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Urban farming with rooftop greenhouses: A systematic literature review

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ABSTRACT

The environmental impacts of food systems will increase in tandem with rapid urban population growth, which calls for alternative solutions, such as urban agriculture, to reach the United Nations Sustainable Development Goals. Among several urban agriculture systems, rooftop farming and its subset, rooftop greenhouses, are promising technologies. They optimize land use, increase profitability for building owners, deliver good yields per unit area, increase water use efficiency, and reduce the energy use of both greenhouse and host buildings while mitigating the urban heat island effect. A systematic literature review of the rooftop greenhouse technology was carried out to examine the benefits and challenges associated with this technology. This review was based on 45 articles, covering themes such as the impact of rooftop greenhouse technology on yields, energy use, water use, environmental impacts, and life-cycle costs; some benefits identified are the symbiotic heat, water, and CO_2 exchanges between the rooftop greenhouse and its host building, and the possibility of delivering year-round production. The additional investment, operational costs, limited availability of flat roofs, and various regulations were challenges to overcome. The relevance of symbiosis between rooftop greenhouses and buildings to enhancing sustainability, and meeting the SDGs was explored. This review also outlines that rooftop greenhouses are increasing in scale, system diversity, societal acceptance and popularity among commercial operations in large cities. The future of rooftop farming lies in customizing the right technology for selected building typologies globally, where food production is fully integrated into the urban landscape.

1. Introduction

The world's urban population is expected to grow to 6.7 billion by 2050 [1], representing an increase of 50 % or 2.5 billion people in 30 years. As more people move to cities, the demand for food increases, which exerts pressure on existing food systems. As a result, urban populations are increasingly reliant on food produced in rural areas or imported from other regions. Moreover, the distance between food production and consumption increases as cities develop. When considering the whole life cycle, transport-linked emissions of food systems represent a fifth of the total food system's emissions [2]. Note also that increasing the distance between the inhabitants and land that supports them alters ecosystem services [3]. The current food systems contribute to one-third of global greenhouse gas (GHG) emissions [4]. Clark et al. [5] demonstrated that even if fossil fuel emissions were eliminated immediately, emissions from the global food system alone would make it impossible to limit warming to 1.5 °C and pose difficulties in achieving the 2 °C target. Thus, major paradigm shifts in food production are urgently needed if humanity intends to meet the Paris Agreement's goals. Climate change impacts are also anticipated to increase the variability and the uncertainty of food production [6]. Several cities are developing urban agriculture (UA, also called urban farming) systems to reduce the reliance on imported food to address these challenges. However, it is worth mentioning that literature on UA includes peri-urban agriculture, which may exaggerate the expectation of inner-city farming. There is probably a higher potential for RTGs in peri-urban areas than in the inner city as the inner city is normally very dense.

Rooftop farming (RTF) is one of the promising futuristic solutions since rooftops constitute one-fourth of all urban surfaces [7]. Orsini et al.

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Abbreviations

BIA	Building Integrated Agriculture
CEA	Controlled Environment Agriculture
ESG	Environmental, social, and governance
GHG	Greenhouse gas
GWP	Global Warming Potential
HVAC	Heating, Ventilation, and Air Conditioning
IRTG	Integrated rooftop greenhouse
iRTG	Intelligent rooftop greenhouse
LCA	Life-cycle assessment
LCC	Life-cycle cost
LED	Light emitting diode
PV	Photovoltaics
PFAL	Plant factory with artificial lighting
RA	Rooftop agriculture
RTG	Rooftop greenhouse
RTF	Rooftop farming
SDGs	Sustainable Development Goals
SLR	Systematic literature review
STPV	Semi-transparent photovoltaics
UA	Urban agriculture
VF	Vertical farming or farm
ZFarming	Zero acreage farming

[8] estimated that not less than 77 % of Bologna's vegetable demand could be met by cultivating on flat roofs. This solution has several benefits: space optimisation and economic development, urban heat island (UHI) mitigation, energy savings, etc. Space optimisation is highly desirable in areas with little or no arable land. Many RTF projects are characterized by the non-use of land or acreage for farming activities, referred to as 'Zero-Acreage Farming' (ZFarming) [3]. This is an important development since projections indicated that arable land per person will have decreased to one-third of its 1970 value by 2050 [9].

Rooftop greenhouses (RTGs), a subset of RTF and building-integrated agriculture (BIA), are interesting in colder climates as they provide an optimal environment for plants by controlling temperature, humidity, and light (Fig. 1). RTGs are found on various building types (commercial, industrial, residential); they can be permanent or temporary structures involving different technologies e.g., hydroponics, aeroponics, aquaponics, vertical farming (VF), etc., allowing for efficient space and resource use. Hydroponic systems [10], and aeroponics are used in RTGs due to their lightweight. Note that these systems are highly efficient and one of the key reasons for reduced water use [11,12]. Some of the most recent RTGs (De Schilde [13] and Urban Farmers AG [14], in The Hague, Netherlands; Ferme Abattoir [15], in Brussels; Sky Greens in Singapore, etc.) even integrate aquaponics (use of fish waste to fertilise crops) with or without a rooftop garden [16].

RTGs also form a subset of the broader Controlled Environment Agriculture (CEA) category, offering localized urban production with biosecurity, pest and drought mitigation, and year-round profitable crop production [17]. CEA contributes indirectly to natural ecosystems by reclaiming the land lost to farming while providing jobs locally [18]. Other forms of CEA include ordinary greenhouses, VFs, and plant factories with artificial lighting (PFALs), sometimes called closed plant production systems. Most recent publications on CEA have focused on VFs [19], as these can increase crop yields by 10–100 times in a limited space compared to traditional farming [20]. Conversely, a drawback of PFALs is the energy cost associated with lighting.

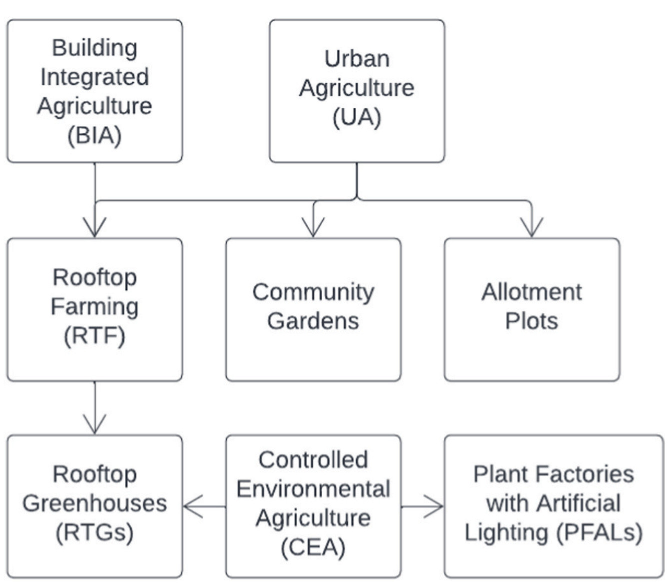

Fig. 1. Illustration showing the different urban agriculture concepts discussed in the introduction.

To better harness energy transfer and optimisation [21,22], RTGs can be advantageously integrated with the host building, which involves exchanging energy, water and CO_2 (Fig. 2). The higher CO_2 concentration and moisture levels in the residual air act as enhancers that increase plant growth [23]. This integration is possible if the RTG and building can exchange residual air and collect rainwater or use treated grey water for irrigation [24,25]. Since significant amounts of non-renewable energy are used to operate greenhouses in Europe, an integrated method could decarbonise greenhouse-based production and promote efficient greenhouse heating [26,27]. The development of integrated rooftop greenhouses (IRTGs) allows local production and consumption ("zero km") of vegetables with negligible change in the energy use of buildings [23]. In recent publications, integrated RTGs were aptly called building-integrated rooftop greenhouses (BIRTGs) [28]. With further evolution, the concept of intelligent rooftop greenhouses (iRTGs) was enhanced and implemented [29]. Through an advanced controller, the iRTG optimises the resource symbiosis between the greenhouse and the host building. For example, the oxygen produced by the plants is recirculated into the host building, while the CO_2 produced during respiration by inhabitants is delivered to the plants.

From the operational perspective, RTGs entail some challenges, such as low solar transmission due to the poor transmissivity of coverings and additional structural elements needed to comply with the building code [25]. RTGs also require additional maintenance, ventilation, and structural stability against external perturbations [30]. In some scenarios, investments in equipment, such as lighting, heating, and cooling systems, may be needed, increasing energy requirements and costs [3]. UA stakeholders also highlighted that existing laws and regulations constrain cultivation on or in buildings [31,32]. Another limitation is the characteristics of existing buildings, including load capacity or fire safety regulations. Table 1 summarises the strengths, weaknesses, opportunities, and threats (SWOT) of RTG technology. Despite these challenges, RTGs have been widely implemented in cities like New York, Montreal, Berlin, etc. Table 2 shows a non-exhaustive global list of RTGs.

