categories. To mitigate its negative effects, the nutrient solution should be adjusted according to the plant requirements thus avoiding the leaching of excess nutrients (Sanjuan-Delmas et al., 2018).

GWP, CED and energy savings

At the farm gate, the production of 1 kg of tomatoes in an RTG had a GWP of 216 g of CO_2 equivalent and a CED of 3.25 MJ. The impact of the production inputs was comparable for both RTG and conventional production system, while auxiliary equipment such as water and energy consumption contributed the most to the cumulative energy demand (≈ 40%) and fertilizers contributed the most to GWP (≈53 %) (Sanyé-Mengual et al., 2015a). Goldstein and colleagues (2016) found that when energy exchanges are integrated between the RTG and the host building, considerable energy savings can be achieved which in turn contributes to a reduced climate change impact potential (Goldstein et al., 2016).

Water and nutrient savings

When assessing the contribution of URF to water savings, it was found that tomato production in RTG can significantly decrease the water depletion potential of conventional production up to 98% from the addition of a rainwater harvesting system on top of the building (Sanyé-Mengual et al., 2015a). Moreover, water savings can be achieved from rainwater irrigation in turn reducing the municipal water demand. Nevertheless, rainwater capture may induce water stress and deprive surrounding catchment of water, depleting local water resources, although the significant benefits such as flood mitigation and reduced risk of sewage overflow events were not included by the authors (Goldstein et al., 2016).

Furthermore, significant water savings along with nutrient savings were achieved when URFs utilize closed loop irrigation systems. The life cycle impacts associated with the production of 1 kg of beans revealed that close-loop systems save 40% of irrigation water and between 35 and 54% of nutrients (Rufí-Salís et al., 2020). However, the technology used in closed-loop systems being more complex than that of open hydroponic systems, more filtering and disinfecting devices would be required, implying additional energy expenditures (Sanjuan-Delmas et al., 2018).

Land use

Concerning the land use impact category, placing farms on top of buildings was seen to alleviate the pressure on agricultural land and resulted in a 96% reduction in the agricultural land transformation impact (Sanyé-Mengual et al., 2015a). However, although URF initiatives are seemingly devoid of direct land use, they nonetheless have significant indirect land use related to the significant land occupation required for the extraction of natural gas and the steel used for the structure of greenhouses (Goldstein et al., 2016).

Waste reduction

More generally, the cradle to grave analysis of i-RTG showed that it had a greater environmental performance than a conventional greenhouse with 50 to 75% lower impact largely due to the reduced packaging and transport requirements (Sanjuan-Delmas et al., 2018). These findings were also observed by Torres Pineda and colleagues (2020) where the reduced distribution distances led to large reduction in the URF's overall impact while the refrigeration and losses occurring during product handling were avoided (Torres Pineda et al., 2020).

Food affordability

The result of an economic assessment of RTG tomato production at the farm gate found that the costs of 1kg of tomato is 0.74€, which was found to be 21% more expensive than tomatoes produced in a conventional system. This difference in price is largely due to the costs of the greenhouse structure. However, as profits are assessed based on production costs, the RTG tomato production was found to be 21% more profitable than multi-tunnel tomato production. Indeed, the RTG can provide higher crop yields as it is designed to combine two crop cycles in a year. This resulted in a total profit per kilogram of 0.045€ for RTG tomatoes while the total profit of conventionally produced tomatoes was 0.036€ (Sanyé-Mengual et al., 2015a).

4.3.6 Consumption

One study extended its system boundaries to include a cradle to consumer perspective (Sanyé-Mengual et al., 2015a). A comparison could be made between tomato consumption produced in an RTG and in conventional multi-tunnel greenhouse settings. The system boundaries were thus expanded to encompass agricultural production, packaging production, distribution, and retail. At the consumption point, locally supplied RTG tomatoes had an environmental impact between 33% to 42% lower than those produced in conventional supply chain, depending on the indicators. The life cycle of 1kg of tomatoes produced in a local RTG had a GWP of 0.78 kg of CO_2 equivalent and a CED of 8.44 MJ with the packaging stage seen to contribute the most to GWP (69.5%) and CED (61.5%). However, the type of packaging whether it be single-use or re-usable was seen to significantly affect the results. When packaging options were reevaluated to encompass the use of a re-usable system (20 times), the environmental impact of the RTG supply chain was found to be 41 to 98% lower than the conventional supply chain scenario using single-use packaging. Lastly, transportation from the RTG to the consumption point has a minimal environmental impact accounting for less than 1% (Sanyé-Mengual et al., 2015a). However, assessing the sensitivity of transport distance is important to understand its impact on the overall environmental performance. To be more environmentally friendly than their conventionally produced counterpart, tomatoes grown locally would have to replace tomatoes that have been conventionally produced in areas situated between 120 and 870 km away from the point of consumption (Sanyé-Mengual et al., 2015a).

Considering the economic performance, tomato locally produced in RTGs were found to be cheaper in terms of economic costs than those provided through convention supply chains at the consumption point. More specifically, the costs were 21% cheaper due to avoided costs of transportation. However, this was noted to be highly dependent on the extent to which the distribution stage and food waste production are avoided. Moreover, the type of packaging also influences the economic performance (Sanye Mengual et al., 2015a).

4.3.7 Overall findings

When comparing the environmental performance of URF to that of conventional farming, URFs were found to be generally less environmentally impactful than conventional farming. A greater environmental performance can be attributed to a lower impact from decreased land use, water and energy savings along with reduced packaging and transport requirements and avoided food losses (Sanyé-Mengual et al., 2015a; Sanjuan-Delmas et al., 2018; Goldstein et al., 2016). Additionally, the reduced use of inorganic fertilizers and pesticides in URF initiatives results in a lower impact regarding freshwater and marine water eutrophication than in conventional production. Nevertheless, the distinction between rooftop farming types is also of importance as not all URFs lead to the same sustainability impact and benefits. Moreover, the crop yield of the URF also influences the environmental impact, with higher crop yields in URF resulting in less environmental burden than conventional farming.

URFs also present a number of key environmental benefits. Indeed, considerable reduction in agricultural land transformation are achieved with the installation of URF allowing to alleviate the pressure on farmland. Moreover, important energy savings can be achieved when energy exchanges are integrated between the RTG and the host building, leading to a reduced climate change impact potential (Goldstein et al., 2016). The installation of rainwater harvesting system and close loop hydroponic systems with recirculating water can achieve significant water savings. Moreover, less transport and packaging requirements reduce the overall environmental and economic costs subsequently leading to potentially more affordable foods.

Despite the numerous sustainability benefits that URF can provide, they can present several negative impacts. In the form of RTGs, the greenhouse structure is seen to negatively contribute to the environmental and economic impact of the URF. The use of steel, polycarbonate and glass in the greenhouse structure significantly contributes to the global warming potential and total costs. In soil systems, the replenishment of lightweight soil appears to be the stage resulting in the highest environmental burden. Although URF can use less fertilizer than conventional farming, when sprayed onto crops, an impact on climate change, terrestrial acidification and ecotoxicity can be observed.

To reach their full sustainability potential, certain aspects can be improved to reduce the environmental impact of URF. For instance, the high environmental burden associated with the structure of RTGs can be lowered through the integration of re-used materials. Moreover, to limit the negative environmental impact and costs related to the use of pesticides and fertilizers, their use should be optimized by using crop-specific irrigation sectors and adjusting the amount based on the plant requirements (Sanjuan-Delmas et al., 2018). In soil system, a reduced impact can also be achieved with the use of substrate mixtures containing compost inoculated with worms. Lastly, integrating the energy fluxes from the host building into the rooftop farming structure can result in considerable energy savings.

4.4 Key design criteria for sustainable urban rooftop farms

Based on the sustainability assessment of URFs, a number of aspects regarding the design and operation of URF have been encountered in order to fulfill their sustainability potential. The multifunctionality of URF projects can bring about many sustainability benefits depending on their installation and functioning. However, it is important to note that no one-way solution exists for setting up and operating URFs in the most sustainable way as it varies depending on the context, geographical area, and main objective of the project. However, certain tradeoffs must be considered when making decision on the structure, substrate, type of food grown and overall purpose of the URF. Based on these findings, the following key criteria for the design of sustainable URFs can be put forward.

