Chapter 21
Aquaponics in the Built Environment

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Abstract Aquaponics' potential to transform urban food production has been documented in a rapid increase of academic research and public interest in the field. To translate this publicity into real-world impact, the creation of commercial farms and their relationship to the urban environment have to be further examined. This research has to bridge the gap between existing literature on growing system performance and urban metabolic flows by considering the built form of aquaponic farms. To assess the potential for urban integration of aquaponics, existing case studies are classified by the typology of their building enclosure, with the two main categories being greenhouses and indoor environments. This classification allows for some assumptions about the farms' performance in their context, but a more in-depth life cycle assessment (LCA) is necessary to evaluate different configurations. The LCA approach is presented as a way to inventory design criteria and respective strategies which can influence the environmental impact of aquaponic systems in the context of urban built environments.

Keywords Aquaponics classification · Urban aquaponics · Enclosure typologies · Greenhouses · Indoor growing · Controlled environment agriculture · Life cycle assessment

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21.1 Introduction

Aquaponics has been recognized as one of "ten technologies which could change our lives" by merit of its potential to revolutionize how we feed growing urban populations (Van Woensel et al. 2015). This soilless recirculating growing system has stimulated increasing academic research over the last few years and inspired interest in members of the public as documented by a high ratio of Google to Google Scholar search results in 2016 (Junge et al. 2017). For a long time, aquaponics has been primarily practiced as a backyard hobby. It is now increasingly used commercially due to strong consumer interest in organic, sustainable farming methods. A survey conducted by the CITYFOOD team at the University of Washington in July 2018 shows that the number of commercial aquaponic operations has rapidly increased over the last 6 years. This focused search for aquaponic operations identified 142 active for-profit aquaponic operations in North America. Based on online information, 94% of the farms have started their commercial-scale operation since 2012; only nine commercial aquaponic farms have been in operation for more than 6 years (Fig. 21.1).

Most of the surveyed aquaponic operations are located in rural areas and are often connected to existing farms to take advantage of low land prices, available

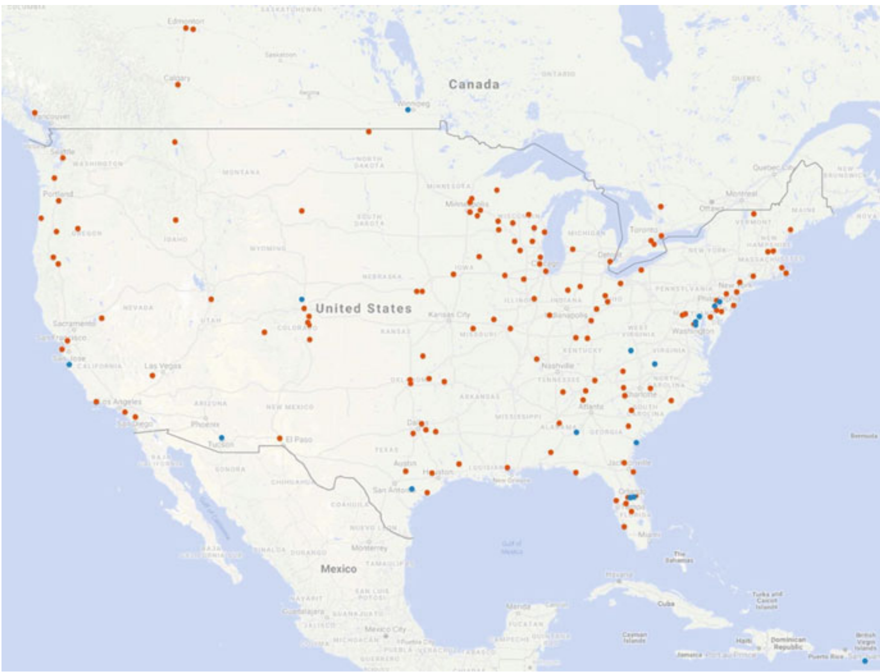

Fig. 21.1 Existing aquaponic practitioners in North America, 142 commercial companies (red) and 17 research centers (blue), (CITYFOOD, July 2018)

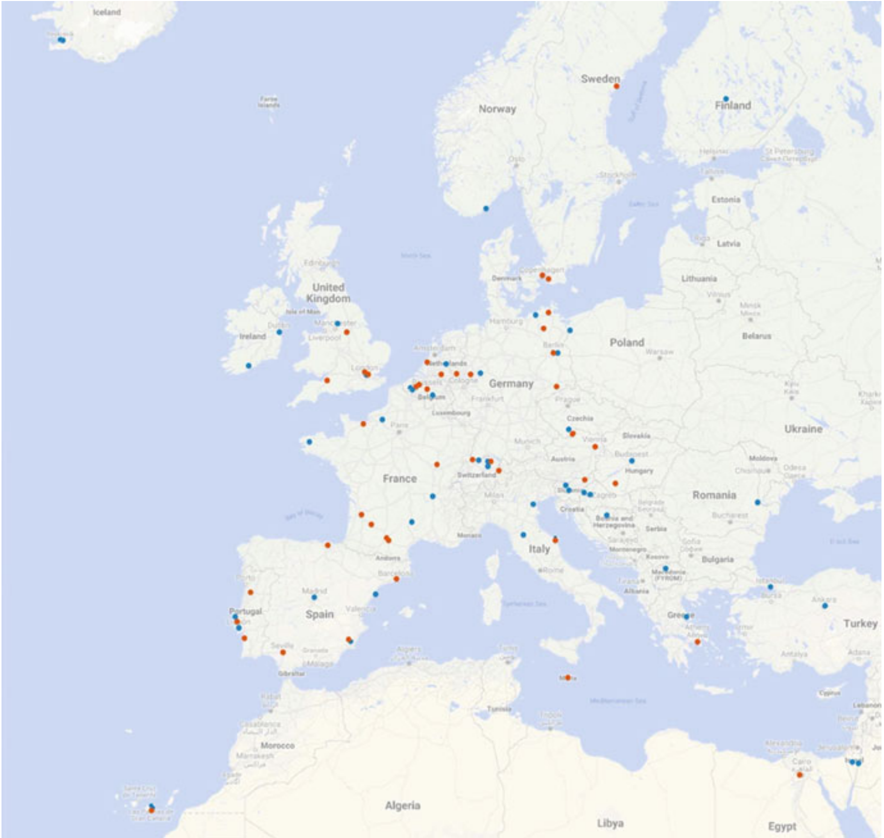

Fig. 21.2 Aquaponics across Europe: 50 research centers (blue) and 45 commercial companies (red). (EU Aquaponics Hub 2017)

infrastructure, and conducive building codes for agricultural structures. Regardless, a growing number of aquaponic operations are also located in cities. Due to their relatively small physical footprint and high productivity, aquaponic operations are well suited to practice in urban environments (Junge et al. 2017). Surveys undertaken under the auspices of the European Union (EU) Aquaponics Hub in 2017 identified 50 research centers and 45 commercial companies operating in the European Union (Fig. 21.2). These companies range in size from small to medium sized.

21.1.1 Aquaponics in Urban Environments

Space is a valuable commodity in cities. Urban farms have to be resourceful to find available sites such as vacant lots, existing rooftops, and underutilized warehouses that are affordable for an agricultural business (de Graaf 2012; De La Salle and Holland 2010). Urban aquaponic farms need to balance higher production costs with competitive marketing and distribution advantages that urban locations offer. The largest benefit for locating aquaponic operations in cities is a growing consumer market with an interest in fresh, high-quality and locally grown produce. When complying with local regulations for organic produce, urban farms can achieve premium prices for their aquaponically grown leafy greens, herbs, and tomatoes (Quagrainie et al. 2018). Unlike hydroponics, aquaponics also has the capacity to produce fish, further enhancing economic viability in an urban setting which often has diverse dietary needs (König et al. 2016). Urban aquaponic farms can also save some operational costs by reducing transportation distance to the consumer and reducing the need for crop storage (dos Santos 2016).

Urban environmental conditions can also be advantageous for aquaponic farms. Average temperatures in cities are higher than in rural surroundings (Stewart and Oke 2010). In colder regions particularly, farms can benefit from a warmer urban climate, which can help reduce heating demand and operational costs (Proksch 2017). Aquaponic farms that are integrated with the building systems of a host building can further utilize urban resources such as waste heat and CO_2 in exhaust air to benefit the growth of plants as an alternative to conventional CO_2 fertilization. Urban farms can also help mitigate the negative aspects of the urban heat island effect during the summer months. The additional vegetation, even if grown in greenhouses, helps to reduce the ambient temperature through increased evapotranspiration (Pearson et al. 2010). In aquaponics, the use of recirculating water infrastructure reduces overall water consumption for the production of both fish and lettuce and can, therefore, have a positive effect on the urban water cycle. Aquaponically-grown produce strives to close the nutrient cycle, thereby avoiding the production of agricultural run-off. Through smart resource management within major environmental systems, aquaponics helps to reduce excessive water consumption and eutrophication usually created by industrial agriculture.

