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Review

Narratives and Benefits of Agricultural Technology in Urban Buildings: A Review

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Abstract: The literature on agricultural technology (ag-tech) for urban agriculture (UA) offers many narratives about its benefits in addressing the challenges of sustainability and food security for urban environments. In this paper, we present a literature review for the period 2015–2022 of research carried out on currently active UA installations. We aim to systematise the most common narratives regarding the benefits of controlled environment agriculture (CEA) and soil-less growing systems in urban buildings and assess the existence of peer-reviewed data supporting these claims. The review was based on 28 articles that provided detailed information about 68 active UA installations depicting multiple types of ag-tech and regions. The results show that most research conducted for commercial UA-CEA installations was carried out in North America. Standalone CEA greenhouses or plant factories as commercial producers for urban areas were mostly found in Asia and Europe. The most often cited benefits are that the integration of multiple CEA technologies with energy systems or building climate systems enables the transfer of heat through thermal airflow exchange and CO_2 fertilisation to improve commercial production. However, this review shows that the data quantifying the benefits are limited and, therefore, the exact environmental effects of CEA are undetermined.

Keywords: urban agriculture; controlled environment agriculture; urban buildings; indoor vertical farming

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1. Introduction

There is a rising concern about the contribution of cities to the production of greenhouse gases (GHGs) across the globe as forecasts for 2050 point to the population reaching 10 billion [1]. Examining all factors contributing to the emission of GHG, the literature has identified multiple dimensions to this problem. Energy and food underpin the quality of life lived in urban areas. The production, distribution and consumption of food and the associated waste generation are key factors contributing to GHG emissions globally and the connection between agriculture and climate change has been well established [2–5]. Many factors contribute to GHGs in agriculture, from upstream preproduction processes of inputs, such as fertilizers, to the farm-level production management of environment control and resource use, and post-production distribution and processing [6]. A major contributor to those emissions is energy use in production and distribution, which is highly dependent on the combination of agriculture technologies, cultivation environment and location [7–9]. Food demand alone will increase by approximately 50% in a context of land degradation, desertification and deforestation [10]. Increased demand will drive the necessity for urban planners and policy makers to support other solutions and technologies that can concurrently address GHG production and food security [11].

Urban agriculture (UA) is an emerging industry that aims to produce and improve access to healthy food in densely populated areas by growing food where it is consumed [12].

By bringing the farm to the urban doorstep [13,14], UA can take targeted action towards circular economy, social inclusion and climate change mitigation [15]. Urban agriculture can also enable the reuse of urban organic waste [8,16], reduce food miles and GHG emissions through concepts such as 'zero-acreage farming' or 'Zfarming' [17]. Despite multiple claimed benefits, Weidner, Yang and Hamm [18] suggested that, used as an all-inclusive term, UA has drawn as much pessimism as optimism for addressing the diagnosed symptoms of urbanisation, food security and climate change. In fact, actual examples of UA installations are highly heterogeneous. There are multiple types of UA and technologies used for achieving an impact across social, environmental and economic dimensions [3,8,18,19].

Although agricultural technologies (ag-techs) are traditionally anchored in soil and dirt, UA project designers seeking to address multiple urban challenges in 2022 have access to various ag-techs for growing food beyond soil, the natural environment and the horizontal plane [18]. Agfunder in 2015 launched market research reports into ag-tech investments analysing the commercialization of technologies by category [20]. Advances in soil-less growing technologies, environmental control, automation and integration in built areas are increasing; the 'novel farming systems' sector of the ag-tech industry attracted an investment of USD 596 million in 2018 [21] and in 2021 this increased to USD 2.3 billion [22]. This expansion over a short timeframe resulted in some conceptual confusion regarding the types of technologies available and their effects. The most successful examples of ag-tech in UA installations are only anecdotal or pilot-based and fail to make a compelling case for the economic viability of the technologies' application in UA [3]. The challenge for city planners, UA designers and entrepreneurs is to understand multiple ag-tech solutions available for application in urban environments and buildings, and to have access to information about the effectiveness of ag-techs for mitigating the problems facing cities, which is based on active real-world installations.

UA installations operating in commercial production combine different ag-tech in order to achieve business goals. An installation can grow a range of leafy greens, fruits, vegetables or fish. These groups of products require different inputs and conditions, which can be provided by specialized ag-tech installed to deliver the selected crops [23,24]. A single UA installation in most cases consist of a minimum of three ag-tech systems: the controlled cultivation environment, a soil-less growing system and a lighting system. This complexity makes access to crop production and combined ag-tech data mandatory for any meaningful analysis to be performed [8].

In terms of climate change, locating novel farming systems in urban environments can have a positive effect through reduced transportation and decreased production waste due to technological efficiencies [25,26]. However, there are also negative effects due to the volume of materials, combination of technology required for infrastructure and electricity consumption when assessed per kilogram of similar crops produced in an urban and conventional farm. For example, conventional agriculture can produce a kilogram of lettuce at 0.33 CO_2e per kg in summer and 2.62 CO_2e per kg in winter, which compares with a controlled lab vertical farm producing spinach, with significantly higher emissions of 6.4 CO_2e per kg [18]. The known drawback of ag-tech and indoor farming is the high energy demand, and consequently potentially higher GHG emissions, due to the cost of controlling environmental conditions and applying LED lighting to mimic the sunlight for plant growth [27–29].

This comparison, however, should be made carefully as there are known inconsistencies regarding the quantification of environmental impacts of UA installations and conventional farms. In fact, methods such as Life Cycle Assessment, which offer structure to evaluating impacts, face variations in functional units used, scope of system boundaries, ag-tech infrastructure and data sources considered, make it difficult to draw definitive conclusions about the impacts and benefits of ag-tech in UA [8].

This narrative review focuses on documented and active UA installations using soil-less and controlled environment agricultural (CEA) technologies. The aim is to assess and systematise the potential environmentally beneficial effects of food production in real-world installations of UA solutions while describing the ag-tech used. To avoid using unchecked claims of sustainability, we aim to include evidence documented in the scientific literature. This focus on research carried out in the installations is meant to ensure that the quantitative evidence for benefits is validated and peer-reviewed. Consequently, the study does not aim to list all UA installations nor all ag-tech systems actively operating globally, but rather to pinpoint specific ag-tech systems in UA that have demonstrated and well quantified benefits for food security or the environment—and assess if that evidence is sufficient to justify narratives about benefits. We therefore carried out a review of the literature over the last 6 years (2015 to 2022). The originality of the study was therefore the systematization of narratives about benefits for ag-tech technologies and the existence of validated evidence. We start by introducing the key concepts in UA that are required to understand the diversity of installations and approaches. Then, the methods used for the literature review and selection of installations of interest are presented. The results describe the geographic scope of the installations found in the peer-reviewed literature, the types of ag-tech used and the reported benefits of those systems. Finally, we discuss the results in terms of environment types, popular narratives, evidence of benefits and present the main take-home messages from the review.

2. Materials and Methods

2.1. Key Concepts

Owing to the diffuse terminology often used in the UA literature, we next define some key terms used in this review. The literature was assessed, as shown later in Section 3, using the definitions presented here.

2.1.1. Ag-Tech

Ag-tech encompasses a broad range of sectors, technologies and products, establishing itself to include the digitisation, robotics, automation, machinery, biotechnology and a broad range of technologies related to food production and growing systems. Following the successful funding of firms over the last six years, this first wave of start-ups is the beginning of a new industry forecasted to achieve approximately USD 3 trillion in the future [30]. This review targets the sub-sector of ag-tech used for indoor agriculture systems applying CEA, known as 'novel farming systems' [22]. All signs point to a booming industry as individual installations for new or existing installations attract multi-million-dollar investments, which seek to double yields per growing area of hydroponics and greenhouse production [18].

2.1.2. Controlled Environment Agriculture

Defined by Kozai et al. [31] as enabling 'the grower to manipulate the cultivation environment to the desired conditions, and that is useful for isolating specific environmental variables for more precise studies on plant responses to modified sets of environment'. This is possible owing to developments in ag-tech automating software with the capacity for processing and optimizing data from sensors, LED lighting equipment and environmental conditions for cultivating different crop types [25,32]. This contributes to high-energy requirements of the ag-tech operations and is a well-known drawback due to the costs to regulate the atmosphere and to use LED lighting to simulate sunshine for plant growth [27–29]. The CEA method primarily applies hydroponic growing methods, where plants are grown in substrates or the roots are saturated with water or mist-dosed nutrient mixes [18,33]. When software, LED spectrum and nutrient dosing regulation are coupled with air-conditioning air flow dynamics and CO_2 fertilisation, the full benefits of advanced plant growth can be achieved with CEA [34–36].

