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ORIGINAL PAPER

Translating Environmental Potential to Economic Reality: Assessment of Commercial Aquaponics through Sustainability Transitions Theory

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Abstract
Despite popular interest and recent industry growth, commercial-scale aquaponics still faces economic and regulatory barriers primarily resulting from political and economic systems which insufficiently address pressing environmental challenges. The sustainability potential of aquaponic food production can help address and overcome such challenges while contributing to the broader development of circular economy and sustainable development of food systems. In response to the current counterproductive gap between potential applications and industry development, the interdisciplinary team of authors identifies pathways to translate the environmental potential of commercial aquaponics into economic success through a sustainability transition theory lens. To evaluate the industry's current state-of-the-art, drivers, barriers, and future potential, interview data from 25 North American producers collected in 2021, literature, and policy are analyzed through a Technological Innovation System (TIS) assessment within a Multi-Level Perspective (MLP) approach. This supports the consideration of pathways for industry development of aquaponics as an aspect of circular economy within a dynamic sustainable development context. These pathways for action include (1.) advancing clear standards and policies for aquaponics as part of a circular economy, increasing funding and incentives, and reducing support and subsidies for competing unsustainable food production; (2.) developing and promoting cost-effective technologies; and (3.) bolstering consumer preferences for sustainable and healthy food sources.

Keywords Commercial aquaponics · Circular economy (CE) · Technological Innovation System (TIS) · Multi-Level Perspective (MLP) · Sustainability transition pathways · Controlled-environment agriculture (CEA)

Introduction

Recent interest in aquaponics reflects its positioning as a technology able to help advance implementation of circular economy (CE) in food systems to address pressing socio-ecological challenges. Further exploitation of natural resources will not sustain demands of

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the food system as anthropogenically driven pressures—particularly climate change—increase on natural resources essential to food production [1–3]. CE for the food system enacts regenerative practices to avoid the production of waste, instead of using principles of reducing, reusing, and recycling output resource flows as feedstocks for other processes [4]. To address crucial supply needs effectively will therefore necessitate sustainable and innovative solutions [5–8]. Aquaponics, widely considered to be a sustainable food production technology due to its potential efficiency and integration of sustainable resources, is among these solutions [9–13]. The growing system's potential for operational circularity is particularly evident in its capacity to enable nutrient recovery and water efficiency [14]—through which it embodies core CE principles by reducing, reusing, and recycling resources within the aquaponic system [12, 15–17]. Aquaponics combines recirculating aquaculture and hydroponic (soilless) crop cultivation in a symbiotic growing system that facilitates nutrient recovery from fish production to fertilize plants [14, 18–21]. Within the system, microbes help convert fish wastes into forms of nutrients suitable for uptake by plants [11, 12, 21, 22]. Due to this inbuilt resource circularity of water and nutrients—enabled by operationalizing a productive living ecosystem in a controlled environment—aquaponics has been viewed as a valuable means to help to shift to a more circular economy and sustainable society that minimizes waste, recycles nutrients and water, and supports healthy dietary choices through resource efficiency and sustainability benefits within the food system [1, 23, 24].

Yet to leverage the capacity of aquaponics to actually perform effectively as a sustainable food production at a large scale over a longer-term future—and not fall flat as merely hype [25]—critical approaches to its development as a technological production system and commercial industry are needed as a part of serious informational and resource investment in driving forward and removing barriers to circular food economies. Sustainable and affordable models are needed to produce food more widely and accessibly to a variety of consumers in the long term. The sustainability performance of aquaponics is ultimately dependent on the design, context, and location of a given system and thus cannot be perfectly generalized [16, 26]. Its most inherent sustainable qualities are those shaped by the core growing system such as water efficiency, nutrient efficiency, and space efficiency of production [3, 14]. These benefits, combined with those of controlled-environment agriculture growing conditions such as greenhouse production with supplemental lighting and climate control, can provide further advantages by allowing production even in extreme climate conditions and beyond the limitations of typical regional growing seasons [27]. This can require energy input and infrastructure which can impact the carbon footprint of aquaponic operations, an aspect likely to vary considerably among existing farms. Energy-efficient design, CE approaches to materials and construction, and renewable power sources can significantly minimize this footprint, shaping potential for net-zero performance; thus, achieving broad access to and implementation of these practices—as well as optimization of other performance metrics—as a part of sustainability transitions is particularly crucial to fully translating the sustainability potential of commercial aquaponics. Moreover, the capacity of aquaponics to help achieve broad CE implementation hinges in part on producing enough food to substantially augment other forms of food production and ultimately to competitively provide produce and fish protein to a large consumer base. The development of commercial aquaponics is therefore an important scale to scrutinize within the context of CE. While public interest, hobbyist-practice, start-up of commercial farms, and academic research on aquaponics have increased within the last 15 years, commercial producers remain a relative minority as the aquaponics industry has not yet scaled up to compete with related production systems, such as hydroponics and aquaculture [13, 28–30]. Technological developments in aquaponic growing systems—benefitting from its subsystem sibling industries in aquaculture and hydroponics—have progressed to a point that aquaponic systems have potential to approach economic feasibility and the industry is growing [31]. Still, aquaponics has not yet had a large-scale commercial breakthrough [6, 10, 29, 32–35], and profitability has been a challenge inasmuch as there remain many barriers to further development [2, 14, 23, 34–36]. To shed more light on these obstacles and potential solutions, several of which are shared with other means of CE implementation, there is a need for holistic consideration of the forces shaping the developmental context of commercial aquaponics.

The difficulty of translating resource circularity and sustainability measures into broadly accepted economic and social value forms many of these developmental challenges. In this regard, as a regenerative technology regularly included within CE literature, commercial aquaponics faces many shared challenges to wider implementation as those discussed in the context of larger CE transitions. To develop functional understandings of barriers and drivers to the uptake of circular technologies like aquaponics and identify means of achieving successful sustainability transitions through actionable pathways necessitates systematic approaches. Assessing commercial aquaponics through socio-technical transitions theory, and specifically, through a Technological Innovation System Framework (TIS), can provide these much-needed insights into developmental dynamics of commercial aquaponic food production. Over the last decade, sustainability transitions research has gained prominence as a means to analyze environmental challenges that necessitate significant socio-technical systems change [37, 38]. Previous analysis of the broader aquaponics field as an emerging TIS has been undertaken for Europe in 2018 as well as specifically for the Netherlands [39]. An updated analysis reflective of more recent developments has not yet been advanced. Moreover, assessments focusing on the commercial sector, and comparable analysis in the context of North America, where commercial aquaponics has followed a different developmental pattern, are still lacking. To address this research gap, this study applies a lens of sustainability transitions theory to the development of commercial aquaponics to assess pathways to the successful realization of the potential sustainability benefits it offers at scale. A TIS framework and collaborative interdisciplinary assessment process is used to develop a qualitative analysis of functions revealing current drivers and barriers to the success of commercial aquaponics informed by semi-structured interviews with North American aquaponics operators (n=25) in 2021, policy analysis, and literature. Likewise, the application of Multi-Level Perspectives [40] incorporates the analysis of key socio-ecological landscape factors (i.e., climate change and resource scarcity, global supply chains, and environmental awareness) and responsive actions that shape possible pathways to achieve relevant sustainability outcomes in a developed regional context through the wider implementation of commercial aquaponic production.

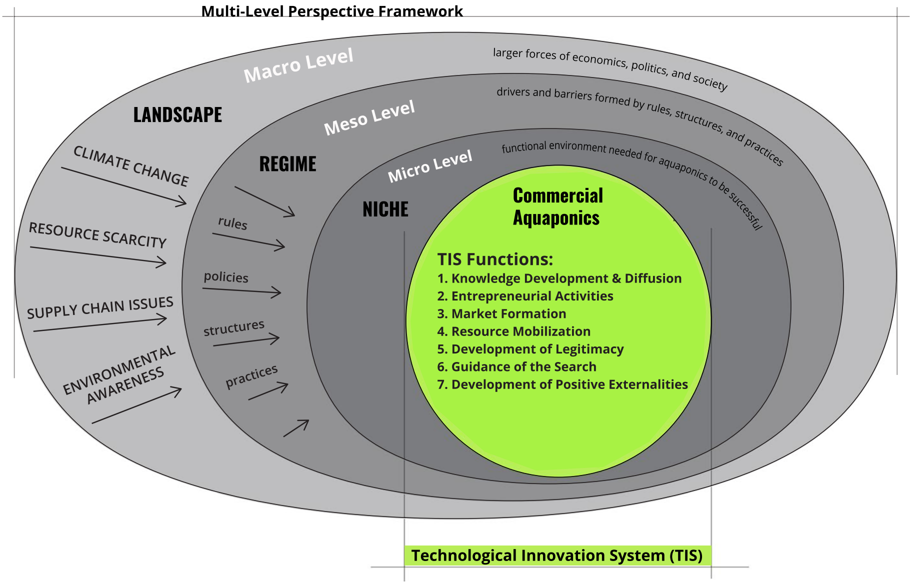
Elevating practitioner voices through a multi-level transitions framework allows for the development of both a contemporary functional assessment of the industry and a forward-looking analysis of developmental pathways to support the commercial advancement of aquaponics as an effective contributing technology for food production within CE. Accordingly, this investigation systematically elucidates the pulse of the current North American aquaponics industry for the broader sustainability community and aquaponics experts alike as a scaffold upon which transition pathways can then be understood and advanced for use in advocacy and advancement of commercial aquaponics within CE development. Accordingly, findings are intended to serve not only the aquaponics industry but also provide valuable insights and platform for critical comparison to CE implementation among the broader sustainability community who are pondering similar questions of systems and technological transition.

