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Understanding the complexities of Building-Integrated Agriculture. Can food shape the future built environment?

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ABSTRACT

Our food system is facing an unprecedented challenge: feeding a fast growing population without depleting precious resources like energy, soil, and water. Furthermore, the increasing urbanization has rapidly exacerbated the gap between farm to plate, leaving cities vulnerable to changes in the production and supply chain, as demonstrated by recent pandemics and wars. In this context, emerging technologies that allow plants to grow in absence of soil, permit to produce food in high densely built-up areas, bringing food production right were most consumers live. These initiatives enter within the so called Building-Integrated Agriculture (BIA), which is referred as the practice of locating greenhouses and soilless plant cultivation technologies on top and inside mixed-use buildings to exploit the synergies between the building environment and agriculture, involving resource recovery such as water, energy and nutrient flows. This paper aims at determining strategies, objectives, and best practices of BIA projects through the review of 21 case studies, to understand how a new advanced and future-oriented agriculture applied within the cities borders, can possibly shape the urban built environment and food systems of the future.

1. Introduction

In the movie Soylent Green (1973), set in a then futuristic 2022, director R. Fleisher describes an overcrowded New York, battered by climate change, where the natural environment is practically extinct. The torrid climate has swept away the alternation between seasons leaving only a constant, incredibly warm summer. In this anti-utopian vision of Fleisher, the greatest problem of humanity is represented by the impossibility of finding food which is only available in the form of innatural, man-made nutritional bars called 'Soylent green'. Fleisher's dystopian view of the future, 50 years ago, brought him to represent on the big screen a today-present where the Western Food Security was crashed by the unavoidable global warming. The dystopian culture of the 20th and 21st century is, in-fact, reflection of a society that fear for its own future (Zaffi & D'Ostuni, 2020), succumbed to its impulses, often defeated either by climate change or technological development (Mirenayat & Soofastaei, 2015). Accordingly, fictional representations are an important component to future studies, representing the 'warning signal' (Bina et al., 2020) embodied by the mass culture of contemporary societies. The recent pandemic and new geo-political assets leading to wars and energetic crisis, are highlighting the vulnerability of the urban systems of European countries and beyond presenting us with various scenarios for anti-utopian futures. Indeed, cities are strongly dependent on outside resources, resulting in a limited resilience capacity. As more than half of world population lives in cities,

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this aspect acquires particular importance, especially for what concerns food purchase. Moreover, due to the constant urbanization, current food systems will have to adjust to satisfy the rising food demand for an increasing urban population (FAO, 2011). Cities depend on huge and complex international supply networks, relying on distant elsewhere for food, energy, and consumer goods. Accordingly, the complex food chains that bring food into urban settlements are subject to multiple systemic risks where economic, social or political shocks in one region of the World could influence food distribution and production globally (Hamilton et al., 2020). Furthermore, industrial agriculture is creating vast, mono-cultural surfaces, where large amounts of synthetic herbicides and pesticides are often applied, causing the desertification of agricultural soils, the depletion and pollution of important water resources and the loss of biodiversity (Orsini & D'Ostuni, 2022). The environmental effects of these practices are devastating, and it is possible to see their impact in the four ecological pillars of the food system: soil, water, biodiversity, and climate (FAO, 2017). The depletion of soils together with the scarcity of land and a reduced capacity of fresh water reservoirs mark the necessity for a transition towards more sustainable and fair production systems. In this scenario, even if it is generally acknowledged that the modern agro-business will be able to produce enough food for a growing population in the future (Holt-Giménez et al., 2012), it is also recognized that this will not occur in an inclusive and sustainable manner (FAO, 2018). Several solutions have emerged, promoting a shift towards more sustainable food production practices, often complementary to each other. A strategy that is catching on a growing interest is the possibility to implement food production systems within cities and large urban environments (Cockrall-King, 2016), with the objective of promoting local and fresh food for the urban population. The recent fortune of this practice, known as Urban Agriculture (UA), is connected to its capacity to target both urban and agricultural issues, proposing solutions that promote a sustainable transition of urban food systems as well as new healthy urban lifestyles in future cities. The confluence of users, business, and resources like land, labor, energy, and water together with a ready-made market for all kinds of food produce (Cockrall-King, 2016), make cities the ideal hubs for a renovated local food production. Here, citizens are not only the final users but could also be the co-producers of new UA based food systems.

In this context, making cities partially autonomous as regards the production of vegetal crops and energy is crucial to create more resilient urban systems, capable of absorbing possible shocks in the food supply chain at the global scale. In this sense, the technological development of new soilless production technologies (e.g. hydroponics, aeroponics, and aquaponics) theoretically allows today to integrate intensive food production in urban areas in and on mixed use buildings and districts (Thomaier et al., 2014). Cities, in fact, abound in vacant or under-used spaces like horizontal and vertical surfaces, such as rooftops, façades, squares, and interior spaces, that can actively host a diffuse, large-scale urban food production, with the advantage of taking off pressure from agricultural land (Specht et al., 2014). The practice of integrating soilless farming systems in the built environment is today named Building-Integrated Agriculture (BIA), which is characterized by the non-use of farmland or open space, thereby differentiating building-related forms of UA from those in parks, gardens, and urban wastelands (Specht et al., 2014). BIA can be considered as a practice complementary to ground-based UA (Fig. 1), that, in advance, offers opportunities to exploit the resource-efficiency synergies between buildings and farming (Thomaier et al., 2014). In this sense, BIA should not be considered just as a food-related practice, but also a tool for planners and practitioners to boost future cities sustainable development and green buildings design, representing a clear opportunity for

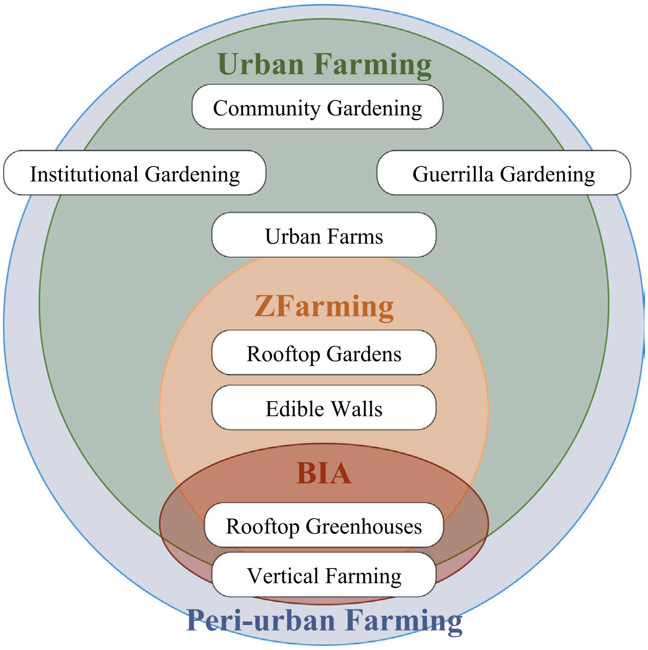

Fig. 1. : Building-Integrated Agriculture (BIA) as a subtype of Urban Agriculture (UA). Building-Integrated Agriculture (BIA) is subtype of Zero Acreage Farming (ZFarming) and can be defined as the practice of locating high-performance off-soil greenhouse systems, such as hydroponics, aeroponics, and aquaponics, on and in mixed-use buildings to exploit the synergies between the building environment and the production system.

planners, architects, and engineers to use soilless food production systems to create a new urban metabolism (Zaffi & D'Ostuni, 2020). Thus, BIA closed-loop systems may recycle and reuse nearly every element from the building to the farming process, including energy, water, nutrients and even CO_2 (Al-Kodmany, 2018). However, the future implementation of BIA models within the urban environment requires new regulation frameworks as well as an advanced technical knowledge of the production systems, which, so far, may have limited the expansion of these types of UA compared to ground-based practices. In this context, understanding the strengths and weaknesses of BIA is crucial to develop precise guidelines for its expansion in cities.