Climate-controlled environments for growing vegetables have been heavily researched as approaches to increase yields, improve quality and seek a deeper understanding of environmental factors on plant growth [25,37]. These approaches have led to the integration of indoor hydroponic growing systems with different environments, specifically shipping containers (SCs) [27], greenhouses [38] and plant factories [4,31,39,40]. This integration demonstrated benefits regarding plant quality through input and output control of material flow [31]. These advancements have allowed for food to be grown closer to where it is consumed in urban areas across the globe [37]. Research has, therefore, been promising for positioning CEA as a player in the future of urban food production [18].

2.1.3. Soil-Less Growing Systems

The term soil-less growing system is a main order category applied to a collection of ag-tech where plants are grown without soil and includes growing systems where the plant roots float in deep water culture, root in non-soil substrates with drip irrigation (hydroponics), float in deep water aquaculture with fish (aquaponics) or are directly sprayed by a mist (aeroponics) to receive nutrients [33,41,42]. A key concept applied throughout this study, soil-less growing systems are a critical component in CEA and a standard technology for vertical farming systems [31,43]. Cultivation success drives production and revenue in commercial vertical farms, and the resource use and quality of the final product are believed to be optimized through the control of water, root aeration and availability nutrients [19,44,45]. Each system uses different methods to achieve this control. Hydroponics, aeroponics and aquaponics all apply techniques that focus on maintaining a living water culture promoting root health for plant growth [33,46–49]. Descriptions of the individual soil-less growing systems identified in this study are included in the Results Section.

Soil-less growing systems are not suitable in all circumstances nor for growth of all plant species and crop selection is critical to UA installation success [50,51]. Depending on the desired goals for the final product grown, kilograms of fresh weight for sale or bioactive properties, these systems can be beneficial for a range of plants but not all [7,24,50,52]. The higher production costs of vertical farming make growing commodity crops, such as rice, wheat, corn or soybean, not economically viable due to the low price and length of plant growth cycle in time and cost to maintain the functioning of LED in CEA over this same period [44]. Even though the use of close-loop irrigation or recirculating of wastewater in soil-less growing systems can reduce water consumption and eliminate the direct run-off of leachates, this benefit does not offset the high electricity demand in vertical farms [5,7,35,53,54]. These challenges are known in commercial vertical farms that focus on fresh vegetable crops. UA installations primarily grow leafy greens, herbs or fruiting crops, such as tomatoes and strawberries, as final products of high volume consumption in urban areas [44]. The study acknowledges that the use of soil-less growing systems can be particularly advantageous for certain plants, but the analysis of results focuses on the environmental narratives of the combination of ag-tech in each UA installations and not the selected plants. Any information duly documented in the literature was included in Supplementary Materials.

2.1.4. Urban Buildings

Buildings provide the structures critical for operating CEA. There are two broad types of buildings that can be used: (i) a built structure such as a warehouse or large greenhouse with the sole purpose of commercial food production to supply urban areas; and (ii) low use spaces identified in urban buildings with sufficient room for CEA system installation and urban farm operations [55–58]. The first are typically constructed for the specific purposes of installation and the second are pre-existing buildings in urban areas where a CEA system is installed in rooftop, carpark or technical spaces. These two types of buildings offer different levels of integration for CEA based on the type of building structure. The level of integration is highly dependent on the ag-tech installed, the building's function and its existing equipment for energy or climate system operations. There are challenges that emerge when working with urban buildings due to limitations of the existing infrastructure, which require evaluation to assess if in some cases peri-urban buildings built for CEA purposes may provide better commercial outcomes, depending on the UA installation [56,59,60].

Cities take many forms across the globe, bringing a variety of challenges depending on the location. A consistent view is that cities are central hubs of consumption, distribution, production and waste generation [61,62]. One way to understand this flow of materials is through urban metabolism so as to discover ways of closing the loop on materials, such as food and water, or reducing CO_2 emissions through energy efficiency [1]. As aggregators of a wide spectrum of materials, the current flow of materials and energy into cities contributes between 60% and 80% of GHG emissions [63]. In the European Union (EU), buildings, when considered as the point of consumption, account for approximately 40% of final energy consumption [64] and a third of the world's CO_2 emissions [28]. For these reasons, UA designers and city planners consider urban buildings as ideal locations for UA installations.

Within UA, there is an emerging subset called urban agriculture in or on buildings, where UA installations target synergy across material flows between the building and the growing system [64,65]. This concept includes rooftop agriculture (RT), rooftop greenhouses (RTG) and integrated rooftop greenhouses, all of which target the rooftops of urban buildings using a wide variety of ag-techs [15]. The latter RTG can, in principle, offer the most impact by enhancing the building's integrated system's synergy of material flows through the bidirectional transfer of heat and CO_2 [66]. In this type of architecture, also known as building-integrated agriculture (BIA), high-performance soil-less farming systems are installed on and in buildings to take advantage of local sources of water and renewable energy [67,68]. The main benefits of synergy are the reduction in food miles and land and water use, while improving food production through soil-less growing technologies [69]. This BIA subset of UA is important to understand and validate, for how UA can achieve its proposed benefits beyond food security.

2.2. Methods

This narrative review was undertaken to globally identify active, operating UA installations with CEA that have been used as the basis of peer-reviewed literature (e.g., for data collection). We sampled installations from a keyword search limited to the specific point of exploration of this review. The keywords used were "controlled environment agriculture" AND "urban buildings". Google Scholar has been shown to provide the most comprehensive range of results when compared with Web of Science and Scopus, which produce similar results [70]. With the use of Google Scholar, the search was undertaken in April 2022 and limited to references published between 2015 and 2022 to ensure a focus on the most recent literature and to discover installations actively operating ag-tech. We limited the search to recent publications only to ensure that early pilot installations and trial cases were excluded. The narratives and benefits stemming from pilot installations run through scientific or start-up projects may not be representative of real-world commercially exploited UA farms, and therefore we focused only on the latter. Although installations were found using scientific articles, the ultimate goal of the search was to identify individual installations and a depiction of their technical setup and operational results.

Web searches were conducted in English, specifically when the website link was not provided in the articles. In cases when no website in English was available, the website was visited in its native language and translated into English. In all cases where no link was provided or the website did not work, a Google search of installation name and location was undertaken. For results returned in a language native to the location, websites were translated and considered as included. However, when no online reference material was identified, the installations were excluded.

The inclusion criteria for each article were based on the level of information provided about installations combining UA and CEA and being currently in operation. To be included in this review, each article had to provide the following detailed information about the installations outlined: project name, location, growing area, crop type and a description of the ag-tech growing systems including CEA environment type. If more than one article mentioned an individual installation, the information was collated and included from the multiple sources. Articles mentioning only the name, location and website of installations were excluded, as they provided limited peer-reviewed technical information. Furthermore, articles focused on proposed or designed installations not yet operating and/or modelling scenarios based on limited real-world data were excluded. This choice was made to ensure that only duly documented and active installations were assessed.

Two stages of review were used to test the level of detail provided and ensure consistency of inclusion criteria. For the installations selected during the first stage, as described previously, we conducted a secondary review of website checks to collect additional details. This verification also tested whether the websites for the installations were active and up to date and whether their information supported claims made in the articles. Installation website checks were, therefore, used to validate the detailed information provided in the literature. In circumstances where no live website could be found and no additional data or verification was achievable, the installations were excluded from the analysis because this review is focused on operating installations.

3. Results

3.1. Articles Included

The original search returned 122 references in total, which were initially reviewed to identify articles that mentioned installations using CEA and two immediately removed due to failed links. Inclusion for this review focused on academic information published on ag-tech for growing and cultivation environments in operating installations to identify narratives, first in published articles and second on websites. The 17 articles that mentioned an installation by name and included a website but no additional information or data were excluded. Several papers explored different ag-tech solutions in depth, including analysis of growing systems, such as aquaponics, and proposed UA designs for building integration or large vertical farms that used those solutions. These articles did not provide detailed information about farm size, crop types, production volumes, benefits, limitations or research detail of active installations and a total of 77 were excluded. Finally, we reviewed the remaining papers to ensure that they reported data and/or included a technical description of the physical UA installation. This was the case for 28 articles published between 2015 and 2022, which included detailed information about real-world installations. These 28 papers mention 124 individual UA installations applying CEA across the globe.

3.2. Sample of Urban Agriculture Installations

Following website checks, we excluded a total of 37 installations from the sample of 124 installations because the verification of websites was impossible. The review of the remaining 87 installations determined 19 of these had an online presence, but were found to be closed. All used a range of technologies and closed due to the completion of research projects or financial issues in commercial installations. For example, the Fertilecity Project, an integrated rooftop greenhouse in Belterra, Spain, was mentioned in 10 articles and is now closed as the research was completed [8,29,71–75].