Analytical Framework and Methodology

Sustainability transitions theory poses a useful mechanism of connecting consideration of larger systems interactions, such as those conceptualized within the Food-Water-Energy Nexus and CE, to specific mechanisms of change to support the ability of particular technologies like aquaponics to contribute to implementation of more sustainable and circular resource use paradigms. The Food-Water-Energy Nexus has been an important concept within aquaponics research as a means of describing and assessing the complex interactions of food, water, and energy systems and the role that aquaponics can play as a CE-advancing technology in altering these interactions into more synergetic and circular modes [41]. To consider the question, therefore, of how such shifts toward circularity might be achieved at an industry level, a sustainability transitions approach is applied in this investigation. The concept of socio-technical transition pathways provides a means of investigating the interactions between an innovation system and its context [42–45]. Economic viability for commercial aquaponics can be shaped by contextual factors like climate, location, regulatory environment, certification, resource access and costs, local wages, public acceptance, and consumer interest as well as operational factors like fish and plant selection, energy consumption, workforce needs, business model, aquaponics knowledge, and technology use [23, 25, 30, 34, 46]. To actualize potential benefits of aquaponics, there is a need for elaboration of relevant social, economic, environmental, and legislative issues through organized frameworks [47]. Emerging sustainability innovations like aquaponics have been noted as often facing a "scaling-aversion dilemma" in which there is tension between "remaining in a small, alternative, and unique niche versus growing in size and striving for broader societal adoption" [48]. The Technological Innovation System (TIS) Framework provides a structure for qualitative functional analysis of the system of innovation around a specific technology, including ongoing development, use, and diffusion and can be utilized to assess aquaponics in this manner.

Framework Selection

To systematically evaluate drivers, barriers, and opportunities for innovation and industry advancement, this study applies the TIS framework to commercial aquaponics within the context of sustainability transitions to CE in food systems [42, 49, 50]. A set of seven functions are evaluated, characterizing the performance and dynamics of the system modeled on the precedent of TIS assessments in literature [49, 51, 52]. Recognizing the call for improving the theoretical foundations of agro-food-system transition studies [53], the approach at hand expands the TIS framework in response to the common critique that it does not sufficiently address the influence of surrounding contextual dynamics. This is approached by incorporating the Multi-Level Perspective (MLP) framework to support an analytical scope which is responsive to the multilevel complexities and interdependencies of biocircular food industry development [42, 44, 54]. Sustainability transitions literature helps to describe the interactions of three analytical levels shaping socio-technical change, a key determinant of successful CE implementation. These levels, commonly defined as landscape, regime, and niche (Fig. 1), are assessed within the MLP framework [38, 43,



Definitions for Commercial Aquaponics:

Landscape: (macro level) The landscape level is composed of socio-ecological forces including macro-economics, politics, and society which impact the need for, success of, and trajectory of commercial aquaponics.

Regime: (meso level) The dominant rules, structures, and practices that impact innovation and niche consolidation for commercial aquaponics.

Niche: (micro level) The functional environment needed for commercial aquaponics to be successful.

Function 1: **Knowledge Development and Diffusion**
Existing qualities of the knowledge base of commercial aquaponics and its development, including different types of knowledge, knowledge creation, and information sharing among actors.

Function 2: **Entrepreneurial Activities**
Interest and activities shown by actors within the TIS of commercial aquaponics, including the development and testing of new technologies and practices.

Function 3: **Market Formation**
Factors and mechanisms driving the entry of commercial aquaponics into relevant markets.

Function 4: **Resource Mobilization**
How financial resources are allocated and to what extent actors in the TIS of commercial aquaponics can access and mobilize financial and human capital and necessary infrastructure.

Function 5: **Development of Legitimacy**
The status and processes of social and institutional acceptance of aquaponics.

Function 6: **Guidance of the Search**
Describes the incentives and pressures for the growth of the field of commercial aquaponics and entrance of new participants.

Function 7: **Development of Positive Externalities**
Describes system dynamics in the TIS of commercial aquaponics through which externalities magnify the strength of the other functions and have further impacts beyond the TIS.

Fig. 1 Integration of Technological Innovation Systems (TIS) based on [42, 49, 50] and Multi-Level Perspective (MLP) frameworks, per [38, 43, 55–57], for the assessment of sustainability transitions of commercial aquaponics

55–57] and roughly align with the three CE levels (macro-, meso-, and micro-). These MLP levels can be interpreted as an expanded conceptualization of the three levels of CE which in this investigation are defined by their functional relationships to the innovation system of aquaponics. The landscape level is composed of socio-ecological forces including macro-economics and politics and is similar to the macro-level dimension of CE. The regime level is composed of dominant rules, structures, and practices, which are often self-reinforcing but can undergo incremental change [38]. It may be viewed as the socio-ecological parallel to the meso-level of CE. The niche level is the functional environment needed for aquaponics to be successful, e.g., the space occupied by the micro-level in CE, and can be characterized by the TIS function assessment. Utilizing a framework which considers all three levels is necessary to prevent oversimplification, as many of the landscape socio-ecological changes which shape the need for sustainability transitions, particularly of food systems, drive the niche formation of commercial aquaponics and comprise dynamic conditions for the development of the industry. Many of these larger environmental drivers, such as resource scarcity and climate change, are also key to shaping the need for CE implementation more broadly. For the study scale of commercial aquaponics, these changes act as landscape factors (macro-level) transforming demand and political and economic structures (regime) over time, shaping the context for commercial aquaponics and the functional environment it operates in (niche/micro-level). Accordingly, pertinent landscape factors which are influential on how commercial aquaponics functions in a context of regime change are evaluated [42, 43, 51, 58, 59]. This supports the consideration of sustainability transition pathways in which landscape factors drive and inform regime changes which can shape sustainability transition pathways through policy and economic changes, innovation, research, and social shifts needed to fully realize the sustainability potential of aquaponics by forming a supportive niche with strong performance in all TIS functions.

Data Collection and Analysis

The current state of commercial aquaponics was investigated through a mixed methods process which brought together data from semi-structured interviews with commercial aquaponics producers representing a cross section of the North American aquaponics industry and supplementary analysis of literature and policy review. Commercial aquaponics producers from a database of active commercial aquaponic farms in North America (*n*~152) were recruited in telephone calls for semi-structured interviews. The Circular City and Living Systems Lab (CCLS) led by Professor Proksch maintains a database of aquaponics related organizations and businesses globally. This database included 152 active commercial aquaponic farms located in North America in 2022. The recruitment received a positive response rate of nearly 17% and conducted 25 interviews. The interviewed farms are a representative sample of the known, active commercial aquaponic operations in terms of geographic location, approximate size of (hydroponic) growing area, and distribution of business models (Fig. 2).

The interviews included questions on farm background, producer experiences, system operations and design, future goals, and challenges (Appendix). The interview guide went through an internal review process with several rounds of review and edits by the authorial team as well as through the University of Washington Institutional Review Board (IRB) review (IRB Exempt: STUDY00013037). Interviews (*n*=25) were conducted in May–July 2021 and qualitatively content coded utilizing the TIS framework structure within the qualitative data analysis software Atlas.ti. The collaborative analysis and review process of interview, literature, and policy data integrate the interdisciplinary expertise of the authorial team in sustainability, aquaponics, aquaculture, engineering, and the built environment (Fig. 3). Reviewed literature included scholarly, general, and industry sources. To reflect the international scope of industry development and knowledge exchange, this review also included consideration of the EU environment for aquaponics where there has been more research and policy developments in recent years. This is reflected within the existing literature pool and is observable among the reviewed papers, of which approximately 25% are from North America and 50% from Europe. Though it should be noted that these also

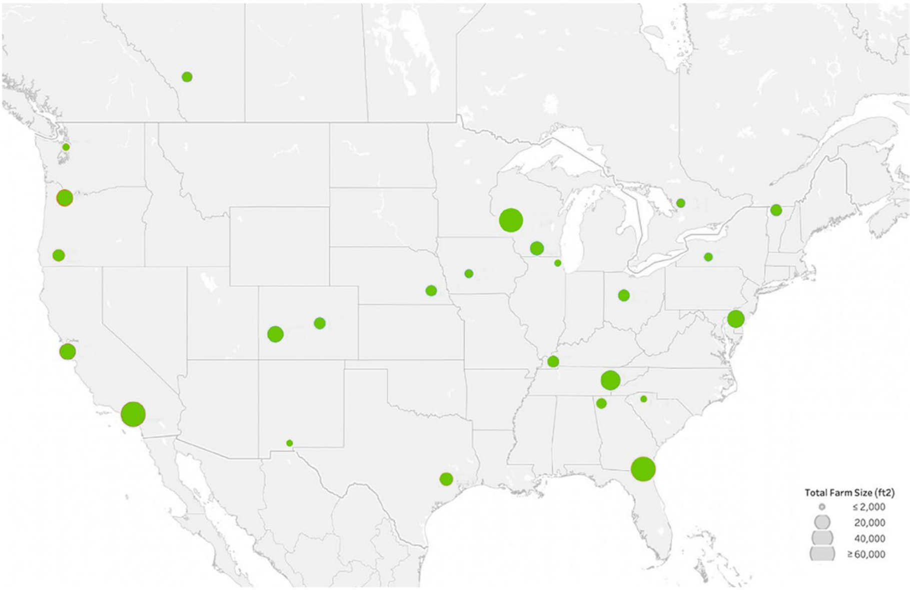


Fig. 2 Geographic locations of the interviewed farms in North America with approximate size of the growing area

included sustainability transitions and frameworks literature, the majority of which were written in Europe. While this in-depth report focuses on the state-of-the-art of commercial aquaponics in North America, the analysis considers both material describing the situation in North America and relevant literature and policy analysis documenting the situation in Europe and similarly developed nations, noting relevant similarities and differences. The resulting TIS assessment considers the current state of aquaponics, drivers and barriers, and the ideal niche for successful commercial operations. The discussion is shaped around an MLP lens, addressing pertinent landscape factors derived from landscape level topics most mentioned in the interviews and aquaponics literature and the regime changes they necessitate. Sustainability drivers are thus brought in conversation with the TIS functions to explore transition pathways between landscape (macro-), regime (meso-), and niche (micro-) levels toward the realization of the commercial and sustainability potential of aquaponics.