1.1. *Objectives and originality of the research*

This paper will elaborate on objectives and strategies, as well as successful and failing experiences of BIA projects by analyzing 21 case studies that set the course for the future development of a new green food-productive architecture.

This research started from the necessity to understand how the integration of soilless agricultural systems in BIA projects can improve the design of green buildings and the development of sustainable urban planning for the foreseeable future. Specific focus was also put on the factors that are hindering most of the projects to be realized and used as a comparative tool to understand what the actual limitations to the diffusion of BIA initiatives are. To this end, the case studies analysis has been aided by an extensive literature review with the intention to compare the theoretical research on BIA with the empirical practice of the realized or designed projects.

In this sense, the analysis of the 21 selected case studies and the literature review brings together a better understanding on why, how, and whether or not integrating soilless, advanced, agricultural practices in and on buildings could benefit the future development of urban areas. For this purpose, the main goals of this review are to:

- Determine the current trends and best practices of BIA projects and the relationship between food production and the architectural objects.
- Define the most used circular and sustainable strategies to improve urban and buildings green design, providing architects and practitioners with design and planning guidelines for the upscaling of BIA projects.
- Determine technological optimization to maximize yields and resource use efficiency in BIA projects.

2. Materials and methods

To comprehend the complexity of BIA initiatives, 21 case studies were analyzed with regard to the following topics:

- The potential economic, social, and environmental impacts that the selected BIA case studies may have on the local community if implemented and realized.
- The technology used to harvest vegetable crops within buildings and urban areas.
- The integration of the food production systems with regards to the development of shared sustainable design strategies.
- The synergistic relationships developed between the architectural object and the production systems with regards to the development of future circular design strategies.

The methodology used for this review consists in 5 steps, from the identification of the case studies to the interpretation of the data collected during the construction of the framework of the state of the art. The five steps were divided as follows:

Step 1: Case studies selection. Case studies were selected based on extensive literature review, expert consultation, and participation to UA conferences.[1]

Step 2: Case studies classification. The selected projects were divided into 6 macro categories, each one representing the urban scale related to the analyzed project. Each case study was then assigned tags based on its main function (research, educational, commercial, promotional), status (built, about to be built, concept), typology of intervention (new construction or renovation), and level of technology used for the production system (high, medium, low).

Step 3: Data collection. Data collection was preliminarily performed through in-depth review of existing literature and followed by specific site visits (whenever possible) and direct interactions (oral or written interviews) with architects/developers of the selected projects.

Step 4: Data analysis. All the selected projects were analyzed following a methodological structure in order to be able to compare different projects bearing in mind their different location and scale. The analysis of the data was made on two specific points: i) Circular goals and strategies of the projects; and ii) Food production goals and technical integration within the project.

Step 5: Data interpretation. The final step compared the findings with the literature review and extrapolated objectives, strategies, limitations, and advantages of BIA projects for its future development in cities.

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[1] Most used databases were Researchgate, Google Scholar, and WUR e-depot, using keywords such as "hydroponic greenhouses", "building-integrated agriculture", "soilless urban agriculture", and "vertical farming".Usable data were also retrieved from international conferences such as "Floriade Dialogue" in Almere (NL) in 2019, "Green Tech Amsterdam" in 2019, "European Urban Green Infrastructure Conference" in London (UK) in 2019.

2.1. Case studies selection

The selection of the case studies was performed building on a preliminary review of more than 50 BIA projects around the world of different scales and locations that were either already described in literature or discussed in international conferences. The final 21 case studies selected for this research were finally chosen based on their relevance with regards to their architectural design as well as for the possibility to retrieve further information directly visiting the site or through interviews with the architects/developers that carried on the projects.

2.2. Case studies classification

One of the main problems connected to the analysis of BIA case studies is that they do not belong to just one building type, neither to a precise urban scale. Accordingly, all projects were primarily classified into macro categories. Each category represents a specific scale of urban design that can be reconnected to specific typologies of intervention. This choice allowed to compare projects of similar scale and goals. The following macro categories were used:

1. Urban scale projects (UA projects involving entire neighborhoods or city districts).
2. Urban installations (temporary and movable installations related for food production).
3. Buildings (urban building integrating diffuse indoor cultivation systems).
4. Rooftop greenhouses (protected cultivation systems installed on top of buildings).
5. Facades or envelopes (food production systems coating the building).
6. Green design products (small scale, micro soilless farming systems that can be integrated in living or commercial spaces).

Besides, four strict sub-categories were identified, each defining project peculiarities (Tables 1a and 1b). The adopted sub-categories were the following:

- Technological level: High (H), Medium (M), Low (L)
- Building type: Renovation (R), New Construction (NC)
- Project Status: Built (B), About to be built (AB), Concept (C)
- Main Functions: Research (Re), Educational (E), Commercial (Co), Promotional (P).

Further characteristics of each case study were reported in Table 1b regarding quantitative data of each project (i.e. total built surface, numbers of inhabitants, costs of implementation, food production system dimension).

Table 1a

Scale, perculiarities and ID codes of the selected case studies*.

Scale	*Characteristics*	*ID code*	*Food technology*			*Type*		*Status*			*Main Function*			
	Name/Location		H	M	L	R	NC	B	AB	C	Re	E	Co	P
Urban scale projects	Bijlmerbajes Kwartier - Amsterdam (NL)	U01		X		X			X		X			
	ReGen - Amsterdam (NL)	U02	X				X			X				X
	Home Farm - Singapore	U03		X			X			X		X		
	Santa Clara AgriHood (USA)	U04			X		X		X					X
Urban installations	UrbanFarmers BOX - Zurich (SW)	UI01	X				X	X				X		
	SHJWorks Biotope - Versatile Locations	UI02			X		X	X						X
Buildings	Tropicalia Bio-dome Opal Cost (FR)	B01		X			X			X				X
	The FarmHouse by Precht - No location	B02	X				X			X				X
	Office with Greenhouse - Oberhausen (DE)	B03	X				X	X			X			
	The Greenhouse Restaurant - Utrecht (NL)	B04	X				X	X					X	
	Mochi Restaurant - Denver (US)	B05	X				X	X					X	
Rooftop greenhouses	Sunwork Centre - Manhattan NY (NYS)	RG01	X				X	X				X		
	Urban Farmers - Den Haag (NL)	RG02	X			X		X					X	
	Gotham Greens - Brooklyn NY (NYS)	RG03	X				X	X					X	
	Research Centre ICTA-ICP - Barcelona (SP)	RG04	X				X	X			X			
Facades or envelopes	EcoLogic Studio's Urban Algae Canopy @EXPO2015 - Milan (IT)	F01			X		X	X						X
	Green Market - Abudaabi	F02	X				X			X				X
	GreenBelly - Versatile location	F03		X		X				X			X	
Indoor Green design products	Infarm Berlin - Prototype in Germany, Vesratile Location	I01	X				X	X					X	
	Hydroponic Farm by Ikea @Lab Space 10 - Versatile Location	I02	X				X	X					X	
	GrowX	I03	X			X		X					X	

[*] List of acronyms - H: Hight, M: Medium, L: Low; R: Renovation, NC: New Construction; B: Built, AB: About to be Built, C: Concept; Re: Research, E: Educational, Co: Commercial, P: Promotional

Table 1b
Characteristics of the selected case studies.