Commercial businesses operate the majority of installations in the sample and can be either fresh food producers or technology providers. There are cases of businesses of both kinds also shutting down. Of these, a majority were due to financial issues. FarmedHere closed in 2017 [65], the Urban Farmers project in The Netherlands declared bankruptcy in 2018 and Nutraponics Sherwood, Canada, raised USD 2 million of funds in 2014, but are not online. A technology provider, Podponics, which raised USD 14 million, appear to be closed or acquired and Agricool went into receivership in 2022 after raising EUR 35 million to service 100 retail stores across Île-de-France [19,76,77]. Those cases were excluded from the final list of active installations used in this review.

Due to the focus of this study on CEA and soilless growing systems, installations using soil-based growing systems (total of nine) were removed [78]. Mentioned in the sample articles were multiple installations, such as Nuvege Plant Factory in Japan and Green Spirit Farms in Michigan, USA, which had website domains but no active websites [38,78–80]. The final sample of 68 active installations, based on the 28 articles included and subsequent website checks, provided the remainder of the information mentioned in this review.

3.3. Installations by Region

The active installations found in the literature through the application of the criteria previously explained are primarily based in Northern Hemisphere countries, as shown in Figure 1 and details provided in Table 1. When classified into global regions, North America is the most prominent, with 33 installations [3,17,35,36,38,57,65,68,77,79,81–85]. The Asian region has nine documented installations and the only project in the southern hemisphere was in Australia and was included in the sample for Asia [36,38,49,68,77,79,80,86]. A total of 26 installations was found for Europe [3,5,19,26,38,49,77,79,87,88]. There is a predominance of countries where economic development in capital markets have driven the application of innovative technologies. These types of installations require significant investment to launch due to the technology costs, retro-fitting and construction. Once launched, the ag-tech offers a level of control and efficiency, but the operational costs to produce crops often come with high energy costs depending on the sources. Both initial investment and operating costs require a robust business case to attract funding for capital investment often via venture capital funds, private equity and institutional loans. Access to these types of investors is higher in countries of the Global North.

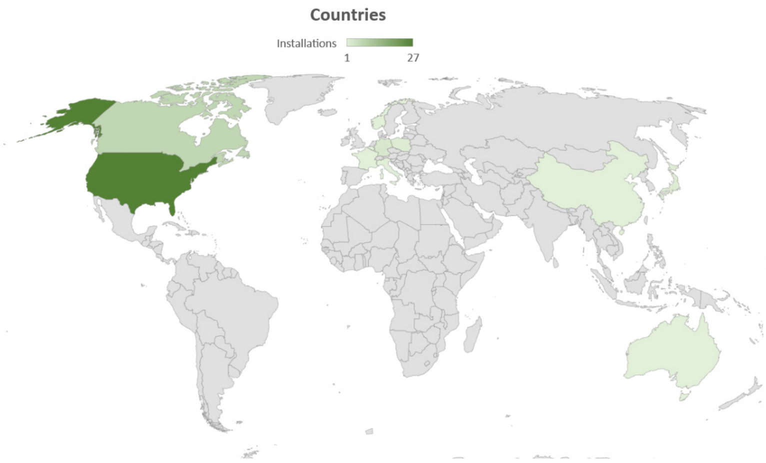

Figure 1. World map from Table 1 of active CEA installations by country.

The following subsections describe each of the installations by region based on the type of environment and growing system. Given the methods applied here, it should be noted that these are the locations for commercial and currently active urban farms where research has been carried out. Figure 1 illustrates the regional clusters of the sample in this study and should not be interpreted as a map with all existing UA farm locations in the World.

3.3.1. North America

Two companies, Gotham Greens and Lufa Farms both launching commercial food production installations in 2011, account for eight of the total 33 installations in North America. Gotham Greens are based in the USA operating at four sites across New York (NY) and Chicago, exploiting rooftops with CEA greenhouses using hydroponics [36,65,68,77,81]. Lufa Farms, a Canadian company operating four installations in Montreal, uses CEA in greenhouses on rooftops, combining vertical hydroponics with LED and natural light [85,87,89]. Combined, both companies contribute to the demonstration of CEA integrated in urban environments with commercial success.

Table 1. Active UA installations with CEA by country, start year, the 'type' of location of technology (BD: inside built structure, RT: on building rooftop, SC: inside a shipping container near buildings, IS: Instore of retailers), built urban environment (MF: across multiple floors, SF: installed in a single floor, WH: a specific warehouse, CC: a climate chamber, OD: outdoor on rooftops), growing systems (VA: vertical aeroponics, VH: vertical hydroponics, H: hydroponics, A: aquaponics) and purpose of the installation.

No	Installation	Start	Country	Type	Environment	Growing System	Purpose	References
1	Sky Green Farm	2009	Singapore	BD	GH	VH	C	[36,38,68,77,79,80,86]
2	Verticrop TM	2009	Canada	RT	GH	VH	C	[36,38,79,81,86]
3	Gotham Greens—Greenpoint	2011	USA	RT	GH	VH	C	[3,36,38,57,65,68,83,85]
4	Mirai Company	2015	Japan	BD	SF	VH	C	[3,38,77,81]
5	PlantLab VF	2011	The Netherlands	BD	MF	VA	C	[3,38,77,79]
6	Vertical Harvest plans2	2012	USA	BD	MF	VH	C	[38,68,79]
7	Green Sense Farms 1	2016	China	BD	WH	VH	C	[38,86]
8	Green Sense Farms 2	2014	USA	BD	WH	VH	C	[38,86]
9	Aero Farms	2012	USA	BD	WH	VA	C	[36,38,81,82,86]
10	Bright Farms	2011	USA	BD	GH	H	C	[3,38,57]
11	Lufa Farms 1	2013	Canada	RT	GH	VH	C	[3,35,38,57,83–85]
12	Lufa Farms 2	2011	Canada	RT	GH	VH	C	[35,38,83,84]
13	Freight Farms	2010	USA	SC	SC	VH	TP	[38]
14	Thanet Earth Farm	2008	UK	BD	SF	H	C	[38,49]
15	Gotham Greens—Pullman	2015	USA	RT	GH	VH	C	[65,81,82]
16	Gotham Greens—Gowanus	2013	USA	RT	GH	VH	C	[65,81,82]
17	Gotham Greens—Hollis	2015	USA	RT	GH	VH	C	[65,81,82]
18	Edenworks	2013	USA	RT	GH	A	C	[82]
19	Square Roots	2016	USA	SC	SC	VH	C	[82]
20	Farm.One	2016	USA	BD	WH	VH	C	[82]
21	Sky Vegetables	2012	USA	RT	GH	H	C	[82]
22	Eli Zabar: rooftop-grown	1995	USA	RT	GH	H	C	[17,82]
23	Oko Farms	2013	USA	RT	OD	A	C	[82]
24	Plenty Unlimited	2014	USA	BD	WH	VH	C	[35]
25	GrowX (now GrowY)	2017	The Netherlands	BD	WH	VH	C	[5]
26	Food Roof Farm	2013	USA	RT	CC	VH	C	[65]
27	GreenBox	2019	USA	BD	WH	H	Tech-provider	[78]
28	Ouroboros Farms	2012	USA	BD	GH	A	Commercial	[49]
29	Sustainable Harvesters	2012	USA	BD	GH	A	Commercial	[49]
30	Eco-ark greenhouse at Finn & Roots		USA	BD	GH	A	Commercial	[49]
31	Superior Fresh Farms	2015	USA	BD	GH	A	Commercial	[49]
32	Blue Smart Farms	2005	Australia	BD	MF	A	Commercial	[49]
33	Ecco-jäger Aquaponik Dachfarm		Switzerland	RT	MF	A	Commercial	[49]
34	BIGHs Ferme Abattoir	2018	Belgium	RT	GH	A	Commercial	[49]
35	Great Northern Hydroponics	1998	Canada	BD	GH	H	Commercial	[81]
36	Listny Cud		Poland	BD	SF	VH	Commercial	[81]
37	Urbanika Farms	2015	Poland	BD	SF	VH	Commercial	[81]
38	Green Spirit Farms	2011	USA	BD	SF	VH	Commercial	[3,77]
39	Green Girls Produce	2012	USA	BD	SF	VH	Commercial	[68,77]
40	Grönska	2014	Sweden	BD	SF	VH	Tech-provider	[87,88]
41	IronOx	2015	USA	BD	WH	Hydro	Tech-provider	[36]
42	Spread Co	2015	Japan	BD	MF	VH	Commercial	[80]
43	Citiponics Farm	2016	Singapore	RT	OD	VH	Commercial	[86]
44	Orchidville		Singapore	BD	GH	A	Commercial	[86]
45	WOHA	2017	Singapore	RT	OD	A	Commercial	[86]
46	Fairmont Singapore/Swissotel Stamford -Project		Singapore	RT	GH	A	Commercial	[86]
47	Lufa Farms Inc. (Ville)	2019	Canada	RT	GH	VH	Commercial	[3,35]
48	Lufa Farms Inc. (Anjou)	2017	Canada	RT	GH	VH	Commercial	[3,35]
49	Intergrow	1998	USA	BD	GH	H	Commercial	[82]
50	Growing Underground	2015	UK	BD	SF	H	Commercial	[19,26]
51	Jones Food Company	2018	UK	BD	SF	VH	Commercial	[19]
52	Infarm	2013	Germany	BD	WH	VH	Tech-provider	[19]
53	B-Four Agro	2006	The Netherlands	BD	GH	A	Commercial	[19]
54	Byspire	2016	Norway	BD	SF	VH	Commercial	[19]
55	Deliscious	2012	The Netherlands	BD	GH	H	Commercial	[19]
56	Duurzame kost	2015	The Netherlands	BD	SF	A	Commercial	[19]
57	Tuinderij Bevelander	1970	The Netherlands	BD	GH	H	Commercial	[19]
58	Restaurant of the Future (restaurant)		The Netherlands	IS	CC	VH	Retailer	[19]
59	The Green House (restaurant)		The Netherlands	RT	GH	H	Commercial	[19]
60	Auchan (retailer)		Italy	IS	CC	VH	Retailer	[19]
61	Auchan (retailer)		Luxemburg	IS	CC	VH	Retailer	[19]
62	Coop Butiker & Stormarknader (retailer)		Sweden	IS	CC	VH	Retailer	[19]
63	Edeka (retailer)		Germany	IS	CC	VH	Retailer	[19]
64	Casino (retailer)		France	IS	CC	VH	Retailer	[19]
65	Metro (retailer)		Germany	IS	CC	VH	Retailer	[19]
66	Migros (retailer)		Switzerland	IS	CC	VH	Retailer	[19]
67	Ikea (retailer)		Sweden	SC	SC	H	Retailer	[19]
68	We the roots	2017	Canada	BD	WH	VH	Commercial	[68]