Several studies have investigated various aspects of RTG farming, including energy and water conservation, local job creation, economic profitability, global warming potential (GWP), etc. This article presents a systematic literature review (SLR) about RTGs to provide a better understanding and overview of the RTG technology. The method for searching, collecting, selecting, and summarising the articles is first presented, followed by categorising the main results under identified subthemes. The review includes only studies focusing on RTGs and does

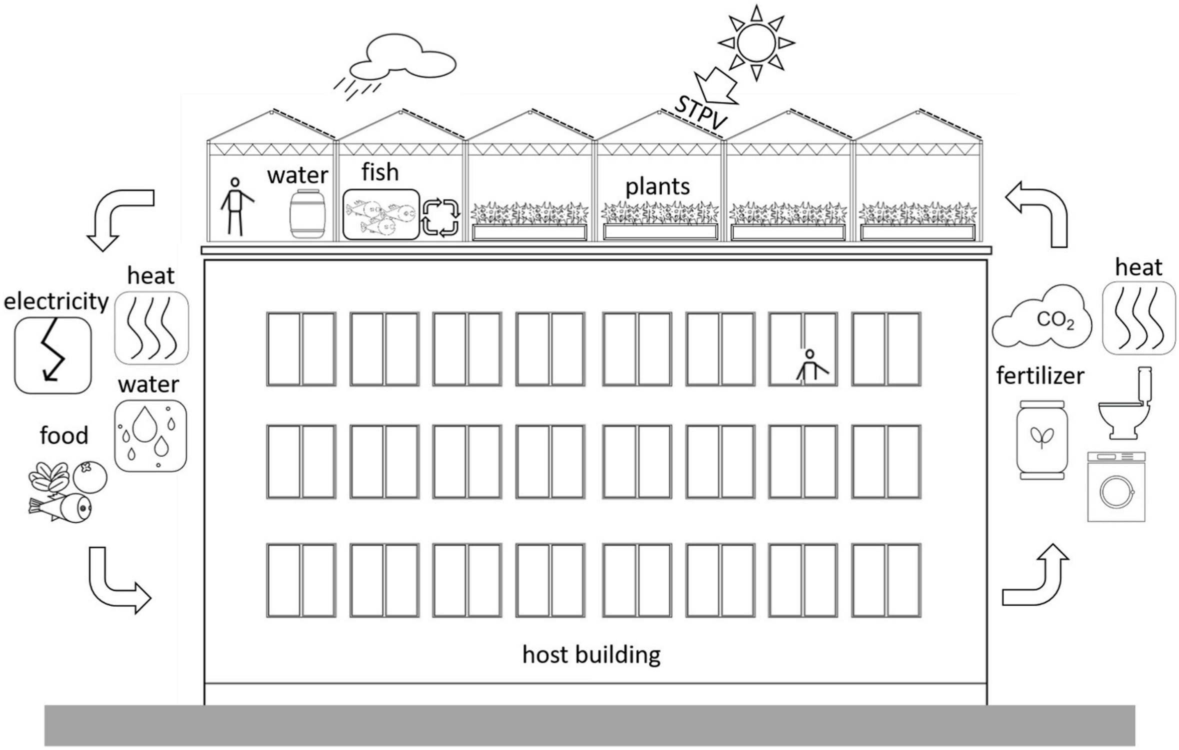

Fig. 2. Integrated rooftop greenhouse (IRTG), using heat and respired CO_2 from host building and delivering electricity, heat, water, and food to host building.

Table 1
SWOT analysis of RTGs.

Strengths	Weaknesses
- Higher energy efficiency of greenhouse and host building - Land optimisation - Low transport energy of products - Higher yield than conventional agriculture - Water conservation - Added social values - Local job creation - No pesticides - Less load capacity than edible green roofs	- High investment costs (equipment, heating, ventilation, lighting) - Need for extra structural elements - Low solar transmission of coverings due to structural elements - Limited availability of flat roofs (with slope $< 5^{\circ}$) - Need for accessibility either through interior or exterior stairs and elevators - Limited habitat creation and biodiversity
Opportunities	**Threats**
- Growing urban population, increased need for food - Climate change uncertainty - Dietary changes (replacing meat with vegetables) - Climate emissions and costs of transport - Awareness of local food production	- Municipal laws and regulations - Fire regulations - Societal regulations - Stakeholder interests - Consumer acceptance - Scarcity of holistic studies on RTGs

not cover open-air rooftop farming. The United Nations Sustainable Development Goals (SDGs) are to be fulfilled by 2030 [33] and the implementation of RTG technology will have a positive impact related to several goals. RTGs in urban location will increase the availability of healthy food, contributing to both SDG 2 (zero hunger) and SDG 3 (good health and well-being). Several RTG projects are focusing on social sustainability, where greenhouses are located near schools fulfilling SDG 4 (quality education), when children and adults can learn practical aspects of cultivation. For environmental sustainability, the use of hydroponics and recirculation of water in RTGs will contribute to SDG 6 (clean water and sanitation), ensuring sustainable water management. In addition, the structural symbiosis between RTG and the host building, fulfils SDG 7 (affordable and clean energy) through efficient energy utilization. Adoption of innovations such as RTG technology and BIA will also contribute to SDG 9 (industry, innovation and infrastructure), with more sustainable production integrated in the city, this also enhances SDG 11 (sustainable cities and communities). Finally, the implementation of RTGs holistically contributes to SDG 12 (responsible production and consumption), where reduced transportation and decreased CO_2 emissions also fulfils SDG 13 (climate action).

2. Method

A systematic literature review (SLR) was carried out, based on articles published in scientific journals in the period January 1, 2009 to 6 March 2023. An extensive search was initiated focusing on rooftop farming. Subsequently, the search was limited to only include articles with rooftop greenhouses since this was the main interest. Production systems with RTGs are an emerging area involving new terminology (e.g., in abbreviation list) that appeared in these reviewed articles. The SLR was selected as research methodology, as it is the most valuable research method providing a strong basis for the next steps in a larger ongoing research on rooftop technologies in Northern Europe. The RTG technology was selected as one of the most promising technologies since it offers a higher potential for year-round cultivation, which is especially relevant to cold or temperate climates. A SLR provides a comprehensive and unbiased overview of the existing body of knowledge about a topic as it "aggregates, critically appraises, and synthesizes in a single source all available empirical evidence that meet a set of pre-specified eligibility criteria aiming to answer in depth a clearly formulated research question to support evidence-based decision-making" [34]. It also follows a rigorous methodology and a stepwise procedure [35], which helps minimize bias in the selection and analysis of studies. The SLR process is transparent and documented, facilitating replication of the study or verification of the findings, thus promoting scientific rigor. This reduces the risk of cherry-picking data that supports a particular viewpoint. By systematically reviewing the literature, this SLR allows to

Table 2
Non-exhaustive global list of RTGs.

Country	Company	City	Built	Size (m^2)	Website
USA	Gotham Greens	Chicago, Illinois	2015	6968	https://www.gothamgreens.com/
		Queens, New York	2015	5574	
		Brooklyn, New York	2013	1858	
		Brooklyn, New York	2011	1394	
	The Vinegar Factory	NYC, New York	1995	2043	https://www.elizabar.com/The-Vinegar-Factory.aspx
	Sky vegetables	Bronx, New York	2013	743	https://www.agritecture.com/sky-veg https://www.skyvegetables.com/
	The Urban Gardens, (Greenhouse Project lab)	Manhattan, New York	2010	130	https://www.urbangardensweb.com/2011/11/16/nyc-classroom-in-an-urban-rooftop-farm/
	Arbor House	Bronx, New York	2012	930	https://greenhomenyc.org/building/arbor-house/https://www.taxcreditcoalition.org/gallery/arbor-house/ https://www.architectmagazine.com/technology/developer-raises-the-bar-in-the-bronx_o
	Edenworks	Brooklyn	later than 2013	74/unit	https://inhabitat.com/rooftop-aquaponic-farmlab-uses-tilapia-fish-to-grow-edible-plants/
	Loyola University	Chicago	n/a	288	https://stories.luc.edu/institute-for-environmental-sustainability https://schulershook.com/projects/loyola-university-institute-of-environmental-sustainability
Canada	Lufa Farms	Saint-Laurent	2020	15 218	https://montreal.lufa.com/en/about
		Anjou, Montreal	2017	5853	
		Laval, Montreal	2013	3995	
		Ahuntsic, Montreal	2011	2880	
	Maison Productive House	Montreal	2010	n/a	https://www.ecohabitation.com/guides/2079/la-maison-productive-house-mph-un-ecosysteme-dans-le-quartier-pointe-st-charles/
Germany	inFarming by Fraunhofer UMSICHT	Oberhausen	n/a	n/a	https://infarming.de/en/homepage/ https://divisare.com/projects/415461-kuehn-malvezzi-hiepler-brunier-administration-building-with-rooftop-greenhouse
	Dachfarm Berlin	Several projects in cities	n/a	n/a	http://www.dachfarmberlin.com/#referenzen-section https://partnerundpartner.com/en/projects/rooftop-farm-in-oberhausen-oberhausen-2016/ https://herne.we-house.life/ https://we-house.life/oeko-prinzip/
	Roof Water-Farm	Berlin	n/a	n/a	http://www.roofwaterfarm.com
	Rewe Green Farming	ErbenheimWiesbaden	2021	2000	https://www.rewe.de/nachhaltigkeit/nachhaltig-einkaufen/green-farming/?ecid=pos_nachhaltigkeit_greenfarming_direct-link_nn_nn_nn_nn_nn https://acme.ac/blogs/projects/rewe-green-farming
The Netherlands	UrbanFarmers AG	The Hague	2015	1200	https://www.urbanfarming-greenhouse.eu/the-new-farm-in-den-haag-operated-b
France	Sous les fraises	Paris	2018	400	https://www.souslesfraises.com/histoire/
Switzerland	UrbanFarmers AG	Basel	2012	260	https://digitalcollection.zhaw.ch/handle/11475/2471
	Rooftop Farm Ecco Jäger	Bad Ragaz	2015	1000	https://www.ecco-jaeger.ch/ https://www.ecf-farmsystems.com/referenzen?lang=en
Belgium	Ferme Abattoir BIGH	Bruxelles	2018	2000	https://bigh.farm/fr/ferme-abattoir/
	Agrotopia	Roeselare	2022	9500	https://www.dezeen.com/2022/02/04/rooftop-greenhouse-agrotopia-urban-agriculture-architecture-belgium/
Spain	University of Barcelona	Barcelona	2014	512	https://inhabitat.com/responsive-bioclimatic-skin-wraps-around-leed-gold-icta-icp-building-in-barcelona/icta-icp-by-h-arquitectes-14/ https://www.uab.cat/web/sala-de-premsa-icta-uab/detall-noticia/building-integrated-rooftop-greenhouses-an-energy-and-environmental-assessment-in-the-mediterranean-context-1345819915004.html?detid=1345815808101
Singapore	Sky Greens	Singapore	2012	670	https://www.skygreens.com/about-skygreens/
	Comcrop	Singapore	2011	2800	http://comcrop.com https://www.sfa.gov.sg/fromSGtoSG/farms/farm/Detail/comcrop