Firstly, setting up open-air URFs should be favored over RTGs. Open-air URFs are generally found to be the most environmentally friendly type of rooftop agriculture. Although URFs projects that incorporate greenhouses are more impactful than open-air systems, due to the environmental burden caused by the greenhouse structure and the energy required to operate it, they can still have a have a lower environmental impact than conventional farming, depending on the type of product grown. In the case that RTG is chosen as a design, best environmental and economic performance can be observed when the bidirectional flows of residual heat and CO_2 from the building and the rooftop farm are used. Regarding the farming system, simple soil systems were preferred although soilless system were found to be more eco-efficient than conventional farming techniques. If using a soilless system like hydroponics, a floating technique has a lower environmental burden than NFT and is an efficient way of producing food. In terms of substrate selection, the use of compost as fertilizer inoculated with earthworms and other organism is recommended in soil production. Moreover, the use of compost and organic waste in soil system presents multiple benefits. Namely, it avoids the need to rely on non-renewable resources such as peat or the transport of rural soils to the cities. Additionally, it cuts costs and reduces emissions of harmful GHG associated with the transport and processing of organic waste. Organic waste is nutrient rich leading to higher yields and reduces the need for mineral fertilizers (Grard et al., 2018). Lastly, the use of compost in URFs can also form close cycles of organic matter and nutrients when local organic waste is transformed into compost on local scales. Nutrients exports and losses are reduced thereby reducing waste stream and creating a more circular system (Gorgolewski, & Straka, 2017).

To alleviate the environmental burden and costs associated with materials used for the URF structure, a general recommendation is to opt for the integration of re-used elements such as pallets or local and recycled materials into the design (Sanyé-Mengual et al., 2015c). Crop selection also plays an important role on the environmental and economic performance of a URF. Generally, the choice of efficient crop types with high yield and short cultivation periods is preferred. As a higher crop yield reduces the environmental impact per kg of product, fruit vegetables are found to be better than leafy vegetables (Sanyé Megal et al., 2015c). The choice of crop type also plays a critical role in the creation of diverse habitats to attract a wide range of organisms. Hence, diversity of crops is primordial to create multiple habitats and favored over monocultural crops. Crops that produce flowers and attract pollinators or provide large amounts of shade to develop habitats for certain invertebrates are recommended. Moreover, many techniques such as plant companionship, intercropping and the development of pollinator habitats have been proven to improve biodiversity on roofs. In turn, the yield of many vegetable crops can increase when the URF is designed to sustain bees and other pollinator insect populations (Walters & Stoelzle Midden, 2018). When designing polyculture, it is also suggested to organize the plants into differentiated areas where the specific requirements of each crop can be adjusted for a most efficient use of resources (Sanyé-Mengual et al., 2017). Finally, considering the distribution process, re-usable packaging should be used to over single-use options as it is found to have a lower environmental impact.

5. Discussion

In this section, the lesson learned from the results and their broader implications are drawn. First, a discussion of the URF classification is provided followed by the key sustainability aspects driving their implementation. In addition, the implications of the environmental and economic performance of URF projects and the theoretical implications are discussed. Thereafter, the limitations of the research are presented.

5.1 Classification of urban rooftop farms

The classification of ongoing URF initiatives revealed that a vast majority of projects were predominantly found in countries of the global north. Large disparities can be observed in the number of projects at the city level. Green ambitions of certain cities have resulted in a fast-paced development of URF projects. This is for instance seen in the cities of Paris, New York or Hong Kong. In recent years, the incentivization of green and URF initiatives has been integrated in supporting policies by some municipalities (Orsini et al., 2020). However, more support may be necessary for URF projects to become a widespread practice. Current barriers and challenges such as legal aspects (e.g., resistance of building materials, secure access to roofs, waste management), neighborhoods acceptance, competitive real estate market, or installation costs render their implementation more difficult (Sanyé-Mengual et al., 2014). Notwithstanding that more than 200 cities worldwide have signed the Milan Urban Food Policy Pact in 2015 to develop more sustainable urban food systems, a consistent uptake at a global scale is still lacking (Orsini et al., 2020). As most URF projects were observed in Western countries while issues of food insecurity are prevalent on every continent, there is a need to develop more URF initiatives in countries of the global south as well. Nonetheless, the emergence of the multitude of URF projects over the past years illustrates a growing trend towards a diversification of agricultural networks while stepping away and reimagining the currently fragile food system. A shift towards local, organic, and environmentally friendly systems is becoming more prevalent where closed loops are at the center as a growing desire to reconnect people with their foods and nature is on the rise.

Although a variety in the types of URFs has been found, the classification of ongoing URF projects revealed that a majority were seen to be in open-air settings using soil systems. On the contrary, hydroponic systems and other soilless cultivation methods were less prevalent. Despite the fact that they are efficient and can lead to water and nutrient savings, they are more expensive to set up and thus less common. Moreover, projects are seen to have various functions and sizes. Larger URF initiatives appear to have a commercial function as their primary goal and are often installed on industrial buildings or atop supermarkets. Small-scale URF initiatives tend to use low-input systems and fulfill educational or life-quality improvement goals. Generally, the choice of URF inputs is driven by the impacts it aims to achieve.

5.2 Key sustainability aspects and performance of urban rooftop farms

Diving into the key sustainability impacts driving the implementation of URF initiatives, many recurring themes were encountered in the literature as rooftop farming has been linked to many benefits depending on their function and inputs. Notwithstanding the constraints and limitations of URF, many opportunities exist for URF to contribute to enhancing the sustainability of cities. Among them, the potential of URFs for water savings, climate mitigation, food provision, biodiversity increase, community building and urban heat island effect reduction, or improved health and wellbeing appeared to be some of the most reoccurring aspects. URF can generally enhance the resilience of cities by improving their ability to face crisis while increasing the access to healthy foods for urban dwellers. If URF initiative were to be implemented on large scales, cities could largely satisfy the demand for fresh fruits and vegetables while reducing the need for non-renewable resources and thus significantly increase food security. Moreover, the creation of habitat for insects and through increased biodiversity provides cities with crucial ecosystem services subsequently lowering the ecological footprint of urban areas. When URF initiatives have a life quality improvement orientation, their development may provide additional spaces for recreation and thus promote social cohesion. The potential for community building and the health impact of involving people in gardening activities further demonstrate the potential benefits of URF. Additional benefits are seen regarding education where people can reconnect with their food and learn how it is grown. Furthermore, significant energy savings can be achieved depending on the type of farming system utilized by the URF. The water retention abilities of rooftop farming also contribute to mitigating the risk of floods. With the addition of a rainwater harvesting system, the integration of the URF within the building's metabolism allowing for the exchange of residual heat and CO_2 and the implementation of a compost system, fewer primary resources are required and thus avoided emissions can be reached.

On an increasingly warmer planet, the implementation of URF can lead to reduced peripheral temperatures around building and thus has the potential to significantly cool down the urban environment. However, as more temperature reduction can be reached with increased solar intensity the cooling effect of URF may not necessarily be of interest and beneficial in all contexts. On local scales, URFs have an impact on the microclimate and can lead to temperature reduction. The implementation of URF for its cooling effect would thus only be beneficial in countries with warm climates. Nevertheless, to fulfill their sustainability potential and curb the urban heat island effect, URF initiatives would have to be implemented on large scale. If the goal is to reduce temperature locally more research focusing on the extent to which URF initiatives could have a significant microclimatic effect would be needed.

Although the deployment of URFs appear to have many sustainability benefits, their implementation may not be sustainable by default. A certain number of aspects must be considered during their conception and operation. As noted by Begum and colleagues (2021), when proper investments and carrying of URF is undertaken, incomes are higher and overall economic growth for improved wellbeing and longer-term food security. In addition, Specht and colleagues (2014) highlight the need to incorporate recycling and recirculating systems at the organic waste, water and energy levels which in turn contributes to reducing associated pollution and overall reduce environmental and economic impact. The production of food on local scale implies a reduced need for transport which inevitably saves CO_2 emissions. However, the tendency to assume that local food production is inherently more desirable and environmentally friendly may be overestimated. As the findings of this research point out, the environmental impacts associated with the installation, operation, production, and distributions stages in the life cycle of an URF can be just as harmful as conventional farming. This in turn renders the benefits associated with short transportation meager. Hence, production on local scale is not good per se as it depends on other underlying factors. Indeed, the effect of reduced transport miles is not always significant depending on the conventionally produced food the URF replaces.