Results of Technical Innovation System Assessment of Commercial Aquaponics

Knowledge Development and Diffusion

Knowledge creation, access, and diffusion within aquaponics are driven by strong producer engagement and motivation for learning and teaching, as well as public interest in the topic on social media and the internet [60]. This is reflected in the number of internet searches related to aquaponics and the volume of research publications and associated funding [22,

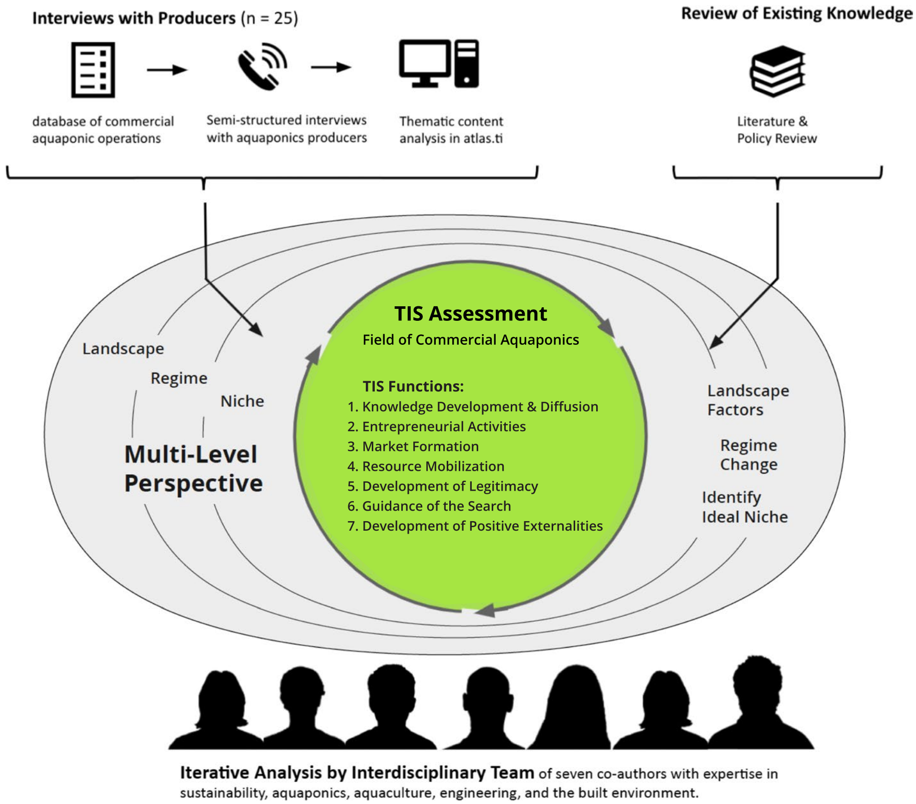


Fig. 3 Data collection process, review methods, and iterative analysis process conducted by the authorial team

61]. To successfully operate aquaponic systems necessitates a broad skill set and thorough knowledge of the system and its internal ecosystem [14]. Design and operation require an understanding of plant and fish biology, biochemistry, and microbiology, civil, environmental, and mechanical engineering, as well as interdisciplinary skills in business management, economics, and marketing [13, 46]. To address the full range of knowledge pertinent to an integrated production system, commercial producers can also benefit from access to third party expertise and consultation [11, 13, 23]. Although a trained workforce is an important ingredient in farm success, there is not a clear path to study aquaponics, especially as relevant technical knowledge can be siloed among disparate domains. Available training in aquaponics is largely offered through consultants, on-farm experience, university extension programs, and online or community education, including courses offered by practitioners and associations.

Roughly 30% of the interviewed producers had higher-education degrees in related fields (including agriculture or aquaculture) aligning with the observations previously made by Love et al. 2014 [33] though some leaders from larger companies came from business backgrounds (n=4) and employed technically trained staff. Of the interviewees, approximately half (n=13) were largely self-taught, and many (n~9) had taken aquaponics courses or trained with experts. Interviewees frequently mentioned Google and YouTube as sources of information. Likewise, several described experiencing difficulty filtering through information available online and in books for knowledge relevant to their commercial scale needs, particularly noting the saturation of hobbyist-directed content. Aquaponics has a popular following as a form of backyard or community-scale food production, particularly in urban areas, and serves frequently as an educational tool for multiple purposes, such as in schools, community projects, or prisons [11, 62–65]. Few interviewees reported that their primary source of knowledge about innovation came from academic research. Only 20% reported engagement and collaboration with researchers and universities though several reported reading scientific and industry trade journals when seeking information. A few interviewees (n=3) also noted their involvement in conferences and associations as an important means of information exchange and networking. About 70% (n=17) described having a network of key contacts that they relied upon when they had questions, including other producers, consultants, researchers, and educators. A few of the interviewed producers however, noted that they lacked industry contacts to ask for advice when they needed help. Pattillo et al. (2022) likewise express the importance of credible and accessible information on best practices to support new producers [31].

As such, knowledge development and diffusion can be further strengthened by increasing the availability of professional training, resources, and institutions for developing a technically skilled workforce equipped to operate aquaponic systems at a commercial scale. Recent research has demonstrated the need to include multiple stakeholders to move the industry forward through knowledge co-production approaches [66]. Innovation to bridge the gap between producers, researchers, and investors could also help enable pathways for the effective formation and distribution of knowledge on the practice and sustainability of commercial aquaponics.

Entrepreneurial Activities

Technological innovation is essential to improving aquaponics' economic feasibility, system performance, and sustainability [14]. Aquaponics is an infrastructure and technology intensive operation, wherein commercial farms in most climates require three types of infrastructure: (1) recirculating aquaculture fish tanks, (2) a hydroponic system that distributes the nutrient-rich water to the crops, and (3) enclosures, such as a greenhouse or an indoor space with grow lights for plant production and a well-insulated space for the aquaculture equipment. The enclosure turns the operation into Controlled Environment Agriculture which is essential in most climate zones for either heating or cooling [27]. The benefits originally discussed in the context of CE stem from a closed loop or coupled systems. Recent discussions in the industry investigate the advantages of decoupled systems, which transfer fish water to the hydroponics system and then recirculate it within the plant production system. While water recovery is possible in a coupled system, a decoupled system still allows for both nutrient and energy recovery while potentially improving optimization of both aquaculture and greenhouse performance.

The small financial resource influx into the field of aquaponics is a notable barrier to innovation of commercial aquaponics. Most aquaponic farms are self-funded and adjust their technology levels to their budget, even when more sophisticated solutions are available. Of the interviewees, only one exceptional aquaponic operation with access to substantial funding sources was able to develop a sophisticated cold water salmon aquaculture system combined with a large-scale state-of-the-art hydroponics system. This is also by far the largest operation with approximately 600,000 sf/ 60,000 m^2 controlled growing area.

Many producers will favor low-tech designs to lower the start-up capital required, even if they know in the long term that other solutions may be able to reduce their ongoing production costs. Interviewed producers were highly engaged and interested in improving and optimizing their systems, though many described difficulties affording desired upgrades. Due to the culture of disseminating knowledge through informal applied pathways, many aquaponic operations develop their own technology and use at least partly self-engineered systems. The analysis of the interviewed farms (n=25) reflects this observation, with some overlap noted; thirteen primarily rely on low-tech, self-constructed systems, seven of the farms utilize partly self-engineered infrastructure, and seven use professionally engineered systems installed by a commercial supplier. Largely similar proportions were observed in Pattillo et al. (2022)'s survey of aquaponics stakeholders, of whom 84% were located in the USA [31].