Scale	ID code	Surface area	Architects/Designers	Description
Urban scale projects	U01	Tot. Area: 7.5 ha Built Area: 135,000 m^2	OMA + FabriCATIONS + Lola Landscape	A renovation project of the former Bijlmerbajes prison area in Amsterdam that will host 1350 residential units and a Vertical Farm
	U02	Tot. Area: 20 ha Built Area: 15,500 m^2	EFFEKT	Project concept for the new development of Oosterworld in Almere (NL) with 203 residential units integrated with soilless and ground-based agriculture practices
	U03	Tot. Area: Unknown Built Area: Unknown	SPARK	A conceptual proposal for the next generation of urban retirement housing that combine residential facilities for elder people and vertical farming concepts
	U04	Tot. Area: 2,4 ha Built Area: 24,300 m^2	Steinberg Hart	Mixed residential units to satisfy the increasing demand for houses in Santa Clara offering new opportunities for the inhabitants to work in the integrated farmland
Urban installations	UI01	Built Area: 20 m^2	Urban Farmers	A 20 m^2 mobile urban farming unit used for events, and teaching about sustainable urban food production
	UI02	Built Area: 84 m^3	SHJworks	It is a temporary project that present a self-sustaining eco-system within an inaccessible shell
Buildings	B01	Built Area: 2000 m^2	Coldefy & Associates	A single-domed tropical greenhouse located in the metropolitan area of the Opal Cost (FR)
	B02	Built Area: Unknown	Studio Precht	Concept design for replicable modular housing units where residents can produce their own food in integrated Vertical Farms
	B03	Built Area: 7839 m^2 GH Area: 1000 m^2	Kuehn Malvezzi	Office building integrated with a greenhouse structure from bottom to top where experiment with plants for urban food production
	B04	Built Area: 680 m^2 GH Area: 80 m^2	cepezed	This restaurant in Utrecht integrates a greenhouse in its structure where all the herbs are harvested on-site and processed right in the kitchen downstairs
	B05	Built Area: 534 m^2 GH Area: 650 m^2	Tres Bird Workshop	This restaurants integrate a greenhouse on the roof used to cultivate micro-greens directly served in the kitchen
Rooftop greenhouses	RG01	Built Area: 150 m^2	Kiss + Cathcart Architecture	A rooftop environmental education greenhouse, producing hydroponically grown vegetables on top of a primary school in the Upper West Side
	RG02	Built Area: 1200 m^2	Sasha Glasl	Largest aquaponics rooftop farm on top of an old under-used Philipp building in Den Haag - Bankrupted
	RG03	Built Area: 15,000 m^2	Unknown	Commercial farm distributed over four rooftops in New York and Chicago
	RG04	Built Area: 250 m^2	H Arquitectes + DATAAE	A research-oriented greenhouse placed on the rooftop of the ICTA-ICP building in the Universitat Autònoma de Barcelona
Facades or envelopes	F01	Built Area: 250 m^2	ecologicstudio + Carlo Ratti	Bio-digital canopy integrating microalgal cultures within a unique ETFE architectural cladding system
	F02	Built Area: 8100 m^2	Kiss + Cathcart Architecture	Complex envelope that utilize solar energy to grow crops, while providing shade, ventilation, and cooling to an enclosed space that is dedicated to other uses
	F03	Single module: 7 m^2	AVL Studio	Vertical garden self-standing modules that can be easily attached on existing facades
Indoor Green design products	I01	Built Area: 250 m^2	AKKA architects	GrowX grows various types of vegetables in an indoor space of a corporate building in Amsterdam
	I02	Single module: 25 m^2	InFarm	Urban farming services company that develops farming modules for grocery stores, restaurants, and local distribution centres
	I03	Unknown	IKEA + Space10 Lab	Vertical mini-farm pop-up used to prepare 2000 nutritional salads during the London Design Festival 2017

2.3. Data collection

The analysis of the case studies was performed over two-years, from 2019 to 2021. It consisted in two main phases: the first phase concerned an in-depth analysis of the literature, mainly encountered on dedicated websites (i.e. agritecture.tumblr.com; dezeen.com; inhabitat.com;) and in recent publications. To this end, the attached Supplementary Materials report the list of the complete bibliography used to analyze each case study. After determining the characteristics of each project, the second phase consisted in specific site visits for most of the reachable projects (compatible with the flight limitations associated with pandemics), together with interviews with those practitioners such as architects, agronomists, and developers that contributed to the development of the analyzed project (Supplementary Material).

Since some of the needed data were not available online or in the reviewed literature, semi-structured interviews were elaborated, enabling to complete the analysis of the quantitative data of some of the case studies while also accounting for differences in scale, type and costs. Accordingly, the quantitative and qualitative data retrieved for each project were reported in analytic sheets with a tight structure organized as follows:

- Projects characteristics and description.
- Construction details of the selected project, including client; designer; year of construction (if built); year of design (when not built); cost of construction (or expected costs); size; project-specific details.
- Circular strategies enhanced by the project.
- Food production characteristics and plants integration.

The rigid structure of the analytic sheets permitted a comparative analysis of the selected projects.

2.4. Data analysis

This analysis started from the consideration that cities are now provided with new opportunities to improve resource consumption efficiency by embedding circular economy principles in urban infrastructures and services, from buildings to mobility, energy, and healthcare (WEF, 2018). In an era where the exhaustion of fossil fuels is a foreseeable future and where human activities are damaging both soil and water resources (Holt-Giménez, 2018), transitioning towards re-using resources in highly polluting urban environments may be a possible solution to foster climate change mitigation and resilience. At the same time, farming in constructed urban settlements can be an opportunity to introduce a new production paradigm, shifting from horizontal food practices to vertical multi-layer, soilless systems. In this case, the new food production paradigm may be a key contributor to enhance circular strategies in urban areas, re-using construction materials, limiting water consumption, and implementing resource exchange between buildings and farming spaces.

Keeping this in mind, the analysis of the selected projects focused on how technological innovation can implement circular features in a building-integrated food production scenarios to assess the possible success of future BIA initiatives. Specifically, this analysis focused on comparing the circular features identified for each project to evaluate key development strategies to maximize circular processes in BIA. Since most projects shared some of the circular features, each specific feature was divided by total amount of encountered elements of circularity. Accordingly, it was possible to determine the total percentage of each feature, assessing circularity trends and commonalities among BIA projects.

3. Results and discussion

The first step to interpret the selected case studies was to assess the potential impact of BIA projects on the three dimensions of sustainable development: social, economic, and environmental. Six potential impacts were encountered during the analysis of the case studies (Fig. 2): three referred to the environmental dimension: (i) improve biodiversity, (ii) land saving, and (iii) reduce food-miles; two were associated with the social dimension: (i) social embedding & urban transformation, (ii) education - raising awareness on the food production topics; and one connected to the economic dimension: (i) economic development & value creation.

3.1. Environmental functions of BIA projects

3.1.1. BIA for improved biodiversity

Cities and nature have been perceived for more than a century as two separated worlds. The emergency of climate change and the

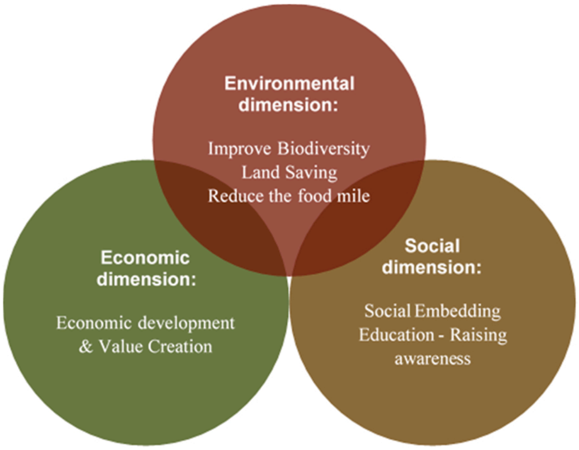

Fig. 2. Potential impacts of BIA projects.

documented health risks connected to the urban reality call for actions to reduce the green/natural gap in our cities (Egli et al., 2016). The selected food production projects fit in this new trend, aiming at the implementation of new urban green infrastructure. Most of the selected projects aim to improve biodiversity through the building components or, in the case of the urban scale projects, even with the integration of trees and wider green spaces. Some projects (e.g., F01) tend to promote photosynthesizing organisms with innovative perspiring materials and the integration of algae as urban oxygen producers. Wider, expositive buildings (e.g., B01), aim to boost biodiversity through the integration of a forest-like environment. This same objective was also evidenced in the project U04, where urban gardens and interior forests are planted to maximize new habitats for local organisms, insects, and birds toward restoring the micro-urban flora and fauna that has growingly been disappearing in cities. On a smaller scale, even temporary urban installations can improve urban biodiversity, as in the case of UI02, which designed a special beehive connected to an envelope that allows bees to have direct access to the inside of the Biotope.