identify gaps in the current body of knowledge leading to the formulation of research questions and directions for the continuation of research on RTGs. In addition, this SLR is solely based on peer-reviewed publications, which ensures that research findings are based on high-quality studies. Conducting a SLR is time-consuming, but it is more time-efficient than repeating existing studies, which avoids duplication of effort and resources by consolidating the existing knowledge base. Finally, this SLR allows for the synthesis of data from studies with different methodologies, sample sizes, and geographical locations, which deliver a holistic understanding of this topic.

While the SLR is a powerful research method, it also contains intrinsic boundaries and limitations, which are briefly discussed below. Firstly, the SLR may be susceptible to publication bias since it typically includes only published studies. It was evident that studies with statistically significant or positive results are more likely to be published, which may lead to an overrepresentation of such findings [36]. Secondly, most articles reviewed in this SLR were published in English, which introduces a language bias. Note that the SLR cannot either consider contextual factors that could influence the results of individual studies, which in turn affects the generalizability of findings. Thirdly, the comprehensiveness of this SLR depends on the databases and sources searched. Relevant studies may not be indexed in the selected databases, potentially leading to the omission of important research. Fourthly, while defining clear inclusion and exclusion criteria is essential, this process introduces a degree of subjectivity, potentially affecting the review's outcomes. Fifthly, the authors found that studies included in this SLR vary broadly in terms of quality, methodologies, systems, technologies, and outcomes measured. This heterogeneity has made it challenging to analyse the data in a consistent manner. Finally, this SLR is based on existing literature, and therefore, it does not include the recent research developments in this field. This review is thus intrinsically limited as it cannot provide recent empirical data. In rapidly evolving fields, such as is the case for urban agriculture, the SLR may become rapidly outdated as new research constantly emerges. Also, in the context of private businesses, commercial or legal restrictions on data sharing and access may have limited the inclusion of certain studies, which is also one important limitation of this SLR.

The assessment method involved at least ten steps (Fig. 3).

Step 1 included searches in Web of Science Core Collection, Scopus and EBSCO (Garden, Landscape & Horticulture Index). The full search was (rooftop OR "roof top") near/2 (garden* or farm* or agriculture* or greenhouse*), with W instead of near for the search in Scopus. The broader search queries served to reduce the risk of excluding relevant papers. The final search was made on March 6, 2023, to allow database indexing, which would lag behind the last publication year. Subsequently, keyword search with (" … " AND " … *") AND " … " in the databases: Web of Science core collection, Scopus and EBSCO (Garden, Landscape & Horticulture Index) resulted in retrieving 686 records. Step 2 involved removing duplicates (n = 147), which left 539 records. Step 3 involved setting up exclusion criteria, which resulted in the removal of 101 articles and 438 kept for further analysis. The exclusion criteria were determined by the authors, and focused on selecting studies that would be relevant to cold or temperate climates; thus, an inevitable element of subjectivity in the methodology may be present. The exclusion criteria were: RTF = rooftop farming without a greenhouse, RG = rooftop garden without a greenhouse, GR = green roof, and C = excluded due to climate (and country); included articles from European, North American or South Korean climate. The inclusion criteria were: RTG = rooftop greenhouse in a European, North American or South Korean climate. Step 4 involved reading all titles and excluding articles that were not relevant. Step 5 involved reading the abstract and classifying it individually according to a code ranging from 1 (highly relevant) to 4 (not relevant). The relevance was again, attributed based on judgement of the authors, which also introduces an element of subjectivity. Step 6 consisted of reading all articles with code 1 or 2 and excluding all articles that were assessed to be irrelevant. In step 7, a final selection was made (n = 45), while step 8 entailed preparing notes for each article. Besides bibliographical information, the reading notes included information about the aim of the study, methodology, significant results, main conclusions, and limitations (according to the reader). These notes were shared between all co-authors. Step 9 consisted of grouping and classifying each reviewed article according to a set of identified subthemes. Finally, step 10 consisted of writing a first draft of the literature review based on the reading notes.

3. Results

Table 2 presents a non-exhaustive overview of the RTGs with the

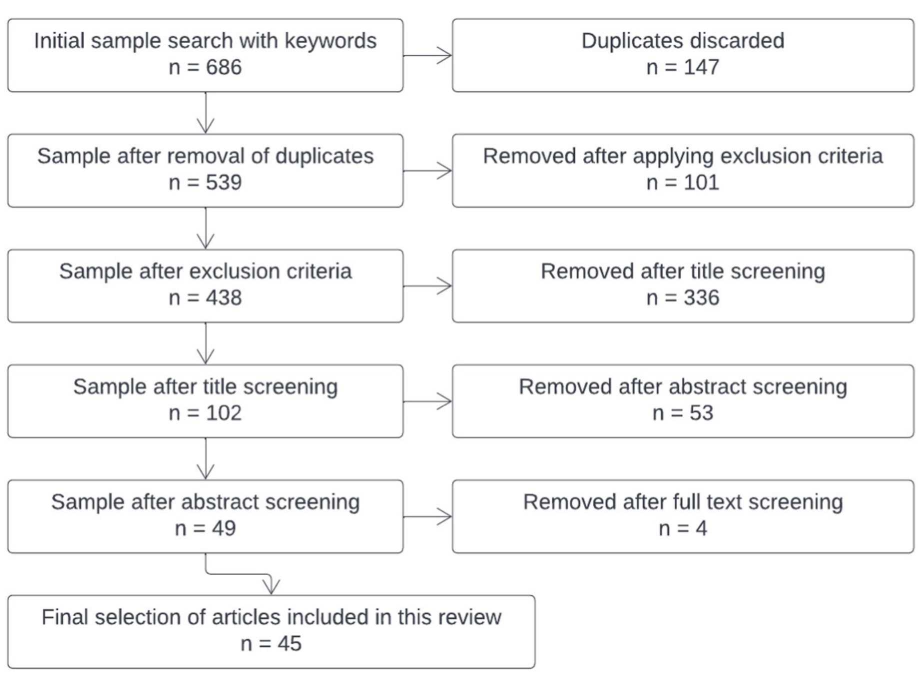

Fig. 3. Schematic diagram showing the procedure for searching, selecting, and summarising the articles.

examples dating from 1995 (The Vinegar Factory). It also shows that the largest RTG, covering 15 218 m^2, is in Montreal, Canada. Interestingly, some large companies have built several RTGs, starting with smaller ones and increasing in size with each new installation (i.e., modular approach), highlighting the importance of scale to ensure economic profitability. The following sections present a brief review of relevant articles grouped according to a few subthemes. Moreover, each of the 45 included publications was coded in a summary in Table 3 with details available in the Appendix section concerning year, type of RTG, country, salient features, notable output or learnings and author.

3.1. Effects of RTGs on yield

Five articles were reviewed regarding yield in RTGs. In three articles [25,37,38], it was found that RTG technology increased yields often in combination with other technologies i.e., VF [37] or light emitting diode (LED) [38]. Cerón-Palma et al. [39] also highlighted the potential for yield enhancement. Rufí-Salís et al. [40] focused on comparisons between different crops in RTGs and highlighted that greater species diversity leads to better performance. Cerón-Palma et al. [39] investigated barriers and opportunities of RTGs in the Mediterranean climate. The issues were analysed across three scenarios: residential, educational or cultural, and industrial buildings. The structural interconnection of the building and RTG optimized the usage of water, energy, and CO_2 flows in combination with reducing food transport. They found that urban horticulture has the potential to supply the city's needs. Depending on crop type, urban greenhouses may yield from 10 to 50 kg/m^2 per year of fresh fruits and leafy vegetables.

Montero et al. [25] investigated the climate and productivity of an integrated rooftop greenhouse (IRTG) in Barcelona, Spain. They found that while the IRTG had a poor transmission of radiation, it had a high natural ventilation capacity due to its size and large ventilator/ground ratio, low humidity regime, and suitable night-time temperature. This study used the KASPRO greenhouse climate model to simulate an IRTG model and compare its yield to a conventional soil-based greenhouse. They showed that an increase in light, CO_2 enrichment, and a longer growing cycle by cultivating during the winter months led to more than double the yield compared to the measured crop yield. Rufí-Salís et al. [40] also studied vegetable production in an IRTG in Barcelona over four years using life-cycle assessment (LCA) on 25 different crop cycles and seven species. Results showed that spring tomato cycles created the lowest impacts (CO_2 eq./kg), due to high yields. Conversely, spinach and arugula cultivation were associated with high impacts. Growing two serial tomato cycles is the best approach with a functional unit of yield (0.49 kg CO_2 eq./kg), although a long spring tomato cycle combined with bean and lettuce in autumn/winter is the best scenario when using market (0.70 kg CO_2 eq./€) and nutritional value ($3.18 \cdot 10^{-3}$ kg CO_2/kcal). This study showed that greater species diversity in a production system leads to a better environmental performance when suitable crops are selected for different seasons.