The recent development of URF has generated growing interest amongst the scientific community. Nonetheless, there currently exists only a limited number of studies assessing their sustainability performance. As very little data exists, assessing the environmental, economic, and social impact of URF proves to be challenging. From the identified studies, a general focus on analyzing the environmental performance of URF through LCA could be observed while LCC studies are sparser. Non-economic benefits of URF such as social wellbeing and biodiversity improvements are often not included in the scientific literature as their monetary values are more complex to evaluate (Teotónio, Silva & Cruz, 2018). More research has yet to be done to fully understand their sustainability potential. As few URF LCA studies exist, there is a need to evaluate more projects to contribute to the growing body of literature and enable more informed decisions making about their implementation. More specifically, future analysis should focus on studying other factors such as heat island effect reduction, food security, biodiversity improvements, climate change adaptation effects or community building.

Furthermore, it is clear from the first part of the research that URFs under open-air settings are most commonly implemented while a greater emphasis on RTGs is apparent in the LCA literature. This may be due to the fact that such systems are most frequently associated to research functions and make use of controllable environments facilitating their assessment. Future research must examine the impacts of open-air URF more specifically. Although one could argue that the impacts of an open-air URF may be similar to the ones of in-ground conventional agriculture, there are still other aspects that must be taken into account such as the impact of their installation along with their effect on biodiversity, social cohesion, or urban heat island effect reduction. Moreover, a general focus seems to be given to projects in Western countries while studies in the Southern hemisphere are nonexistent. Future research should seek to bridge this gap in knowledge and encompass greater spatial diversification as it is important to understand the sustainability aspects under other climatic conditions and different social contexts. In addition, cradle-to-grave studies of URF projects are still limited in number. More comprehensive research is needed to compare the sustainability among urban and traditional agriculture with sufficient emphasis on all stages associated with the installation and operation of URFs. Future research must focus on assessing the entire process from the extraction and manufacturing of all necessary materials for the fabrication of URF to the operation of the farming system, harvesting, distribution and consumption of produced goods and all other related activities. Moreover, there is a need to assess the end of life and maintenance of these initiatives.

5.3 Theoretical implications

According to this research, URF presents an environmentally friendly way of producing food and generates less environmental impact than conventional agriculture. Results vary depending on the type of URF, the growing method and type of crop produced emphasizing the importance of design decisions in the overall impacts of products grown in rooftop farming conditions. Generally, open-air URF initiatives using soil systems and growing fruits and vegetables were seen to be the most eco-efficient options. Nonetheless, even though the LCA approach is one of the most popular tools to assess the environmental impact of goods and services, LCA can be criticized as it does not evaluate all necessary aspects of a system. When URFs are put forward as way to produce food in an efficient way, LCA remains an appropriate decision-making tool to select the most environmentally performant substrate or growing media and type of crop grown. However, this is often not the sole purpose of URF. Food production is only one of the objectives of URF while other environmental, economic, and social purposes are aimed to be achieved. In these cases, the evaluation of efficient use of inputs for growing food compared to conventional agriculture does not appear to be relevant. LCA solely encapsulates a fraction of what URF can be. The full benefits of URF considering the environmental, economic, and social dimensions are thus found to be fundamentally outside the scope of LCA. Considering URF LCA, the metrics being used and the system boundaries of the projects under study did not always encompass the entire life cycle of URF initiatives and are thus not fully conclusive in terms of sustainability impact including all three dimensions. An importance was given to GWP and CED as a metric to assess the environmental impact of URF projects while other aspects of URF such as heat island effect mitigation and biodiversity improvements were not measured. There is thus a need to incorporate the metrics that have not yet been explored and that are the reason why URF initiatives can have such a long-term valuable impact. Future research must be conducted to establish and incorporate new metrics and indicators to assess the impact of URF on these aspects and fully depict the environmental, social, and economic benefits of these initiatives. This in turn can inform decision making and allow to understand how projects can best be optimized.

Evidence shows that URF initiatives can contribute to making cities more resilient and food secure. At present, key sustainability benefits and recommendations for sustainable URF design has been uncovered. The multifunctionality of urban rooftop agriculture make it an interesting solution as its integration into urban spaces can be beneficial on multiple levels. Their implementation on a large scale, whether they have a commercial orientation or more life quality improvement function, could be a significant step towards a more sustainable world. Especially in cities where cooling will become an important adaptation to climate change, implementing greening projects will be a necessary endeavor. The installation of URF has been seen to contribute to curbing the urban heat island effect which is being increasingly experienced in cities globally. Although studies have not focused on quantifying the cooling benefits of a large-scale implementation of URF, it will undoubtably be a useful strategy to contribute to decreasing temperatures locally. Cooling cities through green initiatives may in turn decrease the reliance on non-renewable resources. Additionally, as certain cities are becoming increasingly at risk of flooding events, there is a need to implement more climate adaptation strategies. Due to its water retention capacity, URFs can be an interesting solution for flood mitigation. However, there is a need to integrate this aspect into the environmental assessment of URF initiatives and to further investigate how they can contribute to the amelioration of the urban environment. Furthermore, the integration of the metabolic fluxes of the building and the rooftop farm can result in significant energy savings and thus reduce the ecological footprint of buildings and enhancing their circularity. Moreover, the application of local compost can promote the formation of closed cycles where organic matter and nutrient exports and losses are reduced further contributing to a more circular system on city scales.

In the face of climate change and resource scarcity, there is an evident need to implement these projects on a more global level. Nevertheless, the scaling of URF initiatives generally necessitates further exploration. A large-scale deployment of URF subsequently entails the need for more inputs and thus potential impacts if not operated sustainably. Additionally, before URF can be efficiently incorporated on a larger scale, existing barriers relating to their installation costs, weight load limitations and legal requirements should be addressed (Walters & Stoelzle Midden, 2018). Moreover, cities seeking to implement them should critically assess the environmental, social, and economic potential of the URF projects to ensure that they provide clear community benefits (Goodman & Minner, 2019).

Next to the urban benefits URFs can bring, the implementation of URF initiatives allows to address issues of food insecurity by providing access to nutritious food. Depending on the type of food produced and yield, URF can assist in the provision of fresh produce to satisfy the demand of urban populations. Moreover, the production of food on local scales in URF settings can also alleviate the pressure on land and lessen the environmental burden that conventional intensive agriculture poses. However, URF projects should not be thought as initiatives that can fully replace large-scale agricultural production. Rather, RA initiatives can be complementary to the conventional agricultural industry and enhance the urban food movement by adding another source of local, fresh foods (Walters & Stoelzle Midden, 2018). Indeed, cites may not become completely self-sufficient on local scales, as they will still rely on the harvest of other cash crops that URF will not be able to sustain. Nevertheless, if implemented in combination with other sustainable and regenerative urban agricultural initiatives such as green walls and peri-urban agricultural projects, they can together contribute to greater food security and resilience of a city and eventually self-sufficiency.

Besides the eco-environmental benefits, URFs can present a constructive social enterprise and can be used as a tool to create stronger communities, more social cohesion, and provide education on food production. However, it is important to note that the social sustainability benefits associated with URF will also depend on their typology and function. A next important step is to establish how their operation can be designed such that they are sustainable on a social level. One may wonder about their potential for connecting people with foods by offering them the possibility to eat more nutritiously while learning how to grow food. As community gardening and being in contact with nature has proven to have benefits for wellbeing and mental health, certain health hazard may be reduced. However, since their operation can also accentuate social disparities when the access to URF is imbalance, careful attention should be placed when planning their implementation. In order to advance the development of URFs in a socially just way, there is a need to develop better metrics to understand the social impacts of URFs. Social LCAs should therefore be adapted to incorporate the different social dimensions that are associated with URFs. New indicators need to evaluate accessibility to nutritious food, contribution to solving food insecurity or social cohesion.

Other studies have already put forward different methods and combined disciplines to assess the sustainability of URF initiatives. For instance, Grard and colleagues (2018) used an ecosystem services approach to understand the environmental performance of URF and allow a comprehensive comparison between different management options. Sanyé-Mengual and colleagues (2017) employed a multidisciplinary approach and combine several methods such as interviews, geographic information systems, LCA and LCC to assess the sustainability potential of URF implementation. The use of an LCA in combination with an Integrated Value Model for Sustainable Assessment (MIVES) was put forward by Pons and colleagues (2015) to examine the sustainability of implementing RTGs. Lastly Nadal and colleagues (2018) also made use of the MIVES approach and other indicators to assess the potential of RTG implementation on school buildings. These different methodologies illustrate the need to use a multidisciplinary lens when evaluating the sustainability of URF initiatives along with the involvement of all stakeholders participating in the project.