21.1.2 Aquaponics as Controlled Environment Agriculture (CEA)

Traditional agricultural techniques to extend the natural crop-growing season range from minimal environmental modifications, such as temporary hoop houses used on soil-based fields, to full environmental control in permanent facilities that allow for year-round production regardless of the local climate (Controlled Environment Agriculture 1973). The latter strategy is also known as controlled environment agriculture (CEA) and includes both greenhouses and indoor growing facilities. In addition to controlling the indoor climate, CEA also significantly reduces the risk of crop loss to natural calamities and the need for herbicides and pesticides (Benke and Tomkins 2017). Most aquaponic operations are conceived as CEA since they combine two complex growing systems (aquaculture and hydroponics), which both require controlled growing conditions to guarantee optimal productivity. Additionally, CEA enables year-round production to amortize high investment in aquaponic infrastructure and achieve premium crop prices at the market outside of the natural growing season. The performance of aquaponic farm enclosures is highly dependent on local climate and seasonal swings (Graamans et al. 2018).

As aquaponics is a relatively young discipline, most of the existing research is focused at the system level – for example, studies evaluating the technical integration of aquaculture with hydroponics in different configurations (Fang et al. 2017; Lastiri et al. 2018; Monsees et al. 2017). Whilst individual aquaponic system components and their interactions can still be further optimized for productivity, their performance within a controlled environment envelope has not been comprehensively addressed. Recent research in CEA has begun to assess hydroponic system performance in tandem with built environment performance, although there is only one study to date that models aquaponic system performance in a controlled envelope (Benis et al. 2017a; Körner et al. 2017; Molin and Martin 2018a; Sanjuan-Delmás et al. 2018).

21.1.3 Aquaponics Research Collaborations

The current expansion in interest in aquaponics led to the creation of several interdisciplinary aquaponics related research collaborations funded by the European Union (EU). The COST FA1305 project, which created the EU Aquaponics Hub (2014–2018) brought together aquaponics research and commercial producers to better understand the state of the art in aquaponics and to generate coordinated research and education efforts across the EU and around the world. Innovative Aquaponics for Professional Application (INAPRO) (2014–2017), a consortium of 17 international partners, aimed to advance current approaches to rural and urban aquaponics through the development of models and construction of prototypical greenhouses. The project CITYFOOD (2018–2021) within the Sustainable Urban Growth Initiative (SUGI), co-funded by the EU, Belmont Forum, and respective science foundations, investigates the integration of aquaponics in the urban context and its potential impact on global challenges of the food-water-energy nexus.

21.2 Classification of Controlled Environment Aquaponics

The term aquaponics is used to describe a wide range of different systems and operations, greatly varying in size, technology level, enclosure type, main purpose, and geographic context (Junge et al. 2017). The first version of the classification criteria for aquaponic farms included stakeholder objectives, tank volume, and parameters describing aquaculture and hydroponic system components (Maucieri

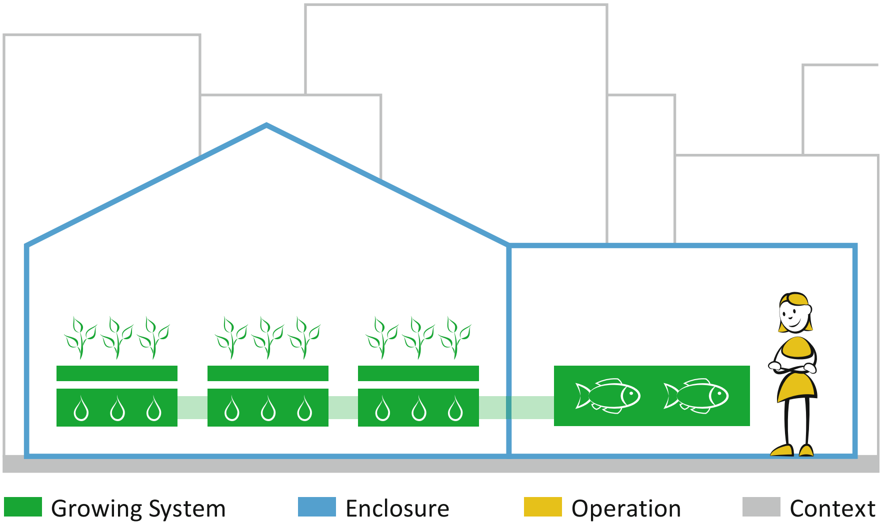

Fig. 21.3 Classification criteria for identifying aquaponic farm types

et al. 2018). Additional work was undertaken by a large group of researchers to further define aquaponics and to present a nomenclature based on international consensus (Palm et al. 2018). This led to a comprehensive discussion on system types and scales and most importantly a definition of aquaponics which is: "*the majority (> 50%) of nutrients sustaining the optimal plant growth must derive from waste originating from feeding the aquatic organisms.*" However, both definitions focus on the growing systems and do not consider other essential aspects of a functioning commercial aquaponics farm. As aquaponic operations become part of local economies, classification criteria identified by interdisciplinary research in fields like architecture, economics, and sociology will also become essential.

This classification proposal focuses on the emerging field of commercial aquaponic operations through the lens of the built environment. The key characteristics that describe an aquaponic operation fall into four different categories: growing system, enclosure, operation, and context (Fig. 21.3). These categories for classification criteria impact one other across scales, where growing system configurations can affect the contextual performance of the farm as a business, or local market demands can determine the type of crop grown in the aquaponic system. Some farm classification criteria are relevant on all scales, such as "size," measured in tank volume, growing area, number of employees, and annual revenue (Table 21.1).

- *Growing system* classification criteria describe the configuration of the interconnected aquaculture and hydroponic system. This includes specifications for the physical components that enable water and nutrient recirculation (such as water tanks, filters, pumps, and piping), living organisms that transform available nutrients at different stages (including fish, plant, and microorganism species) and

Table 21.1 Possible classification criteria for aquaponic farm types

Growing system	Enclosure	Operation	Context
Aquaculture system type	Enclosure typology	Purpose	Geographical location
Fish species	Structural system	Stakeholders	Physical context
Water temperature	Envelope assembly cover material	Business model	Environmental impact
Filtration system	Heating/cooling systems	Labor distribution	Socioeconomic context
Feed type	Light source	Funding type	Social impact
Hydroponic system type	Ventilation system	Marketing scheme	
Crop species	Host building integration	Distribution model	
Water distribution system			

values describing the physical performance of the system, such as temperature, pH levels, oxygen/carbon content, and electrical conductivity (Alsanius et al. 2017).

- *Enclosure* classification criteria define characteristics of the buildings that house the growing systems, at the next scale. Most aquaponic farms use CEA enclosures that vary by identifying typology (such as a greenhouse or warehouse), structural system, heating and cooling systems, lighting, ventilation, and humidity control systems (Benke and Tomkins 2017).
- *Operations* classification criteria describe how each aquaponic farm operates as a business and farm, which includes human expertise and labor input necessary for growing and selling produce. Criteria in this section include funding type, business structure and management, labor requirements and division, marketing scheme, produce distribution model, and overall purpose of the aquaponics facility.
- *Context* classification criteria, at the largest scale, describe the geographic location, physical context, urban integration, and overall social impact of aquaponic farms. Context criteria describe how an aquaponic farm is part of the urban food chain and built environment, capable of influencing economic growth, social involvement and large-scale environmental impacts on a city-wide scale (dos Santos 2016).

21.3 Enclosure Typologies and Case Studies of Commercial Farms

This further investigation focuses on defining aquaponic classification criteria at the enclosure level to complement existing system-level definitions. The enclosure types discussed here work with different construction systems, levels of technological control, passive climate control strategies, and energy sources to achieve an appropriate indoor climate. The best application of each enclosure typology depends primarily on the size of operation, geographic location, local climate, targeted fish and crop species, required parameters of the systems it houses, and the budget. This study identifies five different enclosure typologies and defines the characteristics of indoor spaces that house aquaculture infrastructure.