Investigating the yield of UA systems compared to conventional on-soil agriculture, through a meta-analysis of 200 articles, Payen et al. [37] found that UA yields (per unit area) were similar to or greater than global average yields of conventional agriculture. Although their study did not allow for differentiating between open-air rooftops and RTG, they reported yields for rooftops in the range of 2–3 kg/m^2, depending on the species. They discovered that hydroponic systems delivered higher average yields than soil-based systems while VF also led to higher yields than horizontal farming.

Appolloni et al. [38] recently evaluated supplemental LED light in IRTG for tomato production. They showed that LED light increased yield by 17 % compared to natural illumination (CK). Fruit ripening was also affected, with an increase of 35 % red proximal fruit in LED-treated plants.

3.2. Effects of RTGs on energy use

Nine articles examined the effects of RTGs on energy use, highlighting that RTGs can lead to energy savings in heating and cooling demands compared to conventional greenhouses [23,28,30,41–46]. Combining thermal exchange, high-performance glazing, and shading solutions in RTGs can improve energy efficiency. Additionally, integrating RTGs with host buildings and employing ventilation systems can yield further energy co-benefits. Bambara and Athienitis [41] conducted a study in Montreal, Canada, to validate a Transient System Simulation energy model of a semi-transparent photovoltaic (STPV) greenhouse. They compared the energy performance of a greenhouse (4000 m^2) and a vertically stacked VF (four floors, 1000 m^2 each) illuminated by LED lights, both using STPV. The simulations tested single- and double-glazed STPV cladding and showed that the VF used 31 % and 18 % less heating energy annually than the greenhouse for single and double-glazed STPV, respectively. Cooling energy use was almost equal for both glazing solutions. Double-glazing reduced the heating demand by 76 % for the greenhouse and 72 % for the VF, but increased cooling requirements by 35 % and 26 %, respectively. Nadal et al. [23] studied energy use of the first IRTG in Spain, which exchanged heat, CO_2, and rainwater with the host building. They compared the IRTG energy use to that of a freestanding greenhouse using the EnergyPlus computer simulation software. This research exemplified the significant energy, carbon, and financial savings achieved by coupling the thermal exchange between the IRTG and the host building.

A similar study using the same building (ICTA) as Nadal et al. [23] was conducted based on simulations. Muñoz-Liesa et al. [42] obtained heating-related savings of 31.9 kWh/m^2yr due to the additional thermal buffering effect of the IRTG. However, the authors did not observe the cooling-driven effects of the IRTG via plant transpiration in winter (Nov–Mar). Transpirational cooling was only observed during spring and summer under the Mediterranean climate. They concluded that more research on the dynamic microclimatic causes was needed to better estimate the potential cooling impact by plants.

Jans-Singh et al. [43] created a combined simulation model of an archetype school building with a greenhouse zone to analyse the heat and mass transfer between the classroom and the IRTG. The simulation results showed that air with low CO_2 levels and temperatures from the IRTG can reduce ventilation demand in the classroom for heating and cooling by 33 %–57 % annually. Conversely, the reuse of waste streams, such as warm air with enriched CO_2 from the IRTG to the host building, was beneficial for plant growth.

Gholami et al. [44] evaluated three roofing technologies using a two-dimensional hygrothermal simulation. The study analysed the impact of water on the roof thermal behaviour and the feasibility of designing a building with little cooling needs. The study used a precise localised microclimate model of a neighbourhood in Bologna, Italy, to estimate buildings' cooling and heating loads. The three solutions analysed were insulated roof, green roof, and RTG, and their thermal performance was evaluated in four aspects (energy calculation, the impact of moisture on energy performance, thermal performance of passive-designed RTG, and zero-cooling need building). The performance of the RTG was effective with a 50 % reduction in cooling loads. The insulated roofs and RTG scenarios showed improvements of 20 % and 15 % in annual heating and cooling loads, while the green roof yielded a 7 % improvement compared to the baseline. Additionally, the impact of moisture on green roofs was considered a negative factor for thermal and energy performance in this climate. The results thus highlighted the potential of passively designed RTG to create a building with little cooling needs.

In Sweden, Zhang et al. [45] investigated energy use for an existing warehouse fitted with an RTG in Malmö, using the dynamic energy simulation program IDA-ICE. The effects on energy use by combining RTG and warehouse were analysed by altering the parameters of RTG (glazing materials and shading devices). The results showed that the warehouse had a lower heating and cooling demand by 11 % and 7 % respectively when fitted with an RTG. Interestingly, the RTG had a 10 % lower heating demand and a 12 % lower cooling demand than the soil-based greenhouse. Overall, this study showed that the combination of RTG and warehouse is mutually beneficial for overall energy efficiency. Furthermore, the results showed that the glazing and shading solutions are important aspects affecting the energy efficiency of the whole system. Combining high thermal resistance glazed envelopes and an external shading system for the RTG can substantially improve energy performance. The study also showed that the energy use for electric lighting in a RTG can be reduced by 60 % compared to an indoor horizontal farm of the same size illuminated by LED lamps.

Muñoz-Liesa et al. [46] examined the energy co-benefits between a host building and an IRTG using integrated active ventilation systems. The results indicated that the IRTG harvested 198 kWh/m^{2}yr of waste heat from the host building for its own thermal and ventilation needs while delivering 205.2 kWh/m^{2}yr of solar energy to the host building as sensible heating gains in the ventilation system. The authors noted that when ventilation needs are higher, as in, for example, educational buildings, the magnitude of potential solar energy recovery from IRTG could increase to 61 % compared to an office building. Furthermore, the total energy savings were equivalent to 8 % of the host building's annual energy demand.

Yeo et al. [28] designed and validated a building energy simulation model for a naturally ventilated greenhouse with tomatoes in South Korea. Their study, involving time-dependent measurements, was achieved using full-scale assessments. The greenhouse BES model was validated by comparing the simulation results for air temperature and relative humidity to the ones obtained by direct measurements in the greenhouse.

In another study, Yeo et al. [30] analysed energy savings from installing an RTG using the building energy simulation and CFD software TRNSYS and ANSYS. Interestingly, the annual energy demand of a greenhouse for tomatoes was reduced by 5 % by using the RTG and this saving was attributed to thermal energy transmitted from the host building to the greenhouse. After integrating air temperature management, a technology for reducing energy loads by changing the set temperature over time, the heating energy savings reached 12 %. They also discovered that by installing a single-span greenhouse without tomato crops on the roof, the annual energy demand of the office building could be reduced by 11 %. The energy use reduction was lowered when the tomato crop was included in the calculations. This multi-disciplinary research is one of the thorough studies involving the effects of crops on the energy use of buildings and RTG.

3.3. Effect of RTGs on yield, water and energy use, and global warming potential

Two publications indicated that RTGs have the potential to significantly reduce water consumption, greenhouse gas emissions, and reliance on food imports [47,48]. High-tech farms, including RTGs, demonstrate improved efficiency and sustainability compared to conventional farming, especially when incorporating soilless cultivation techniques and utilizing natural resources such as rainwater. Additionally, integrating RTGs with building heating systems and solar power can further reduce CO_2 emissions.

Gould and Caplow [48] outlined that 1 ha of rooftop vegetable farm has the potential to save 20 ha of rural land in the USA, where each ha can save 74 000 tons/yr of fresh water on average. In their survey of environmental impacts of growing tomatoes, they found that the freshwater consumption of RTGs was 16 % that of conventional farms, while avoiding pesticides and reducing GHG emissions by 60 %. Furthermore, they estimated that when the RTGs are integrated with the building heating systems and onsite solar power; further reductions of 1000 tons of CO_2 emissions are obtained annually compared with conventional greenhouses. They showed that a single acre of BrightFarms greenhouse in Chicago could yield approximately 230 000 kg of produce, capturing 20 million litres of rainwater, mitigating 740 tons of CO_2, and avoiding 195 kg of pesticides annually, based on estimates by Gould and Caplow [49].

Benis et al. [47] conducted an exhaustive study to assess the resource use of several BIA solutions in urban areas. They used a performance-based simulation workflow to compare the environmental impacts of three hi-tech urban farms located in Lisbon, Portugal, with different designs and growing technologies:

1) a polycarbonate RTG, 2) an indoor VF with windows and skylights on the top floor of a building, and 3) a completely opaque artificially illuminated VF on the building's ground floor. The type of urban farm significantly affected emissions and water usage, with the RTG and top floor VF yielding lower GWP than the current supply chain for tomatoes. The high-tech farms' year-round production and higher plant density of soilless cultivation resulted in a factor of four efficiency gains. The study also found that high-tech farms with no daylight penetration performed poorly, requiring 205 % more energy than the greenhouse, mostly for electric lighting (91 %). Importantly, the year-round production in the metropolitan area reduced the need for food imports and the transportation burden, thus making high-tech farms more sustainable than conventional farms.