3.1.2. Land saving

In soil-based industrial agriculture, soil health is the most important foundation of a healthy farm ecosystem (iPES FOOD, 2019). Nowadays, common farming techniques employed in industrial crop production, often including over-fertilization and mono-cropping, can degrade soil over time, causing a cascade of problems, that ultimately requires for the application of even more inputs, which in turn further contribute to climate change (HLPE, 2012). Some of the selected BIA projects, e.g., rooftop greenhouses, or indoor vertical farming (e.g., I03), aims at limiting soil degradation by taking intensive production within cities. Indoor (and vertically staked) crops are much more productive than traditional soil-based ones (Orsini et al., 2020): for instance, according to the data reported by the CEO of the case study RG03, their 1.4 ha greenhouse produce yields equivalent to over 40 ha of conventional field farming, reaching a production which is 35 times more efficient than ground-based agriculture (USDA, 2021). Therefore, if rooftop farms were to be expanded to city scale, they could limit land grabbing and generate new available land opportunities for agriculture. Old buildings and empty flat rooftops could therefore be converted into urban farmlands without occupying new plots in the city (Sanyé-Mengual, 2015).

3.1.3. Reducing food miles

The so-called "food mile" is a unit used to measure the distance that a food product travels from where it is produced to where it is sold or consumed. A food mile is calculated by taking the distance traveled by each food ingredient and multiplying it by the quantity of the carbon that is produced by the type of transport used (MacDonald & Reitmeier, 2017). One of the characteristics that the selected BIA projects have in common is to sell the produce in proximity to its customers, eliminating the need for long-distance, refrigerated food transportation. This is especially the case in those projects where the farming system is integrated into places where the food produce is then sold. Projects like the B05 in Denver and the B04 in Utrecht have based their selling strategy to serve mostly vegetables coming from the integrated hydroponic greenhouses. One step further in this direction has been made by I01, who based its entire business model on selling hydroponic production modules, e.g., to supermarkets, potentially eliminating the distance between the production site and consumers.

3.2. Social functions of BIA projects

The social function of UA and BIA projects have been often reported in literature as one of the benefits of these practices in urban areas. Nonetheless, while many ground-based UA initiatives have been active for years, most of the BIA projects reported in this analysis are too recent (or not even yet realized), to allow the proper assessment of their social impacts on local communities. Accordingly, their two main identified functions are those emerged from journals or web-streamed interviews to project managers or promoters.

3.2.1. Social embedding

Most of the analyzed projects tend to remark the importance of UA as a boost for social integration (Orsini et al., 2020). It is noticed that this is considered a fundamental goal in most urban transformation projects (e.g., new rooftop greenhouses or district projects, e.g., the U01 in Amsterdam). The pillar of social embedding is the integration of new groups of people in an already consolidated social environment, creating new job opportunities within the production process, while also providing job-training to unemployed users.

3.2.2. Education - awareness creation on urban food systems

Some of the selected projects share, altogether with food production, educational goals. It is the case e.g., in the RG01, included in B04, which reflects the vision of a group of parents and educators to create environmental science laboratories on the rooftops of NYC's public schools. In this case, students experience science through interactive technologies such as hydroponic vegetable farming, solar panels, a rainwater catchment system, a weather station, worm composting, and a kitchen corner. The idea of educating children about sustainability and healthy food from an early age has been considered more and more important through the years to build a more conscious future society (Abagna Azunre et al., 2019). Food consumption can, in-fact, have dramatic impacts on climate change, and education of sustainable food habits is crucial to ensure that adults of tomorrow adopts eco-friendly food choices (Sandell et al., 2016).

3.3. Economic functions of BIA projects

3.3.1. Economic development & Value creation

Upon the analysis of the selected projects, it emerged that high tech UA projects require for high investments (Lorleberg, 2016). Both small, big, and urban scale projects had to face the importance of an economic return to comply with the loans or the initial investment. It has been noticed that in those BIA projects where practitioners only produce and sell food there is a much higher failure risk. Accordingly, most of the projects elaborate innovative business models where food or plant production is the core of a more complex multi-functional building. In this sense, the production of food is integrated into the buildings completing circular flows, creating new lifestyle models and overall increasing the value of the real estate. In B01, food production has been reduced to just one of the six towers that are renovated, while the whole neighborhood proposes a diversified set of activities and different housing models. This strategy can comply with different demands, making the differentiation of functions and house typologies the core of its business model. When approaching smaller scale projects, it appears clear that edible walls and productive facades face much more difficulties in accessing funding. This probably depends on the fact that this typology appears to be more difficult to manage, not guaranteeing secure economic returns. On the other hand, intensive indoor farming is flourishing now, with projects like I01 getting more investments (both by the government and the banks), and big corporations like IKEA supporting research on compact, accessible hydroponic modules for all (Butturini and Marcelis, 2020). The improvement in LED technology as well as tri-generation climate control that allow to produce food indoor with a lower resource consumption is rapidly increasing the number of vertical farms in urban areas, indicating a clear growth trend for the future (Kozai, Niu, & Takagaki, 2020).

3.4. Embedded Circular Features (CF) in BIA projects

This analysis focused both on food production strategies as well as construction materials and methods. In this regard, circular economy here is intended as that process where the value of products and materials is maintained for as long as possible. Thus, waste and resource use are minimized, and when a product reaches the end of its life, it is used again to create further value (Roggema, 2016). This could bring major economic and environmental benefits, contributing to innovation, growth, and job creation (Zeunert, 2016). The analysis of the relationship between the architectural object and the integrated food production systems has produced eight common circular features that appears to be key points for the development and the upscaling of BIA projects:

3.4.1. CF1: Urban transformation (in case of retrofitting projects)

Transformation, instead of demolition and reconstruction, is about physically preserving buildings or building components (Trombadore et al., 2019). The concept is to functionally repurpose them as construction parts of the new buildings. This process has been encountered in B01 in Amsterdam, where concrete walls, steel doors, and corridors from the old prisons have been included in the Masterplan as new construction materials. On a smaller scale, also B04 used parts of the old demolished barrack for the new building. Here, the old glass panels determined the height of the greenhouse. Furthermore, being a temporary installation, the architects designed the building already thinking of its future demolition. In this case, it will be possible to dismantle the building and either reconstruct it elsewhere or reuse those materials for other building constructions.

3.4.2. CF2: Material reuse and recycling

In addition to transformation, building components can be reused and made visible in new buildings as interior parts: this is how wasted materials can be incorporated in building construction. In B04, almost all interior furniture was made of recycled materials, as well as floors and even screws. Also, it is possible to re-use other architectural elements and give them a new life, as in the case of the UI01, designed by the Urban Farmers in Switzerland. Here, the old container has been repurposed and used as an installation technical box to feed and monitor a small greenhouse placed on top of it. Material Reuse and Recycling is different from the Transformation feature in terms of scales and repurposing. In the first case, the elements of the pre-existing building (such as windows, facades, and even structural components) are used to transform it, giving it a new architectural life. In the second case, materials are recycled from other parts of the city and other buildings and used for completely different new functions.

Both Transformation and Material Reuse and Recycling are important features of BIA projects that interact with the built environment, using the soilless production systems to add new values to a lost urban heritage that could potentially foster the future development of circular cities.