Other commercially viable installations using CEA greenhouses includes one of the four BrightFarm's owned farms in NY using hydroponics and the oldest rooftop installation by The Vinegar Factory-Eli Zabar, NY, servicing local food businesses using hydroponics, which began in 1995 [17,82]. Furthermore, in Vancouver, Canada, a rooftop greenhouse using vertical hydroponics is operated by Verticrop since 2009 and Great Northern Hydroponics from Quebec has operated a greenhouse with hydroponics installation since 1998 [81,86].

Some CEA vertical farms installations use multiple levels operating across multiple floors, such as Vertical Harvest in Wyoming, USA, a vertical hydroponics installation. Green Girls Produce in Memphis, Tennessee, only grows microgreens on a single building floor in a CEA designed installation. For commercial installations, often a fit-for-purpose warehouse was constructed to accommodate advanced vertical farming technology, such as is the case with Plenty Unlimited in San Francisco [35]. AeroFarms are the only company in North America known to be applying aeroponics vertically in a CEA warehouse for large-scale food production in New Jersey, USA [81].

The remaining installations are notable because of the innovative application of ag-tech to develop indoor vertical farming products as technology providers. Freight Farms based in Boston successfully use upcycled SCs as the chamber for CEA in combination with vertical hydroponics. These SC-style farms are directly purchasable for farmers, such as Square Roots in NY, who set up multiple farms in a successful community driven to produce grow leafy green vegetables [82]. Other companies offering ag-tech solutions with active installations are IronOx in California and Greenbox out of Connecticut [36,78].

3.3.2. Asia

Of the nine installations in Asia, all were commercial and none of the documented technology involved CEA on rooftops of buildings. Asia includes one project in China: Green Sense Farms began in Portage, Indiana, USA, in 2014 and expanded with a second installation in Shenzhen, China, in 2016 [36,86]. Both use CEA in warehouses operating large-scale vertical hydroponic systems. There were two installations in Japan, namely the Mirai Project in Chiba, which is one of many CEA warehouses using indoor vertical hydroponics systems operated by this company worldwide, and Spread Co from Kyoto, which operate a vertical farm across multiple floors for the commercial production of lettuce [76].

In Singapore, Sky Green Farms manages six active installations, the oldest in the sample for Asia. They launched in 2009 and use single floored greenhouses with vertical hydroponics without LED lighting to grow a wide variety of Asian greens. The other vertical farm operated by Citiponics in Ang Mo Kio uses a hydroponic system outdoor on a building rooftop [86]. The remaining three installations in Singapore all apply aquaponics and Blue Smart Farms, the only case in Australia, NSW uses aquaponics across multi-ple floors in a building [49,80].

3.3.3. Europe

The 26 installations in Europe are located in ten different countries. The Netherlands (NL) had the most active installations with eight; Sweden, Germany, Switzerland, Poland and the UK had three; and the remaining installations are distributed across individual countries. Commercial-purposed installations represented 15 installations, technology providers two companies and retailer stores emerged as operating eight small CEA systems instore and one shipping container CEA in the carpark of Ikea in Sweden.

This sample shows the diversity in application of technology. NL offers examples of seven commercial installations in total and one retailer instore climate chamber in Wageningen. Two installed aquaponics B-Four Agro in Warmenhuizen and Duurzame Kost in Eindhoven offering fish and fresh greens [19]. Operating across multiple floors of a building using different technologies are PlantLab, Den Bosch, NL, who operate an indoor vertical farm using aeroponics in combination with hydroponics for leaf greens production.

The only rooftop greenhouse system was The Green House, a restaurant in Utrecht using hydroponics and established in 2017. GrowX are based in Amsterdam, cultivating herbs and microgreens in a single floor warehouse with vertical hydroponics [5].

Europe offers two technology providers of importance as they operate their own facilities for research and production, while servicing other installations in the sample with their ag-tech. Infarm are a company of interest in Berlin, Germany. Following a fundraising round in December 2021, the company was valued at USD one billion to expand large-scale warehouse vertical farms for food production and continue offering turn-key climate chambers to retailers [90]. They service six retailers with small scale climate chambers for instore vertical farm point of sale systems for customers to select fresh leafy green products [19]. Grönska in Stockholm, Sweden, operate a vertical farm in a single floor and offer retailers small climate chamber systems for instore use; Coop Butiker & Stormarknader was the only retailer in this sample using this technology [87,88].

3.4. Installation Soil-Less Growing Systems

The 68 installations all use soil-less growing systems in combination with CEA in buildings or rooftop locations for production. A novel definition of soil-less growing systems used in this review is that it is an approach to plant cultivation without the use of soil, where growth is facilitated through substrate or water culture [87,91–93]. In some cases, the installation had a combination of growing technologies, and the primary system was selected for reporting results. The study sample included four different types of growing systems: Aquaponics, Hydroponics, Vertical Aeroponics (VAs) and Vertical Hydroponics (VHs). For the purpose of clarification, Table 2 provides a description of each system and the application in the sample installations.

Table 2. This is a table of the description and application of soil-less growing systems in the literature. The study sample included four different types of growing systems: Aquaponics, Hydroponics, Vertical Aeroponics (VAs) and Vertical Hydroponics.

Soil-Less Systems	Number in Sample	Description
Aquaponics	14	Recirculating aquaculture and hydroponic system for fish and vegetable production
Hydroponics	13	The art of growing plants in water with nutrient solutions and without soil in floating beds or with nutrient films in a horizontal plane
Vertical Hydroponics (VHs)	39	Hydroponic systems grown in a vertical plane or in multiple layers of stacked horizontal hydroponics systems
Aeroponics (VAs)	2	Considered a variation of vertical hydroponics where plant roots do not require soil or substrate culture as this air–water cultivation system sprays a nutrient solution in a mist

3.5. Installation Types by Region

A review of the different growing systems used across each of the regions, as presented in Table 1, shows that all six installations in Asia use similar VH technology systems located inside building or warehouses with one setup across multiple floors and are documented as plant factories [38,86].

This term was coined in the research undertaken by Kozai et al. (2016) (p. 39 [31]), with contributors from across Asia where ag-tech is well established in commercial food production. Working in large warehouses or single floored greenhouses with VH systems has been the norm for supplementing conventional agriculture to such an extent that following the tsunami that hit the Pacific coast of Japan in 2011 and its impact on food security in Fukushima, plant factories were subsidised to ensure a clean food supply for the country, which offers a potential explanation for the lack of mention of BIA or other growing systems for the Asian region in the literature.