3.4. Environmental assessment and economic profitability of RTGs

Various studies and their findings related to the environmental assessment and economic profitability of RTGs in different locations are discussed [12,49–60]. It is noteworthy that while RTGs may have higher initial costs associated with the greenhouse structure, they can offer lower environmental impacts, reduced transportation and distribution losses, increased food security, and potential productivity gains. The economic viability of RTGs can vary depending on factors such as yields, prices, and specific local conditions. Therefore, a comprehensive assessment of environmental and economic aspects is necessary when evaluating the feasibility and profitability of RTGs in different locations.

In a case study located in Barcelona, Sanyé-Mengual et al. [50] quantified the environmental benefits of RTGs. They found that switching from a linear to an RTG system for tomato cultivation resulted in significant environmental impact reductions of 44–76 % per kg in various categories. The main reductions were achieved through changes in packaging, transportation, and retail stages to minimize produce losses. The IRTG system also allowed for year-round crop production, potentially reaching productivity rates of 56.5 kg/m^2, which is twice the productivity of RTGs (25 kg/m^2) [59].

Sanyé-Mengual et al. [12] analysed RTGs' environmental and economic performance using LCA and life-cycle cost (LCC) analysis for a real project in Barcelona. The results showed that the greenhouse structure of an RTG has an environmental impact 17–75 % higher and an economic cost 2.8 times bigger than a multi-tunnel greenhouse. At the consumption point, environmental savings were up to 42 % for local RTG-produced tomatoes, which were also 21 % cheaper than conventional tomatoes from multi-tunnel greenhouses in Almeria. The study concluded that RTGs face law-related limitations that make the greenhouse structure less environmentally friendly and economically competitive than current industrial greenhouses.

Pons et al. [51] used a technological and sustainability approach to analyse a new agricultural production system by integrating RTGs in Mediterranean urban areas — the IRTG energy, water, and CO_2 flow in the metabolism of the building. The project used multiple methods such as LCA and the Integrated Value Model for Sustainable Assessment. In the case of IRTG, the authors concluded that the LCA demonstrated that from a cradle-to-consumer point of view, locally cultivated tomatoes in RTG-Lab are cheaper and have lower environmental impacts.

Sanyé-Mengual et al. [52] conducted a multi-national environmental assessment focusing on urban horticulture in retail parks. They performed an LCA on the implementation of RTG in eight sites in seven different cities in Europe and South America with specific requirements. The evaluation focused on geographical contrasts and compared differences between isolated and integrated RTGs by evaluating symbiotic metabolism. Their results showed that retail parks have the potential to implement RTGs, where between 53 % and 98 % of the buildings had rooftops that are technically and economically feasible. Interestingly, retail parks performed better than industrial parks and logistic parks.

Sanjuan-Delmás et al. [53] performed an LCA on VF consisting of a RTG connected to a university building in Barcelona. The goal was to determine the feasibility of producing food, while examining potential issues. This included an evaluation of the system's environmental performance to analyse both the crop and its association with the building with respect to rainwater, residual heat (energy), residual air (CO_2) and food from an industrial ecology perspective. They concluded that this system could be an alternative to conventional production and an opportunity to improve food security and self-sufficiency in cities.

Benis et al. [54] compared different rooftop systems by examining the economic sustainability and net social welfare of a set of options over a 50-year life cycle. A Cost-Benefit Analysis approach was applied to compare the conventional unused flat roofs: (1) Rooftop farms for open-air production, (2) "Low-tech" Rooftop Greenhouse (RTG) farms, (3) "High-tech" RTG farms with controlled-environment production, (4) Building Integrated Photovoltaics energy systems. The economic sustainability of alternative rooftop systems was dependent on yields and prices. The authors concluded that food production to be more beneficial than energy generation for both the owner of the system and the local community when considering financial return and local job creation. Conversely, Corcelli et al. [55] conducted an LCA to assess the environmental impacts of urban rooftops with building-applied solar photovoltaic systems and RTG systems in Mediterranean regions. Their results indicated that building applied photovoltaic systems were more environmentally friendly due to lower impacts on climate and fossil depletion (-430 kg CO_2 eq./m^2 and -110 kg oil eq./m^2) compared to RTG systems (-22 kg CO_2 eq./m^2 and -4.7 kg oil eq./m^2).

Muñoz-Liesa et al. [56] reported the energy benefits of BIA through (i) a calibrated energy model and (ii) a thermal analysis of a selected building with IRTG in a Mediterranean region. The case study was previously assessed with a calibrated energy model that quantified the recovered heat from the building and the IRTG. The authors demonstrated the potential effectiveness of bidirectional energy symbiosis of IRTG to improve their efficiency. Simulation results indicated that the IRTG passively recovered an equivalent annual heating energy of 98 kWh/m^2yr from the building (especially during night-time) if heated with the same heating, ventilation, and air conditioning (HVAC) system as the host building. Simulation work also revealed that the IRTG provided an added insulation value especially in winter, which resulted in an annual energy saving of 35 kWh/m^2yr. In the humid continental temperate climate of South Korea, Torres Pineda et al. [57] performed an LCA on tomato production, comparing conventional greenhouse and RTG. Their results showed that RTGs required 19 % less energy for heating and 38 % more for cooling than greenhouses. Interestingly, RTGs total energy load reduction was 13 % due to smaller heat losses during colder months.

Parada et al. [49] performed an LCA-based analysis on three fertigation practices used in an RTG for tomatoes in Barcelona: 1) open management, 2) recirculation, where 30 % of drained, unused water was used to irrigate the crops, and 3) same recirculated management of recirculation with a further reduction in freshwater input of 15 % leachate recirculation. Interestingly, all three irrigation practices delivered similar yields. Concerning environmental benefits, recirculation delivered the best performance in almost all impact categories.

Subsequently, Muñoz-Liesa et al. [58] discovered that through structural improvements, the environmental impact of IRTG systems decreased by 24 %. Furthermore, their findings [59] also demonstrated that an optimized steel structure utilizing tensioned cables offered a potential reduction of up to 36 % of the IRTG steel provision, thereby cutting 16 % of environmental impacts due to GHG emissions. In addition, Muñoz-Liesa et al. [60] used experimental data integrated with a modelling approach to compare tomato yields and the environmental impacts in an IRTG using different covering materials in Barcelona, Spain.

From the analyses of various aspects of the structural RTG-building symbiosis (3.1, 3.2, 3.3, 3.4), increasing food production was possible while decreasing resource usage and input costs could contribute to the achievement of many SDGs: SDG 1, 2, 6, 7, 9, 11, 12 and 13.

3.5. Life-cycle cost assessments of RTGs

Using the LCC methodology, Peña et al. [61] examined the economic viability of tomato production in an innovative building with an IRTG located in Barcelona. Data was collected from two stages: i) infrastructure and ii) production. Production costs entailed labour, external services, and various materials. The calculations included fixed and variable costs. The main cost drivers for tomato production in IRTG representing 61 % of total costs, were labour (25 %), the IRTG infrastructure (15 %), external pest control services (13 %), and the rainwater harvesting system (10 %). The sensitivity analysis indicated that the infrastructure costs could be reduced further to ensure economic viability, while rainwater harvesting costs could be reduced by optimising the rainwater tank size as a function of the productive area.

3.6. Intelligent rooftop greenhouses

With the availability of intelligent and sophisticated control systems, the challenge to deliver successful rooftop greenhouses with integrated food production management, renewable energy utilization, water resources, and atmospheric gas composition, is achievable [29,62–64].

These successful studies revealed that implementing iRTGs with sophisticated control systems could contribute to the creation of environmentally friendly cities with low carbon footprints, high carbon offsets, and a strong human-plant symbiosis.

Balas et al. [62] and Balas et al. [63] developed the concept of iRTG, which is similar to IRTG but with a more sophisticated control system to manage the energy, CO_2–O_2, and water exchanges between RTG and host building. The iRTG typically has a two-way ventilation system conveying O_2-enriched air from the RTG to the building and CO_2-enriched air from the building to the RTG. In conclusion, they anticipated that the iRTG can deliver an integrated management of food production, renewable energies, water resources, and atmospheric gas composition. With optimized iRTGs and implemented widely throughout a city, it is possible to create a "Green-Skyline City" i.e., a city having all buildings covered by passive greenhouses, with low carbon footprint, high carbon offset, local production, and a tight human-plant symbiosis.

Balas et al. [64] proposed a Simulink model for an iRTG focusing on gas exchange control. Better measurements regarding iRTG air composition could be achieved by using a fuzzy-interpolative expert system with self-adaptive capabilities and receiving accurate geometric variables, implemented by harnessing the look-up tables with linear interpolation. They would develop the iRTG model for further research by incorporating gas (CO_2, O_2, water vapours) and heat exchanges from humans and plants.

Recently, Popa et al. [29] developed fuzzy self-adaptive interpolative controllers based on an earlier model of iRTG with distributed ventilation fans, for different environmental conditions. They proposed that a locally adapted flexible and distributed fans network, working under the control of temperature self-adaptive interpolative controllers, could assist the iRTG to operate effectively over a broader range of conditions.

3.7. Potential area of implementation for RTGs

Two review articles focused on implementing RTGs in industrial and logistics parks. These areas appeared to be ideal locations for commercial RTG implementation due to their roof ownership, larger size, homogeneous shape and stronger structural materials, and potential reduction of heating and cooling requirements compared to residential buildings [39,65]. Sanye-Mengual et al. [65] also designed a guide using a geographic information system and LCA tool to assess RTG implementation potential in industrial and logistics parks. The case study at Zona Franca Park (Barcelona, Spain) revealed a high potential, with 87 % of rooftops deemed feasible for long-term or mid-term RTG implementation. The estimated annual tomato production could reach nearly 2000 tons, meeting the demand of 150 000 people and potentially replacing imported tomatoes.