Generally, not all URF initiatives have the same sustainability performance as it depends on their installation and operation. However, cities and URF practitioners should strive towards achieving sustainable URF initiatives. When the ultimate goal of shifting towards a food secure world where the finite carrying capacity of the planet is considered under a changing climate, URF constitutes one of the many necessary solutions to tackling the myriad of challenges associated with the urban environment and current food system. On the one hand, the multifunctionality of URF renders it a potential solution to address the issues related to production by retrofitting it on local scales. On the other hand, it is also necessary to address the issue of over-consumption of high-intensity foods such as meat and dairy and consider the food waste problem where a third of edible foods are discarded every year.

5.4 Limitations

When conducting this research, several limitations were encountered which may impede on the validity of the findings. Firstly, the classification of projects can be considered biased as an emphasis was put on countries for which projects could be found with certainty and thus may have ignored existing projects in other countries. In addition, ongoing rooftop farming initiatives are not all documented. URF initiatives for which no website or online information exists could not be accounted for. The resulting classification can thus not be considered fully representative as it does not encompass all existing projects. Furthermore, the surface area of certain identified URF projects may not be fully representative as cultivated area and total surface area are not the same. It may be that the amount of space reserved for food production is significantly smaller than the total surface area of the roof and certain projects do not differ between the two. In addition, some surface areas had to be approximated based on the area of the rented parcels and their number. Moreover, the type of food grown was not always mentioned in project descriptions and had to be identified from pictures. The use of broad categories such as vegetables, aromatic herbs, and fruits although accurate may not be the most representative. As the production of certain foods may be more impactful especially in terms of environment and economic than others future research could specifying the exact food grown and quantify their impact to understand which crops would be most sustainably beneficial. Furthermore, to eliminate any of the uncertainties and limitations due to impreciseness or a lack of available data and obtain a fully representative and accurate classification, future research should focus on individually contacting projects to obtain all necessary information.

Concerning the key sustainability aspects driving the implementation of URF, as UA and URF have been gaining momentum over the past few decades, only a limited amount of literature is currently available on their sustainability drivers and impact. Studies have largely focused on the implementation and sustainability aspect of UA more generally as opposed to URF specifically. This in turn makes it difficult to see the benefits of one over the other. Future research should seek to bridge that gap and focus on studying URF more specifically.

Furthermore, most of the available URF LCAs investigate greenhouse systems when most of the URFs are open systems. Hence, this may limit the interpretation of the LCA results.

Finally, the comparison of LCA and LCC was proven to be complex since different functional units and system boundaries were used depending on the study. Additionally, different climate regions and types of URF systems were investigated resulting in a lack of consistency in the studies and rendering comparisons more challenging. Nonetheless, the fact that a majority studies use the i-RTG-Lab as a case study imply that the results are largely influence by the design and operation of this specific example. Furthermore, the assessment of the overall sustainability of these initiatives appears to be limited as a number of factors are not included in the studies. Research has mostly focused on evaluating the environmental and economic performance of URFs while their social impacts are harder to quantify and thus often overlooked.

6. Conclusion

This research contributes to the current theoretical knowledge on the sustainability of urban rooftop farming. By investigating the critical aspects influencing the sustainability of URF initiatives, this study demonstrates that there is no one clear-cut way of designing and operating sustainable URF. Nevertheless, results show that certain elements are important to consider to reach their full sustainability potential. Key factors are seen to influence the sustainability impact of URF including farming methods, primary function, or crop selection. Additionally, when comparing the environmental and economic performance of URF to that of conventional farming, rooftop farming can present lower environmental burden and costs attributable to decreased land use, water and energy savings along with reduced packaging and transport requirements. However, other aspects such as greenhouse structure, use of fertilizer and substrate selection can negatively impact the overall performance of URFs.

Rooftop farming as a field has been gaining momentum but research is still in its infancy. The current tools being used to assess the performance of URFs do not provide a complete picture of the sustainability impacts of URFs. Recent studies have largely focused on investigating environmental aspects of URF while other dimension namely the social perspective tends to be overlooked. Improved tools to analyze their sustainability performance should thus be incorporated to understand the impact of URF. Moreover, there are more, and better assessments of open-air URF needed as a focus on RTG is observed. Furthermore, there remains a large potential to further contribute to the gap in knowledge as to how URF projects can be implemented on a wider level. Indeed, their large-scale implementation could be an efficient measure towards climate change mitigation and adaptation while creating social cohesion. More research is still needed to estimate the feasibility of such initiatives for instance by creating a roadmap for their implementation on local, regional, and national scales in different geographical areas. As the key drivers for their implementation may vary depending on the context, research should seek to understand the best URF practices to enable a strategic implementation and allow informed decision making.

7. References

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8. Appendix 1

Name	City	Country	Continent	Area (m^2)	Year	Farming method	Building	Function	Type of food	Source
Jardin Perché Annecy	Annecy	France	Europe	600	2017	Open-air, in soil	Shopping center	Commercial, life quality	Aromatic herbs, edible flowers	https://www.souslesfraises.com/jardin-perche-annecy/
Agripolis - Hotel Accor	Boulogne	France	Europe	300	2017	Open-air, aeroponics	Hotel	Commericial	Vegetables, aromatic herbs	https://agripolis.eu/project/boulogne-toit-hotel/
Agripolis – Sodexo	Issy les moulineaux	France	Europe	250	2018	Open-air, aeroponics	Office building	Life-quality	Vegetables, aromatic herbs	https://agripolis.eu/project/issy-sodexo/
Jardin Perché de Caluire	Lyon	France	Europe	4000	2018	Open-air, in soil	Parking lot	Commercial, life quality	Vegetables, fruits, edible flowers	https://www.souslesfraises.com/jardin-perche-caluire/ https://www.caluire.jardinperche.fr/
Farmhouse so West	Levallois Perret	France	Europe	600	2018	Open-air, in soil	Shopping center	Commercial, life quality	Vegetables	https://www.souslesfraises.com/farmhouse-so-ouest/
Farm West	Colombes	France	Europe	850	2021	Open-air, aeroponics	Office building	Life quality	Vegetables, fruits, aromatic herbs	https://www.cueilletteurbaine.com/farm-west-defense-ouest-colombes/
L'Arche Végétale	Paris	France	Europe	800	2019	Open-air, aquaponics, aeroponics, raised beds	School	Educational / social, commercial	Vegetables, aromatics herbs, edible flowers, fish	https://www.cueilletteurbaine.com/realisations/ateliers-team-building-et-formation/ https://www.paris.fr/pages/l-arche-vegetale-de-la-ferme-urbaine-aux-assiettes-de-thierry-marx-11846
Culina Hortus	Paris	France	Europe	200	2020	Open-air, aquaponics	Office building	Research	Vegetables, edible flowers, fish	https://www.cueilletteurbaine.com/realisations/ferme-urbaine-multifonctionnelle/
Rooftop de la Ruche	Paris	France	Europe	300	2017	Open-air, raised beds	Co-working space	Life quality	Vegetables, aromatic herbs	https://www.cueilletteurbaine.com/rooftop-de-la-ruche/

Ferme aeroponic de l'Hopital Sainte-Périne	Paris	France	Europe	5000	2019	Open-air, aeroponics	Hospital	Commercial	Vegetables, fruits, aromatic herbs	https://www.cueilletteurbaine.com/ferme-aeroponique-de-lhopital-sainte-perine/
Fédération Française de Football	Paris	France	Europe	340	2020	Open-air, raised beds, aeroponics	Office building	Life quality	Vegetables, flowers, beehives	https://www.cueilletteurbaine.com/federation-francaise-de-football-fff/
La Serre Perchée	Paris	France	Europe	1000	2018	In door, Greenhouse	Residential building	Commercial, educational	Ornamental plants	https://www.souslesfraises.com/serre-perchee-menilmontant/
Le Jardin Perché Marais	Paris	France	Europe	1420	2017	Open-air, vertical walls	Shopping center	Commercial	Fruits, aromatic herbs, edible flowers, bees	https://www.souslesfraises.com/jardin-perche-marais/ https://www.bhv.fr/e1/vivez-bhv/le-bhv-marais/garden-perched-our-rooftop
Jardin Perché Haussmann	Paris	France	Europe	1200	2015	Open-air, vertical walls	Shopping center	Commercial	Fruits, vegetables, aromatic herbs, flowers	https://www.souslesfraises.com/jardin-perche-haussmann/
Nature Urbaine	Paris	France	Europe	15000	2020	Open air / Greenhouse Hydroponics, aeroponics	Exhibition center	Commercial, life-quality	Fruits and vegetables	https://www.nu-paris.com/nature-urbaine/#2
La Plantation	Paris	France	Europe	7000	2020	Open air, in soil, indoor, greenhouse	Industrial building	Commercial, life quality	Vegetables, fruits, aromatic herbs	https://www.plantation.paris/
Agripolis – Piscine Cour des Lions	Paris	France	Europe	800	2018	Open air / Aeroponic	Gymnasium	Commercial	Fruits and vegetables	https://agripolis.eu/project/paris-16-piscine-cour-des-lions/
Agripolis – Collège Eugène Delacroix	Paris	France	Europe	1200	2018	Open-air / Aeroponic	School	Commercial	Fruits and vegetable	https://agripolis.eu/project/paris-16-college-delacroix/
Peas&Love Yooma	Paris	France	Europe	1000	2018	Open-air, in soil, vertical walls	Hotel	Life quality	Fruits, vegetables, aromatic herbs	https://www.peasandlove.com/pages/potager-nos-fermes