In North America, the installations discovered through the methods applied here use a diverse range of growing systems for commercial purposes. The dominant growing technology was 57% VHs with 19% hydroponics and 20% aquaponics, indicating that these ag-tech are accepted by mainstream food producers. Two installations use a combination of VHs with aquaponics for commercial production, whereas others use more classic aquaponics with hydroponics systems. The last in the region, considered one of the world leaders in vertical aeroponics, is Aerofarms, which is leading the way in aeroponic systems with high levels of automation for smart farming [36,38].

Of the 26 installations in Europe, eight retailer installations use VH systems in small scale climate chambers and raise questions about their consideration as UA installations or another point of sale offering products direct to customers. When retailers and technology providers are removed to focus on the 15 commercial installations, VH and H systems each account for 33% of the sample, 27% use aquaponics and only one aeroponic system.

3.6. Documented Benefits

A diverse range of benefits has been mentioned in the literature, although, in most cases, this was not the primary focus of the authors. That is one of the reasons why past reviews call into question whether the benefits are a result of being UA or the ag-tech applied [8]. To explain the application of ag-tech in UA installations beyond the production of food in the location it is consumed, the benefits of the sample installations described in the literature are outlined in Table 3.

The articles identified through this method included limited data or evidence in support of documented environmental benefits. Prior reviews focused on LCA results for UA installations showed the limitations of data availability from operating installations applied in assessments [8] and similar challenges in aquaponic LCA models due to variation of installation sizes [89]. With the exclusion of the Fertilecity Project, the only documented LCA study in the sample aimed at quantifying environmental impacts was carried out for the Grönska vertical farm system, producing 60,000 plants in pots [87,88].

Table 3 shows the benefit documented in the sample used in this paper. This does not imply data or supporting environmental assessments were evidenced; they claimed benefits rather than fully and transparently reported and quantified effects. The benefits outlined in Table 3 were assessed for the 68 installations, and 41 had at least one environmental benefit reported. Other benefits for UA may have been covered in the literature, but without specific reference to individual real-world installations and therefore not included. The table also presents the type of system, which relates to whether the installed CEA system documented was in or on a building.

3.6.1. Water Use Reduction

The majority (31) of installations with documented narratives mentioned benefits related to 'water use reduction', reuse or rainwater. Often a narrative generalized in UA due to the application of hydroponic systems, this narrative implies the amount of water used for growing the plants is lower than that used in conventional open-field methods due to the technology [93]. In most cases, this difference can be attributed to the installed soil-less growing systems as no data related to water consumption per plant was reported [33]. Depending on the installed systems, more than 90% reduction in water use in plant cultivation can be achieved because recirculating hydroponic systems are designed to reuse water in CEA [80,93]. Installations with VH systems reported water benefits in 18 cases, including 5 operating rainwater systems and 1 building integrated for water reuse. The narrative of reduced water use is a known benefit of soil-less growing system regardless of location and almost half of the installations in the study sample reported this narrative with no data provided on its impact.

Table 3. This is a table of the sample of active installations with the location type and the described benefits are noted as 'yes' to indicate that the benefit was duly documented and 'BIA' when building integration was identified. Blank cells indicate that no information was documented and cases without any benefits were removed. Installation locations are BD: Inside a Building, RT: Rooftop of a Building, SC: Shipping Container, CC: Climate Chamber. Renewable energy options included Solar: for generation with photo-voltaic, Sun Direct: for sites using sunlight during the day, Combination: a combination of renewable energy technology was identified, such as biogas generation combined with sun direct.

No	Installation	Type	Water Reduction	Heat Transfer	Renewable Energy	CO_2 Fertilization	Organic Waste Reuse
1	Sky Green Farm	BD	Yes		Sun direct		Yes
2	Verticrop TM	RT	Yes		Sun direct		
3	Gotham Greens—Greenpoint	RT	Yes		Combination		Yes
6	Vertical Harvest Plant	BD	Yes				
7	Green Sense Farms 1	BD	Yes				
8	Green Sense Farms 2	BD	Yes				
9	Aero Farms	BD	Yes		Solar		
10	Bright Farms	BD	Yes		Sun direct		Yes
11	Lufa Farms 1	RT	BIA	BIA			
12	Lufa Farms 2	RT		BIA			
13	Freight Farms	SC	Yes				
14	Thanet Earth Farm	BD			Combination		
15	Gotham Greens—Pullman	RT		BIA	Combination		
16	Gotham Greens—Gowanus	RT			Combination		
17	Gotham Greens—Hollis	RT			Combination		
18	Edenworks	RT			Sun direct		
22	Eli Zabar: rooftop-grown	RT		BIA			
23	Oko Farms	RT			Sun direct		
24	Plenty Unlimited	BD	Yes				
26	Food Roof Farm	RT	Rainwater				
27	GreenBox	BD			Sun direct		
28	Ouroboros Farms	BD	Yes		Sun direct		
29	Sustainable Harvesters	BD	Yes		Sun direct		
30	Eco-ark at Finn & Roots	BD	Yes		Solar		
31	Superior Fresh Farms	BD	Yes		Sun direct		
32	Blue Smart Farms	BD	Yes				
33	Ecco-jäger Aquaponik Dachfarm	RT	Yes	Yes	Sun direct		
34	BIGHs Ferme Abattoir	RT	Yes		Sun direct		
36	Great Northern Hydroponics	BD	Yes	Yes	Combination	Yes	Yes
39	Green Girls Produce	BD	Yes				
40	Grönska	BD	Yes				
42	Spread Co	BD	Yes				
43	Citiponics Farm	RT	Yes		Sun direct		
47	Lufa Farms Inc. (Ville)	RT	Rainwater				
48	Lufa Farms Inc. (Anjou)	RT	Rainwater				
49	Intergrow	BD	Rainwater	Yes	Combination	Yes	Yes
51	Jones Food Company	BD	Yes		Solar		
54	Byspire	BD	Yes				
55	Deliscious	BD	Rainwater				
56	Duurzame kost	BD	Yes				
67	Ikea	SC					Yes

The advantages of water use reduction in this context also include the replacement of water from other sources. In the case of the five installations operating hydroponic systems connected to a rainwater tank, the benefit exists only when the ag-tech is installed inside, on roof tops or in close proximity to built structures that collect rainwater. The volume of water replaced during operations for each UA installation remains unknown. However, Food Roof Farms, a rooftop vertical farm in Saint Louis, US, integrates a 17,000-gallon tank to capture rainwater in storms to mitigate issues off stormwater runoff in the downtown city [65]. In one case, Brookyln Grange NY, collects storm water from the green rooftop system each and is said to result in partial reduction in water consumption of the whole system; however due to the primary growth in soil, it was excluded [35]. Although water use in this case was reduced, the selection of a non-closed-loop system leads to the production of leachates, where wastewater containing excess fertilisers exists the system to the immediate environment [94]. Additional technology, such as water collection and storage, in building-integrated designed UA installations can directly replace local purchased water. However, due to the limited data, it is unclear what are the requirements for water treatment needed for replacing this primary input for plant growth.

3.6.2. Renewable Energy

Renewable energy is a broad term used to encompass all mentions in the literature of sustainable electricity or other energy sources, such as sunlight, green electricity sources from national grids or electricity generation technology, was installed in the sample [95]. Although the use of renewable energy, as all other benefits reviewed here, is a potentially positive measure for any production system, it has specific advantages in UA. Sources of energy are documented consistently as an important factor for UA project design decisions when using CEA, owing to the high energy costs per plant. Given the extremely high demand of electricity, a critical difference compared with conventional farming, electricity sources are uniquely important in ag-tech and represent a specific bottleneck for UA due to the replacement of sunlight with LED lighting. Put simply, the two main contributors to the energy consumption in CEA are lighting and climate control systems, which vary depending on the growing environment and location requirements for heating, cooling and dehumidification [35,82]. For example, in RTGs and greenhouses, energy consumption is reduced by using the sun as a primary light source for plant growth. However, energy (and electricity in particular) demand remains high due to heating, airflow and lighting supplementation, depending on the geographical location and weather [5]. Therefore, the source of electricity is a critical aspect for reducing environmental impacts and improving economic sustainability. A renewable electricity source for UA food production becomes the most important resource to manage, whereas in conventional food production the major energy burden is attributed to transportation and fertilizers [7–9]. Table 3 depicts 23 installations describing the use of renewable energy sources. These sources include the use of direct sun light, solar electricity generation through photovoltaic systems and organic waste for biogas generation [95].