3.8. Stakeholders' perceptions and social acceptance of RTGs

Five review articles focused on the social science perspective, while the other three articles [31,66,67] evaluated stakeholder perceptions and examined potential benefits and challenges, related to societal risks and policy making. From these articles, RTG was generally recognized as a promising model. The other two articles focused on sustainability assessment [68] and consumer perception [69]. The articles generally noted high acceptance of RTGs among stakeholders and consumers.

Specht et al. [66] investigated stakeholders' perception of buildings with agricultural production and focused on resolving various issues associated with introducing ZFarming in Berlin. Stakeholders perceived potential benefits and challenges related to ZFarming in all dimensions (economic, social, environmental, and political). The stakeholders also identified RTGs as the most promising farming model for Berlin. Specht et al. [31] reported further on the participatory approach, aptly termed Regional Open Innovation Roadmapping, which focused on bringing together different actors. In later studies, Specht and Sanyé-Mengual [67] examined the stakeholder perspectives on understanding risks and policy making associated with urban horticulture. Nadal et al. [68] also investigated RTG focusing on social science sustainability assessment. Ercilla-Montserrat et al. [69] studied consumers' perception of the soilless system in RTG; they observed that 94 % of people approved of the quality of rooftop agriculture (RA) products and perceived them to be local and fresh.

3.9. Reviews of cases and systematic literature reviews focusing on RTGs

Five review articles focused on comparing multiple cases or presenting a SLR [70,71]. Generally, RTGs could deliver sustainable food production with efficient use of resources, although the RTG sector is still relatively small and often not orientated towards commercial interests. The other three articles were about SLRs and examined different systems including RTGs such as CEA [20,72] and BIA [73].

Harada and Whitlow [70] discussed the concept of urban green infrastructure, with a focus on rooftop agriculture. They highlighted the opportunities and challenges associated with advancing the science and technology of these constructed ecosystems, with a specific focus on rooftop agriculture. They outlined that RTG has the potential to achieve increased yield, water use efficiency, and stormwater retention, making it a promising approach for sustainable food production. However, they emphasized that while RTGs offer benefits for food production, they do not provide habitat creation opportunities.

Appolloni et al. [71] presented the status of RA through a database of 185 cases. Their study showed that 84 % of practices are open-air farms and gardens and the growing sector of RTGs is still relatively small. Results also indicated a greater emphasis on RA in North America (44 % of the cases). Most RA cases in their database targeted social and educational goals or seeking improvement in urban living quality, with less emphasis on commercial cases. There are untapped business opportunities that can contribute to developing more sustainable and resilient urban food systems providing fresh products from the inner urban areas. The study revealed a rising global interest in RA and stronger policy intervention is crucial to upscale RA practices to achieve self-sufficiency in urban food production.

A critical review of CEA by Engler and Krarti [20] provided key information relevant to greenhouses and RTGs. They identified the high operating costs and unfavourable carbon footprint as major constraints affecting CEA operations. Lowering energy use by the CEA facilities was essential to attract urban users. They reviewed energy efficiency measures, covering building envelope improvements, distributed generation technologies, low-energy HVAC systems, and energy-efficient lighting. The addition of thermal insulation was found to reduce the cooling demand by 19–30 %, depending on the climatic zones. Using thermal mass could reduce heating demand by 32 %, while shading devices could reduce cooling by 30 %. Natural ventilation in dry climates and other passive heating and cooling strategies could reduce HVAC loads and energy use by up to 31 %. As electricity usage for lighting needs for plant growth is usually the largest in CEA (up to 70 % of total energy use), their review suggested that incorporating LED lights could reduce electricity use by up to 76 %.

More recently, Orsini et al. [73] presented a review of BIA focusing on food production in cities. The development of building-integrated technologies has led to an evolution of traditional UA systems (e.g., community gardens) to include the built landscape (e.g., VF and RTGs). BIA often uses soilless production methods and the production is known as CEA (including greenhouses and indoor growing facilities). The main difference between greenhouses and indoor facilities is that the greenhouse is a semi-controlled environment with a transparent design influenced by exterior climates. Solar energy is harnessed naturally for plant growth via photosynthesis, while passive ventilation in greenhouses is provided through evaporative cooling during plant transpiration. Indoor facilities (e.g., PFALs) do not permit any interaction with the outdoor climate during plant growth. The study also highlighted the different dimensions of sustainability and the strengths and weaknesses of the different production systems.

The future of BIA lies in customizing the right production methods for selected building typologies. A successful BIA is achieved when a novel and circular food economy is developed, where food production is fully integrated into the architectural landscape while delivering excellent human liveability and food self-sufficiency amidst natural biodiversity.

Glaros et al. [72] presented another review comparing the impacts of five food production models ("frontiers") for the global food system in 2050. One suggested frontier CEA included novel designs such as RTGs. The novel building designs were often profitable and had greater water use efficiency, but they also reported higher energy use than conventionally grown produce. Results confirmed that CEA-grown plants have dietary benefits. CEA was ranked as the most feasible frontier to be implemented by 2050 compared to the other systems. Interestingly, compared to others, CEA was considered the most feasible and compatible technology to implement globally. To attain these sustainable goals during food production, future work is needed to decarbonise energy sources and integrate various operations that enhance circular resource with minimal environmental impacts. Further social and scientific engagements are needed to better understand the often complex political and institutional frameworks hindering the implementation of the food frontiers.

4. Discussion

This article presented a systematic literature review (SLR) of rooftop greenhouse (RTG) systems. The salient information is as follows:

The urban population is expected to represent more than two-thirds of the global population by 2050, putting unprecedented pressure on food systems. As cities increase in size, the distance between food production and consumption increases, which increases transport energy. Conventional cultivation is currently responsible for one-third of global GHG emissions, and 70 % of global freshwater use. Transport emissions of food systems represent one-fifth of the total food system's GHG emissions. UA may involve a combination of several cultivation systems. RTG is a plausible solution as it provides several benefits such as higher yield, decreased transportation energy and costs, community enhancement, increased urban resilience and food security, nutrient cycling, local availability of fresh products, and mitigation of the UHI effect.

Some cities have indicated a potential for self-sufficiency of up to 70–80 % in fruits and vegetables by exploiting a combination of UA systems. However, electric lighting requirements and GHG are major issues of PFALs. Within the realm of UA, rooftop farming, which includes both open-air and RTGs is one of several approaches with a large potential as rooftops constitute one-fourth of all urban surfaces, and recent research indicates that RTGs have several benefits.

Several studies showed that IRTGs could reduce the cooling and heating loads of the host building by reducing the exposure of building surfaces to heat gains and losses through the roof. When crops are grown on a roof, the roof temperatures and internal air temperatures of the greenhouse can be decreased through shading and evapotranspiration of crops, which concomitantly reduce the host building's cooling demand. The heating demand of the RTG is also reduced compared to that of a soil-based greenhouse since the RTG uses low-grade heat losses from the host building. Electric lighting of the RTG is reduced substantially (up to 60 %) compared to the case of PFALs. As they normally fall under CEA, RTGs generally do not use pesticides. Since they are normally based on hydroponics-related cultivation techniques, RTGs save more water (> 70 %) than conventional soil systems. Rooftop technologies use no additional land and thus contribute to space optimisation (ZFarming) through roof space utilization. RTGs generally can provide increased revenue for the owner of the host building through the leasing of the roof space.

Recent developments in RTG technology such as IRTG and iRTG have delivered higher energy savings, while providing other benefits such as enhanced photosynthesis by CO_2 enrichment and additional water savings. The more advanced control systems used in iRTG can also allow better temperature mitigation for the RTG and host building. One study indicated that high-tech conditioned RTGs could be more sustainable than conventional unconditioned greenhouses for crop production. The same study indicated that high-tech RTGs generate more jobs and less GWP than conventional rooftop photovoltaics.

The tradeoff between renewable energy (e.g., PV) and agricultural production on urban rooftops involves considerations such as energy efficiency, economic viability, spatial conflicts, and environmental benefits. PV systems are more energy-efficient and financially lucrative, while high-value rooftop farming can provide economic benefits and local food production. Spatial conflicts may arise when allocating limited rooftop space. Both options have environmental benefits. A single article comparing PV with RTG was found by Benis et al. [54] and showed that when considering financial returns and local job creation, food production proved to be more advantageous than energy generation for both the system owner and the local community. Technological advances, like integrating transparent solar panels, can minimize the tradeoff. Balancing these factors is crucial to developing comprehensive strategies promoting sustainable energy generation and urban agriculture. Some RTG projects are integrating VF with plants arranged on A-frames to maximize irradiance and photosynthesis. Others integrate aquaponics, to allow for concomitant aquatic (mainly protein) production.