3.4.3. CF3: water management & water conservation

Today modern industrialized agriculture accounts for about 70% of global freshwater withdrawals. Besides, future food production will have to increase by more than 50% by 2050 to feed the prospected world population (FAO, 2017). However, the amount of water withdrawn by agriculture can increase by only 10%, provided that irrigation practices are improved, and yields increase (FAO, 2017). Future food practices will have to consider water management and water conservation to reduce the use of freshwater in the production systems. Accordingly, integrated hydroponic production may take advantage of water outputs flowing out from the buildings for agriculture irrigation (Magwaza et al., 2020). Indeed, in the analyzed BIA projects, water management and conservation appear among the most important goals to achieve. This is because both buildings and soilless farming systems require a relevant amount of water to satisfy the needs of their users (both people and plants). The integration of buildings and soilless farming has resulted in a win-win combination in some of the selected projects, as both the greywater from the buildings and collected rainwater are diverted toward the farming system. Rooftop greenhouse projects seemed to be particularly efficient in this sense. For example, the integrated

Rooftop Greenhouse (iRTG) of the case study RG04 successfully managed to use collected rainwater for crops irrigation (Nadal et al., 2015). Here, rainwater is stored in a 135 cubic meter tank in the basement and treated before watering the crops. As the amount of collected rainwater is four times the greenhouse demand, it can be then redirected to the office spaces and used for different purposes. Furthermore, in closed hydroponic systems water can be reused multiple times. This is the case of RG03 where it is claimed that water used is diminished by ten folds as compared to traditional agriculture, while also reducing to a minimum the farming runoffs. A different example was found in B03, where greywater from the building is processed in the cellar and re-used in the offices. The extra water is pumped into the integrated greenhouse and used as irrigation for the plants in the nutrient solution. Another interesting concept was studied in UI02, where the polycarbonate shell collects rainwater and leads it into the soil through small holes in the envelope. As the installation is temporary and nobody can access the inside, the idea was to build a self-watering greenhouse where plants could grow on soil.

3.4.4. *CF4: waste recycling*

Industrialized urban areas are immense waste hubs, as most outputs produced by citizens are difficult to reuse (Harder et al., 2019). New planning strategies for the future of smart cities are targeting waste as a key element to propose new circular urban models (Ellen MacArthur Foundation, 2019). BIA projects might help the transition from linear to circular systems: cities, in fact, produce large amount of waste in the form of water, heat, CO_2, and organic matter that are the perfect ingredients for plants to grow (Kozai et al., 2020). Accordingly, when investigating how to recycle waste in the BIA projects, there are two aspects to keep in mind. The first one regards waste produced by human activities, which can be redirected into the farming spaces. The second one concerns wastes produced by the farming activities which must be minimized. Human organic waste is identified in some projects, like U02, as a powerful source of energy that can be used as alternative biogas. A similar concept has been used in U03, where agricultural waste, consisting of plant cuttings and other materials used for maintaining the farm, was used to feed a biogas power plant. The ashes produced by the power plant were then supposed to act as fertilizer for the traditional gardening area. In U01 project, organic waste could also be sold as a natural fertilizer to the local community creating a micro-economy itself.

3.4.5. *CF5: use of renewable energies & energy flows*

The use of renewable energy is reported in almost every analyzed case study. This is probably connected to the fact that indoor farming and soilless greenhouses require large amounts of energy to operate (Graamans et al., 2017). In order to reduce energy needs, solar and photovoltaic panels are often adopted to partially power buildings and farming areas. Projects at the urban scale reported more complex energy systems: high-tech energy generators like solar cells, photovoltaic panels, heat pumps, geothermic pumps, and bio-gases are used to link homes, buildings, and clusters to a smart grid in urban scale projects. However, most of the selected urban scale projects are not yet being completed (like the Groene Tower in U01) or will probably never be built (like U02 and U03). This causes a lack in the practice of most of the energetic concepts they proudly carry on. In this sense, solar energy together with smart energy strategies seem to be most effective and practicable so far. Smart energy strategies include the exchange of heating and cooling between architectural objects and farming spaces. For instance, in B03, the waste heat is led from the job center directly into the greenhouse area. In B05, solar gain is contained in the greenhouse where the large concrete slab acts like a thermal mass, regulating temperatures in the spaces above and below it. Another state-of-the-art functional example is represented by RG04, where the iRTG-Lab uses the residual air of the offices and laboratories as a thermal buffer to regulate the greenhouse temperature. The building air can then be used for both heating and cooling the i-RTG.

3.4.6. *CF6: transportation management*

In a global food system, a great part of the food that is encountered on supermarket shelves of industrialized cities generally comes from distant regions of the World (Steel, 2013). BIA projects aim to dramatically reduce the distance between areas of consumption and production. In most urban scale projects, this is also connected to strategies aimed to reduce vehicle trips, excessive parking, and greenhouse gases (GHG) emission. However, contrary to common belief that consider zero-km an important feature to reduce CO_2 emissions along the food supply chain, the effect of transportation on the global sustainability of new food systems seems to be quite limited (Crippa et al., 2021). Indeed, recent data showed that transports contribute very little to the overall carbon footprint of commercialized products and European diets (Poore & Nemecek, 2018; Sandström et al., 2018). Despite that, commercial projects (e.g., RG03 spread in various US cities), aim to sell locally to reduce the issues connected to refrigerated transportation. This concept has been perfectly interpreted by I01, where food is produced, stored, and eventually consumed directly in Supermarkets. Accordingly, shortening food supply chains could be a way in the future to reduce the period between harvest and purchase, with a high potential to reduce food waste derived from transport spoilage due to inconsistent cooling practices and perturbation damage, resulting in a longer shelf life of the commercialized produce (Van Delden et al., 2021).

3.4.7. *CF7: material choice & passive solutions*

Material choices and passive solution strategies were used in most built projects to reduce energy consumption, maximizing the efficiency of the farming spaces (Hussain et al., 2014). Proposed construction materials (both reused and new) can improve energy conservation as well as reduce carbon emissions emitted by the material itself or during its fabrication. Together with the use of smart materials, implementing passive solutions can be a powerful tool to reduce energy loss. For instance, in RG04, sensors around the greenhouse allow to turn on fans or heaters, open up roof and side vents to adjust the humidity and temperatures depending on the internal and external climatic conditions. In rooftop greenhouses, it is extremely important to consider how both external and indoor climatic conditions will affect fruits and vegetable production. In RG03, for example, the completely translucent rooftop greenhouse relies exclusively on solar light, and no artificial lighting is provided. While this may be a benefit in terms of energy saving, it should be outbalanced by satisfactory yield performances, that in rooftop greenhouses are often hindered by poor solar radiation transmissivity, due to stronger framing required and cladding material choices limited by fire-prevention rules (Appolloni et al., 2021).

3.5. Data interpretation

3.5.1. Geographic location

Most of the literature regarding UA projects states that their application and design greatly depend on the context in which they are developed. When analyzing the case studies, it was noted that most of the high-tech BIA systems took place in industrialized Asia, Europe, and North America (Fig. 3**)**. This might be explained considering that the technical knowledge needed to operate such systems as well as the required technology and the high initial investment costs can be a limiting factor for the development of BIA projects in developing countries (Orsinit al., 2020), where UA objectives differ from the ones in the industrialized World. As a matter of fact, the UA relevance for community food security varies geographically. For instance, the very rapid urbanization in many low-income countries calls for actions to address food security issues, which differs from the purposes of urban food movements seen in developed countries, which aims to foster cities' smart ways of living (Mylonaki et al., 2016). As confirmed in the reviewed literature, BIA in developed countries mainly targeted the implementation of the overall sustainability of the urban eco-system, creating design strategies linked to promote new food experiences, and to foster social inclusion in a multicultural society (Tuijl et al., 2018). Therefore, while the future development of UA initiatives in developing countries will have to target the aspects of food security, involving local communities scattered throughout the city, future BIA practices, to be more effective, will have to be part of comprehensive planning strategies in urban areas to better exploit the synergies with the built environment.