21.3.1 Greenhouse Typologies

This classification includes four categories of greenhouses – medium-tech greenhouses, passive solar greenhouses, high-tech greenhouses, and rooftop greenhouses – that are applicable to commercial-level aquaponic operations (Table 21.2). Existing greenhouses may not exactly fit a single typology, but fall within a spectrum from medium-tech to high-tech by selectively incorporating active and passive environmental control techniques.

Medium-Tech Greenhouses Greenhouses with intermediate levels of technology to control the indoor climate include freestanding or gutter-connected Quonset (Nissen hut type), hoop house (polytunnel) and even-span greenhouses. They are usually covered with double polyethylene film (PE) or rigid plastic panels, such as acrylic panels (PMMA) and polycarbonate panels (PC). These greenhouses are less expensive to install, though film cladding needs to be replaced frequently due to rapid deterioration caused by constant exposure to UV radiation (Proksch 2017). These greenhouses protect crops from extreme weather events and to some extent pathogens, but they offer only a limited level of active climate controls. Instead, they rely on solar radiation, simple shading systems, and natural ventilation. With their limited ability to modify growing conditions within a certain range, medium-tech greenhouses are rarely used for housing aquaponic farms in cold climates. This is because the high initial investment into the hydroponic and aquaculture components requires a stable environment and reliable year-round production to be commercially viable.

Aquaponic operations in warmer climates have successfully demonstrated the use of medium-tech greenhouses that employ evaporative cooling and simple heating systems. For example, Sustainable Harvesters in Hockley, Texas, USA uses a simple Quonset greenhouse (12,000 sf/1110 m^2) for year-round lettuce production without relying on extensive supplemental heating or lighting. Ouroboros Farms in Half Moon Bay, California, USA uses an existing greenhouse (20,000 sf/1860 m^2) to produce lettuce, leafy greens, and herbs (Fig. 21.4). Due to the mild climate, the farm uses primarily static shading and little supplemental heating and cooling. Both farms, as many smaller medium-tech operations, place their fish tanks in the same greenhouse space as the hydroponic crop growing system. The farms grow fish species that tolerate a wide temperature range (tilapia) and shade aquaculture tanks to prevent overheating and algae growth.

Table 21.2 Comparison of case studies by enclosure typologies

CEA type	Case studies	Construction system	Controls	Growing season[a] and latitude	Hardiness zone[b]
Medium-tech greenhouses	Ouroboros Farms, Half Moon Bay, CA, USA (20,000 sf/1860 m^2)	Existing, gutter-connected GH with two even spans, clad with single-pane glass, fish tanks in GH	Static shading, shading curtains	319 days/ 10.6 months 37.5° N	10a 30 to 35 °F −1.1 to 1 .7 °C
	Sustainable Harvesters, Hockley, TX, USA (12,000 sf/1110 m^2)	Quonset frame, multi-tunnel (3) GH, clad with PE- film and rigid plastic panels, fish tanks in GH	Evaporative cooling, forced ventilation	272 days/ nine months 30.0° N	8b 15 to 20 °F −9.4 to 6 .7 °C
Passive solar greenhouses	Aquaponic solar green-house, Neuenburg am Rhein, Germany (2000 sf/180 m^2)	(Chinese) solar greenhouse, with adobe wall as additional thermal mass, clad with ETFE film, fish tanks in GH	Custom-built photovoltaic modules for shading and energy production	202 months/ 6.6 months 47.8° N	8a 10–15 °F −12.2 to −9 .4°C
	Eco-ark greenhouse at Finn & Roots, Bakersfield, VT, USA (6000sf/ 560 m^2)	Solar green-house, earth sheltered, steep angle of south facing roof (ca. 60°), thick insulation, spe-cial solar collecting glaz-ing, fish tanks in northern, sub-terranean side	Wood-fuelled radiant heat, energy curtain, ventilation with stack-effect, supple-mental LED lighting	108 days/ 3.6 months 44.8° N	4a −30 to −25 °F −34.4 to −31.7 °C
High-tech greenhouses	Superior Fresh Farms, Hixton, WI, USA (123,000 sf/11,430 m^2)	Venlo-style, gutter-connected, (20 × 41 bays), clad with glass, fish tanks in separate building	Computer-con-trolled CEA environment, supplemental LED lighting,	122 days/ 4.1 months 44.4° N	4b −25 to −20 °F −31.7 to −28.9 °C
	Blue Smart Farms, Cobbitty, NSW, Australia (53,800 sf/5000 m^2)	Venlo-style, gutter-connected, (14 × 18 bays), clad with glass, two-story con-struction, fish tanks on the lower level	Computer-con-trolled CEA environment biological pest control	300 days/ 10 months 34.0°S	9b 25 to 30 °F −3.9 to −1.1 °C

(continued)

Table 21.2 (continued)

CEA type	Case studies	Construction system	Controls	Growing season[a] and latitude	Hardiness zone[b]
Rooftop greenhouses	Ecco-jäger Aquaponik Dachfarm, Bad Ragaz, Switzerland (12,900 sf/1200 m^2)	Venlo-style, gutter-connected, (7 × 13 bays), clad with glass, fish tanks on the lower level	CEA environment, supplemental LED lighting, use of exhaust heat from cooling facility	199 days/ 6.6 months	7b 5 to 10 °F
				47.0° N	−15.0 to −12.2 °C
	BIGH's Ferme abattoir, Brussels, Belgium (21,600 sf/2000 m^2)	Venlo-style, gutter-connected, (15 × 10 bays), clad with glass, fish tanks on the lower level	CEA environment, supplemental LED lighting	224 days/ 7.3 months	8b 15 to 20 °F
				50.8° N	−9.4 to −6 .7 °C
Indoor growing spaces	Urban Organics, Schmidt's Brewery, St. Paul, MN, USA (87,000 sf/8080 m^2)	Steel-frame warehouse, highly insulated, stacked growing, fish tanks in separate space	Fluorescent UV lighting, computer-controlled CEA environment	140 days/ 4.7 months	4b −25 to −20 °F
				45.0° N	−31.7 to 28.9 °C
	Nutraponics, Sherwood Park, AB, Canada (10,800 sf/1000 m^2)	Steel-frame warehouse, highly insulated, stacked growing, fish tanks in separate space	LED lighting, computer-controlled CEA environment	121 days/ 4 months	4a −30 to −25 °F
				53.5° N	−34.4 to −31.7 °C

[a]Frost-free growing season, National Gardening Association, Tools and Apps, https://garden.org/apps/calendar/
[b]Based on the USDA Hardiness Zone Map, which identifies the average annual minimum winter temperature (1976–2005), divided into 10° F zones. Plant Maps, https://www.plantmaps.com/index.php

Passive Solar Greenhouses This greenhouse type is designed to be solely heated by solar energy. Substantial thermal mass elements, such as a solid north-facing wall, store solar energy in form of heat that is then re-radiated during colder periods at night. This approach buffers air temperature swings and can reduce or eliminate the need for fossil fuels. Solar greenhouses have a transparent south-facing side and an opaque, massive, highly insulated north-facing side. The integration of large volumes of water in form of fish tanks is an asset for the thermal performance of this greenhouse type. Furthermore, the tanks can be located in areas of the greenhouse that are less suited for plant cultivation or partly submerged into the ground for added thermal stability.

Fig. 21.4 Ouroboros Farms (Half Moon Bay, California, USA)

The Aquaponic solar greenhouse (2000 sf/180 m^2), developed and tested by Franz Schreier, has proven as a suitable environment for housing a small aquaponic system in southern Germany. The greenhouse collects solar energy through its south-facing arched roof and wall clad with ethylene tetrafluoroethylene (ETFE) film. Heat is stored in partially submerged fish tanks, floor, and adobe-clad northern wall to be dissipated at night. The greenhouse's custom-built photovoltaic (PV) panels transform solar radiation into power. Located in the colder climate of Vermont, USA, the Eco-Ark Greenhouse at the Finn & Roots farm (6000 sf/560 m^2) houses an aquaponic system that works with a similar passive solar approach. The greenhouse has a steep (approx. 60°) south-facing transparent roof with special solar-collecting glazing (Fig. 21.5). Its highly insulated, opaque northern side is submerged into a hillside and houses the fish tanks. In addition to these passive controls, the Eco-Ark has a radiant floor heating that supplements heating during the coldest seasons.

High-Tech Greenhouses Venlo-style, high-tech greenhouses that feature a high level of technology to control the indoor climate are the standard for commercial-scale hydroponic CEA. High-tech greenhouses are characterized by computerized controls and automated infrastructure, such as automatic thermal curtains, automatic lighting arrays, and forced-air ventilation systems. These technologies enable a high level of environmental control, though they come at the cost of high energy consumption.