Greenhouses are the most prominent in the study sample, with 16 installations advocating the use of the sunlight as the direct source or a combination of solar and other technology. Eight installations take advantage of sunlight, two supplement electricity for climate control with solar energy only and the remaining greenhouses use a combination of technology for electricity and climate control. The four RTG installations owned by Gotham Greens combine sunlight and solar panels on rooftops in building-integrated designs, rather than positioning them as sustainable technologies competing for the roof top space [54]. Reports of energy savings in Gotham Greens installations are due to evaporative cooling, heat storage and solar electricity generation of 55 kW, yet no data of significance was provided. None of the retailer-operated small scale vertical farm systems documented the use of renewable energy as a benefit associated with the installation.

Eight installations documented photovoltaic energy as the electricity source for operating a variety of growing systems and environments. Due to the high-energy challenge per plant faced by CEA and UA installations, it was surprising that only 11% of the sample reported solar energy. Of those reporting it, half were combined in greenhouses and only one reported the total number of panels used. B-Four Agro, a commercial aquaponics operator in NL, installed 1000 solar panels on the roof of a building next to the greenhouse [17]. This raises the question of how many UA installations efficiently apply renewable energy generation technology. The question is whether the low penetration of photovoltaic technologies is due to the costs involved or the lack of space available in the buildings for installation.

Great Northern Hydroponics combines multiple technologies, including an integrated anaerobic digester to transform organic materials into biogas and into a natural gas turbine to generate electricity for multiple food businesses [81]. Integrow combines the technology of biogas gas generation, sun direct growing with supplementary lighting supplied by solar and internal heating rails. Organic waste reuse was noted in a total six installations with a variety of applications other than energy generation, such as compost production or in the case of Ikea's shipping container system as a nutrient source for plant growth [19].

3.6.3. Heat Transfer

Heat transfer is used as broad term to designate important innovations emerging in the field of BI-UA for buildings and other built structures with access renewable energy technologies onsite. Excess heat is produced via solar radiation as a direct source of light for plant growth, accumulating in the top of the structure, and heat is normally ventilated to the local environment. The functioning of LEDs is used to supplement light for greenhouses in winter and 100% of growth in CEA operations, which produces heat that is dispersed using cooling or ventilation. The advantages of reusing this heat depend heavily on the combination of technology, location of building integration and the weather conditions of the urban location. The emerging narrative for UA installations integrating these types of CEA systems is that they find ways of transferring or exchanging heat with buildings and energy systems and reuse the extra energy. This gives rise to two potential opportunities. The first is for the building to take advantage of the excess energy and heat produced by the UA installations for heating the building [96,97]. The second is the utilisation of excess heat from the building for heating the UA installation through residual heat in airflow [83] or thermal inertia created through the connection of two thermally controlled bodies, a CEA system and a building [84].

The study sample included eight installations applying this concept in the real world: building-integrated RTGs and greenhouses with integrated energy systems were the main types of environments actively applying this solution. In the commercial RTG examples, Lufa Farms have both their installations taking advantage of building integration for heat transfer and operating for at least five years. Gotham Greens have four installations in the study sample, growing leafy greens. However, only one of these sites in Pullman was documented as utilizing heat transfer, demonstrating a benefit of direct coupling of CEA systems with building energy systems for optimisation of excess energy [3]. Beyond reporting the narrative, no data were provided for the benefits effect on production or environment impacts. In light of this, it remains unclear how this heat transfer is regulated or whether the RTG transfers heat to the building or vice versa.

Additionally, heat transfer is possible with built structures, such as UA installations, in peri-urban greenhouse facilities documented as combined benefits in renewable energy with integrated energy generation technologies [81]. Two companies in the sample operated large-scale tomato growing greenhouses in North America and Canada, which take advantage of combined heat and power (CHP) systems for electricity generation with simultaneous heating. Based on website search results, Intergrow and Great Northern Hydroponics installations have integrated gas powered CHP systems to reduce overall electricity costs and environmental impact through cogeneration [98,99]. In the case of Great Northern Hydroponics, they deliver an excess of 12 megawatts of electricity supplied to the Ontario power grid; however, this information was not in the scientific literature.

3.6.4. CO_2 Fertilisation

CO_2 concentration is critical for plant photosynthesis as plants absorb light to convert CO_2 and water into carbohydrates and oxygen, which is highly variable depending on the crop type [24]. Research in CEA settings demonstrate that CO_2 fertilisation between 260–495 ppm increases radiant energy transformation into plant biomass and varies depending on the ambient concentration of CO_2 in the natural environment [100,101]. In order to increase biomass production, industrial CO_2 is purchased to enrich CO_2 concentration in CEA from 400 ppm to 1000 pm, achieving a 25% to 60% yield increase [101]. The enrichment of CO_2 for CEA production is achieved through a gas cylinder installed with regulated dosing or through CHP integration using gases flues and air filtration [85,98,102]. Another potential advantage of coupling climate control and energy systems with CEA is gaining access to the CO_2-rich airflow from the building [96,103]. Rooms occupied by humans working create an environment higher in CO_2 concentration than ambient levels [104,105]. Past research projects such as Fertilecity Project, a UA installation, utilised residual CO_2 concentrations accumulated inside the building as a natural fertiliser; however, it is unclear what effect this had on plant growth and its significance for commercial production [102,106]. From this active sample of UA installations, no RTG system documented the benefits of building integration for CO_2 fertilization.

Two installations presented the technology integration of greenhouses and energy generation systems with airflow exchange for fertilisation. Confirmed on their websites, Intergrow and Great Northern Hydroponics take advantage of the CO_2 extracted from anaerobic digestion or a CO_2 collection manifold system connected to turbine generation exhaust [81]. Further research is needed to understand the coupling of CO_2 flow of human produced CO_2 in buildings and energy system exhaust integration for use in commercial production.

4. Discussion

All UA installations summarised in the study use CEA as the foundational ag-tech for improving the efficient use of resources of crops produced and take advantage of market trends for controlling the conditions for cultivation in an artificial environment [45]. The use of CEA continues to be substantiated as a mechanism for removing environmental risks associated with conventional agriculture, allowing for annual production to be independent of the effects of extreme weather [107]. Moreover, the enhanced processing of sensor data and meta-processing lead to better decision making based on high-precision crop monitoring systems, which allows for increased yield [36,108]. The number of commercial UA installations in the study sample indicates a certain level of popularity for CEA in combination with buildings to supply urban areas, at least in North America and Europe.

4.1. Controlled Environment Type

Using the terms CEA and urban buildings for the search method demonstrated that different combinations of ag-tech are used, four different physical environments to control the climate: 27 greenhouses, 27 inside buildings (including warehouses), 9 climate chambers and 3 shipping containers, excluding 3 outdoors installations.

Shipping container farms are flexible, scalable farming solution for food security in urban areas using CEA and VH inside old shipping containers [107]. The advantages claimed, such as reduced water per plant or year-round food production, are more specific to the combination of soil-less growing systems and the environment type [27]. Although shipping containers are mentioned in this study, the sourced information is specific to Freight Farms, a technology provider, and not identified as a commercial producer [38]. An example is Square Roots, who operates Freight Farms ag-tech across a number of locations in NY as per their website, whereas the literature only mentions the company and its technology, not the individual locations [82]. While UA benefits associated with reduced transportation are relevant to units installed in urban areas, there are issues of long-term economic viability linked to significant energy consumption [10].

The climate chambers defined in Table 1 accounted for 14% of the sample and are essentially a point-of-sale equipment similar to product dairy refrigerators in supermarkets. They are small CEA-VH systems with a glass door or walls found inside the stores of food retailers. Infarm is a technology provider that operates these climate chambers in six retailers stores across Italy, Luxemburg, Germany, France and Switzerland [19]. These turnkey solutions are a ‘plug and grow’ technology where there is no integration and are not dependent on the location; however it is not clear if the plants are grown from seeds all on site in the Infarm systems. The use of these climate chambers as part of the customers’ retail experience and leads to generalised benefits of UA similar to shipping containers; however, no evidence was documented in the literature for this environment type.

Installations inside buildings or warehouses existed in all regions, and when greenhouses were removed, these CEA environment types accounted for 41% of the study sample. Considered here as plant factories and multi-storey plant factories (also referred to as indoor vertical farms or vertical farming), these installations are completely dependent on artificial sources of lighting [19,39,109,110]. The conditions created for optimum plant growth rely on lighting sources, heating, cooling and airflow circulation, which is associated with a high-energy burden [39]. There is a balance between year-round consistent cultivation and the costs of purchased electricity when UA designers consider plant factories over greenhouses [40]. Only two plant factories were documented as supplementing energy through solar, and two applied a combination of renewable energy solutions; however, no references were made to direct impact on GHG emissions, total energy replaced or LCA [111]. This points to further research needs, namely, directly contacting the UA installation operators to validate the effect of the energy source on production.