3.5.2. Status of the projects

After the analysis of the case studies, the differentiation between realized and not realized projects seemed to provide an interesting reading key of the current situation of BIA initiatives around the globe. Out of the 21 selected projects, 14 were built (around 66% of the total). However, if confronted with the scale of the project, it is possible to see that none of the biggest projects at the Urban/District scale were implemented, and only U01 and U04 are under development. Compared to U02 and U03, these two projects are part of bigger urban planning strategies linked to new green policies developed by the cities where they are located. Especially U01 is integrated in a much bigger strategy proposed by the municipality of Amsterdam that set the objective of becoming a fully circular city by 2050 acknowledging that a systemic change is needed to achieve this ambition. In this sense, the city of Amsterdam is the first city in the world to use the Doughnut economics model, which allows city planners to model an integral circular economy strategy for the period 2020–2025. In this scenario, the city decided to prioritize the value chains of three key sectors: i) construction; ii) biomass and food; iii) consumer goods (City of Amsterdam, 2019). Concurrently, façades projects are struggling to be realized. Between the analyzed projects, only F01 was realized as a small prototype, but never really succeeded in developing on a bigger scale. In this sense,

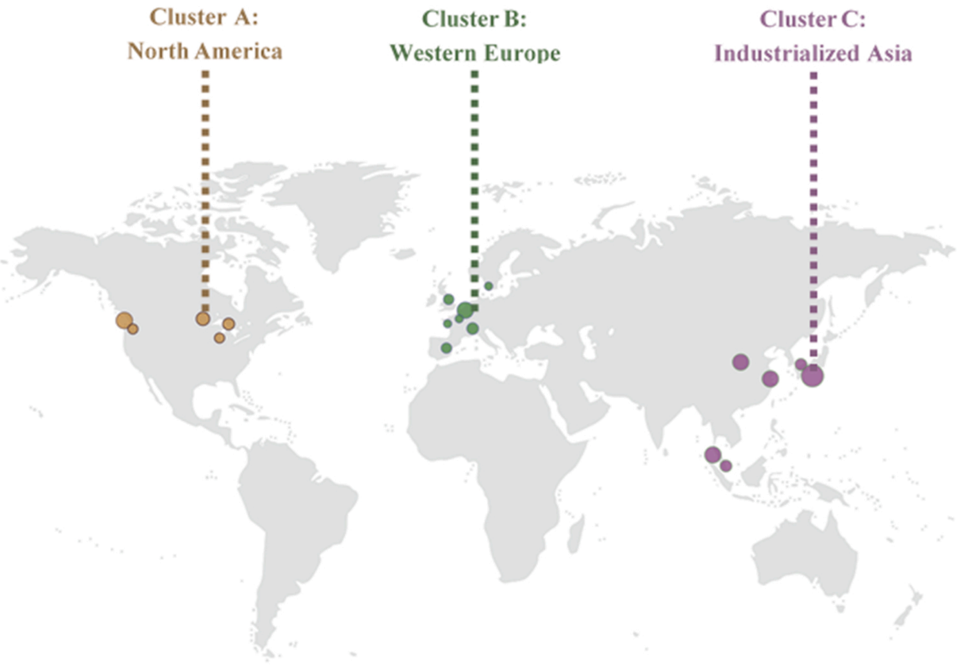

Fig. 3. The three macro geographical area where BIA projects were found in the analysis of the case studies. Larger bubbles indicate concentration of a higher number of case studies.

after comparing Table 1a and Table 1b, it appears that the easiest BIA projects to be realized are rooftop greenhouses and small scale urban installations and hydroponic furniture design. Furthermore, the commercial function of hydroponic furniture products, as well as their replicability, can attract high investment from the private sector. This was especially the case of I02 that has raised 200 millions dollar in 2021 mostly funded by the Qatar Investment Authority (QIA). Therefore, replicable hydroponic furnitures appear to be easily scalable and highly profitable compared, for instance, to hydroponic façades, which are still seen as an investment hazard considering the high level of technology required to operate them, as well as for the small surface they could dedicate to food production, which may not guarantee enough economic returns for the investors. The high investment and managing costs of most of BIA projects seems to be the main factors that are hindering the development of these practices today as well as the realization of the most ambitious projects (e.g. U02 and U03). Accordingly, future BIA upscaling will have to pass through more consolidated and diverse business plans, lower energy costs, and economic incentives from regional and municipal governments. The economic aspects of BIA projects are, in fact, crucial for their development. Indeed, out of the 21 analyzed case studies, two projects (e.g., UI01 and RG03) went bankrupt after only few years of operation. Both projects were realized by the same company and the failure of the RG03 experience caused the bankruptcy of the whole company which was forced to also dismantle the UF Box. RG03 rooftop greenhouse was the largest rooftop farm in Europe at the time it was built. Based on a dedicated report (Ancion et al., 2019), the bankruptcy didn't really come as a surprise: when the project was realized in 2013, many were skeptic about its success as it was located only few kilometers away from the Wasteland region, the biggest greenhouse production hub of The Netherlands. Furthermore, the company decided to produce the same crops (e.g., tomato and cucumber), that were produced in the nearby greenhouses. As a result, the company struggled to compete with the prices offered by local greenhouse farmers, and eventually had to declare the bankruptcy in 2018. In this sense, it also emerges clearly that the choice of the right crops may widely determine project viability. This theory can be validated comparing the failure of RG03 in Rotterdam with the success of I03 in Amsterdam, only 60 kilometers away. Here, the producers offer high value micro-greens and leafy vegetables, with a business model that sells directly to restaurants and hotels. Therefore, differentiating crops, making local market surveys and plan a diversified offer (both in crops and functions) could determine the survival or the failure of commercial BIA projects in urban areas.

3.5.3. Main impacts and circular features of the selected case studies

Each selected project shared one or more circular features, characterizing different approaches towards circularity depending on the scale of application and the main project functions. In BIA projects, circularity goals apply to two entities: (i) the buildings, and (ii) the farming systems. Thus, the great potential of these initiatives consists of creating osmotic relationships between them. Accordingly, Table 2 connects circular features to each of the selected case studies, enabling to assess the total usage of each feature.

Extrapolating the results from Table 2, it is possible to see that CF3 (Water Management) and CF5 (Use of Renewable Energies) were the more used features to boost circularity and sustainability in the selected projects respectively used in 17 and 14 projects. Mostly, these two features were accompanied by the use of recycled materials and passive envelope solutions. Another feature that was encountered in most projects was related to food delivery, with 12 projects clearly stating they intended to dramatically reduce food transport by selling within the same area of production. Less common features were Transformation and Waste Recycle. **(**Fig. 4**)**.

Table 2
Circular features associated with to each case study.

Name of the project	CF. 1	CF. 2	CF. 3	CF. 4	CF. 5	CF. 6	CF. 7
Bijlmerbajes Kwartier - Amsterdam (NL)	X	X	X	X	X		X
ReGen - Amsterdam (NL)		X	X	X	X		
Home Farm - Singapore		X	X	X	X		
Santa Clara AgriHood (USA)			X		X	X	
UrbanFarmers BOX - Zurich (SW)		X	X		X		
SHJWorks Biotope - Versatile Locations			X			X	
Tropicalia Bio-dome Opal Cost (FR)			X		X		X
The FarmHouse by Precht - No location		X					X
Office with Greenhouse - Oberhausen (DE)		X	X	X	X	X	X
The Greenhouse Restaurant - Utrecht (NL)		X			X	X	X
Mochi Restaurant - Denver (US)		X			X	X	X
Sunwork Centre - Manhattan NY (NYS)			X		X		
Urban Farmers - Den Haag (NL)	X		X		X	X	
Gotham Greens - Brooklyn NY (NYS)	X		X	X		X	
Research Centre ICTA-ICP - Barcelona (SP)			X		X		X
EcoLogic Studio's Urban Algae Canopy @EXPO2015 - Milan (IT)			X				X
Green Market - Abudaabi			X			X	X
GreenBelly - Versatile location	X	X		X		X	X
Infarm Berlin - Prototype in Germany, Vesratile Location			X		X	X	
Hydroponic Farm by Ikea @Lab Space 10 - Versatile Location			X			X	
GrowX	X		X		X	X	
Total	7%	12%	23%	8%	19%	16%	14%