Le Cordon Bleu Ferme	Paris	France	Europe	800	2016	Open-air, raised beds in soil	School	Life quality, educational	Fruits, vegetables, bees	https://zinco-greenroof.co.uk/projects/le-cordon-bleu-paris
Le Bon Marché	Paris	France	Europe	700	2017	Open-air, raised beds in soil	Shopping center	Commercial, educational	Vegetables, aromatic herbs, edible flowers	http://topager.com/portfolio-item/le-bon-marche-suivit/
Opéra Bastille	Paris	France	Europe	2500	2018	Open-air, in soil	Opera	Commercial, life-quality	Vegetables, fruits, aromatic herbs, edible flowers	http://topager.com/
Potager Thérapeutique Robert Doisneau	Paris	France	Europe	500	2014	Open-air, raised beds in soil	Hospital	Life quality	Vegetables, aromatic herbs	http://topager.com/portfolio-item/un-jardin-therapeutique-sur-le-centre-robert-doisneau/
Deskopolitan	Paris	France	Europe	160	2019	Open-air, raised beds in soil	Office building	Commercial Life quality	Aromatic herbs, fruits	http://topager.com/portfolio-item/deskopolitan/
Petit Potager Participatif	Issy Les Moulineaux	France	Europe	10	2017	Open-air, raised beds in soil	Office building	Life quality	Vegetables, aromatic herbs	https://www.cueilletteurbaine.com/petit-potager-participatif/
Les Jardins Perchés	Tours	France	Europe	760	2021	Indoor, greenhouse and aeroponics	Residential building	Commercial, life quality	Vegetables, aromatic herbs	https://www.cueilletteurbaine.com/jardins-perches-tours/
Jardin Perché Lyon Caluire	Caluire	France	Europe	4000	2018	Open-air, vertical wall,	Parking lot	Commercial, life quality	Vegetables, fruits, aromatic herbs, beehives	https://www.souslesfraises.com/en/jardin-perche-caluire/
Jardin Perché – Annecy	Annecy	France	Europe	600	2017	Open-air, in soil, vertical walls	Shopping center	Life quality	Edible flowers, aromatic herbs, bees	https://www.souslesfraises.com/en/jardin-perche-annecy/
Jardin partagé	Sèvres	France	Europe	800	2015	Open-air, raised beds in soil	Gymnasium	Life quality	Vegetables, aromatic herbs	http://topager.com/portfolio-item/un-jardin-partage-sur-le-toit-d-un-gymnase/
Jardins Potagers	Ivry-sur-Seine	France	Europe	450	2017	Open-air, raised beds in soil	Residential building	Life quality	Vegetables, fruits, aromatic herbs, edible flowers	http://topager.com/portfolio-item/ivry-madiba/

Pulse	Aubervilliers	France	Europe	350	2019	Open-air, raised beds in soil	Office building	Commercial	Vegetables, aromatic herbs	http://topager.com/portfolio-item/pulse/
Peas&Love Caméléon	Woluwe-Saint-Lambert	Belgium	Europe	640	2017	Open-air, vertical walls, in soil	Shopping center	Commercial, life quality	Vegetables, aromatic herbs	http://topager.com/portfolio-item/pulse/
BIGH	Brussels	Belgium	Europe	4000	2018	In door greenhouse, aquaponics, hydroponics, and open-air	Warehouse	Commercial, life quality	Vegetables, aromatic herbs, fish	https://bigh.farm/farm/
Daktuin Boondael	Brussels	Belgium	Europe	360	2017	Open-air, in soil, in door, greenhouse	Supermarket	Commercial, educational	Vegetables, aromatic herbs	https://www.aholddelhaize.com/en/news/delhaize-opens-first-store-rooftop-farm-in-belgium/
Roof Food	Ghent	Belgium	Europe	500	2014	Open air, raised beds in soil	Business center	Life quality	Vegetables, fruits, aromatic herbs	https://rooffood.be/nl/about
PAKT	Antwerp	Belgium	Europe	1800	2017	Open-air, raised beds in soil, in door greenhouse, vertical walls	Warehouses	Commercial, life quality	Fruits, vegetables, herb, chicken, beehives	https://www.pakt-antwerpen.be/ons-verhaal https://www.pakt-antwerpen.be/
Dakakker	Rotterdam	Netherlands	Europe	1000	2012	Open-air, in soil	Office building	Commercial, educational,	Edible flowers, bees, aromatic herbs, vegetables, chickens	https://dakakker.nl/
Erasmus MC	Rotterdam	Netherlands	Europe	3400	2018	Open air, orchards	Hospital	Social, life-quality	Fruits and nut trees	https://rotterdamsedakendagen.nl/en/erasmusmc/ https://erasmusmcfoundation.nl/erasmus-mc-daktuinen/
Zuidpark	Amsterdam	Netherlands	Europe	3000	2012	Open-air, raised beds in soil	Office building	Commercial, life quality	Fruits and vegetables	http://zuidparkamsterdam.nl/urban-farming-roof/
ØsterGro	Copenhagen	Denmark	Europe	600	2014	Open-air, in soil, raised beds in soil, indoor greenhouse	Parking lot	Commercial, life quality	Bees, chicken, aromatic herbs, edible flowers, fruits and vegetables	https://www.oestergro.dk/om-stergro https://www.kobenhavnergron.dk/place/ostergro/?lang=en

Cork Rooftop Farm	Cork	Ireland	Europe	650	2020	Open-air, raised beds in soil, aeroponics	Warehouse	Commercial	Vegetables, aromatic herbs, Chicken	https://www.echolive.ie/corklives/arid-40111187.html https://www.corkrooftopfarm.ie/about-us/
Garnisonen	Stockholm	Sweden	Europe	350	2016	Open-air, in soil, in door greenhouse	Supermarket	Commercial, educational	Vegetables, aromatic herbs, edible flowers, bees	https://pressrum.coop.se/coop-och-kfs-blir-huvudpartners-till-bee-urbans-stadsodling/ http://www.diva-portal.se/smash/get/diva2:1252946/FULLTEXT01.pdf
Rooftop Farm Ecco Jäger	Bad Ragaz	Switzerland	Europe	1100	2016	Indoor greenhouse, hydroponics, aquaponics	Office building	Commercial	Fish, vegetable, aromatic herbs	http://www.ecco-jaeger.ch/ https://www.ecf-farmsystems.com/referenzen?lang=en
Urban Rooftop Garden Kreuzberg	Berlin	Germany	Europe	200	2011	Open-air, raised beds in soil	Office building	Life quality	Vegetables, aromatic herbs, flowers	http://www.raumstar.de/en/projects/urban-rooftop-garden-berlin-kreuzberg
REWE Green Farming Market	Wiesbaden-Erbenheim	Germany	Europe	1000	2019	Indoors, greenhouse, aquaponics	Supermarket	Commercial	Fish, aromatic herbs	https://www.ecf-farmsystems.com/referenzen?lang=en
Altmarktgarten	Oberhausen	Germany	Europe	1100	2019	Indoor, greenhouse, hydroponics	Office building	Commercial, research	Vegetables, fruits, aromatic herbs	https://altmarktgarten-oberhausen.de/ http://www.dachfarmberlin.com/#referenzen-section
Food from the sky	London	United Kingdom	Europe	400	2010	Open-air, raised beds in soil	Supermarket	Commercial, life-quality	Vegetables, fruits, aromatic herbs	https://foodfromthesky.org.uk/
RISC	Reading	United Kingdom	Europe	200	2001	Open-air, in soil	Community center	Life quality, social / educational	Vegetables, fruits, aromatic herbs	https://www.risc.org.uk/gardens/roof-garden
Ortoalto Baltea	Turin	Italy	Europe	150	2016	Open-air, raised beds in soil	Multipurpose space (bar, bakery, co working space)	Social, life quality	Vegetables, fruits, aromatic herbs	https://ortialti.com/portfolio/ortoalto-baltea/