Greenhouses are the other dominant physical environment with 41%, which for CEA was not unexpected. The engineering of greenhouses has been the topic of research since the 1990s, and modern installations use CEA in some form [38]. Traditional greenhouse sectors are significant in food systems across the world because they excel at maximizing solar energy and optimizing growing conditions without complete dependence on purchased energy [40]. This of course depends on the climate of the region, time of year, expected production volumes and combination of ag-tech installed [10,15]. In warmer climates, CEA greenhouses are equipped to discharge excess heat produced and sourced through solar energy [39]. However, in colder climates, heating comes at a significant cost as the sector has a substantially disproportionate total energy demand and requires innovative solutions for becoming a sustainable food production method [112]. These energy challenges of controlled environments have been addressed in a variety of ways by using a combination of ag-tech and renewable energy through integration of buildings, structures and systems.

4.2. Rooftop Greenhouses

This study sought to discover UA installations and determining the location of each installation as being inside buildings or on top, on the roofs of urban or peri-urban buildings. Removing small scale CEA systems, such as climate chamber and shipping container because they are location agnostic, and the plant factory style, 19 rooftop UA installations were identified. One project, Ecco-jäger Aquaponik Dachfarm Switerzland, uses a rooftop in combination with aquaponics across multiple floors in a building and three are not using CEA as they are outdoor rooftop farms. A total of 79% of this sample operate greenhouses on the roofs of buildings as commercial production installations.

Rooftop greenhouses (RTGs) were the most prominent in the study sample, and it is clear from the results that greenhouses installed on rooftops have become a popular design approach in North America. The concept of food production on rooftops of urban buildings was once considered rather novel [113], but this appears to be shifting, with RTGs accounting for 15 out of 27, more than half of the greenhouse installations reported. The potential UA benefits of BIA are now recognised as RTG installations exploit waste material flow of buildings to improve CEA energy and water inputs [15]. Benefits related to integrating technology of RTGs with the building for factors such as heat transfer and CO_2 flows are being recognised [90]. Globally, there is only a small number of RTG installations physically connected to energy, water and climate control systems (including air ventilation for CO_2 exchange) on site [114]. This narrative review proposes that the increased documentation of RTG physically integrating systems is owed to the progression of ag-tech in greenhouses; its commercial productivity in North American urban environments demonstrates a response to environmental pressures and food security.

4.3. Popular Narratives

Assessing the documented benefits revealed multiple narratives for novel farming systems used in UA both in the scientific and grey literature during website checks. These included reduced food miles, reduced water use and chemical- or pesticide-free vegetables. First, a primary environmental benefit of UA is that growing food where it is consumed reduces the transportation miles, which is not novel and not related to the ag-tech installed [61,78]. In some cases, this is over-emphasised in marketing on websites and was not captured as a benefit in this study. However, the distance between producers and consumers is not the main determinant in the overall sustainability of food products [115]. Research using LCA across multiple installations in Boston found that the focus on food miles undermined the importance of the efficient use of cultivation inputs, demonstrating that in some cases conventional agriculture supply chains had a lower LCA impact than UA installations [3]. This is an issue associated with the defined LCA system boundary and indicates an area for further research to segregate the 'food miles' narrative from LCA impacts directly attributed to BIA, input efficiency or use of experimental versus industry data [8,94,116].

Reduced water consumption was a recurrent narrative across websites and duly documented in the literature. This is consistent with historical narratives directly related to using soil-less growing systems based on hydroponic principles [33], regardless of whether the ag-tech was VAs, VHs, aquaponics or a combination [117]. It was unclear whether the statements in the literature were made in relation to scientific research on real-world installations or based on research associated with specific soil-less growing system [118]. An example is aeroponics, a subset of hydroponics, introduced commercially in 1983 and supported by NASA-funded research. Aeroponics validated the claims of reduced water consumption, along with significant yields [91]. Apart from the claim of reduced water use through an alternative source, such as rainwater collection, the specific water use reduction efficiency associated with other real-world installations remains unclear [114,119]. For installations taking advantage of soil-less growing systems, reduced water use appears to be an appropriate narrative and assumes a comparison to conventional farming of an comparable crop [90].

4.4. Economic Viability

In North America and Europe, the application of ag-tech in commercial production is a result of investment in companies for developing products and the intellectual property may be protected and therefore unreported in the scientific literature. The application of CEA with buildings in urban areas continues to be limited due to the high investment costs required for initial technology installations, business start-up and staff. As seen in the UA installations closed even when large volumes of investment are made in companies, the operationalisation of the ag-tech to achieve economic sustainability over time is not guaranteed. Vertical farming is still an emerging industry with many improvements required to increase the uptake of UA installations as the cost to supply crops and energy fluctuate over time [17]. The number of closed installations due to financial issues is not clearly known as many companies could have been in operation and are now closed. In the case of Agricool the adoption of ag-tech was high with multiple small scale systems combined with a large scale vertical farm operating to supply one major French food retailer with 100 stores. Over 6 years from the initial pre-seed investment in 2015, a total of four investment rounds were based on supply contracts to food retailers. Initially, Shipping Container with ag-tech specific to strawberry growth were installed at retailers building sites, Agricool scaled the crop type and business model to a warehouse vertical farm following the final investment round. This demonstrates that the adoption of ag-tech has increased in the food industry, yet the achievement of operational goals and economic sustainability may prove difficult over time.

4.5. Buildings Integration

Energy use is a challenge faced by all CEA installations in relation to lighting, climatic conditions of heat, cold, air flow and humidity. This challenge intensifies for installations that do not exploit sunlight as a direct source of energy and rely primarily on artificial illumination [10]. Therefore, energy usage can be considered in terms of climatic conditions and electricity. Building-integrated agriculture is emerging as an option for energy efficiency of CEA in aforementioned climatic conditions. This innovative idea of the coupling material flow of buildings with UA installations is becoming a reality [16]. Of the four UA installations reporting heat transfer through BIA for commercial production, none of the provided data about the energy or economic benefits achieved by this physical integration.

Considering the energy requirements for CEA related to climatic conditions, UA installations in BIA were designed using principles that can exploit energy normally wasted by the climate control systems of buildings [16,81]. The concept is to exploit heat generated by the building as a resource to achieve optimal conditions inside RTGs. Depending on the time of year, the RTG can also be used for natural ventilation of the whole building [120]. The technologies required to take advantage of the synergy between UA installations and the climate control systems of buildings have not been discussed in this narrative review. There are few real-world installations carrying out research on this BIA technology, which points to a new field where inputs of CEA systems are systematically integrated with buildings, beyond plug-and-play solutions to physically grow food on site [114]. As commercially focused food producers continue to expand the operations of large-scale RTGs, the industry has become a critical source of real-world installations. Integrated rooftop greenhouses are the only CEA solution employing this level of BIA, whereas shipping containers or climate chambers were not reported to exploit this benefit from buildings.

Nevertheless, the lack of documentation about the sources of energy in real-world installations was noteworthy. A total of 65% of the installations in this sample provided no operational data. Considering the overt challenge of high energy costs in CEA, this would be useful for future installations [113]. This may be because of the intellectual property protection of specific commercially operated installations or a lack of published research, as demonstrated by the study sample used in this narrative review. The field is progressing rapidly to apply artificial intelligence and complex mathematical optimisation algorithms for reducing energy use and modelling CO_2 emissions [121], seeking to not only replace the use of fossil fuels with renewable sources, but also achieve energy-neutral CEA solutions for green infrastructure in urban environments [38,88]. CO_2 fertilization, heat transfer and renewable energy are promising options for reducing greenhouse gas emissions in a commercial context through building integration. However, further energy and environmental assessments are required to fill the existing gap in data for quantifying their exact contribution towards the sustainability of UA [16,18,122]. Existing commercial installations are expanding regionally, such as Gotham Greens across the USA, which demonstrates the economic viability of UA installations as a primary solution to shorten supply chains. In the future, by coupling energy and climate systems in buildings, the synergistic relationship of CEA-UA installations in BIA can exploit available excess energy as inputs and, therefore, open up locations to scale and secure resource efficient food for urban environments.

A narrative that is important specifically in urban regions emerged in the sample of UA installations as six cases identified reuse waste materials as inputs for future production. The use of organic waste referred to biomass or food waste produced by the installation and its potential input use for energy or nutrients. Data on the effect of this benefit in all cases was not available for any of the narratives and combinations of technologies installed. It is, however, possible to present some examples representative of the combinations of ag-tech used in installations where organic waste is reused.