*List of acronyms - CF1: Urban Transformation, CF2: Material Reuse and Recycling, CF3: Water management & water conservation, CF4: Waste recycling, CF5: Use of renewable energies & energy flows, CF6: Transportation management, CF7: Material choice & passive solutions

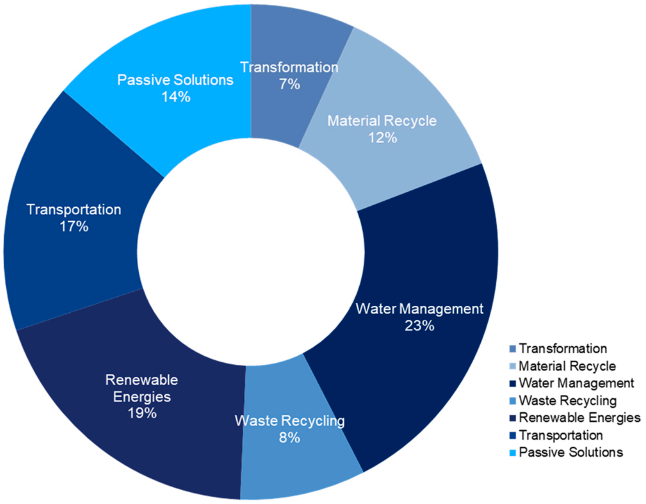

Fig. 4. Application percentage of circular features in the selected case-studies.

3.6. *Main objectives and future challenges of BIA projects*

Implementing new sustainable, environmental and people-friendly urban food systems means transitioning towards a circular food economy and construction strategy. Here, one of the main goals is to reuse all by-products and waste streams along the food supply chain, limiting the use and exhaustion of resources like soil, energy and fertilizer (Keeffe, 2016). Furthermore, circular food strategies must be connected with the built environment and the principles of circular construction, thus promoting sustainable design principles such as modular construction and the use of building materials within high value closed loops for efficient assembly/disassembly techniques.

In this context, circular horticulture is intended as a closed-loop food economy, that consciously emulates natural systems of regeneration, where waste does not exist, but instead works as input for another cycle (Ellen MacArthur Foundation, 2019). Today, thanks to soilless protected cultivation techniques, it is possible to fully integrate greenhouses and plant factories in buildings, generating new synergistic relationships between the two entities (Fig. 5). The target in protected cultivation systems should always be to save resources and energy and to minimize emissions.

Nonetheless, the degree of circularity and sustainability in BIA projects in the future will highly depend on the quality of the inputs (European Commission, 2019). For instance, in hydroponic production, the quality and quantity of water flowing through the system is

Fig. 5. Circular processes in BIA.

fundamental to determine and design the circular production system (Maucieri et al., 2019). In this scenario, recovering water from buildings will enhance the degree of circularity in the food system. Recovering resources from buildings is, in fact, at the core of all the analyzed urban scale projects circular strategies, whether this is done on site or in specifically designed infrastructures, such as digesters and water plants (Prazares et al., 2017). What emerged from this analysis is that buildings are, in fact, hot spots for nutrients and water recovery. Soilless cultivation systems and especially closed or re-circulating hydroponic systems can significantly reduce fertilizer runoff but not eliminate it (European Commission, 2019, Larkin et al., 2020), for this reason integrating them in buildings will benefit both entities developing water and nutrients closed-loops, reducing dangerous runoffs. Nonetheless, even though high-tech greenhouses may present a high level of circularity, they require for high investments, greater installation and running costs, and a high degree of automation and technical skill, which still limit their applications even in industrialized countries (Roth et al., 2019). Municipalities will therefore play a crucial role in the development of BIA initiatives. Cities have the opportunity to spark the transformation towards a circular economy for food, given that most of all food is expected to be consumed by urban population by 2050. Cities have the assets, the technology, and a dense network of highly skilled workers, that represent the ideal conditions for innovation in the food system (Garcés-Ayerbe et al., 2019). This combination of factors confirms that governments and municipalities have the means to implement a food circular economy with specific investment policies and targeted urban planning strategies. Connecting high tech production systems with the construction sectors, providing incentives also to developers and constructors, will foster a diffuse planning of UA and BIA projects in cities, weakening the limitations represented by the initial investment costs and creating the business conditions for new urban food enterprises to thrive.

3.7. Optimizing plant cultivation technologies for BIA

In circular protected horticulture plants grow in closed systems, where water and nutrients are recirculated and reused (Christie, 2014). These systems, like hydroponic or aquaponic greenhouses and indoor plant factories, require adequate management, and a deep knowledge of irrigation and fertigation techniques (Forchino et al., 2017). It emerges that investment in both research programs and on the education of the operators are crucial in urban areas to achieve future high yields with minimal use of natural resources in cities (Pennisi et al., 2021). In BIA, key elements to achieve a circular economy of food are the combination-clustering with buildings and the full control of both input and output. In this sense, good practices for implementing circularity in protected indoor and soilless cultivations when integrated in buildings can be summarized in the utilization of the following production technologies:

3.7.1. Closed-loop hydroponics

These systems collect and re-use the superfluous exceeding nutrients, re-circulating them back into the system. The system can be applied to all sectors and geographical locations but it needs good quality water as an input (Maucieri et al., 2018). However, to apply the hydroponic system in practice, high expertise in water and nutrient management are essential.

3.7.2. Aquaponics

A technology that combines recirculated aquaculture (the activity of breeding, raising and harvesting fishes) with hydroponic vegetable, flower, and herb production (Lennard & Goddek, 2019). The advantages are a reduced need for water and fertilizer in crop production and also less need for water in fish production (Brandon and Zheng, 2019).

3.7.3. Indoor climate control

In order to optimize plants growth in indoor farming and integrated greenhouses, it is fundamental that the growing spaces have controlled temperature and humidity. Technologies for controlling the environment are used in BIA projects to monitor and automatically adjust micro-climatic conditions in the growing areas, a fundamental strategy for guaranteeing a proper plant development (Orsini et al., 2020). On the other hand, analyzed rooftop greenhouses highly rely on passive solutions like solar heating and natural ventilation. However, to achieve best performances, most of the studied greenhouse used smart sensors to connect passive and active solutions to keep temperature and humidity steady.

3.7.4. Artificial lighting

Supplementing lighting can be crucial to achieve higher production, guaranteeing year-round greenhouse operations, especially in northern latitudes. In greenhouses the choice of whether to supplement light or not highly depends on the geographic location and the naturally available daylight (Proksch, 2017). As iRTGs have generally a narrower surface compared to conventional greenhouses, light distribution may be efficiently increased by incorporating reflective surfaces on walls of surrounding buildings and in the floor coating. White paint and aluminum screens are viable passive solutions to increase light diffusion in iRTGs. The current standard supplement of the light source in greenhouses is High-Pressure Sodium (HPS) technology which, however, have an inefficient conversion rate (30%) of electricity into useful light (Orsini et al., 2013). The remaining energy is emitted as heat, which can provide 25–40% of the greenhouse heating requirements during the winter months, but is impractical for indoor growing during warmer periods, often requiring for greenhouse vents opening and increased ventilation. Recently, new LED lights have emerged as more sustainable and efficient solutions, reducing by up to 80% energy requirements as compared with HPS, thus cutting operation and energy costs (Proksch, 2017). Thanks to LED lights, the energy costs for lighting are lowering and yields are increasing, resulting in a growing number of BIA practices in industrialized countries (Kozai et al., 2020), forecasting an even higher growth in the next future.