Despite these benefits, the challenges associated with RTG technology are high infrastructure investment and energy costs (equipment, HVAC, lighting), since constructing and maintaining a RTG can be expensive. The initial investment for building and equipping the greenhouse, can be significant. Additionally, ongoing expenses for maintenance, energy consumption, and staffing can be substantial. The need for additional structural elements and special indoor environmental management, water, and resource management may be substantial. These microclimatic variations can impact plant productivity, requiring careful management within the greenhouse to maintain optimal growth. Efficient water management is crucial for RTGs, as they may have limited access to water sources and face constraints on water availability. Additionally, managing other resources, such as energy consumption and waste disposal, should be considered for a comprehensive sustainability approach. Low solar transmission of coverings due to the additional structural elements, limited availability of flat roofs, need for accessibility through staircases and/or elevators are some of the key challenges. Transporting supplies to the rooftops can be more labour-intensive and time-consuming than traditional ground-level agriculture. This includes structural limitations, where RTGs impose additional weight and structural demands (flat roofs) on buildings. Not all rooftops are designed to support the extra load of a greenhouse, which may require costly structural modifications or reinforcement. Also, ensuring the building's structural integrity is essential to prevent potential risks or damage. Considering limited space and scalability, RTGs have limited available space, which can restrict the scale of agricultural production. The design of the rooftop may pose challenges in meeting commercial-scale demands. Scaling up the production to make it economically viable may not always be feasible due to space limitations. Also, regarding safety and security, RTGs may introduce safety risks during construction, operation, and maintenance. Additionally, RTGs might be more susceptible to vandalism or theft due to their urban location, requiring appropriate security measures.

While RTGs offer benefits for food production, they do not provide opportunities for natural habitat creation and conserving biodiversity. Moreover, several authors mentioned that municipal laws and regulations and fire regulations could also represent a major hindrance to implementing RTG technology in many cities. A suggestion to overcome barriers to implementing RTG technologies was to involve stakeholders to increase understanding of the potential of RTGs in cities. Greater stakeholders' involvement and ownership are likely to affect policy makers. Overall, a limited number of holistic studies on RTG technology were found, which is a restraint for their widespread social acceptance. Another mentioned area was consumer perceptions, which could benefit from further studies especially pilot-scale demonstration projects. Nevertheless, this review suggests that RTG technology is increasing in popularity with many full-scale implementations in the last ten years and witnessing commercially profitable operations in major cities. Several companies are also increasing the size of each new RTG project, probably due to the economy of scale provided by running larger operations. The adoption of the RTG technology is relatively recent, hence, more research is needed for customization in different climates to better understand the potential of this technology to provide fresh food in urban environments at reasonable environmental and economic costs. Future research should focus on matching appropriate technology with different climates and contexts to ensure economic profitability. The future of RTG lies in customizing the right technology for selected building typologies globally. A successful RTG is achieved when food production is fully integrated into the architectural landscape.

5. Conclusions

In conclusion, the study aimed to conduct a systematic literature review of the RTG technology to examine the benefits and challenges associated with this technology. Boundaries and limitations of this SLR have been identified e.g., publication bias (significant or positive findings more often published), language bias (English), etc. Limitations intrinsic to the selected methodology and character of the technology (new) are also discussed in the method section.

This SLR was based on 45 journal articles, covering key subthemes that were described in detail. The study identified that the symbiotic heat, water, and CO_2 exchanges between the RTG and its host building combined with the potential for year-round crop production, are some of the main benefits of RTGs. For example, RTGs can reduce the cooling and heating loads of both greenhouses and host buildings. The roof temperatures and air temperatures of the greenhouse are decreased through shading and evapotranspiration of crops, which concomitantly reduce the host building's cooling demand. The heating demand of the RTG is also reduced compared to that of a soil-based greenhouse since the RTG uses low-grade heat losses from the host building. Electric lighting of the RTG is reduced substantially compared to the case of PFAL. RTGs use no additional land and thus contribute to urban space optimisation. IRTG and iRTG deliver higher energy savings, while providing other benefits such as enhanced photosynthesis by CO_2 enrichment and water savings. The additional investment, operational costs, limited availability of flat roofs, and various regulations are some key challenges to overcome. This review also noted that RTGs are increasing in scale, system diversity, societal acceptance, and popularity among many commercial operations in large cities.

Holistically, RTG technology relates to various aspects of engineering design, building and urban regulations, energy systems, policy, finance, and environmental, social, and governance (ESG) aspects. Concerning engineering design, RTGs require careful consideration of the building's structural integrity to support the added weight of the RTG structure, its soil or water system, as well as plants. Engineering rules and guidelines need to be developed to include rooftop structures that can be safely accounted for in structural calculations. Proper ventilation, heating, and cooling systems are also crucial for maintaining an optimal indoor climate inside the RTG. Engineers need to design efficient HVAC systems that optimize temperature and humidity control of both RTG and host building, taking advantage of the potential symbiosis between the two systems as seen in iRTGs. The design of effective irrigation and drainage systems to minimize water usage and prevent leakage into the building is also required.

In terms of building and urban regulations, RTGs need to comply with local building codes and regulations related to structural stability, fire safety, accessibility, etc. Each city or country needs to develop building regulations to accommodate RTG structures. Urban regulations need to be rewritten taking into consideration the potential addition of an extra floor height for the rooftop structure. In the future, these policies may provide incentives, tax benefits, or zoning accommodations for RTG projects. Government policies and initiatives aimed at reducing carbon emissions and promoting sustainable agriculture should encourage the adoption of RTGs as part of urban planning.

RTGs also require additional electric lighting, ventilation, heating, and cooling, which demands additional energy systems and power supply. Engineers should design energy-efficient systems integrating e.g., solid-state lighting and renewable energy sources such as integrated PV systems, to reduce energy use and GHG emissions.

RTGs can be attractive investments, offering potential revenue from agricultural products and potentially increased property values, while also providing an additional revenue from rent of the host building's roof space. Financial structures and calculation methods need to be developed to assess the feasibility and return on investment for such projects. RTGs align with ESG principles, making them eligible for green financing options and investments from organizations committed to sustainability. RTGs contribute to environmental sustainability by reducing food transportation distances and minimizing the carbon footprint of agriculture, which is in line with ESG criteria related to environmental responsibility. The provision of fresh, locally grown produce, contributing to food security and community well-being is also aligned with ESG as well as many SDGs.

In summary, RTGs address several aspects of engineering design, regulatory compliance, energy efficiency, policy development, financial considerations, ESG and SDGs initiatives, making them a compelling option for sustainable urban development and agriculture in the future global urban realm.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A

Table 3
Articles reviewed with rooftop farming using rooftop greenhouses.

Year	Type of RTG	Country	Main output/learnings	Authors
2012	RTG	Barcelona, Spain	Barriers and opportunities regarding RTGs were investigated focusing on social, economic, environmental and technological aspects. Interconnection of building and RTG improved interactions among water, energy, and CO_2 flows. RTGs yield from 10 to 50 kg/m^2 per year of vegetables.	Cerón-Palma et al. [39]
2012	RTG, IRTG	Chicago, USA	A hectare of rooftop farm could save 20 ha of rural land. The freshwater consumption of RTGs was 16 % that of conventional farms. RTGs reduced GHG emissions by 60 % and avoided pesticides.	Gould and Caplow [48]
2013	RTG	Barcelona, Spain	Switching from a linear system to an RTG system may cut environmental impact by 44–76 % per kg tomatoes, with up to 74 % energy savings. RTG could be key in designing low-carbon Mediterranean cities.	Sanyé-Mengual et al. [50]
2015	RTG, IRTG, multi-tunnel greenhouse, industrial greenhouse	Barcelona, Spain	LCA and LCC on RTG projects show RTG has an environmental impact 17–75 % higher and an economic cost 2.8 times higher than multi-tunnel greenhouse. RTGs face law limitations making greenhouse structures less friendly and less economically competitive than current industrial greenhouses.	Sanyé-Mengual et al. [12]
2015	STPV RTG	Montreal, Canada	Double glazing decreases heating demand by 76 % for the RTG and 72 % for the VF but increases cooling by 35 % and 26 %,	Bambara and Athienitis [41]

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Table 3 (*continued*)