Many producers classified themselves as involved in "research" at the farm level to advance their systems (e.g., experiments focused on increasing growth rates, solving problems with pathogens or other related optimization issues). A number described this ongoing process as "trial-and-error," with 20% (n=5) using the term word for word. Active areas of current research and development include optimizing nutrient recovery within aquaponic systems and developing successful approaches to saltwater aquaponics, which are on the rise [31]. Nutrient recovery in aquaponics is facilitated by microorganisms which help process fish waste into nutrients suitable for uptake by plants [67]. This process is enhanced within biofilters, media beds, and/or digesters [68]. For instance, specific technological interventions to fully utilize not just dissolved organics but also solid wastes make it possible to optimize nutrient recovery [69]. Much of the innovation over the last 15 years has reduced operating costs or allowed for the scaling up of production to achieve economies of scale. Technologies, such as LED lighting, more cost-efficient climate control systems, and the automation of the production process, have emerged from other sectors and have been transferred to the aquaculture, hydroponic, and aquaponics industries [70, 71]. Aquaponics can be further strengthened by advances in system design and technology to improve economic feasibility and sustainability through waste minimization, resource recovery, and competitive innovations.

Market Formation

Global interest in aquaponics has not yet translated into a multitude of commercial aquaponic farms. There are still only a small number, mainly in North America, which can demonstrate profitability and business continuity. The USDA Census counted 73 operating aquaponic farms in 2013 and 83 in 2018; this is compared to numbers of aquaculture operations, 2853 and 2704 respectively [72, 73]. The authors identified 152 active commercial aquaponic farms in 2022 in North America, based on the database maintained by the Circular City and Living Systems Lab (CCLS) led by Professor Proksch, with the acknowledgement that many more have opened and closed in the interim [34, 72, 73].

In general, there are two types of commercial aquaponic operations: type 1 relies primarily on a business model of producing food from plants and fish, while type 2 also produces food but offers other services, which can diversify revenue streams [11, 34, 74]. These additional offers can be aquaponics courses, workshops, consulting, hospitality-related events, food services, or other public installations [27, 33]. Both types face the same challenges in bringing their produce and fish to market. Typically, fish and produce need their own distribution channels. Currently it is difficult for aquaponic products to compete in undifferentiated markets as production costs cannot necessarily be recovered through higher prices without a strong marketing strategy and access to niche markets [10, 11, 36]. Aquaponics is bolstered by its capacity to produce food in a controlled environment year-round in markets with seasonal limitations and to fill local food market niches. Using aquaponics, food can be produced in very close proximity to where it is purchased, sometime even right next to grocery stores or restaurants, providing a particular local appeal and potential for reliable supply. Most producers in the interviews conducted for this study described demand from local restaurants and individual buyers, often in volumes beyond what they were able to supply, driving them to want to invest in scaling up their production. However, accessing capital to do so was not always easy. Most farms had more than one distribution stream, many were selling directly into the restaurant and institutional markets (n=14) or were engaged with consumer sales at the farm level (e.g., on site or at farmers markets) (n=19). Some (n=11) had contracts with grocery chains, or with secondary processors (e.g., for fish products), but few (n=3) reported wholesale markets as their primary target.

Several barriers to market success exist, with producers expressing the difficulty of recovering high production costs and imbalances in the profits derived from the sale of produce and fish. For most enterprises, crops will generate a higher return than fish due to high turnover (such as 6 weeks to market rather than a year or more), particularly when low-value fish like tilapia are chosen [11, 36, 75]. The result of a plant-focused operation such as this often is that fish are not harvested as processing and selling are complicated, so fish are used as a source of nutrients only. The post-harvest handling and sale of live fish were described as difficult by many producers with limited experience in aquaponics, or who did not wish to invest in permits for euthanizing fish and value-adding activities such as fileting, smoking, packaging. Many of the interviewed producers described little contribution of revenue from fish, and more than half (n=14) opted not to sell fish grown within their systems. Approaches to increasing fish profitability include producing higher-value fish species (e.g., trout or sturgeon) or increasing volume of production so that fish sales could be worthwhile [11, 76]. Overall, actions to advance market formation for aquaponics are needed, including increasing access to affordable and reliable processing, storage, and distribution channels, as well as conducting more cost-benefit analyses to better inform decision-making surrounding operational and marketing strategies.

Resource Mobilization

The mobilization of resources within the aquaponics industry is growing although still limited. Currently, the aquaponics industry in North America has not garnered support from two significant pathways which have benefited other agricultural industries, namely government subsidies and technology industry funding. Hydroponic greenhouses and indoor farms have received exorbitantly high investments from the technology industry to advance and sell sensing and automation and sensing equipment at the large scale [70, 71, 77], while the aquaponics industry has not seen the same influx of funding. Notably, some interviewees suggested that the complexity of the two combined growing systems and infrastructure needs were deterrents for investors.

In the EU, financial resources to farms are provided in the form of agricultural subsidies through the Common Agriculture Policy, which does not include aquaponic and hydroponic farming. Although the EU has provided some financial support for research on aquaponics through its funding schemes like The Seventh Framework Program (e.g., INAPRO) and Horizon 2020 (e.g., for COST Action FA1305 2017) much of this support has been aimed at academic and applied research, while support is still needed for commercial development of aquaponics [78, 79]. In the USA, aquaponics is embedded in the latest 2018 Farm Bill, which offers financial support to urban farming operations, including aquaponics, but the actual funding for commercial aquaponics from the bill is relatively insignificant, especially compared to the large upfront capital costs needed for operational infrastructure for commercial scale production [16]. Notably, due to the difficulty of accessing external funding, self-funded projects in North America remain the strongest examples of commercial success thus far. Given that infrastructure costs can prove a challenge, a better scaling of access to sufficient resources, including capital investment, can help farms to enter the market with more success and produce at more competitive commercial scales. However, with more limited resources, starting at smaller production scales and then scaling-up as demand increases is a tactic pursued by many commercial producers.

More pathways should be created for start-up funding and investment including access to loans, government incentives, and grants, as well as access to decision-making tools for optimal location selection and resource synergies with neighboring industries, such as energy producers. Affordable water access and renewable energy sources may also reduce operational costs [11, 33]. Commercial aquaponics can also benefit from affordable land located in proximity to population centers, though interviewees noted that zoning restrictions and competition from other industrial uses can limit site options. To the particular benefit of CE and expansion of industrial symbiosis, there are also opportunities in some locations to integrate synergistically with other systems and resources through co-location such as via integration of resources like excess heat from other industries in close proximity for mutual benefit [80, 81]. This practice is already on the rise in a European context, where useful lessons may be learned. A North American example of this was mentioned in the interviews by a producer who had made progress on a potential partnership with a landfill adjacent to a prospective aquaponics site to use the excess heat from the landfill to heat their greenhouse. Using these types of CE strategies for aquaponics has been considered in literature and practice as a means of resource efficiency and cost reduction in addition to that already facilitated within the aquaponic system itself [14]. Not all of these potential synergies were reported as realizable by interviewees, in part due to the lack of recognition of aquaponics as a viable high-output commercial industry by potential resource-sharing partners.

Development of Legitimacy

There is strong potential to improve the understanding and perception of commercial aquaponics given popular interest in the growing technology and its increasing recognition as a strategy for sustainability and climate-resilience [82]. However, both literature and the interviewed producers noted challenges to the acceptance of commercial aquaponics, including in organic certification, consumer perception, and trust from potential investors and commercial partners.

Organic certification can be expensive and difficult to attain—though is a keyway to justify higher sales prices that are currently needed to cover production costs. In the USA, this certification is possible, though not easy to secure for aquaponic produce, while it is not attainable for typical aquaponic systems in Europe due to definitions of organic that exclude soilless growing [83]. Even in the USA, several issues arise around use of inorganic substrates in hydroponic components, and whether nutrients from fish feed sources can be classified as organic [84]. Several interviewees had pursued organic certification, but most observed high associated costs and expressed frustration, noting the prohibitive certification costs especially for small producers; the need for alternative and more manageable certification schemes for small operation; and challenges securing understanding from certifying bodies. Only a handful (n=4) specifically mentioned that they were maintaining their formal organic certification status. Likewise, the absence of organic certification could be a potential barrier for commercial aquaponics in the EU [79, 85]. A recent study reported that aquaponic products cannot be certified organic under the new Commission Regulation (EU) 2018/848, mainly due to use of soilless production, use of non-organic feeds in fish production, and the cultivation of fish under artificial conditions [86]. It is possible to circumvent this by stretching the bounds of what is conventionally considered aquaponics by cultivating herbs as potted plants that are irrigated with nutrient rich water from the fish and by meeting certain requirements for fish feed and welfare in the aquaculture component [83, 86].

Advancing the perception of aquaponics as natural—even if not organically certified—was a strategy pursued by several interviewees, while others foremost prioritized pursuing lower production costs, which they viewed as most important to consumers. A potential barrier can be consumers' perception of food that is grown out of its ecological context through soilless methods as unnatural [87, 88]. Aquaponics arguably addresses an aspect of this problem by utilizing "natural" nutrient sources from the fish; however, for some, farming fish also raises issues of animal welfare [89]. Legitimation from customers will probably require more effective ways to explain the advantages of the technology which are connected to healthy food, reduced externalities, and resource circularity. Producers accordingly espoused the importance of educating the public about the benefits of aquaponic production, which they pursued through strategies such as tours, classes, and farm-to-table dinners. They likewise expressed the need for further efforts to validate aquaponics, such as via studies on produce quality which could be referenced in marketing settings. Securing trust and buy-in from economic partners was a challenge for several producers (n>5) who mentioned issues with potential banks, investors, and business partners. These either did not know what aquaponics was or wanted more examples of successful large-scale aquaponic operations, which were difficult to provide. Pattillo et al. (2022) noted similar observations in this regard [31]. This reflects a need to validate the technological and commercial viability of aquaponics more fully and particularly to prove economic feasibility in large-scale production as the industry matures [25, 47]. Strategies to advance legitimacy may include developing effective sustainability labeling for aquaponics, and furthering public awareness, recognition from other industries, and governmental support to advance acceptability to stakeholders of aquaponics as part of sustainable food transitions.