3.8. Enabling the policy environment for future BIA upscaling

Due to the building's technical requirements as well as food regulations, including UA in the planning process is crucial to the success of the development of circular horticulture in cities. Accordingly, when these food systems are diffuse over a territory they are much more efficient than single initiatives. "Clustering" is, in fact, a strategy to implement the circularity of the cultivation systems. Furthermore, the development of holistic planning strategies that take into consideration both urban food production and architectural and spatial construction will help with the objective of reducing waste and GHG emissions by maximizing resource flows between urban entities. In order to effectively contribute to GHG emissions reduction and to the creation of new circular models in urban areas, BIA projects must overcome three main challenges:

3.8.1. Land access

to be effective BIA initiatives must be diffused over a territory. Finding farming spaces within the city can prove challenging due to zoning laws, technical feasibility and competition for other revenue-generating uses (Ellen MacArthur Foundation, 2019). New planning strategies will have to facilitate the access to land and buildings for BIA projects.

3.8.2. Crop diversification

As formerly discussed, crop's choice is key to the success or the failure of BIA initiatives. What emerged from the case studies is that there are not best or worse crops, however, there are better ways to choose crops based on local diets and markets that can increase the chances of success of BIA projects. However, crops that are typically produced in indoor greenhouses and vertical farms are still mostly limited to leafy greens, herbs, other vegetables, and selected fruits, such as strawberries and tomatoes (Ellen MacArthur Foundation, 2019; Kozai et al., 2020). Therefore, even if cities were to produce all the required volumes of these food types in indoor urban farms, they would still depend on food from peri-urban and rural areas for other food types. In this scenario, research and development is fundamental to achieve maximum variety in urban crops production. Both costs and yields data are needed to assess the economic feasibility of cultivating a variety of crops within the urban boundaries. In this sense, the technical knowledge connected to the food production provided by agronomists and practitioners is crucial to develop future BIA projects.

3.8.3. Target full circularity

It was clear that, no matter of the intentions, BIA projects today face relevant challenges to become completely circular and sustainable. High-tech soilless farming methods require tailored nutrient solutions, where water pH, and mineral nutrients concentration is manually or automatically controlled. Nutrients used in high-tech hydroponic greenhouses are mostly nitrogen, phosphorus and potassium (Lennard & Goddek, 2019), whose sourcing is often unsustainable. Besides, when not recirculated into the production system, may result in environmentally dangerous runoffs. Furthermore, reaching elevate yields in indoor facilities require high energy inputs for lighting and heating/cooling, which at the moment are generally reliant on fossil fuels (Lennard & Goddek, 2019). Nonetheless, technological innovation, as well as infrastructure planning strategies will help overcome these challenges as high-tech closed production systems have a solid potential in becoming circular. It emerges that the most crucial features to improve overall sustainability of future BIA projects are, to date:

3.8.4. Use of renewable energy (19%)

Using renewable energies would be more effective in clustered BIA initiatives, like shown in U01 in Amsterdam and U02 in Almere, where the projects are integrated in the spacial planning of the city, connecting them with the energy grid used by buildings, or to a newly designed smart energy system.

3.8.5. Sustainable water management in closed-loop hydroponic systems (23%)

To obtain a high degree of circularity for water and nutrients, it is crucial that the water used for irrigation is of high quality (European Commission, 2019). However, the water sources that recirculates from the greenhouse, like drainage-water and wastewater, might contain impurities limiting their application. In this sense, when reclaiming water from waste streams it is important to keep sodium and chloride levels to minimum, as solutes concentration in water could result in salt stress occurrence in plants. Therefore, to be able to safely reuse urban wastewater, indoor production must have the technologies that allow selective sodium removal and more studies are needed on long term effects on growing media, soil or plants (Lennard & Goddek, 2019). However, new on-site Nature-Based Solutions (NBS) that use green walls or green roofs for primary greywater treatments could represent viable ways in the future to use reclaimed greywater for irrigation in integrated agriculture compounds (Boano et al., 2020). As of today, the best alternative water source remains rainwater (as observed in 43% of case studies), which can be easily collected from greenhouse of building roofs and redirected in the production system. Rainwater can be mixed with drainage and wastewater and stored in the proximity of the production area. Stored water must remain clean, thus ultrasonic treatment and UV sterilization systems may be integrated to avoid the spreading of pathogens.

3.8.6. Waste recovery (8%)

Nutrients extraction, for both soilless and traditional agriculture, is one of the most polluting human activity. Phosphorus and nitrogen are essential and irreplaceable elements in food production, but unfortunately phosphate fertilizer recovery from phosphate rocks is causing landscape degradation and high amount of CO_2 emissions associated with both extraction and transport, while nitrogen runoffs released toward the environment are highly contributing to air and water pollution or ultimately to the emergence of

Ocean Dead Zones (Kirchman, 2021). Nonetheless, cities are full of unexpressed potential for nutrients recirculation, being the largest food sink. New state of the art technologies have been developed to actively succeed in treating buildings' wastewater for nutrients extraction (Magwaza et al., 2020). However, their application is still very limited, and none of the analyzed case studies that were actually implemented managed to integrate effective wastewater nutrients treatment. The reason to that might be that the regulation framework is very strict concerning irrigation water, and more research and technological uptake are needed to properly assure producers and consumers that nutrients extraction from wastewater is safe for plants and humans, eliminating possible viruses, bacteria, and pathogens from the waste streams. Accordingly, new planning strategies at the National and European level will be necessary to foster the application of decentralized treatments for wastewater recovery and the use of recovered nutrients in nutrient solutions for integrated hydroponic systems.

The application of these circular features to BIA projects requires for a multidisciplinary approach, as well as dedicated policies and financial aids, the lack of which is slowing down the realization of the most visionary and circular projects (D'Ostuni et al., 2022). A multidisciplinary approach to the topic is crucial to overcome all the challenges that BIA projects are facing (Puri and Caplow, 2009). Indeed, the expressed potential for circularity in BIA initiatives highly depends on the technical knowledge of the production systems. More technology and tighter control may lead to improved circular performances, but they requires high investments and a specific set of expertise that may not be easy to find in urban areas and in certain countries. This is definitely the main reason why BIA projects are mostly developed in industrialized countries, where research and technology development take place. However, advancements in the research, as well as an increased knowledge on soilless systems, may constitute the ground zero for the development of BIA projects in future in urban areas.

4. Conclusions

Cities are focal points of climate change fight and sustainable development of urban areas is a priority in most industrialized countries. In this context, BIA can provide planners and architects with new solutions to implement green architecture and infrastructure. Understanding advantages and limitations of BIA is crucial to develop smart solutions, enhancing the synergies that buildings and food systems can create when juxtaposed. Food production is the core of BIA project, although it cannot really be considered just a food-related practice. In this sense, urban food production cannot feed an entire city, but it can provide an increasing food security in certain communities, as well as several valuable services to cities inhabitants, including helping citizens reconnect with food and better understand where and how it is grown. Social, educational and economic goals must be taken into consideration when approaching BIA as they might be the key for the success of future initiatives. In this context, marketing strategies are fundamental for the acceptance of a new type of food grown without the constraints of the soil and integrated in buildings. In particular, BIA initiatives can involve the participation of a great part of population, as they operate right there where people live and work. They can shape new architectural forms, and urban look, making food visible and livable for all citizens. Reconnecting people with food, educating them to healthy diets, bringing production visible and tangible within the city boundaries, should be considered the main goal of BIA projects. In the next future, this might help cities to change the way citizens see food, creating a ripple effect that may partially or drastically change modern food system. Defining the economic, social, and environmental aspects of these projects is then fundamental for architects and engineers to justify the integration of food production systems within their design. In this regard, BIA can be a source of inspiration for the development of green buildings, both in renovation or new construction projects (Thomaier et al., 2014). Nonetheless, the use of advanced indoor and hydroponic technologies must be approached carefully and with the cooperation of other practitioners like agronomists and engineers to fully integrate the food spaces within the building structure. The 21 case studies that were hereby analyzed clearly show how BIA would benefit from a multidisciplinary approach. In this sense, most of the projects that were not realized lacked in information regarding either the food production systems or the chosen crops, and they represented more interesting architecture designs rather than practicable and realizable solutions.

Declaration of competing interest statement

Authors declare no conflicts of interest.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.futures.2022.103061.

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