Ortoalto Ozanam	Turin	Italy	Europe	150	2016	Open-air, in soil	Industrial building	Social, life quality	Vegetables, aromatic herbs, bees	https://ortialti.com/portfolio/ortoalto-ozanam/
Coabitanti Green	Turin	Italy	Europe	150	2019	Open-air, in soil	Garage of a residential building	Social, life quality	Vegetables, aromatic herbs	https://ortialti.com/portfolio/atc-via-fossata-2-2/
Via Gondusio	Bologna	Italy	Europe	250	2011	Open-air, raised beds in soil, hydroponics	Social housing complex	Social, life quality	Vegetables, aromatic herbs	https://site.unibo.it/susturbanfoods/en/case-studies/viagandusio
ICTA-ICP Lab	Barcelona	Spain	Europe	800	2014	In-door, greenhouse, soil less perlite	University	Research, educational	Vegetables	https://www.researchgate.net/publication/275956813_The_ICTA-ICP_Rooftop_Greenhouse_Lab_RTG-Lab_closing_metabolic_flows_energy_water_CO_2_through_integrated_Rooftop_Greenhouses
Brooklyn Grange – Brooklyn Navy Yard	New York	USA	North America	6000	2012	Open-air, in soil, in door, greenhouse	Industrial building	Commercial, educational	Vegetables, aromatic herbs, bees, chicken	https://www.brooklyngrangefarm.com/about
Brooklyn Grange - Sunset Park Farm	New York	USA	North America	13000	2019	Open-air, in soil	Shopping center	Commercial, educational	Vegetables, aromatic herbs, bees	https://www.brooklyngrangefarm.com/ https://green-roofs.co.uk/worlds-top-rooftop-farms/
Brooklyn Grange – Long Island City	New York	USA	North America	3700	2010	Open-air, in soil	Industrial building	Commercial, educational	Vegetables, aromatic herbs, bees	https://www.brooklyngrangefarm.com/about
Arbor House at Forest Houses	New York	USA	North America	700	2012	Indoor, greenhouse, hydroponics	Residential building	Commercial, social	Vegetables, aromatic herbs	http://www.skyvegetables.com/bio-1
Bell Book & Candle	New York	USA	North America	230	2010	Open-air, aeroponics	Restaurant	Commercial	Vegetables, aromatic herbs	https://www.towerfarms.com/us/en/possibilities/restaurant-farming/bell-book-and-candle https://www.bbandcnyc.com/roof-top-garden

Gotham Greens – Greenpoint	New York	USA	North America	1400	2011	Indoor, greenhouse, hydroponics	Industrial building	Commercial	Vegetables, aromatic herbs	https://www.gothamgreens.com/our-farms/
Gotham Greens – Gowanus	New York	USA	North America	1860	2013	Indoor, greenhouse, hydroponics	Supermarket	Commercial	Vegetables, aromatic herbs	https://www.gothamgreens.com/our-farms/
Gotham Greens – Hollis	New York	USA	North America	5570	2015	Indoor, greenhouse, hydroponics	Industrial building	Commercial	Vegetables, aromatic herbs	https://www.gothamgreens.com/our-farms/
Eagle Street Farm	New York	USA	North America	557	2009	Open-air, in soil	Warehouse	Commercial	Vegetables, aromatic herbs, bee, chicken	https://www.greenroofs.com/projects/eagle-street-rooftop-farm/
Hell's Kitchen Farm Project	New York	USA	North America	380	2010	Open-air, raised beds in soil	Church	Life quality	Vegetables, fruits, aromatic herbs	https://www.hkfp.org/rooftop-farm
The Vinegar Factory	New York	USA	North America	830	1993	Indoor, greenhouse	Supermarket	Commercial	Vegetables, fruits	https://www.ryerson.ca/carrotcity/board_pages/rooftops/NYC_rooftop_greenhouses.html
The Greenhouse Project	New York	USA	North America	130	2010	Indoor, greenhouse, hydroponics, aquaponic, raised beds in soil	School	Educational	Vegetables, fruits, fish	https://www.urbangardensweb.com/2011/11/16/nyc-classroom-in-an-urban-rooftop-farm/
The Visionaire Penthouse Green Roof	New York	USA	North America	204	2010	Open-air, raised bed in soil	Residential building	Life quality	Vegetables	https://www.greenroofs.com/projects/cultivated-abundance-the-visionaire-penthouse-green-roof/
Bronxscape	New York	USA	North America	300	2009	Open-air raised beds in soil	Residential building	Social	Vegetables	https://www.ryerson.ca/carrotcity/board_pages/rooftops/bronxscape.html
5th Street Farm Project	New York	USA	North America	280	2010	Open-air, raised bed in soil	School	Educational	Vegetables, aromatic herbs	https://www.5thstreetfarm.org/

Via Verde	New York	USA	North America	3720	2012	Open air in soil, raised beds in soil	Residential building	Life quality	Vegetables, fruits	https://www.greenroofs.com/projects/via-verde-the-green-way/
Gotham Greens – Pullman	Chicago	USA	North America	6970	2015	Indoor, greenhouse, hydroponics	Industrial building	Commercial	Vegetables, aromatic herbs	https://www.gothamgreens.com/our-farms/
McCormick Place Rooftop Farm	Chicago	USA	North America	2322	2013	Open-air, in soil	Convention center	Commercial	Vegetables, fruits, aromatic herbs	https://www.chicagobotanic.org/urbanagriculture/farms
Hilton Chicago Rooftop Farm	Chicago	USA	North America	46	2013	Open-air, raised beds in soil	Hotel	Commercial, life quality	Vegetables, aromatic herbs, edibles flowers, bees	https://www.chicagobotanic.org/urbanagriculture/farms
Gary Comer Youth Center Green Roof	Chicago	USA	North America	758	2006	Open-air, raised beds in soil	Youth center	Educational	Vegetables, fruits	https://www.greenroofs.com/projects/gary-comer-youth-center-green-roof/
Uncommon Ground restaurant	Chicago	USA	North America	230	2007	Open air, raised beds in soil	Restaurant	Commercial	Vegetables, aromatic herbs	https://www.uncommonground.com/roof-top-farm
Boston Medical Center Rooftop Farm	Boston	USA	North America	247	2017	Open-air, raised beds in soil	Hospital	Social	Vegetables, aromatic herbs, bees	https://www.greenroofs.com/projects/boston-medical-center-rooftop-farm/
Fenway Farms	Boston	USA	North America	650	2015	Open-air, raised beds in soil	Baseball stadium	Commercial, life quality	Vegetables, aromatic herbs, bees	https://www.greenroofs.com/projects/fenway-farms/
Food Roof Farm	St Louis	USA	North America	790	2015	Open-air, in soil, raised beds in soil, hydroponics, indoor greenhouse	Warehouse	Social / educational, life-quality	Vegetables, fruits, aromatic herbs, edible flowers, chicken	https://www.greenroofs.com/projects/food-roof-farm/
The Burnside Rocket	Portland	USA	North America	21	2007	Open-air, in soil, raised beds in soil	Multipurpose space, bar office	Commercial, life quality	Vegetables, aromatic herbs	https://www.greenroofs.com/projects/the-burnside-rocket/
Whole Foods Market	Lynnfield	USA	North America	1579	2013	Open-air, in soil	Supermarket	Commercial	Vegetables, aromatic herbs, edible flowers	https://www.greenroofs.com/projects/whole-foods-market-lynnfield-ma/