Fig. 21.5 Eco-Ark Greenhouse at Finn & Roots Farm (Bakersfield, Vermont, USA)

Some large-scale commercial aquaponic farms use this greenhouse typology for their plant production, such as Superior Fresh farms, located in Hixton, Wisconsin, USA (123,000 sf/11,430 m^2), with the aquaculture systems housed in a separate opaque enclosure. Automated supplemental LED lighting and heating enables Superior Fresh farms to cultivate leafy greens year-round despite lack of daylight in the winter, where the natural, frost-free growing season lasts only 4 months. Automated systems for internal climate control allow high-tech greenhouses to be operated anywhere in the world – Blue Smart Farms greenhouse uses an array of sensors to optimize shading during hot Australian summers.

Thanet Earth, the largest greenhouse complex in the UK, is located in the southeast of England. Its five greenhouses cover more than 17 acres (7 hectares) each, growing tomatoes, peppers, and cucumbers using hydroponics (Fig. 21.6). This enterprise is powered by a combined heat and power system (CHP) that provides power, heat, and CO_2 for the greenhouses. The CHP system operates very efficiently and channels excess energy to the local district by feeding it into the local power supply grid. In addition, computer-controlled technologies such as energy curtains, high-intensity discharge supplemental lighting, and ventilation regulate the indoor growing conditions.

Rooftop Greenhouses This most recent type includes greenhouses built on top of host buildings, either as retrofits of existing structures or as part of new construction. Due to high land costs, saving space is increasingly important to aquaponic farms in urban contexts. Connecting a greenhouse to an existing building is one strategy for urban farmers looking to revitalize underused space and find a central location in the city. Rooftop greenhouses are already used by commercial-scale hydroponic growers but are a relatively rare enclosure type for aquaponic farms due to the

Fig. 21.6 Thanet Earth, state of the art greenhouses with combined heat and power provision, (Isle of Thanet in Kent, England, UK)

additional weight of water which can strain existing structures beyond their loading capacity. The few rooftop aquaponic farms that currently exist prioritize lightweight water distribution systems (nutrient film technique or media-based growing rather than deep water culture) and locate their fish tanks on the level below the crop growing space due to relatively decreased demand for natural light.

Two rooftop farms with high-tech aquaponic systems have recently opened in Europe. Both consulted with Efficient City Farming (ECF) farm systems consultants in Berlin. Ecco-jäger Aquaponik Dachfarm in Bad Ragaz, Switzerland sits on top of a distribution center of a family-owned produce company. The Venlo-style rooftop greenhouse (12,900 sf/1200 m^2) is located on a two-story depot building; the fish tanks are installed on the floor below the greenhouse. By growing leafy greens and herbs on their rooftop, Ecco-jäger reduces the need for transportation and can offer produce immediately after harvest. In addition, the farm takes advantage of waste heat generated by its cold storage to heat the greenhouse. BIGH's Ferme Abattoir (21,600 sf/2000 m^2) is a larger version of a similar Venlo-style rooftop greenhouse (Fig. 21.7), which occupies the roof of the Foodmet market hall in Brussels, Belgium. These early examples point to further potential to optimize both aquaponic and envelope performance through connecting water, energy, and air flows between farm and host building, known as building-integrated agriculture (BIA). Currently, research is being done on the flagship hydroponic integrated rooftop greenhouse located on the building shared by the Institute of Environmental Science and Technology (ICTA) and the Catalan Institute of Paleontology (ICP) at the Autonomous University of Barcelona (UAB) to dermine

Fig. 21.7 BIGH Ferme Abattoir with the high-tech greenhouse in the background (Brussels, Belgium)

the benefits of full building integration, although no such example exists in the field of aquaponics to determine the benefits of full building integration, although no such example exists in the field of aquaponics.

21.3.2 Indoor Growing Type

Indoor growing spaces rely exclusively on artificial light for plant production. Often, these growing spaces are highly insulated and clad in an opaque material, originally intended as storage or industrial manufacture rooms. Indoor growing spaces typically have better insulation than greenhouses due to the envelope material, though cannot rely on daylighting or natural heating. The assumption is that this typology is better suited to extreme climates, where temperature swings are of larger concern than lighting (Graamans et al. 2018), though more conclusive research is needed.

Urban Organics operates two commercial-scale indoor growing aquaponic farms within two refurbished breweries in the industrial core of St. Paul, Minnesota, USA. The two farms cultivate leafy greens and herbs in stacked growing beds illuminated by fluorescent grow lights (Fig. 21.8). Their second site allows Urban Organics to tap into the brewery infrastructure around an existing aquifer; the aquifer water needs minimal treatment and is supplied at 10 °C to arctic char and rainbow trout

Fig. 21.8 Urban Organics (St. Paul, Minnesota, USA)

tanks. Using existing structures lowered construction costs for Urban Organics and offered the opportunity to revitalize a struggling area of the city. In an even colder climate, Nutraponics grows leafy greens in a warehouse on a rural parcel 40 km outside Edmonton, Alberta, Canada. Since local produce is highly dependent on seasonal temperature swings, Nutraponics gains a competitive edge in the market by employing LED lighting to accelerate crop growth year-round (Fig. 21.9).

21.3.3 Enclosures for Aquaculture

The enclosures for the aquaculture component of aquaponic operations are technically not as demanding as the enclosure design for the hydroponic components since fish do not require sunlight to thrive. Nevertheless, control over indoor growing conditions enables farmers to optimize growth, reduce stress, and draw up precise schedules for fish production which gives their stock a competitive edge in the market (Bregnballe 2015). Aquaculture space enclosures are mainly required to keep water temperatures stable. Fish tanks should be able to support comfortable water temperature ranges for specific fish species, warm-water fish 75–86°F (24–30°C) and cold-water fish 54–74°F (12–23°C) (Alsanius et al. 2017). Water and room temperature can be controlled most efficiently if fish tanks are housed in well-

Fig. 21.9 Nutraponics (Sherwood Park, Alberta, Canada)

insulated space with few windows to minimize solar gains during the summer months and temperature losses when the outside temperature drops (Pattillo 2017) as demonstrated in the set-up of the INAPRO enclosure. The large volume of water required for fish cultivation needs to be considered from an architectural perspective, as it carries consequences for structural and conditioning systems within a building.

21.4 Assessing Enclosure Typologies and Possible Applications

The actual performance of aquaponic farms depends on many case-specific factors. Some preliminary conclusions about enclosure typologies' advantages, challenges, and possible applications can be drawn from the comparison of a relatively small set of case studies. An empirical study of a more significant number of existing case studies will be needed to establish a correlation between enclosure type, geographic location, and commercial success.

Medium-tech greenhouses offer a commercially-feasible option for aquaponic operations only in temperate climates with mild winters and moderate summers, due to their limited environmental control capability. In locations that do not require much heating and cooling, farms using this greenhouse typology can operate in a resource-efficient manner with lower upfront investment for their enclosure. These farms usually operate on a lower budget and include the fish tanks in the same greenhouse, which limits their selection of fish species to those with a large temperature tolerance and draws their commercial focus to the production of lettuce, leafy greens, and herbs.

Passive solar greenhouses rely on passive systems, specifically the use of thermal mass, to control the indoor climate. The use of this typology for aquaponic systems is advantageous since the large volume of water in the fish tanks provides additional thermal mass. Due to their energy efficiency, they are often used in northern latitudes where conventional greenhouses would require a high level of supplemental heating. However, operating any greenhouse in those regions relies on the use of supplemental lighting due to low light levels and short daylight hours during the winter season. Although passive solar greenhouses in Europe and North America are currently used on a small experimental scale, the more general successful application of these single-slope, energy-efficient greenhouses on 1.83 million acres (0.74 million hectares) of farmland in China shows that this typology can be successfully implemented on a large scale (Gao et al. 2010).

High-tech greenhouses, especially large Venlo-style, gutter-connected systems, are the industry standard for commercial hydroponic production. The largest well-funded commercial aquaponic farms use this typology for their hydroponic growing systems in conjunction with a separate enclosure for their aquaculture infrastructure. This setup guarantees the highest level of environmental control as well as crop and fish productivity. Technically, this type of greenhouse can be operated anywhere, as long as the revenue produced pays for the high energy and operation costs in extreme climates. However, this type of operation may not be environmentally sensitive in some northern latitudes due to the extensive need for heating and supplemental lighting. The exact environmental footprint of a high-tech greenhouse can only be assessed on a per-project basis and depends mostly on the quality of energy sources used for supplemental heat and light.