Sky Green Farm in Singapore have been operating a vertical hydroponic greenhouse system to produce leafy greens since 2009. The technology is an A-frame aluminium structure with powered hydraulics to rotate the growth tiers of plants from bottom to the top of the controlled environment to increase sunlight exposure. Water use has been replaced through rainwater collection and connected with the hydroponic system. All organic waste from production goes through compost treatment for use as fertilizer. Integration in this case only refers to the rainwater system as it requires the built structure and water tank, but it is unclear if compost treatment is onsite. Despite being stated in the literature and online, these narratives could not be supported with data quantifying the actual benefit in terms of water and fertilizers savings.

Gotham Greens are a major player in commercial production using advanced CEA greenhouse structures all over the USA and new locations opening soon. Their premiere UA installation launched an integrated a rooftop greenhouse with combined lighting to grow leafy greens in a single floor hydroponic system. Building integration allows for access to evaporative cooling and heat capture transfer during the winter. A major benefit to this location is access to a city recycling system covering all waste reuse and access to compost treatment for organic waste produced. Details on the technologies and future application of the waste remains unknown.

Integrow are one of two UA installations in this sample, which reported all benefit narratives identified with advanced integration for water, energy, organise waste and air ventilation equipment. They operate a large-scale greenhouse in New York, USA, since 1998, using a drip feed hydroponic system with tomatoes grown on substrate. Integrated infrastructures collect water to reuse leachates for recycling water and fertiliser, while the pitched roof collects rain equal to 90% of the water needed for irrigation. Grown under sunlight, supplementary lighting uses high-pressure sodium lamps and a climate control system for CEA management. To address the energy demand an onsite, a gas-powered CHP system actively generates electricity to service the lighting, heating and cooling needs via climate control systems with integrated heating rails for heat transfer inside the greenhouse. A supporting technology installed is an anaerobic digester producing natural gas for CHP cogeneration and delivers heat transfer for the greenhouse in winter months. The system takes advantage of wastage, unsold produce, which is used in the anaerobic digester to make natural gas and CO_2 for fertilization. This UA installation and Great Northern Hydroponics were found to have the highest level of building integrated equipment described to support the narratives documented. Both are systems for commercial food production for the high-volume production of tomatoes supplying North American major cities and demonstrate ag-tech integration with building infrastructure, climate and energy system is viable in these conditions. The effect each of the integration on CEA production for these installations and data supporting narratives were mostly absent from publications except when noted in the text and Supplementary Materials.

4.6. Limitations

This review is not an exhaustive literature review of real-world installations in UA, BIA or CEA integrated with urban buildings. The approach used was to first search scientific publications and source an installations sample from the literature, which led to the exclusion of multiple known installations applying ag-tech. Some installations that have been in business for more than 6 years could potentially have been missed due to the timeframe used. This is unlikely due to the growth of the industry being concentrated in this review period. Additionally, we found some of those older installations due to papers being written about them. Because our focus was on installations and not articles, it is unlikely that we would have found additional active installations in older papers. With respect to articles about currently operating installations, a repeated documentation of installations in multiple papers was observed.

An additional limitation of this review was that no direct contact was established with the companies operating the installations included in the study sample to validate the information available on the website. The source literature was limited to articles published in English and available through Google Scholar searched via an IP address in Portugal. The grey literature used was anecdotal and based on installation descriptions and other communications on the website. Further research on real-world installations would need to validate narratives in the scientific and grey literature and compare them with direct contact with installation operators. Another limitation worth noting is the inconsistency of metrics to support benefits or data reported across the installations, such as differences in reported size both in square meters and square feet. It was unclear whether the installation size reported was the size for growing/production or the size of the whole installation. The lack of metrics made it difficult for researchers to source even basic information about plant yields, quality and in some cases the crop grown was named in general terms, such as leafy greens. This inconsistency of metrics and access to data created challenges to quantify any benefits associated with ag-tech integration and its potential to produce a single plant.

Additionally, there was no consistent reporting of production yields by installation nor of LCA profiles in the literature or on websites, which compromises future research seeking to undertake comparative studies or environmental assessments.

4.7. Future Research

Future research suggestions made in this review are critical to the advancement of ag-tech in urban areas and to publish material data of use for the design of UA projects. The narratives of UA installations as a tool for mitigation of climate change through CO_2 emission reduction, efficient use of urban materials and food security for urban environments require deeper analysis. The following outlines areas of focus for CEA in UA to provide information of substance for urban planners and decisions makers designing our future food system. The main action points and research needs are:

- A transparent data disclosure specifically from active commercial farms that enables research to be carried out to validate any claims of benefits or detriments from UA. Data from pilot sites and experiments is insufficient to determine the real-world effects of ag-tech in UA farms. The lack of transparency creates mistrust in the typically cited narratives, and therefore it is in the best interest of commercial players in the market to fully disclose their performance. This will enable further quantitative validation of the most popular narratives described in the sample, such as organic waste or water reuse and use of renewable sources of electricity, to report the tangible impact of these narratives on the real-world installations' production of final products.
- An all-inclusive systematic review of CEA operating in commercial production for urban areas and the level of technological integration. This includes the identification of indicators for success to achieve economic sustainability and provide return on investment.
- A dedicated analysis of UA installations that use coupled systems using CEA with different environment types in building-integrated for renewable energy, heat transfer and CO_2 fertilisation integration to assess the benefits of ag-tech integration.
- A full quantitative analysis of benefits of CEA-UA installations using LCA to compare supply chain impacts between different forms of ag-tech and also the performance of UA farming with conventional farming. LCA methods are not always applied using the same (or comparable) functional units, system boundaries and data sources, and therefore dedicated studies are needed to ensure full compatibility.
- The determination of the potential for biomass growth (production yield) as a function of energy use in the production system (building and CEA system) that enables an optimisation of quantities produced and inputs used towards reduction of environmental impacts.
- A specific analysis of the types of ag-tech that are better suited for each plant type or type of product grown in the installation, including their environmental performance.
- A full sustainability analysis of the installations that also assesses the socio-economic effects of production in the urban environments where the installations are located.

5. Conclusions

This study presented the results of a review of narratives regarding environmental benefits from commercially exploited installations using ag-tech for UA-CEA in buildings. Most of the installations found using these criteria were located in North America. Our first conclusion is that the advantages of specific types of CEA depend on the choice of ag-tech (environment type and growing system), the location, the product and the degree of integration with built structures or existing systems. The direct coupling of building energy and climate systems with RTGs in UA installations had the most stated benefits in the peer-reviewed literature. The literature also cited as potential benefits of CEA effects that are not exclusively used in UA, such as the use of renewable energy sources from biogas generation and combined heat and power energy systems. The synergistic relationship of CEA and built structures to exploit available excess heat and CO_2 for growth inputs is possible and already applied in many commercial installations in large scale. This integration seems to lower economic and energy expenses of farm operations, which is a critical limitation to profitability. The high energy requirement for running CEA systems is the biggest issue facing ag-tech, both economically and environmentally, according to this review, which is consistent with earlier research in the area.

However, data demonstrating the existence of these advantages was not found through this research. We searched specifically through the scientific literature because it ensured the best possible data quality, validated through peer-review, and also the most likely transparency, as all research papers are meant to be replicable and verifiable. Still, we were unable to locate quantified evidence, as a result of direct monitoring and comparison to conventional or other types of farming. For example, UA-CEA installations identified here justify their use of combinations of technology as a strategy to overcome their high energy use. They integrate renewable or combined energy systems to replace the use of purchased energy. However, there was no mention in the articles of how various combinations of ag-tech and renewable energy systems (solar power or biogas generation) affected investment costs, urban environment or GHG emissions.

Therefore, we conclude that ag-tech continues to grow through increased investments and diversity of real-world installations, all of which claim sustainability benefits in relation to other means of production. CEA provides UA with an innovative edge as operational results of commercially focused installations integrated with buildings and those CEA installations also report the most environmental advantages. It is for those installations that there is more documented evidence that integration with climate control and energy systems enables transfer of heat through thermal inertia and airflow exchange, along with CO_2 fertilisation. Other popular narratives about the benefits of these technologies are less supported by data, such as the ideas of saving food miles and providing pesticide-free food. Assessing the level of impact UA installations have on social, environmental and economic challenges requires scientific measurement and data disclosure for active installations.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/atmos13081250/s1. File S1 includes the complete list of active urban agriculture installations applying controlled environment agriculture with the source data for the summary tables in the main article and the final list of source articles: File name 'Narrative and Benefits of Ag-tech_Sample Installation and Articles Data-280622.xls'.

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