Guidance of the Search

Interviews with producers reinforced that the sustainability potential of aquaponics is also a strong motivator for entrants to the field. However, in general, aquaponics producers encounter a complex policy and regulatory environment that does not have specific provisions for "mixed" fish and plant farming [10]. This lack of aquaponics-specific legislation creates economic and logistical challenges, forming "a complex barrier to commercial scaling up and the transition to a more sustainable circular economy" [10].

The US Food and Drug Administration regulates food safety through the Food Safety Modernization Act in which plants are managed under the Produce Safety rule and fish under the seafood HACCP rule [90]. Fish processing requirements were cited as a challenge by many of the interviewees, who described the need for an aquaculture license and food safety training to sell or transport fish and economic difficulty of affording necessary infrastructure, particularly noting the cost of blast freezers. Many consequently focus their commercial model on produce and sell (or give away) their fish directly to a wholesale market that slaughters and distributes them, thus negating a potentially lucrative income stream. Some producers alternatively grow ornamental fish that are not subject to food safety regulations. In the case of produce, "first-cut" harvests do not require food-processing facilities, but any additional processing steps are subject to further regulation. Several interviewees noted the importance of pursuing certifications like GAP, particularly to sell to certain distributors, though some cited restrictive costs of changes needed to meet requirements. Interactions with food safety auditors, certification boards, and regulatory authorities who lacked knowledge of aquaponics were also described as a challenge by several interviewed producers. Local level regulations also frequently exist, including environmental measures preventing invasive fish species that can influence fish selection and breeding and impact market opportunities for producers.

The complex nature of the EU policy and regulatory environment for aquaponics [47, 78, 79, 91] also appears to be a barrier for commercial expansion [25], which is exacerbated by the lack of clear guidelines at country level [91, 92]. Regulatory barriers to aquaponics in the EU stand in contrast with its often-referenced high potential to help achieve policy goals by promoting innovation, enhancing competitiveness and sustainability, improving access to space and water, and advancing resource efficiency [11, 78]. Globally, due to the current barriers in the complexity and insufficiently specific policy environment for aquaponics, there is a need to develop certifiable standards, clear aquaponics-specific policies, and easy approval processes. Further advantages may also be found by embedding aquaponics in integrated policy environments seeking food security and environmental sustainability.

Development of Positive Externalities

Beyond sustainable food production, commercial aquaponics applications also generate societal benefits such as community support as an educational and job training tool [63, 93–96]. These educational activities may also help to develop skilled employees for emerging markets, to increase consumer awareness and acceptance of aquaponics products, and to promote systems thinking and CE [23, 97, 98]. Type 2 aquaponic operations in particular offer other services in addition to food production. Besides opening their doors for events rentals, catering, and community gatherings, many offer educational programs for other operators and entrepreneurs as well as for youth and workforce training. Providing access to food, education, and career development opportunities to minority groups are among the social challenges these farms address [99]. For instance, the Farm on Ogden in Chicago, IL includes a commercial aquaponic system run by the non-profit Windy City Harvest. The organization aims to bring food, health, and jobs to the community through local production and sales of healthy food, distribution of prescribed Veggie Rx packages to patients who are at risk for diet-related diseases, and job training programs in an underserved Lawndale neighborhood.

The positive externalities of commercial aquaponics demonstrated in applications as an educational and job training tool and offerings of community support also help to nurture social awareness of its benefits and potential contribution to CE within food systems.

This contribution could include reducing resource use and waste and reusing and recycling water and nutrients within food production. As widely discussed within literature, food production within cities is considered vital to bolstering sustainability and resilience of urban food systems, reducing environmental footprints of urban food sources and strengthening the dependability of local food availability to urban populations when larger supply chains are strained [6, 100, 101]. The COVID-19 pandemic shaped mixed impacts to producers using controlled-environment growing methods, while some hydroponic farms experienced significant demand increases for fresh local food, other operations lost distribution channels and closed. Likely as a result of this period, local production has been emerging as an increasingly recognized benefit of aquaponics. Moreover, in addition to providing food, aquaponic production can provide other services. For instance, the popular usage of aquaponics as a form of urban agriculture can be integrated symbiotically with other systems (e.g., district heating) seeking to exchange and efficiently cycle resources among food, water, and energy systems, an outcome in alignment with CE practices [74, 102]. By advancing the benefits of commercial aquaponics to societies and communities through educational and community programming and improved resource circularity, continuing to strengthen these additional services of commercial aquaponics is to the advantage of the entire commercial aquaponics industry and may be essential in helping aquaponics serve as a successful vehicle for sustainability transitions.

Discussion of Sustainability Transitions Pathways

TIS Function Assessment

The TIS level analysis of functions shows that the primary drivers of commercial aquaponics fall into three main areas: the recent high research productivity and technological advances in the field, the environmental benefits which this growing method can provide, and the public and consumer interest that these potential benefits generate, as indicated in Table 1. For instance, the TIS analysis indicated that the commercial industry is bolstered by increasing research production, technological advancements, and the engagement of producers in ongoing innovation efforts. Moreover, the sustainability potential of aquaponics was stated by interviewees as a motivating factor for producers entering the industry. Aquaponics is increasingly noted as a strategy among ever-more popular sustainability frameworks, including the Food-Water-Energy nexus and CE, which may play a role in the further optimization and advancement of the industry to reach shared environmental, economic, and social sustainability transition goals. [103]. Likewise, public interest in aquaponics and its ability to contribute to local markets help to drive its commercial potential forward.

However, the TIS findings also indicate that commercial aquaponics still faces significant economic challenges, which generate the main barriers that limit the expansion of the field. Fundamentally, to achieve the environmental sustainability it promises, commercial aquaponics also needs to be operable as a successful business for producers. However, the TIS functions reveal that it currently proves difficult for aquaponics producers to turn sustainability benefits, like water efficiency, into significant business advantages. Notably, many of the system's environmental and social benefits, such as the avoidance of potential water polluting effluents, efficient water use, and capability for local food production even in extreme climates, are external to the producers and therefore do not currently improve

Table 1 Summary of the main findings from the current assessment of the drivers and barriers of TIS functions for commercial aquaponics and key lessons for sustainability transition

TIS Function	Drivers	Barriers	Niche Formation Actions
1. Knowledge Development and Diffusion	Large public interest in aquaponics Existence of research funding (primarily EU, NSF) Consistent increase of research production and publications Producers are motivated and engaged in learning and teaching	**?** Siloed knowledge between hydroponics and aquaculture **$** Challenges finding information appropriate for commercial operations **$** Difficult to find workforce trained in aquaponics	Facilitate easy access to cutting edge knowledge and well-trained workforce (function 1)
2. Entrepreneurial Activities	System innovations improve aquaponics' feasibility and performance Advancement of new technologies and management practices growing out of research and practice Producers are highly motivated to improve their systems.	**$** Aquaponics is an infrastructure and technology-intensive (and therefore costly) operation **$** Producers described difficulty affording desired upgrades	Advance system design and technology to improve economic feasibility and sustainability performance (function 2)
3. Market Formation	Year-round production in markets that are subject to seasonal variations Potential to establish a niche in the local market. Most producers described demand from local restaurants and individuals	**$** Higher overhead increases production costs, which is not recoverable through higher market prices **$** Fish and produce need each their own distribution network **$** Imbalances in profits from produce and fish. North American producers often described little contribution of revenue from fish	Develop cost-effective production and competitive market-integration (function 3)
4. Resource Mobilization	Start-up funding can be scaled based on farm size and location Growth of related fields offer models of success Small-scale, low-tech systems can be feasible under certain peri-urban conditions	**$** Small financial resource influx into the field **$** Self-funded projects remain the strongest examples of commercial success thus far **$** Lack of government subsidies and tech industry funding **$** Access to investment capital is by lack of large-scale models of success	Increase availability of financial and physical resources for aquaponics (function 4)
5. Development of Legitimacy	Popular interest forms starting point to strengthen perception and understanding of aquaponics Recognition of aquaponics as a sustainable growing technology by prominent organizations (UN FAO)	**?** Limited public awareness about circular economy benefits of resource recovery **$** Organic certification can be expensive and difficult to attain for aquaponic operations – though often a keyway to justify higher sales prices	Advance consumer, regulatory, and commercial awareness of advantages of aquaponics (function 5)
6. Guidance of the Search	The sustainability potential of aquaponics is a strong motivator for producer entrants to the field Aquaponics is increasingly noted as a sustainable food production method seeking political support (i.e., Food-Water-Energy Nexus, Circular Economy, etc.)	**?** Complex policy and regulatory environment and approval process, lack of policies specific to aquaponics **?** Lack of knowledge about aquaponics by food safety auditors, certification boards and regulatory authorities **$** Frequent economic and logistical difficulties around fish processing	Develop supportive, clear, and easily navigable aquaponics-specific policies and regulation (function 6)
7. Development of Positive Externalities	Urban and community-based aquaponics can help to increase consumer awareness and acceptance Help drive support for new low-cost approaches to optimizing system performance and sustainability	**?** Underdeveloped awareness about additional benefits beyond food production **?** Limited evidence of commercial success	Strengthen mutually beneficial relationships with other applications of aquaponics (function 7)
Legend	*research and technological advances; public and consumer interest; environmental benefits* **$** economic/financial challenges; **?** lack of knowledge and support ; economic/ financial benefits and support		