Most *rooftop greenhouses* are Venlo-style high-tech greenhouses constructed on rooftops. Whilst similar benefits and challenges apply, the construction of rooftop greenhouses is even more expensive than that of regular high-tech greenhouses, primarily due to building codes and architectural requirements. The structural system of rooftop greenhouses is often over-dimensioned to comply with building codes for commercial office buildings, which are stricter than building code requirements for agricultural structures. Furthermore, aquaponic operations on rooftops need additional infrastructure to access the roof and comply with fire and egress regulations, which has generated a sprinkler equipped-greenhouse in a recent example (Proksch 2017). The most promising application of rooftop greenhouses is on top of host buildings in urban centers. Urban roofs often offer ample access to sunlight, which greenhouses require to function effectively – a resource that is usually lacking, or at least is not consistent due to shadowing, at ground level in dense urban areas (Ackerman 2012). If purposefully designed, host buildings can offer other resources such as exhaust heat and CO_2 that can make the operation of a rooftop aquaponic farm more feasible. This type of integration with the host building can generate energy and environmental synergies that improve the performance of both greenhouse and host building.

Fig. 21.10 INAPRO aquaponics enclosure with two sections, opaque for fish and greenhouse for plants (Murcia, Spain)

Indoor growing spaces depend entirely on artificial lighting and active control systems for heating, cooling, and ventilation, which results in a high level of energy consumption, environmental footprint, and operation cost. This typology is most applicable in areas with cold winters and short growing seasons, where the natural exposure to sunlight and heat gain is low and extensive supplementation is needed to operate a commercial aquaponics greenhouse. The use of an opaque enclosure allows high levels of insulation, which reduces heat loss during winter months and provides autonomy from external temperature swings. Besides its dependence on electrical lighting, indoor growing exceeds the productivity of greenhouses as measured in other resources, such as water, CO_2, and land area (Graamans et al. 2018). Additionally, the production per unit of land area can be much higher through the use of stacked growing systems. Regarding the urban integration of aquaponics in cities, indoor grow spaces allow for the adaptive reuse of industrial buildings and warehouses, which can reduce the up-front cost for the construction of the enclosure and support the integration of aquaponic farms in underserved neighborhoods.

The Innovative Aquaponics for Professional Applications (INAPRO, 2018) project set-up included the comparison of the same state of the art aquaponic system and greenhouse technology, across a number of sites in Germany, Belgium, and Spain. The aquaponics system located in China was housed in a passive solar greenhouse. The INAPRO aquaponics facilities in Europe utilized a glass-clad greenhouse type for plant production and an industrial type shed component for fish tanks and filtration units (Fig. 21.10). The INAPRO project demonstrates that greenhouse technologies need to be adapted and chosen to suit local climate conditions. The Spanish INAPRO team found, that the selected enclosure was well suited for the cooler northern Europe regions, but not the warmer, Mediterranean regions in southern Europe. This observation highlights the importance of more research on the performance of greenhouses typologies to advance the field of commercial aquaponics operations.

While the comparison of the different typologies reveals certain performance patterns between typology, location, and investment (Table 21.3), for a comprehensive understanding of farm performance and environmental impact, a more robust system for the analysis and design of farm enclosures is needed.

21.5 Impact Assessment as a Design Framework

The growth of aquaponics and generalized claims that aquaponics is more sustainable than other forms of food production has stimulated discussion and research into how sustainable these systems actually are. Life cycle assessment (LCA) is one key quantification method that can be used to analyze sustainability in both agriculture and the built environments by evaluating environmental impacts of products throughout their lifespan. For a building, an LCA can be divided into two types of impact – *embodied* impact which includes material extraction, manufacture, construction, demolition and disposal/reuse of said materials, and *operational* impact which refers to building systems maintenance (Simonen 2014). Similarly, conducting an assessment of an agricultural product can be also divided into the *structural* impact of the building envelope and system infrastructure, *production* impact associated with continuous cultivation and *post-harvest* impact of packaging, storage, and distribution (Payen et al. 2015). Conducting an LCA of an aquaponic farm requires the simultaneous understanding of both building and agricultural impacts since there is an overlap in the envelope's *operational* phase with a crop's *production* phase. The way a building operates its heating, cooling, and lighting systems directly influences the cultivation of the crop; conversely, different types of crops require different environmental conditions. Numerous studies exist comparing LCA results for different building types situated in different contexts (Zabalza Bribián et al. 2009). Similarly, LCA has been used by the agricultural sector to compare efficiencies for different crops and cultivation systems (He et al. 2016; Payen et al. 2015). Evaluating the performance of controlled environment agriculture and aquaponics in particular requires a skillful integration of the two methodologies into one assessment (Sanyé-Mengual 2015).

The proposed aquaponic farm LCA framework (Fig. 21.11) is intentionally broad to capture a wide range of farm typologies found in the field. In order to apply the results of LCA to existing farms, factors such as climate and economic data must be included to validate environmental assessment (Goldstein et al. 2016; Rothwell et al. 2016)

The following section discusses a collection of aquaponic farm enclosure design strategies based on the LCA inventory of aquaponic farms that synthesizes existing

Table 21.3 Comparison of controlled environment agriculture typologies

CEA type	Benefits	Challenges	Cost and revenue[a]
Medium-tech greenhouses	Relies almost entirely on solar energy, low additional energy requirement	Limited environmental control options, susceptible to environmental fluctuations	Lower up-front/ construction cost, (approx. 30–100 $\$/m^2$)
	Less reliance on non-renewable materials and energy sources	Only applicable to fish species with a large temperature tolerance, (if tanks are in the greenhouse)	
Passive solar greenhouses	Relies on passive systems, uses thermal mass, (including the fish tanks) to buffer temperature swings	Control with passive systems needs more experience and deliberate design	Lower up-front/ construction cost, (approx. 30–100 $\$/m^2$)
	Low energy consumption, potentially without the need for any fossil fuel	Require supplemental lighting, if located in northern latitudes due to low light levels	
High-tech greenhouses	Highest levels of controls	Relies on active systems for heat, cooling, ventilation and supplemental lighting	High up-front/ construction cost, (approx. 100–200 $\$/m^2$ and more)
	High productivity with the potential to scale up	High energy consumption and operation cost	
Rooftop greenhouses	Highest levels of controls	Relies on active systems for heat, cooling, ventilation and supplemental lighting	Very high up-front/ construction cost (approx. 300–500 $\$/m^2$)
	High productivity		
	Potential for energetic and environmental synergies, if integrated with host building	High energy consumption and operation cost	
		Requires code compliance at the level of commercial office buildings	
		Transport of supplies to rooftop is an infrastructural challenge	
Indoor growing spaces	Adaptive reuse of industrial buildings possible	Depends entirely on electrical lighting and active control systems for heating, cooling, and ventilation	Up-front/construction cost can be lower if existing building can be used
	High productivity per unit of footprint though stacked growing systems	High energy consumption and operation cost	Cost depends also on the growing system, stacking multiple levels
	High level of insulation possible		
	Reduced heat loss during winter months		

[a]Based on Proksch (2017)