Rouses Roots on the Rooftop	New Orleans	USA	North America	75	2012	Open-air, aeroponics	Supermarket	Commercial	Vegetables, aromatic herbs	https://www.towerfarms.com/us/en/possibilities/rooftop-farming/rouses-rooftop-farm
Chapala Garden	Santa Barbara	USA	North America	65	2012	Open-air, aeroponics	Residential building	Commercial, life quality	Vegetables, aromatic herbs	https://www.chapalagardens.com/ https://www.towerfarms.com/us/en/possibilities/rooftop-farming/chapala-gardens
Metro Atlanta Task Force Rooftop Garden	Atlanta	USA	North America	900	2009	Open air, raised beds in soil	Residential building	Social	Vegetables, fruits, bees	https://www.vice.com/en/article/8qkeyv/this-rooftop-garden-is-feeding-atlantas-homeless
Rothenberg Rooftop School Garden	Cincinatti	USA	North America	790	2014	Open-air, raised bed in soil	School	Educational	Vegetables, aromatic herbs	https://www.rothenbergrooftopgarden.com/
Altius Farm	Denver	USA	North America	670	2018	Indoor, aeroponics	Warehouse	Commercial, social	Vegetables, aromatic herbs	https://www.towerfarms.com/us/en/possibilities/rooftop-farming/altius-farms
Lufa - Ahuntsic	Montreal	Canada	North America	2800	2011	Indoor, greenhouse, hydroponics	Industrial building	Commercial	Vegetables, aromatic herbs	https://montreal.lufa.com/en/farms
Lufa – Laval	Montreal	Canada	North America	4000	2013	Indoor, greenhouse, hydroponics	Industrial building	Commercial	Vegetables	https://montreal.lufa.com/en/farms
Lufa - Anjou	Montreal	Canada	North America	5800	2017	Indoor, greenhouse, hydroponics	Industrial building	Commercial	Vegetables, aromatic herbs	https://montreal.lufa.com/en/farms
Lufa - Ville Saint-Laurent	Montreal	Canada	North America	15200	2020	Indoor, greenhouse, hydroponics	Industrial building	Commercial, educational,	Vegetables	https://montreal.lufa.com/en/farms
Santropol Roulant	Montreal	Canada	North America	140	1995	Open air in soil	Residential building	Life quality	Vegetables, aromatic herbs, bees	https://www.ryerson.ca/carrotcity/board_pages/rooftops/santropol_roulant.html

Hôtel du Vieux-Québec rooftop garden	Québec	Canada	North America	300	2009	Open air, raised beds in soil	Hotel	Life quality	Vegetables, aromatic herbs, bees	https://cityfarmer.info/canada-hotel-du-vieux-quebecs-rooftop-garden/
Ryerson Urban Farm	Toronto	Canada	North America	900	2013	Open-air, in soil	School	Educational, commercial	Vegetables	https://www.greenroofs.com/projects/ryerson-urban-farm-formerly-ryes-homegrown/ https://www.ryerson.ca/university-business-services/urban-farm/about/
Fairmont Royal York Hotel	Toronto	Canada	North America	370	1998	Open-air, raised beds in soil	Hotel	Commercial, life quality	Vegetables, fruits, aromatic herbs, edible flowers, bee	https://www.greenroofs.com/projects/fairmont-royal-york/
Carrot Common Green Roof	Toronto	Canada	North America	300	1996	Open air in soil, raised beds in soil	Multipurpose space	Life quality	Vegetables, aromatic herbs	https://www.ryerson.ca/carrotcity/board_pages/rooftops/carrot_green_roof.html
Fairmont Waterfront Hotel	Vancover	Canada	North America	195	1996	Open-air, in soil, raised beds in soil	Hotel	Commercial, life quality	Vegetables, fruits, aromatic herbs, edible flowers, bees	https://www.ryerson.ca/carrotcity/board_pages/rooftops/fairmont.html
Trent University Vegetable Garden	Peterborough	Canada	North America	2790	1996	Open-air, in soil	School	Educational	Vegetables, fruits, aromatic herbs	https://www.greenroofs.com/projects/trent-university-environmental-and-resource-sciences-vegetable-garden/
Eldorado Shopping	Sao Paulo	Brazil	South America	2500	2012	Open-air, raised beds in soil	Shopping center	Life quality	Vegetables, fruits and herbs	https://www.shoppingeldorado.com.br/projeto/telhado-verde https://www.shoppingeldorado.com.br/projeto/telhado-verde https://www.thecivilengineer.org/news-center/latest-news/item/1150-shopping-mall-in-brazil-recycles-all-food-waste-by-growing-vegetables-on-its-roof https://www.researchgate.net/publication/301471849_Enhancing_citizens'_participation_in_decentralized_water_management_systems_in_Sao_Paulo's_Metropolitan_Region
ISLA	Mexico City	Mexico	Central America	293	2014	Open-air, raised beds in soil	Residential building	Life quality	Vegetables	http://isla.pw/en/huerto/

Dizengoff Center Rooftop Farm	Tel Aviv	Israel	Asia	750	2018	Open air, hydroponic, aquaponic	Shopping center	Life quality	Vegetables, aromatic herbs, fish, bees	https://www.treehugger.com/tel-avivs-rooftop-farm-grows-vegetables-thousands-people-4854252
Sky Farm	Shanghai	China	Asia	700	2010	Open-air, raised beds, indoor, greenhouse vertical farm	Industrial building	Commercial, educational	Vegetables	https://www.sixthtone.com/news/1001052/shanghais-edible-rooftops
Jiashan SkyFarm	Shanghai	China	Asia	18	2010	Open-air, in soil	Bar	Life quality, educational	Vegetables, aromatic herbs,	https://jiashan-skyfarm.tumblr.com/
Anken Rooftop Farm	Shanghai	China	Asia	25	2010	Open-air, raised beds in soil	Office building	Life quality, educational	Vegetables, Aromatic herbs	https://shanghai-skyfarms.tumblr.com/ https://www.complete-gardening.com/gardening/anken-rooftop-farm-urban-agriculture-in-shanghai/
CapitaLand (Kaide Qibao) Shopping Plaza Roof Farm	Shanghai	China	Asia	3000	2013	Open-air, raised beds, planters (tunnels) soil less	Shopping mall	Life quality, educational	Vegetables, aromatic herbs	https://archive.shine.cn/district/minhang/Organic-gardening-is-looking-up/shdaily.shtml https://app04.teli.hku.hk/urf/2017/07/07/4021/
Metroplaza Shopping Mall	Hong Kong	China	Asia	3900	2018	Open-air, raised beds in soil	Shopping mall	Commercial, life quality	Fruits, vegetables, edible flowers, aromatic herbs	https://smile.cebupacificair.com/hong-kong-green-future/
Bank of America Tower rooftop farm	Hong Kong	China	Asia	93	2014	Open-air, raised beds in soil	Office building	Social, life quality	Vegetables	https://app04.teli.hku.hk/urf/2017/06/19/bank-of-america-tower-rooftop-farm/
Caritas Lok Kan School	Hong Kong	China	Asia	550	2008	Open-air, raised beds in soil	School	Educational	Vegetable, flowers, aromatic herbs	https://app04.teli.hku.hk/urf/2017/06/16/caritas-lok-kan-school/
CUHK: Library Rooftop Garden	Hong Kong	China	Asia	189	2015	Open-air, in soil	Library	Life quality, educational	Vegetables, fruits, aromatic herbs	https://app04.teli.hku.hk/urf/2017/06/14/209/

CUHK: Teaching Complex	Hong Kong	China	Asia	177	2013	Open air, in soil	School	Life quality, educational	Vegetables, fruits, aromatic herbs	https://app04.teli.hku.hk/urf/2017/06/14/chinese-university-teaching-complex/
City Farm – Kwun Tong	Hong Kong	China	Asia	527	2013	Open-air, raised beds in soil	Industrial building	Educational, life quality	Vegetables, aromatic herbs	https://app04.teli.hku.hk/urf/2017/06/19/city-farm-kwun-tong/
City Farm – Chai Wan	Hong Kong	China	Asia	465	2016	Open-air, raised beds in soil	Industrial building	Educational, life quality	Vegetables, aromatic herbs	https://app04.teli.hku.hk/urf/2017/06/14/city-farm/
City Farm – Tsuen Wan West	Hong Kong	China	Asia	970	2013	Open-air, raised beds in soil	Industrial building	Educational, life quality	Vegetables, aromatic herbs	https://app04.teli.hku.hk/urf/2017/06/14/city-farm-tsuen-wan-west/
Crystal Group Rooftop Farm	Hong Kong	China	Asia	56	2010	Open-air, raised beds in soil	Industrial office	Life quality	Vegetables, fruits, aromatic herbs	https://app04.teli.hku.hk/urf/2017/06/14/crystal-group-rooftop-farm/
Confucius Hall Secondary School	Hong Kong	China	Asia	180	2014	Open-air, raised beds in soil	School	Educational	Vegetables, aromatic herbs	https://app04.teli.hku.hk/urf/2017/06/19/confucius-hall-secondary-school/
Fringe Rooftop Farm	Hong Kong	China	Asia	90	2015	Open-air, raised beds in soil	Cultural center	Life quality	Vegetables, aromatic herbs	https://app04.teli.hku.hk/urf/2017/06/19/fringe-rooftop-farm/
Fun n Farm	Hong Kong	China	Asia	81	2013	Open-air, raised beds	Industrial building	Life quality	Vegetables, aromatic herbs	https://app04.teli.hku.hk/urf/2017/06/14/fun-n-farm/
Urban Farm at Hysan Place	Hong Kong	China	Asia	740	2013	Open-air, in soil	Shopping center	Educational, life-quality	Vegetables, fruits, aromatic herbs	https://app04.teli.hku.hk/urf/2017/06/19/hysan-building-rooftop-farm/
HKU Rooftop Farm	Hong Kong	China	Asia	400	2012	Open-air, raised beds in soil	School	Educational	Vegetables, fruits, aromatic herbs	https://app04.teli.hku.hk/urf/2017/06/14/hku-rooftop-farm/