Table 2 Recommended regime change strategies for stakeholders in policy, society, and industry per TIS [42, 49, 50] and MLP [38, 43, 55–57] assessment findings

Regime changes	Pathways	Example strategies
Develop policies and economic regulations that accurately internalize environmental impacts	***Privileging*** Increase regulations and incentives to confer business advantage for environmental and societal benefits of aquaponics	-Expanding legal flexibility for aquaponics through certifiable standards [79], clear aquaponics specific policies, and easy approval processes [97] -Increasing availability of start-up funds and financial and logistical support for aquaponics producers (functions 1 + 4) e.g., government-backed loans [31] -Making regulation (function 6) and resources for integrated commercial systems and industrial symbiosis more navigable (functions 1 + 4) -Incentivizing water and nutrient efficient food production (function 4) -Embedding the promotion of aquaponics in integrated policy environments that promote national food security (function 6)
	Supporting Promote resource efficiency, carbon emission reductions, and environmental sustainability through policy change	-Creating policies based on circular sustainability frameworks (function 6) -Supporting transitions to renewable energy through incentives and disincentives, e.g., introduction of global GHG emission taxes on food production [41, 111] -Creating payment systems for ecosystem services [112] -Advancing strategies to identify optimal locations and opportunities to integrate synergistically with other businesses and resources (function 1 + 2)
	Rebalancing Decrease support for competing unsustainable production practices	-Reducing excessive subsidies for competing food production industries with high resource use and polluting-processes (e.g., reduced subsidies for high-water usage crop producers) (function 6)

Table 2 (continued)

Regime changes	Pathways	Example strategies
Advance research and development to innovate and optimize performance of aquaponic technology	***Optimizing*** Increase economic feasibility and sustainable performance to advance commercial success of aquaponics through innovation in system design, technology, and operations	-Advancing cost-effective technology for optimizing environmental benefits and nutrient recovery (function 2) -Pursuing operational efficiencies to lower production, processing, and distribution costs and increase reliability (functions 2 + 3)
	Knowing Facilitate easy access to cutting edge knowledge, practical information, and well-trained workforce	-Connecting research and practice, and expanding collaboration, exchange, and dissemination of knowledge (function 1 + 2) -Increasing the availability of professional training, resources, and institutions to develop a technically skilled workforce (function 1)
Strengthen societal interest and understanding of aquaponics to generate social, health, and environmental benefits, and food security	***Promoting*** Nurture broad awareness of benefits of aquaponics such that popularity and high regard within society generates market advantage	-Incentivizing innovation in food distribution to process and market yields from smaller producers [10] -Continuing to strengthen other applications of aquaponics such as an educational tool, community farm, and recreation (function 7)
	Evaluating Develop effective holistic evaluation of aquaponics performance, sustainability, health, and societal benefits	-Conducting economic (e.g., cost-benefit) analysis with consideration of benefits of circularity and avoided life cycle environmental impact (function 5) -Supporting better informed consumer decision making through organic certification and sustainability labeling (function 5)

commercial profitability [2]. A conducive business environment for aquaponics relies on the prices of aquaponics-grown produce and fish becoming more competitive. There is a need for availability of financial resources for aquaponics to increase, production costs to decrease, and resource efficiency and nutrient recovery potential to translate into market share gains. The development of this "ideal niche" for aquaponics will require improvements in all of the seven TIS functions, including, but not limited to, (1) advancing access and dissemination of knowledge, (2+3) innovating system designs and operation to further economic and sustainability performance, (4) increasing availability of financial resources while (5) increasing customer acceptance, (6) removing regulatory barriers, and (7) reducing misconceptions about aquaponic production at both consumer and regulatory levels.

Multi-Level Perspectives

The barriers to the success of commercial aquaponics are largely shaped within existing economic and socio-political structures (regime). The potential environmental benefits of aquaponics can help respond to global challenges and shifts like climate change and resource scarcity, global supply chain changes, and growing environmental awareness. These forces pose landscape factors which drive the need for climate action and sustainability of human systems [104]. There is accordingly potential for aquaponics to overcome economic barriers through regime level changes of regulation, innovation, and societal behavior which will become increasingly necessary in response to pressing global challenges and socio-ecological change.

By recognizing the interaction of landscape factors and corresponding regime changes needed to propel progress rather than maintenance of the status quo, sustainability transition pathways emerge that can transform the operational environment and outlook for commercial aquaponics, thereby fostering the attainment of the environmental and social benefits aquaponics can provide (Fig. 4). Within these pathways, regime changes can be advanced at multiple levels including through political and economic regulation, industry innovation, and societal systems change enacted by stakeholders including policymakers,

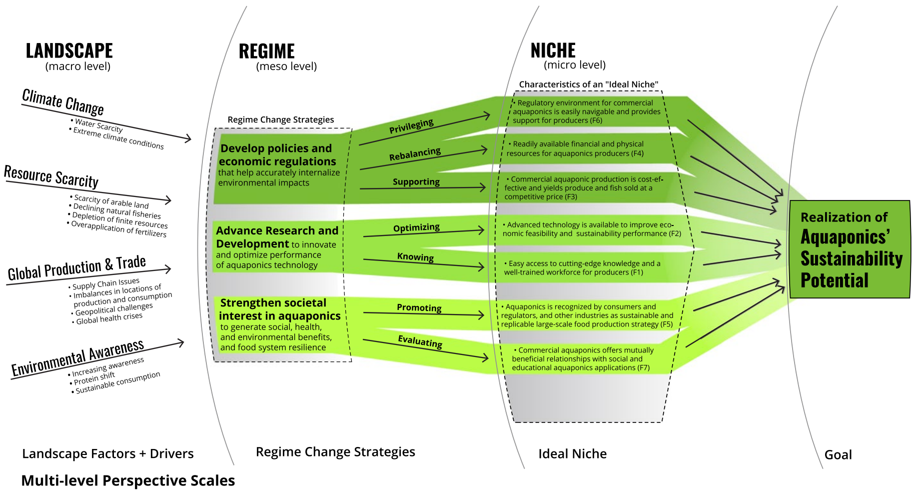


Fig. 4 Overview of sustainability transitions pathways for commercial aquaponics based on Multi-Level Perspective [38, 43, 55–57]

the commercial aquaponics industry, and the public. These actions can help translate the pressures of landscape factors into a more supportive environment (niche) for commercial aquaponics. Pathways include the translation of environmental and societal benefit into business advantage; placement of pressure on unsustainable modes of production; support and leverage of aquaponics' sustainability and efficiency into economic feasibility through technological innovation and development; and advancement of market advantages at a societal level by increasing consumer preferences for sustainable and healthy food sources.

Regime Change Strategies and Stakeholder Actions

Regime change can be categorized into three groups of strategies: (1) political and economic regulation to properly internalize environmental impacts; (2) innovation of aquaponic technologies; and (3) evaluation and promotion of the societal benefits of food system resilience and local production, as shown in Table 2. These strategies shape pathways toward ideal niche formation of aquaponics. Advancing policy and economic regulation to attribute economic value to the environmental benefits of aquaponics may prove pivotal to the successful commercial expansion of aquaponic food production [2, 25, 30, 105]. This generates a pathway characterized by increasing the availability of financial resources while removing regulatory barriers. Measures that incentivize sustainable benefits and disincentivize unsustainable aspects of some existing industrial agriculture practices can both play a role in bolstering the commercial viability of aquaponics [10, 83, 106]. Although policy makers are introducing sustainability-oriented measures with growing frequency, transforming political and economic systems to account for planetary and human health is a complex endeavor which can encounter significant inertia [107]. For aquaponics to help advance food systems sustainability and CE, there is a fundamental need for supportive regulatory and policy measures, including through economic tools like incentives and subsidies. In North America, business development grants and tax incentives can form a successful funding track, but there is minimal support from federal sources for operations categorized as forms of urban agriculture. Hao et al. (2020) likewise emphasize that aquaponics producers cannot afford costs of commercial scale production without policy and market support [22]. Governments and regulatory bodies can further support aquaponics by helping to advance access and dissemination of knowledge. Such actions can be tied to larger sustainability development efforts [10]. Holistic sustainability frameworks like CE, circular city, and the Food-Water-Energy nexus can help frame organized efforts toward the implementation of resource circularity practices in human systems including in the case of the wider integration of commercial aquaponics within food systems and should be supported by technical and organizational research efforts [103].

The second regime change strategy describes the need to continue optimizing aquaponic systems through innovation and evaluation of commercial aquaponic farms. This shapes pathways which can generate a supportive environment for commercial aquaponics, such as by innovating system designs and operation to further economic and sustainability performance and reducing misconceptions about aquaponic production at both consumer and regulatory levels through evaluation. There are further research needs in nutrient management and recovery, system construction, pest-management, and microbial community structure [22]. Strategies to recover nutrients, especially phosphorus, are crucial to prevent global food shortages in the future [108]. The phosphorus sustainability challenges [109], thus, may become a growing driver of implementation of aquaponic production, especially as nutrient recovery may present a market opportunity capable of driving higher uptake.