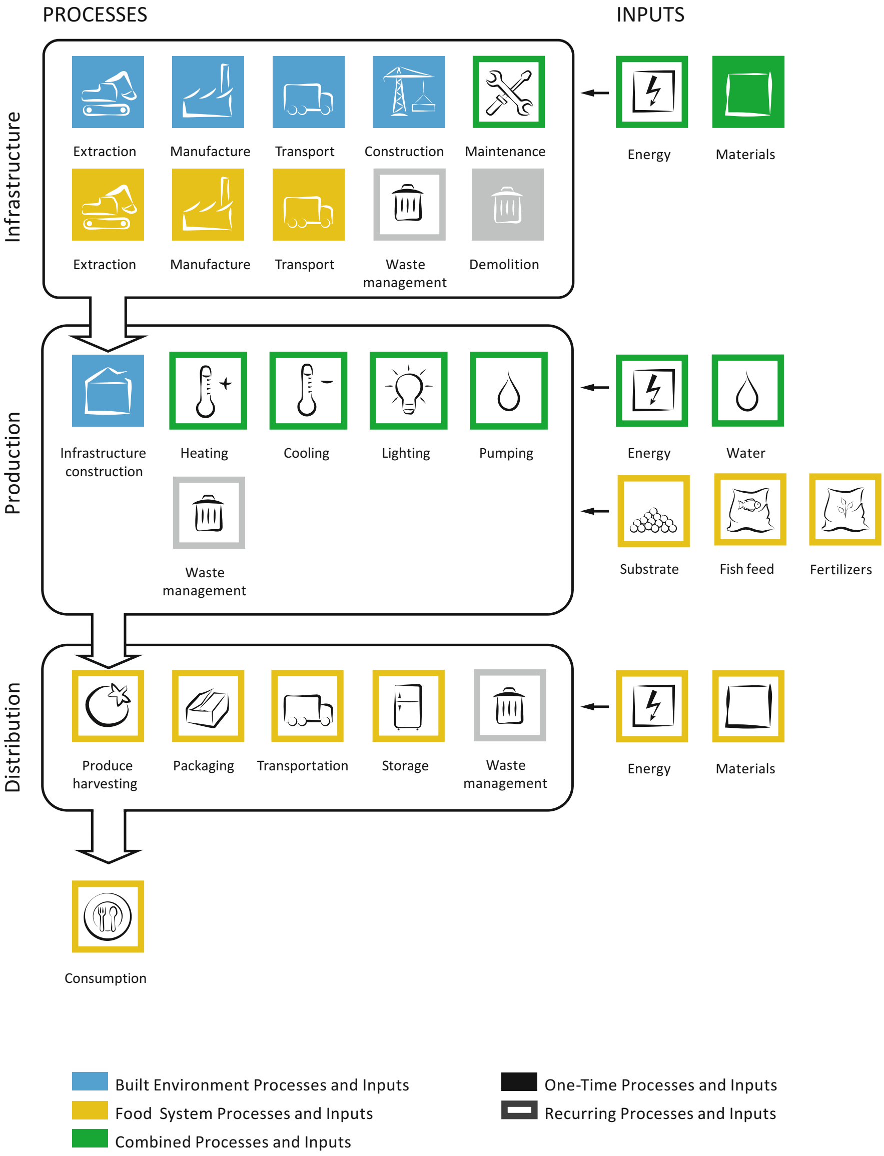

Fig. 21.11 Example of an integrated LCA process including building and aquaponic system performance. (Based on Sanyé-Mengual et al. 2015).

literature with case studies and suggests directions for future work. The unique integration of aquaponic and building-related impacts is of particular interest.

21.5.1 Embodied Impacts: Embodied Energy and Embodied Carbon

Structure Materials and Construction Embodied energy is the calculation of the sum of energy used to extract, refine, process, transport, produce, and assemble a material or product. Embodied carbon is the amount of CO_2 emitted to produce the same material or product. Compared to conventional open-field agricultural operations, the embodied impact of a controlled environment growing system is greater due to increased material extraction and manufacture at the construction stage (Ceron-Palma et al. 2012). For example, in the ICTA-ICP rooftop greenhouse, the structure of the envelope generates 75% more Global Warming Potential (GWP) than a soil-based multi-tunnel greenhouse structure due to the quantity of polycarbonate used in construction (Sanyé-Mengual et al. 2015). Similarly, a building-integrated greenhouse simulation situated in Boston resulted in increased environmental impacts at the construction stage, due to the extraction of iron ores for the manufacture of structural steel (Goldstein 2017). Embodied impacts associated with controlled environment envelopes can be mitigated through smart material use (given that building code adjustments are made to avoid over-sizing structural members) but would nevertheless surpass those of traditional agriculture. Growing food in a constructed envelope will always be more resource-intensive at the beginning compared to simply planting vegetables in an open field, though will also dramatically increase the amount of food that can be produced per area footprint in the same timeframe.

To avoid structure-related environmental impacts, some aquaponic operations make use of existing buildings instead of constructing a new envelope. Urban Organics in St. Paul, Minnesota, USA refurbished two brewery buildings as their indoor growing spaces. In another example of adaptive reuse, The Plant in Chicago, Illinois, USA operates its food incubator and urban farm collective in a 1925 factory building previously used by Peer Foods as a meat-packaging facility (Fig. 21.12). Existing insulation and refrigeration equipment were repurposed to control temperature fluctuations in the experimental aquaponic facility.

Aquaponic Equipment and Substrate When integrated into buildings, the material choice for aquaponic tanks becomes an important design consideration, since it may limit assembly and transport into the building. For example, polyethylene parts can be assembled on-site using plastic welding, but this is not possible with fiberglass parts (Alsanius et al. 2017). Furthermore, the manufacture of aquaponic system equipment can be a significant contributor to overall environmental impact – for

Fig. 21.12 The Plant (Chicago, Illinois, USA)

example, glass fiber-reinforced polyester used for the 100 m^3 water tank at the ICTA-ICP rooftop greenhouse is responsible for 10–25% of environmental impact at the manufacturing stage (Fig. 21.13). The choice of substrate for plants in an aquaponic system has a weight ramification for the structure of the host building, but also contributes to environmental impact. In a recent study done on aquaponics integrated with living walls, mineral wool, and coconut fiber performed comparably, despite one being compostable and the other being single-use (Khandaker and Kotzen 2018).

Structure and Equipment Maintenance Initial material selection for aquaponic equipment and envelope components determines the long-term upkeep of aquaponic farms. Manufacturing more durable materials such as glass or rigid plastics requires a greater initial investment of environmental resources than plastic films; however, films require replacement more frequently – for example, glass is expected to remain functional for 30+ years, whilst more conventional coated polyethylene film can only last 3–5 years before becoming too opaque (Proksch 2017). Depending on the intended lifespan of an aquaponic system envelope, it may be more advantageous to choose a material with a shorter lifespan, and a lesser manufacturing impact. ETFE film used in the Aquaponic solar greenhouse is a promising compromise between longevity and sustainability, although further research is needed. Standard aquaponic equipment consists of water tanks and piping. Piping for aquaponic systems is often manufactured from PVC, which produces a significant environmental impact in its manufacturing process but does not require replacement for up to 75 years. Some aquaponic suppliers offer bamboo as an organic alternative.

Fig. 21.13 Building section with rooftop greenhouses by Harquitectes, ICTA-ICP building (Bellaterra, Spain)

21.5.2 Operational Impacts

Energy In 2017, 39% of total energy consumption within the United States corresponded to the building sector (EIA). The agricultural sector accounted for approximately 1.74% of total U.S. primary energy consumption in 2014, relying heavily on indirect expenditures in the form of fertilizers and pesticides (Hitaj and Suttles 2016). Energy efficiency is a well-established field of research within both the built environment and agriculture, often defining the operational impacts of a product, building, or farm in the overall LCA (Mohareb et al. 2017). Integrating building and agricultural energy use can optimize the performance of both (Sanjuan-Delmás et al. 2018).

Heating Energy requirements for heating growing spaces are of particular interest in the northern climates, where extending a naturally short growing season gives building-integrated aquaponic farms a competitive edge in the market (Benis and Ferrão 2018). However, in colder climates, energy consumption by active heating systems is a significant contributor to overall environmental impact – in an assessment of conditioned growing spaces in Boston, Massachusetts, heating costs neutralized the benefits of eliminating food miles in the urban food chain (Benis et al. 2017b; Goldstein 2017). This does not hold true in Mediterranean climates, where climatic conditions are conducive to agriculture and where nearly year-round and conventional greenhouse structures can rely on passive solar heating (Nadal et al. 2017; Rothwell et al. 2016).

In both cold and warm climates, integrating controlled environment growing systems on existing rooftops can provide insulation to the host building – a farm in Montreal, Quebec reports to capture 50% of the greenhouse heating needs from the existing host structure, thereby reducing heating load (Goldstein 2017). Lighting systems can also be partially responsible for satisfying heating demand in interior vertical growing applications such as plant factories or shipping containers (Benis et al. 2017b).

Residual heat capture is another promising design strategy that can optimize the performance of both the host structure and the growing system. Post-occupancy studies of the experimental rooftop greenhouse at the ICTA-ICP in Bellaterra, Spain indicate that the integration of the building with the greenhouse delivered an equivalent carbon savings of 113.8 kg/m^2/year compared to a conventional free-standing greenhouse heated with oil (Nadal et al. 2017). Without intervention from active heating, ventilation and air conditioning (HVAC) systems, the thermal mass of the host laboratory/office building raised the greenhouse temperature by 4.1°C during the coldest months, enabling the cultivation of the tomato crop year-round.

Cooling In Mediterranean and tropical climates, artificial cooling is often a requirement to grow produce year-round. In a rooftop greenhouse simulation, cooling loads represented up to 55% of total farm energy demands in Singapore and in the more temperate climate of Paris, 30% (Benis et al. 2017b). Cooling energy demands are especially high in arid climates, which can benefit the most from cutting conventional transportation costs for perishable produce (Graamans et al. 2018; Ishii et al. 2016). Evaporative cooling, fog cooling, and shading are some strategies for lowering temperatures in aquaponic farms and improving farm performance in terms of yield.