Year	Type of RTG	Country	Main output/learnings	Authors
			respectively. Due to greater solar exposure, the RTG generated almost twice the solar electricity through STPV compared to VF.	
2015	RTG	Barcelona, Spain	Industrial and logistics parks are ideal for RTG implementation, with 87 % of rooftops deemed feasible for long-term or mid-term RTG implementation in the case study of Zona Franca Park (Barcelona, Spain).	Sanyé-Mengual et al. [65]
2015	IRTG, RTG-Lab	Barcelona, Spain	LCA and Integrated Value Model for Sustainable Assessment were used. LCA shows that locally cultivated tomatoes in RTG-Lab are cheaper and have lower environmental impact. RTG-Lab temperatures are higher at night compared with conventional greenhouses.	Pons et al. [51]
2015	RTG	Berlin, Germany	Stakeholders' perception of benefits and challenges for the introduction of ZFarming. Potential benefits and challenges related to all sustainability dimensions. Stakeholders identified RTGs as the most promising farming model for Berlin.	Specht et al. [66]
2016	RTG	Berlin, Germany	Presentation/evaluation of participatory approach called Regional Open Innovation Roadmapping, focused on bringing together stakeholders. The Regional Open Innovation Roadmapping process simulated new networks, contributed to knowledge and created a common understanding for future implementation of ZFarming.	Specht et al. [31]
2017	IRTG	Barcelona, Spain	An increase in light, CO_2 enrichment, and extension of the growing cycle by cultivating during winter can double the yield compared to measured crop yield.	Montero et al. [25]
2017	IRTG	Barcelona, Spain	IRTG has a higher average hourly temperature in winter and a lower average in summer. It yields significant energy, carbon, and financial savings compared to a freestanding greenhouse.	Nadal et al. [23]
2017	RTG	Lisbon, Portugal	RTG and top-floor VF yield lower GWP than the current supply chain for tomatoes with conventional farming. High-tech farms' year-round production and higher plant density of soilless agriculture result in a factor of four efficiency gains.	Benis et al. [47]
2017	RTG	Berlin, Germany; Barcelona, Spain	Explored stakeholder perspective focusing more on risks in urban horticulture as well as policymaking.	Specht and Sanye-Mengual [67]
2018	RTG in retail parks	Barcelona, Spain; Lisbon, Portugal; Utrecht and Rotterdam, The Netherlands; Berlin, Germany; Manizales, Colombia; Sao Carlos, Brazil	Assessment revealed that 58–98 % retail parks have the potential to implement RTGs. Retail parks also performed better than industrial- and logistic parks. Production was directly sold avoiding distribution costs. IRTGs yielded large production values (31–234 tonnes of tomato per ha), CO_2 savings (16–112 tonnes of CO_2 eq./ha) and self-sufficiency in food.	Sanyé-Mengual et al. [52]
2018	RTG with VF	Barcelona, Spain	System produced 30 kg of tomato per m^2 over 15.5 months, providing 2540 kg of food. The system could grow approximately 1660 kg of tomatoes per year. Synergy with the building afforded significant resource savings, e.g., 80–90 % of the water	Sanjuan-Delmás et al. [53]
2018	RTG	Lisbon, Portugal	Food production by high-tech RTG is more beneficial than energy generation by PV on roof for owner and the local community.	Benis et al. [54]
2018	RTG	Barcelona, Spain	Investigated RTG focusing on social science sustainability assessment.	Nadal et al. [68]
2019	IRTG	Barcelona, Spain	Heating-related savings of the host building can reach 32 kWh/m^2yr due to the additional thermal buffering effect of the IRTG. However, the cooling-driven benefits of IRTG via transpiration are not observed in winter (Nov–Mar) and have positive impact only during spring and summer in the Mediterranean climate.	Muñoz-Liesa et al. [42]
2019	IRTG	London, UK	Using the air with low CO_2 levels and temperatures from the RTG can reduce ventilation demand in classrooms for heating and cooling by 33 %–57 % annually. Conversely, reusing waste streams such as warm air with enriched CO_2 from the host building to the RTG is beneficial for crop growth.	Jans-Singh et al. [43]
2019	IRTG	Barcelona, Spain	Building-applied solar photovoltaic systems have favourable environmental impacts compared to RTG, with reductions of -430 kg CO_2 eq./m^2 and -110 kg oil eq./m^2 in climate change and fossil depletion categories, respectively (compared to -22 kg CO_2 eq./m^2 and -4.7 kg oil eq./m^2 in RTG).	Corcelli et al. [55]
2019	IRTG	Barcelona, Spain	The consumer's perception of a soilless system in RTG was analysed and results showed that 94 % of people approved of the quality of RA products and perceived them to be local and fresh.	Ercilla-Montserrat et al. [69]
2020	IRTG	Barcelona, Spain	LCA on 25 different crop cycles and 7 species over 4 years showed that spring tomato cycles exerted the lowest impacts due to high yields. Growing two serial tomato cycles was the best alternative with a good yield (0.49 kg CO_2 eq./kg). A long spring tomato cycle combined with bean and lettuce in autumn/	Rufí-Salís et al. [40]

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Table 3 (*continued*)

Year	Type of RTG	Country	Main output/learnings	Authors
			winter was the best scenario in terms of market (0.70 kg CO_2 eq./€) and nutritional value ($3.18 \cdot 10^{-3}$ kg CO_2/kcal).	
2020	RTG	Bologna, Italy	Compared to insulated roofs and green roofs, the performance of RTG is best concerning energy and moisture. RTG produced a 50 % reduction in cooling demand.	Gholami et al. [44]
2020	IRTG	Barcelona, Spain	Integrating HVAC systems of building and IRTG offers large potential in energy savings by recovering and exchanging of heating and cooling energy flows. An overall 128 kWh/m^2 of net energy savings and 45.6 kg CO_2 eq./m^2 of savings can be obtained by integrating both systems.	Muñoz-Liesa et al. [56]
2020	RTG	South Korea	LCA on tomato production comparing conventional greenhouse and RTG revealed that RTG required 19 % less energy for heating and 38 % more for cooling than a greenhouse. Total energy load reduction for RTG was 13 % due to smaller heat losses of RTG during colder months. Decreased energy load, combined with shorter transports, storage and distribution stage losses, resulted in 43 % less GWP, 45 % less cumulative energy demand and abiotic depletion, 37 % less photochemical oxidation and acidification, and 27 % less eutrophication for the RTG.	Torres Pineda et al. [57]
2020	RTG, RTF	Several	RTG could achieve increased levels of yield, water use efficiency, and stormwater retention for sustainable food production. However, RTGs do not provide opportunities for natural habitat creation relevant to supporting biodiversity.	Harada and Whitlow [70]
2021	RTG	Barcelona, Spain	They examined the performance and environmental life cycle impacts and benefits of three fertigation management practices used in a RTG for tomato crop in Barcelona. Despite harnessing recirculation methodology and improving water- and nutrient-use efficiencies, all three irrigation management practices resulted in similar yields.	Parada et al. [49]
2021	IRTG	Barcelona, Spain	The environmental impact of IRTG systems decreased by up to 24 % through structural improvements, increased steel strength, and the utilization of lightweight tensioned cables.	Muñoz-Liesa et al. [58]
2021	Open-air farms, RTG	Several (database with 185 different cases)	An analysis of the current status of RA through database with 185 cases revealed that 84 % of practices are open-air farms and gardens. The RTG sector was small but growing steadily.	Appolloni et al. [71]
2021	greenhouses, RTG	Several	Energy efficiency measures, including building envelope improvements, distributed generation technologies, low-energy HVAC systems, and energy-efficient lighting, can reduce the energy use of CEA including greenhouses significantly.	Engler and Krarti [20]
2021	iRTG (intelligent rooftop greenhouses)	Barcelona, Spain	Self-adaptive Proportional Integral Derivative (PID) controller produced an additional performance, resulting in lower energy	Balas et al. [62]
2021	iRTG (intelligent rooftop greenhouses)		use due to robust performance and sharp transient regime avoiding overdrive.	Balas et al. [63]
2021	iRTG (intelligent rooftop greenhouses)	Barcelona, Spain	First simulations regarding iRTG air composition are not very precise, but multiple-input-multiple-output nonlinear system can be dealt with, at this early stage, only by a comprehensive expert system. Future work should focus on how humans and plants consume and exhale CO_2, O_2, water vapour and heat.	Balas et al. [64]
2022	UA general, open-air rooftops and RTG	Several	UA yields were on par with or greater than the global average yields of conventional agriculture. Yields for rooftops (open-air and RTG) were 2–3 kg/m^2, cycle on average depending on crop type.	Payen et al. [37]
2022	IRTG	Barcelona, Spain	Evaluation of supplemental LED light applications in IRTG with tomato production shows LED light increased overall yield by 17 % compared with naturally illuminated plants, which were 9.3 % lighter and 7.2 % fewer than tomatoes grown under LED treatments. Fruit ripening increased by 35 % in red proximal fruit in LED-treated plants.	Appolloni et al. [38]
2022	IRTG	Andong-Si, South Korea	Prediction of air temperatures and RH of naturally ventilated greenhouses with acceptable accuracy was demonstrated using BES and CFD.	Yeo et al. [28]
2022	IRTG	Yeongam–gun, South Korea	IRTG delivered energy savings for both greenhouse and host building.	Yeo et al. [30]
2022	RTG	Malmö, Sweden	Integrating RTG and the host building (a warehouse) was beneficial when assessing overall energy efficiency. The energy use for electric lighting in an RTG can be reduced by 60 % compared to an indoor horizontal farm of the same size illuminated by LED lamps.	Zhang et al. [45]
2022	IRTG	Barcelona, Spain	Integration of active ventilation strategies was 1.9 times more energy-efficient than passive ventilation configurations, which can utilize building assets to improve material and energy circularity, saving 8 % of the annual energy demand of buildings.	Muñoz-Liesa et al. [46]

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Table 3 (*continued*)

Year	Type of RTG	Country	Main output/learnings	Authors
2022	IRTG	Barcelona, Spain	Optimized steel structure that uses tensioned cables showed a potential reduction of up to 36 % of the IRTG steel needs, cutting 16 % GHG emissions.	Muñoz-Liesa et al. [59]
2022	IRTG	Barcelona, Spain	AR-glass and ethylene tetrafluoroethylene film for tomato crops have the least environmental impacts while increasing average lifetime productivity (19.9 ± 2.3 kg/m^2 and 19.2 ± 2.2 kg/m^2 each).	Muñoz-Liesa et al. [60]
2022	IRTG	Barcelona, Spain	Cost drivers for tomato production in the IRTG were: 61.8 % of total costs, for labour 24.7 %, for the IRTG structure 15.0 %, external pest control services 12.6 %, and the rainwater harvesting system 9.5 %.	Peña et al. [61]
2022	IRTG, CEA, PFAL	Several	Development of BIA led to movement from traditional UA systems, including the built landscape (e.g., VF and RTGs). Designing the right treatments for resources from the buildings is crucial for high quality production in BIA developments.	Orsini et al. [73]
2022	iRTG (intelligent rooftop greenhouses)	Any climate	Developing a fuzzy-interpolative control system of temperatures for iRTG allows adaptation to a broader range of climates and better performance.	Popa et al. [29]
2022	Five food production models (frontiers), where one is CEA in general including RTG	Several	Scholarly agreement that CEA has dietary and ecological benefits. CEA is ranked as the most feasible frontier to be implemented by 2050. Future work is needed to decarbonise energy sources or integrate operations in circular resource-use systems to reduce ecological impacts.	Glaros et al. [72]

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