Likewise, as energy costs can pose one of the largest inputs for producers, across global contexts, both sustainability and the costs of doing business will improve as technology advances makes aquaponic systems more energy-efficient, and affordability of renewable power sources improves. Innovative approaches to resource integration with local heating and energy systems and other industries are likewise needed. There is further opportunity to expand awareness of possible symbiosis and optimization possibilities among North American practitioners, as only a subset of those interviewed were actively engaged in thinking about additional opportunities for CE-oriented business partnerships. Moreover, increasing the availability of professional training, resources, and institutions for developing a technically skilled workforce will both support farm success and ongoing innovation in commercial aquaponic technology and operations.

Finally, translating and promoting the value of aquaponics to consumers, policymakers, and investors will be key to sustainability transitions and can be facilitated through effective holistic assessment and communication of sustainability benefits [14]. More transdisciplinary research, including aquaponics operators and stakeholders, is needed to better elucidate the current sustainable performance and practices of commercial aquaponic operations in comparison to the possibilities for documented in literature. Accurate claims and supporting evidence of aquaponics' sustainability are essential to securing legitimacy of the production method, while inaccurate assertions could be detrimental [6]. Therefore, continued optimization and innovation of certification systems is needed, including improving affordability and access to relevant information for producers. Particularly, for some, whether aquaponics is certified organic or sustainability-accredited through similar programs may influence how it is perceived by consumers who may be attracted to associated concepts of healthy food or environmental production practices, which may or may not be truly reflected by the requirements of certifications systems in some cases [110]. Currently, producers may need to carefully weigh the benefits and drawbacks of certification—economic and logistical—for their given markets, and improved certification paths for aquaponics may be broadly beneficial to producers and consumers alike. The enactment of changes like these within political, societal, and industrial structures at the regime level can help commercial aquaponics develop further as a core strategy within crucial sustainability transformations taking shape in the face of macro-level global challenges.

Conclusion

Utilizing a TIS-MLP approach that brings together qualitative assessment of semi-structured interviews with commercial producers, literature and policy review, and expert knowledge, we have examined how the promise of commercial aquaponics can be developed toward commercial success at a scale which can enable the industry to substantially deliver on its sustainability potential such as water and resource efficiency. This assessment can help provide useful reflection of the state and potential of the aquaponics industry for commercial producers as well as provide insight into the potential role of aquaponics as a strategy within circular food systems transitions relevant also to broader sustainability research and assessment efforts. Transition pathways fostered through political, economic, and social action are needed to help scale-up and expand successful and sustainable commercial aquaponic operations such that they are a well-regarded standard rather than exceptional cases. Among the operations interviewed were some of these success stories. The interviewees did not only include the largest aquaponic operation in North America (see Sect. 3.2); the next largest farm increased its controlled growing area fivefold since 2016, and six other businesses opened during that period. We find that widely translating the environmental potential of aquaponics into an economic reality for sustainability transition will require rethinking current modes of evaluation, funding, and regulation; advancing the performance of aquaponic systems; and more effectively communicating its sustainability to consumers. Support for these developments can enable a larger number of commercial aquaponic operations to expand their possible benefits for the CE, particularly via scaled-up contribution to water and nutrient efficient production of fish and vegetables. Promise is observed in the increasing utilization of aquaponics as a local production method and growing efforts to integrate multiple resource streams with other local actors, furthering the potential services provided by aquaponics and increasing the potential depth of its integration with CE through multi-level FEW-nexus interaction, as noted within 3.4 and 3.7. To form a supportive niche for aquaponics, action is needed from policymakers, producers, researchers, and the public to innovate system design to further environmental and economic performance, increase financial resources while removing regulatory barriers, and reduce misconceptions about aquaponic production at both consumer and regulatory levels. In turn, if stakeholders within the aquaponics industry are empowered through access to reliable and relevant knowledge, financial resources, and improved regulatory conditions, they will be better positioned to help respond to pressing global challenges through the realization of beneficial environmental and social impacts of aquaponics at scale. Resource efficient production and contribution to local food system resilience strengthen the development of CE, and deepening these attributes of aquaponics through innovation and streamlined regulatory processes would seem to be closely aligned with the future commercial viability of the industry itself.

Given the considerable socio-ecological challenges of our time, integrating sustainability transitions perspectives within economic and regulatory systems is becoming increasingly crucial. Research on promising technologies and industries which seek to respond to these challenges should also consider developmental pathways through a sustainability transitions lens in order to capture the dynamic nature of drivers, barriers, and development needs shaped by socio-ecological factors. Applying this lens to commercial aquaponics by utilizing a TIS-MLP framework has indicated the need for transdisciplinary efforts to support the development of the industry as an impactful technology for resource circularity and food production, not least by better internalizing economic valuation of potential positive social and environmental impacts of the industry and thus supporting its economic sustainability to shape a well-balanced and successful circular food production strategy at a commercial scale. Moreover, to expand on this work, there is a need to further evaluate the role of scale and resource integration of aquaponics in a context-informed manner and assess potential gaps between current industry operational and technical practices and more optimal sustainability performance, particularly noting increasing economic and supply pressures on energy resources. As resource sharing arrangements (e.g., industrial symbiosis networks) that include processes like aquaponics become more common, there is likely to be a continuing need for transdisciplinary research which considers not only technological development, but organizational and socio-ecological factors that impact the implementation, performance, and success of these promising but complex CE strategies. Through such developments, future assessments can build on this investigation to help translate the environmental potential of aquaponics—and indeed other regenerative and symbiotic production practices—into a flourishing economic reality as part of broader-scale sustainability transitions.

Appendix. Interview Process Protocol

Recruitment Protocol

1. Use *CCLS's Aquaponics Operations Directory* to identify active aquaponics farms in North America.
2. Call the owner or operator of the farm using the recruitment script.
3. Record the response and schedule an interview with the recruited participant.
4. Call again at a different time if you do not reach anybody or not the right person.
5. Send a follow-up email with a Zoom link to the participant.

Interview Protocol

6. Once in zoom call with the recipient, refer to the *Interview Guide.*
7. Follow instructions to conduct the oral consent process, refer to the *Script of Consent.*
8. If interviewee has questions about how their responses will be used and stored, please refer to the *FAQ_sheet document*.
9. If the interviewee consents to be recorded and interviewed, proceed to the next step.
10. Conduct the interview following the structure and questions identified in the *Interview Guide.* Topical coverage noted below.

    a. *Section A*—Introductions, interviewee background, and farm profile basics
    b. *Section B*—Operation details, business model, marketing, and innovation practices
    c. *Section C+D*—Technology use and innovation needs and barriers
    d. *Section E*—Policy and regulation
    e. *Section F*—Business goals and challenges
    f. *Section G*—Circular economy and resource management

Post Interview Processing

11. Securely store and process data. Once the interview has ended, upload all zoom recording files and interview notes to the secure interview folder under farm id#.
12. Using the *farm profile* information that you have verified with the interviewee, input this data into the data spreadsheet in an entry for the interview number code (farm id#).
13. Process auto-generated transcript and edit for accuracy by listening back to the recording file and correcting the transcription.
14. Save this corrected copy with an indication that it has been proofed.

Data Analysis

15. Conduct qualitative coding analysis in Atlas.ti using TIS framework per codebook*
16. Review of interview data by two additional members of the authorial team

Codebook excerpt:

Structure of the system	**Structure**	**Structure_actors**	*What actors do they mention*
		Structure_networks	*E.g., industry networks or partnerships mentioned by interviewees*
		Structure_institutions	*What institutions do they mention, like laws, regulations, cultural practices, norms, and established routines*
Knowledge development and diffusion	**F1_Knowledge**	**F1_Knowledge_Sources**	*Sources used*
		F1_Knowledge_Perception	*Perception (of sources/ resources)*
		F1_Knowledge_Background	*Educational background of practitioners*
		F1_Knowledge_Interactions	*Interactions with researchers/ academia*
		F1_Knowledge_Programs	*Educational programs offered by practitioners*
		F1_Knowledge_Niche	*Ideal niche (function qualities); changes they would like to see (in function)*
		F1_Knowledge_Drivers	*Drivers of transition to ideal niche*
		F1_Knowledge_Barriers	*Barriers of transition to ideal niche*
Entrepreneurial activities	**F2_EntrepAct**	**F2_EntrepAct_Gaps**	*Gaps—Areas where innovation/research needed and why*
		F2_EntrepAct_Awareness	*Practitioner awareness of nutrient recovery opportunities + tech*
		F2_EntrepAct_Process	*Process—How new innovations are introduced*
		F2_EntrepAct_Emerging	*Emerging technologies/topics*
		F2_EntrepAct_Ideal niche	*Ideal niche—What supports innovation?; how would they handle fish waste with unlimited resources**
		F2_EntrepAct_Drivers	*Drivers of innovation**
		F2_EntrepAct_Barriers	*Barriers of innovation*