Building-integrated aquaponic systems have the advantage of storing thermal mass in fish tanks to alleviate cooling as well as heating loads. In cases where this mode of passive cooling does not satisfy the cooling demand, evaporative cooling is most commonly used. The Sustainable Harvesters greenhouse produces lettuce for the Houston, Texas, USA area year-round by using a fan and pad cooling system, a subset of evaporative cooling technology. Hot air from outside the envelope first passes through a wet cellulose medium before entering the growing space. As a result, the interior air is cooler and more humid. Evaporative cooling is most effective in dry climates but requires high water use, which may be a limitation to farms in arid areas of the world.

Fog cooling is an alternative strategy. In a fog-cooled greenhouse, plants are periodically misted with water from overhead sprinklers/misters until the space reaches the desired temperature for cultivation. Fog cooling uses less water than evaporative cooling but increases the relative humidity of a growing space. If paired with the right ventilation strategy, fog cooling can be a water-saving technology particularly suited to arid regions (Ishii et al. 2016). Additionally, fog cooling decreases the rate of evapotranspiration in plants, which is critical to optimizing plant metabolism in aquaponic systems (Goddek 2017). The flagship greenhouse of Superior Fresh farms uses a computerized fog-cooling system to maintain cultivation temperatures during the hot season.

Shading devices can also contribute to lowering greenhouse temperatures. Traditionally, the seasonal lime whitewashing of greenhouses was used to reduce solar radiation levels during the hottest months (*Controlled Environment Agriculture* 1973). However, shading can be integrated with other building functions. A promising shading strategy is using semi-transparent photovoltaic modules to simultaneously cool the space and produce energy (Hassanien and Ming 2017). The Aquaponic solar greenhouse combines its photovoltaic array with shading functionality; it uses rotating aluminium panels as shading devices that operate as solar collectors with the help of mounted photovoltaic cells. The integrated photovoltaic system then transforms excess solar radiation into electrical energy.

Lighting The main advantage of greenhouses over indoor growing spaces is their ability to capitalize on daylight to facilitate photosynthesis. However, farms in extreme climates may find that satisfying heating or cooling loads for a transparent envelope is not financially feasible; in this case, farmers may choose to cultivate crop in indoor growing spaces with an insulated envelope (Graamans et al. 2018). Aquaponic farms that operate in indoor growing spaces rely on efficient electrical lighting to produce crops.

Many advances in contemporary farm lighting originated in Japanese plant factories, used to optimize plant yields in dense hydroponic systems by replacing sunlight with engineered light wavelengths (Kozai et al. 2015). Currently, LED lighting is the most popular choice for electrical horticultural lighting systems. They are 80% more efficient than high-intensity discharge lamps and 30% more efficient than their fluorescent counterparts (Proksch 2017). LED lighting continues to be investigated to optimize energy efficiency and crop yield (Zhang et al. 2017). Large-scale greenhouses like Superior Fresh, Wisconsin, USA rely on computerized, supplemental lighting regimes to extend the photosynthesis period of its crop in northern latitudes.

Energy Generation Constrained by the same factors as all CEA, the energy management of an aquaponic farm depends on exterior climate, crop selection, the production system, and structure design (Graamans et al. 2018). Growing produce through aquaponics is not inherently sustainable if not managed properly – all of the factors above can affect energy efficiency for the better or worse (Buehler and Junge 2016). In many cases, CEA is more energy-intensive than conventional open-field agriculture; however, higher energy expenditures may be justified if the way we source energy shifts toward renewable sources and efficient strategies for heating, cooling, and lighting are incorporated into the design of the farm.

Photovoltaic (PV) power generation can play an important part in offsetting operational impacts for controlled environment aquaponics, reducing environmental strain. In an example of a high-tech greenhouse in Australia, using energy from a PV array caused a 50% reduction in lifecycle greenhouse gas emissions compared to the conventional grid scenario (Rothwell et al. 2016). Renewable energy generation can be combined with aquaponic farms, space permitting – for example, the Lucky Clays Fresh aquaponic greenhouse on a rural farm in North Carolina runs on energy generated by wind turbines and photovoltaic panels that are situated elsewhere on the owner's land parcel.

Water Water use efficiency has been often cited as a major benefit of CEA and hydroponic systems (Despommier 2013; Specht et al. 2014). Aquaponic systems are even better suited to increase water efficiency – where 1 kg of fish produced in a conventional aquaculture system requires between 2500 and 375,000 L, the same amount of fish raised in an aquaponic system requires less than 100 L (Goddek et al. 2015). Rainwater capture and greywater reuse have been proposed as two strategies to offset the watershed impacts of operating a hydroponic or aquaponic farm even further. At the existing ICTA-ICP greenhouse, 80–90% of the water needs for the production of tomatoes in an aggregate hydroponic system were covered by rainwater capture within a year of operation (Sanjuan-Delmás et al. 2018). However, the ability of rainwater capture to meet crop demand depends on the climatic context. In a study evaluating the viability of rooftop greenhouse production on existing retail parks in eight cities around the world, seven met crop self-sufficiency through rainwater capture – only Berlin did not (Sanyé-Mengual et al. 2018).

Some existing CEA facilities already reuse greywater to improve efficiency (Benke and Tomkins 2017). However, greywater reuse in an urban context is currently limited due to lacking regulatory support and currently-lacking research on the health risks of using greywater in agriculture. A pilot of greywater reuse, the Maison Productive in Montréal collects greywater from household uses to supplement its rainwater collection to irrigate gardens and a communal greenhouse for food production that nine residential units share (Thomaier et al. 2015). With further advances in policy on the treatment of greywater, building-integrated aquaponics can tap into the existing water cycle instead of relying on municipal sources.

From an architectural standpoint, water distribution in an aquaponic system is likely to present a structural challenge. Aquaponic fish tanks weigh more than hydroponic grow beds and may limit what types of structures are feasible for retrofitting an aquaponic farm. The growing medium also requires consideration – deep water culture (DWC) systems require a large and heavy volume of water, whilst nutrient film technique (NFT) systems are lightweight but expensive to manufacture (Goddek et al. 2015).

Nutrients Compared to conventional open-field farming, CEA reduces the need for fertilizers and pesticides, as the farmer can physically separate the crop from harsh external conditions (Benke and Tomkins 2017). However, due to the density of an aquaponic system, plant or fish diseases can spread quickly if a pathogen infiltrates the space. Preventative options such as the use of predator insects or tight environmental control measures such as a "buffer" entryways can avert this risk (Goddek et al. 2015).

The integration of different fish and crop nutrient needs is a challenge in single-recirculating aquaponic systems (Alsanius et al. 2017). Generally, plants require higher nitrogen concentrations than fish can withstand and careful crop and fish selection can match nutrient requirements to optimize yields, but is still difficult to achieve. Decoupled systems (DRAPS) have been proposed to separate the aquaculture water cycle from the hydroponic one to achieve desired nutrient concentrations, but is not yet commonly applied in commercial farms (Suhl et al. 2016). Urban Organics based in St. Paul, Minnesota, USA chose to develop a DRAPS system for their second farm to optimize both crop and fish yields and avoid crop loss in case of nutrient imbalances within fish tanks. ECF Farm in Berlin, Germany, and Superior Fresh farms in Wisconsin, USA also operate decoupled systems to optimize fish and plant growth.

Alternatively, aquaponic nutrient cycles can be optimized through the introduction of an anaerobic reactor to transform solid fish waste into plant-digestible phosphorus (Goddek et al. 2016). Currently, The Plant in Chicago, USA is planning to operate an anaerobic digester which may play a part in optimizing nutrient cycles for crop growth. The mechanical system requirements for DRAPS and anaerobic digestion will influence the performance as well as the spatial layout of an aquaponic farm.

21.5.3 End-of-Life Impacts

Materials Waste Management A theoretical advantage of CEA over open-field farming is the ability to control materials waste runoff, preventing leaching (Despommier 2013; Gould and Caplow 2012). A tight envelope can play a role in efficient materials waste management. One pathway of recycling organic waste matter to improve building performance is the use of plant stalks for the production of insulating biochar, although this research is in early stages (Llorach-Massana et al. 2017). Additionally, considering the incorporation of waste management components such as a filtration bed, an anaerobic digester or a heat recovery ventilator into the enclosure design at an early stage can close energy, nutrient, and water loops for the farm.