Green Monday	Hong Kong	China	Asia	500	2015	Open-air, raised beds in soil	Office building	Life quality, educational	Vegetables, aromatic herbs	https://app04.teli.hku.hk/urf/2017/06/19/green-monday/#more-742
Chengdu rooftop farm	Chengdu	China	Asia	10000	2016	Open-air, raised beds in soil	Shopping mall	Life quality, educational	Vegetables, fruits, rabbit	https://cityfarmer.info/rooftop-farming-arrives-in-chengdu-china/#more-311864
Chengdu vegetable garden	Chengdu	China	Asia	50	2017	Open-air in soil	Garage	Life quality	Vegetables	http://en.people.cn/n3/2017/0801/c90000-9249695.html
Chongqing rooftop farm	Chongqing	China	Asia	10000	2014	Open air in soil	Industrial building	Life quality	Vegetables, chicken	https://green-roofs.co.uk/worlds-top-rooftop-farms/
Comcrop	Singapore	Singapore	Asia	4000	2014	Indoor, greenhouse, hydroponics	Shopping mall	Commercial, social	Vegetables, aromatic herbs	http://comcrop.com/
Fairmont	Singapore	Singapore	Asia	450	2019	Indoor, greenhouse, aquaponics	Hotel	Commercial	Vegetables, aromatic herbs, edible flowers fish	https://www.channelnewsasia.com/singapore/aquaponics-rooftop-farm-fairmont-swissotel-stamford-hotels-849191
Changi General Hospital	Singapore	Singapore	Asia	186	1988	Open-air, hydroponic raised beds	Hospital	Social	Vegetables, aromatic herbs	https://www.greenroofs.com/projects/changi-general-hospital/
Khoo Teck Puat Hospital	Singapore	Singapore	Asia	7339	2010	Open air, raised beds in soil	Hospital	Social	Vegetables, fruits, aromatic herbs, edible flowers	https://www.greenroofs.com/projects/khoo-teck-puat-hospital-ktph/
Thammasat University Green Roof	Bangkok	Thailand	Asia	7000	2019	Open-air, in soil	University	Educational	Vegetables, fruits aromatic herbs, rice	https://www.greenroofs.com/projects/thammasat-university-urban-rooftop-farm-turf/ https://worldlandscapearchitect.com/thammasat-university-the-largest-urban-rooftop-farm-in-asia/

Anantara Riverside Bangkok Resort Rooftop Hydroponic Farm	Bangkok	Thailand	Asia	2800	2016	Indoor, hydroponic	Hotel	Commercial, educational	Vegetables, aromatic herbs, fruits	https://www.greenroofs.com/projects/anantara-riverside-bangkok-resort-rooftop-hydroponic-farm/
City Farm Odaiba	Tokyo	Japan	Asia	1180	2012	Open-air, raised beds in soil	Shopping center	Commercial, life-quality	Vegetables, fruits, rice	https://app04.teli.hku.hk/urf/2017/07/07/3937/ https://www.city-farm.jp/institution/
NTT East Group Green Potato Project	Tokyo	Japan	Asia	30	2008	Open-air, aerohydroponics	Office building	Educational, life-quality	Vegetable	http://www.ntt-gp.com/eco-products/greenpotato.html https://app04.teli.hku.hk/urf/2017/07/07/4046/
Soradofarm - Abeno Harukas Farms	Tokyo	Japan	Asia	200	2010	Open-air, in soil	Shopping center	Life-quality, commercial	Vegetables, aromatic herbs, fruits	https://www.machinaka-saien.jp/products/detail/3
Soradofarm – LUMINE	Tokyo	Japan	Asia	535	2010	Open-air, in soil	Shopping center	Life quality	Vegetables, aromatic herbs	https://www.japanfs.org/en/news/archives/news_id030807.html https://www.machinaka-saien.jp/products/detail/2
Soradofarm - Celeo Hachioji	Tokyo	Japan	Asia	120	2010	Open-air, in soil	Shopping center	Life quality	Vegetables, aromatic herbs	https://www.machinaka-saien.jp/products/detail/4
Soradofarm – Nara family	Tokyo	Japan	Asia	100	2010	Open-air, in soil	Shopping center	Life quality	Vegetables, aromatic herbs	https://www.machinaka-saien.jp/products/detail/8
Tamachi Building Co. Rooftop Garden	Tokyo	Japan	Asia	219	2009	Open-air, in soil	Office building	Life quality, educational	Vegetables, fruits	https://www.mhi.com/news/1110241458.html
Pajeori	Seoul	South Korea	Asia	198	2012	Open-air, in soil	Office building	Life-quality	Vegetables, fruits, aromatic herbs	http://www.koreaherald.com/view.php?ud=20160603000690 https://www.goethe.de/prj/eco/en/wan/21674088.html

Flyover Farm	Mumbai	India	Asia	460	2010	Open-air, raised bed in soil	Residential building	Life-quality, social / educational, research	Vegetables, fruits, aromatic herbs	https://www.kickstarter.com/projects/495230553/flyover-farm?ref=card
Mumbai Port Trust Terrace Urban Leaves	Mumbai	India	Asia	280	2001	Open-air, raised beds in soil	Office building	Life-quality	Vegetables, aromatic herbs, fruits	https://www.thebetterindia.com/249086/how-to-rooftop-terrace-garden-preeti-patil-mumbai-farm-plants-food-waste-sustainable/
Mirpur rooftop farm	Dhaka	Bangladesh	Asia	250	2011	Open-air, raised beds in soil	Residential building	Life-quality	Vegetables, fruits	https://www.sciencedirect.com/science/article/pii/S2226585617300407
Mohammadpur rooftop farm	Dhaka	Bangladesh	Asia	110	2004	Open-air, raised beds in soil	Residential building	Life-quality	Vegetables	https://www.sciencedirect.com/science/article/pii/S2226585617300407
Priority Zone Rooftop Garden	Durban	South Africa	Africa	1300	2010	Open-air, raised beds in soil	Warehouse	Life-quality	Vegetables, fruits, aromatic herbs	https://letsfoodideas.com/en/initiative/jardin-sur-le-toit-de-la-municipalite-de-durban-itrump/ http://priorityzone.weebly.com/rooftop-garden.html
Gegezi Organics	Johannesburg	South Africa	Africa	66	2017	Open-air, hydroponics	Office building	Commercial	Vegetables, aromatic herbs	https://www.jicp.org.za/urban-agriculture-initiative/ https://www.jicp.org.za/news/update-urban-agriculture-initiative/
Neighbor Roots	Johannesburg	South Africa	Africa	300	2019	Open-air, in soil, in door, greenhouse, hydroponics	Shopping center	Commercial, educational	Vegetables, fruits, aromatic herbs	https://www.morningsideshops.co.za/neighbour-roots/
Shagara at School	Cairo	Egypt	Africa	340	2013	Open-air, raised beds in soil	School	Educational	Vegetables	https://www.egypttoday.com/Article/6/29570/Shagara-A-harbinger-of-Egyptian-green-schools

Wayside Chapel - Kings Cross Rooftop Garden	Sydney	Australia	Oceania	200	2011	Open air, raised beds in soil	Church	Social, life-quality	Fruits, aromatic herbs, vegetables, bees	https://www.waysidechapel.org.au/spaces/