Distribution Chains Packaging has been a hotspot in various farm LCAs assessing the impact of production. It is responsible for as much as 45% of the total impact for a tomato in Bologna, Italy, and is the largest contributor to the environmental impacts of indoor hydroponic systems in Stockholm, Sweden (Molin and Martin 2018b; Orsini et al. 2017; Rothwell et al. 2016). Siting aquaponic farms close to consumers can reduce the need for packaging, storage, and transport as with other forms of urban agriculture, if local retailers and distributors collaborate with farmers (Specht et al. 2014). Unfortunately, due to consumer acceptance, most large-scale retailers currently require standard plastic packaging for aquaponic produce to be sold alongside conventional brands - – therefore, selecting a site close to a consumer market for controlled environment aquaponics does not guarantee significant changes in the overall performance of the farm.

Reduced transportation, or food-miles, is often cited in the literature as a major advantage of urban agriculture (Benke and Tomkins 2017; Despommier 2013; Sanjuan-Delmás et al. 2018). However, it is important to note that the relative contribution of shortened transportation chains varies on a case-by-case basis. In Singapore, where nearly all food has to be imported from neighboring countries, cutting transportation chains makes sense financially and in terms of environmental impact (Astee and Kishnani 2010). The same cannot be said for Spain, where the conventional supply chain of tomatoes from farm to city is already short (Sanjuan-Delmás et al. 2018). Cities with the longest supply chains can benefit from localized food production, but the benefits of cutting transportation must be weighed against operational and embodied impacts. In the case of Boston, the benefits of reduced transportation were entirely negated by the impact of heating and operating a greenhouse inside the city (Goldstein 2017). Despite long conventional food supply chains, transportation impacts were similarly insignificant in the bigger picture of CEA performance in Stockholm (Molin and Martin 2018a).

Consumption and Diet Aquaponic farms in cities can alter urban diets, which play a significant role in the environmental impact of food consumption (Benis and Ferrão 2017). Meat consumption via the conventional chain produces the largest share of the current environmental footprint and seeking protein alternatives has the potential for a larger impact than the widespread implementation of urban agriculture (Goldstein 2017). Since aquaponics produces fish as well as vegetables, this potential to change protein diets on a large scale should not be ignored in larger assessments of environmental performance.

21.6 Integrated Urban Aquaponics

When deliberately designed with respect to environmental impact, aquaponic farms can become part of a resource-efficient urban food system. No aquaponic farm operates in isolation since when crops are harvested and reach the farm gate, they enter a larger socioeconomic food network as fish and produce is distributed to customers. At this stage, the performance of aquaponic farms is no longer confined to the growing system and envelope – economics, marketing, education, and social outreach are also involved. Urban aquaponic farms will need to operate as competitive businesses and good neighbors to be successfully integrated into city life.

21.6.1 Economic Viability

The economic viability of aquaponic farms depends on many contextual factors where both local conventional fish production chains and open-field farming must be matched (Stadler et al. 2017). While aquaponics requires a relatively costly initial investment, it may outperform conventional farming during the production and distribution phase where the design of the recirculating water system reduces water costs, and greatly reduces the need for fertilizers, which usually comprise between 5% and 10% of overall farm costs (Hochmuth and Hanlon 2010). However, estimating the economic viability of aquaponic farms is particularly challenging due to the range of dynamic factors affecting performance including the local price for labor and energy being two examples (Goddek et al. 2015). In an economic analysis of aquaponic farms in the Midwestern United States, labor constituted 49% of all operational costs despite the assumption that only minimum wages would be paid. In reality, the wide range of expertise required to operate an aquaponic system will likely warrant higher wages in an urban farm scenario (Quagrainie et al. 2018).

Site selection and envelope design have a direct relationship to the profitability of an aquaponic farm by affecting operation efficiency and how broad the potential market can be. Aquaponic farms located in urban environments can tap into multiple markets outside agricultural production, where many aquaponic farms offer tours, workshops, design consulting services, and supply backyard aquaponic systems for hobbyists. Integrating agriculture with other types of spaces within urban environments can contribute to the financial health of aquaponic farms. The ECF aquaponic farm is located on the work yard of the industrial landmark building Malzfabrik, Berlin, Germany, which operates a cultural center and houses work spaces for artists and designers.

21.6.2 Accessibility and Food Security

Urban agriculture is often cited as a strategy to provide fresh food for underserved communities located in food deserts, yet few commercial urban farms target this demographic, proving that commercial-scale urban agriculture can be just as exclusionary as conventional supply chains (Gould and Caplow 2012; Sanyé-Mengual et al. 2018; Thomaier et al. 2015). Aquaponic farms that use high-tech infrastructure try to redeem their high investments by achieving premium prices in urban markets, though aquaponics can also stem from grassroots and hobbyist applications. Aquaponics may also have the potential to increase food security for urban residents. This is evidenced in the lasting legacy of Growing Power, a non-profit organization that until recently, ran an urban farm in Milwaukee, Wisconsin, USA started by Will Allen in 1993. Many current aquaponic farmers attended Growing Power's workshops, in which Allen championed an aquaponic model that gives back to the surrounding community by means of community-supported agriculture boxes and classes. Initiated by Growing Power's educational programs, other aquaponic non-profit organizations have taken up to the torch such as Dre Taylor with Nile Valley Aquaponics in Kansas City, Kansas, USA. This farm aims to provide 100,000 pounds (45,400 kg) of local produce to the surrounding community in an award-winning new campus for the expanding farm (Fig. 21.14).

Fig. 21.14 Proposed Nile Valley Aquaponics campus (Kansas City, Kansas, USA) by HOK Architects

21.6.3 Education and Job Training

Aquaponics can be used as an educational tool to promote systems thinking and environmental mindfulness (Junge et al. 2014; Specht et al. 2014). In urban applications, aquaponic systems could be used to raise awareness of ecological cycles much like existing soil-based farms (Kulak et al. 2013). The Greenhouse Project in New York City translates this into a new approach to science education in public schools. The Greenhouse Project aims to build 100 rooftop greenhouses on public schools as science classrooms. These greenhouses, customized for their dual mission of growing and learning, all include an aquaponic system. However, aquaponic systems also require greater collaboration between existing academic disciplines in order to move forward in this new multidisciplinary academic field (Goddek et al. 2015). The collaboration of aquaculture and horticulture specialists, engineers, business strategists, and built environment professionals amongst many others is necessary to turn aquaponics into an important contributor to sustainable urban development.

21.7 Conclusions

There is an array of criteria that contribute to the performance of each farm and their number grows with the number of disciplines involved in this the interdisciplinary field of aquaponics. Of note is an earlier study that has provided a definition of aquaponics and a classification of the types of aquaponics based on size and system

(Palm et al. 2018). Many criteria for the analysis of the enclosure type identified in this study stem from immediate farm context – local climate, the quality of the built environment context, energy sourcing practices, costs, market, and local regulatory frameworks. An aquaponic greenhouse in a rural context performs differently than one in a city, just as farms in arid climates do not share the same requirements as their counterparts in colder areas. In general, greenhouses classified as medium-tech and passive solar offer a lower cost, environmentally sustainable enclosure option, currently only used by smaller aquaponic operations. However, due to their intentionally limited level of technical environmental controls, they only perform well in specific climate zones. In comparison, high-tech and rooftop greenhouses can be technically implemented anywhere, though in extreme climate conditions they generate high operational costs and larger environmental footprints. Recent case studies show that indoor growing facilities can be financially feasible, but due to their exclusive reliance on electrical lighting, their resource use efficiency and environmental footprint are of concern. Further research is needed to establish the relationship of specific aquaponic farms and their enclosures to existing resource networks. This work can help connect aquaponics to research done on urban metabolism.

Other criteria determining farm typology and performance are internal. These include environmental control levels, crop and fish selection, aquaponic system type and scale and enclosure type and scale. Taking on an integrated LCA approach, the relationship between all factors have to be assessed throughout the lifespan of the farm, from cradle to grave. Life cycle assessment of aquaponic farms must include both building impacts and growing system impacts since there is overlap in the farm operation phase. A series of promising strategies in heating, cooling, lighting, and material design can improve overall farm efficiency throughout the entire lifespan of the farm. Beyond accounting for environmental impact, LCA can become a design framework for horticulture experts, aquaculture specialists, architects, and investors.

Continuing to survey existing commercial aquaponic farms is important to validate LCA models, identify strategies, and cataloguing aquaponic operations emerging on a larger scale. Combining modeling with case study research on controlled environment aquaponics has the potential to connect aquaponics to the larger scope of urban sustainability.

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