Market formation	**F3_MarketFm**	**F3_MarketFm_Business model**	*What do they sell? Where do they sell? Revenue generating products and services Most important: greens or fish? Justification for fish selection*
		F3_MarketFm_Resource_reqs	*Resource requirements for system- which part is more demanding*
		F3_MarketFm_Barriers	*Barriers to innovation/progress in market fm? / Economic barriers*
		F3_MarketFm_Drivers	*Drivers of innovation/progress in market fm?*
		F3_MarketFm_Industry State	*Industry state of development*
		F3_MarketFm_Opinions	*Opinions on aqp industry*
Resource mobilization	**F4_ ResourceMb**	**F4_ ResourceMb_experiences**	*What were their experiences accessing resources?*
		F4_ ResourceMb_support	*What factors support access to resources?*
		F4_ ResourceMb_integration	*Resource integration/CE opportunities*
		F4_ ResourceMb_changes	*What changes are needed to better support resource mobilization?*
		F4_ ResourceMb_Drivers	*Drivers of resource mobilization*
		F4_ ResourceMb_Barriers	*Barriers of resource mobilization*
		F4_ ResourceMb_Ideal niche	*Ideal niche—subsidies, changes, what would they do with unlimited resources?*
		F4_ ResourceMb_Future plans	*Future_Practitioner plans on business expansion*
Creation of legitimacy	**F5_Legitimacy**	**F5_Legitimacy_Recognition**	*Recognition status of aquaponics*
		F5_Legitimacy_Barriers	*Barriers to legitimacy*
		F5_Legitimacy_Drivers	*Drivers of legitimacy*
Direction of the search	**F6_Direction**	**F6_Direction_CurrentEnv**	*Current (Policy) environment*
		F6_Direction_Barriers	*Policy barriers*
		F6_Direction_Drivers	*Policy drivers*
		F6_Direction_Niche	*Policy—ideal niche, what changes do they want to see*
		F6_Direction_Opinions	*Opinions on state/direction of the industry*
		F6_Direction_Goals	*Goals of practitioners for their farms*

Positive externalities	**F7_PositiveExt**	**F7_PositiveExt_Community**	*Benefits to communities described by practitioners*
		F7_PositiveExt_Education	*Educational benefits/ programs described by practitioners*
		F7_PositiveExt_Health	*Benefits for health described by practitioners*
		F7_PositiveExt_Resilience	*Benefits/impacts to systems described by practitioners*
		F7_PositiveExt_Partnerships	*Business partnerships and CE*
		F7_PositiveExt_Environmental	*Considerations of environmental sustainability*
		F7_PositiveExt_Awareness	*Practitioner awareness of global phosphorus scarcity*

Iterative Writing Process

17. Following qualitative coding, describe and summarize interview findings in text and integrate with literature review and policy review
18. Proceed through iterative review of data analysis/interpretation and manuscript by full authorial team.
19. Repeat this review process until consensus and approval from all authors is obtained prior to submission for publication.

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Author Contributions **EH:** writing—original draft, review and editing, conceptualization, investigation, methodology. **AJ:** writing—review and editing, investigation, funding acquisition. **RBC:** writing—review and editing, investigation. **SC:** writing—review and editing, investigation. **BJ:** writing—review and editing, methodology. **MW:** writing—review and editing. **GP:** supervision project administration, conceptualization, writing—review and editing, visualization, funding acquisition.

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Data Availability Information on interview and data-analysis protocol is available through the Appendix.

Declarations

Ethics Approval and Consent to Participate This study was deemed exempt by the University of Washington Institutional Review Board (IRB Exempt: STUDY00013037) as category 2 exempt research, as it only includes interactions involving interview procedures and records data in a manner that does not identify the human participants involved. Informed consent to participate was freely given by all subjects prior to interview proceedings.

Consent for Publication All participants gave informed consent for research utilizing their responses to be published. Identifying information was excluded from this article.

Competing Interests The authors declare no competing interests.

References

1. Folorunso EA, Roy K, Gebauer R, Bohatá A, Mraz J (2021) Integrated pest and disease management in aquaponics: a metadata-based review. Rev Aquac 13:971–995. https://doi.org/10.1111/raq.12508
2. Greenfeld A, Becker N, Bornman JF, Spatari S, Angel DL (2021) Monetizing environmental impact of integrated aquaponic farming compared to separate systems. Sci Total Environ 792:148459. https://doi.org/10.1016/j.scitotenv.2021.148459
3. Joyce A, Goddek S, Kotzen B, Wuertz S (2019) Aquaponics: closing the cycle on limited water, land and nutrient resources. In: Goddek S, Joyce A, Kotzen B, Burnell GM (eds) Aquaponics food production systems: combined aquaculture and hydroponic production technologies for the future. Springer International Publishing, Cham, pp 19–34
4. Ellen MacArthur Foundation (2019) Cities and circular economy for food. Ellen MacArthur Foundation. https://ellenmacarthurfoundation.org/cities-and-circular-economy-for-food. Accessed 18 June 2019
5. Garnett T (2011) Where are the best opportunities for reducing greenhouse gas emissions in the food system (including the food chain)? Food Policy 36:S23–S32. https://doi.org/10.1016/j.foodpol.2010.10.010
6. König B, Janker J, Reinhardt T, Villarroel M, Junge R (2018) Analysis of aquaponics as an emerging technological innovation system. J Clean Prod 180:232–243. https://doi.org/10.1016/j.jclepro.2018.01.037
7. van der Goot AJ, Pelgrom PJM, Berghout JAM, Geerts MEJ, Jankowiak L, Hardt NA, Keijer J, Schutyser MAI, Nikiforidis CV, Boom RM (2016) Concepts for further sustainable production of foods. J Food Eng 168:42–51. https://doi.org/10.1016/j.jfoodeng.2015.07.010
8. Tacon AGJ, Metian M, Turchini GM, De Silva SS (2009) Responsible aquaculture and trophic level implications to global fish supply. Rev Fish Sci 18:94–105. https://doi.org/10.1080/10641260903325680
9. Blidariu F, Grozea A (2011) Increasing the economical efficiency and sustainability of indoor fish farming by means of aquaponics—review. J Anim Sci Biotechnol 44:1–8
10. Gregg JS, Jürgens J, Sandvold HN, Olsen DS (2019) The transition to aquaponics in support of a circular bioeconomy: policy recommendations to overcome geographical and scale barriers. In: International Sustainability Transitions Conference 2019, Ottawa, Canada. https://orbit.dtu.dk/en/publications/the-transition-to-aquaponics-in-support-of-a-circular-bioeconomy
11. Petrea Ș-M, Bandi A-C, Cristea D, Neculiță M (2019) Cost-benefit analysis into integrated aquaponics systems. Cust Agronegocio 15:31
12. Wirza R, Nazir S (2021) Urban aquaponics farming and cities—a systematic literature review. Rev Environ Health 36:47–61. https://doi.org/10.1515/reveh-2020-0064
13. Goddek S, Delaide B, Mankasingh U, Ragnarsdottir KV, Jijakli H, Thorarinsdottir R (2015) Challenges of sustainable and commercial aquaponics. Sustainability 7:4199–4224. https://doi.org/10.3390/su7044199
14. Estim A, SR MS, Shapawi R, Saufie S, Mustafa S (2020) Maximizing efficiency and sustainability of aquatic food production from aquaponics systems—a critical review of challenges and solution options. AquaSt 20:65–72. https://doi.org/10.4194/2618-6381-v20_1_08
15. Francis C, Lieblein G, Gliessman S, Breland TA, Creamer N, Harwood R, Salomonsson L, Helenius J, Rickerl D, Salvador R, Wiedenhoeft M, Simmons S, Allen P, Altieri M, Flora C, Poincelot R (2003) Agroecology: the ecology of food systems. J Sustain Agric 22:99–118. https://doi.org/10.1300/J064v22n03_10
16. Reyes-Lúa A, Straus J, Skjervold VT, Durakovic G, Nordtvedt TS (2021) A novel concept for sustainable food production utilizing low temperature industrial surplus heat. Sustainability 13:9786. https://doi.org/10.3390/su13179786
17. Aleksić N, Šušteršič V (2020) Analysis of application of aquaponic system as a model of the circular economy: a review. Recycl Sustain Dev 13:73–86. https://doi.org/10.5937/ror2001073A

18. Abusin SAA, Mandikiana BW (2020) Towards sustainable food production systems in Qatar: assessment of the viability of aquaponics. Glob Food Sec:100349. https://doi.org/10.1016/j.gfs.2020.100349
19. Bhakar V, Kaur K, Singh H (2021) Analyzing the environmental burden of an aquaponics system using LCA. Procedia CIRP 98:223–228. https://doi.org/10.1016/j.procir.2021.01.034
20. Rakocy JE (2012) Aquaponics—integrating fish and plant culture. In: Tidwell J (ed) Aquaculture production systems, first edn. Wiley-Blackwell, pp 344–386
21. Wu Y, Song K (2021) Source, treatment, and disposal of aquaculture solid waste: a review. J Environ Eng 147:03120012. https://doi.org/10.1061/(ASCE)EE.1943-7870.0001850
22. Hao Y, Ding K, Xu Y, Tang Y, Liu D, Li G (2020) States, trends, and future of aquaponics research. Sustainability 12:7783. https://doi.org/10.3390/su12187783
23. Li C, Lee CT, Gao Y, Hashim H, Zhang X, Wei-Min W, Zhang Z (2018) Prospect of aquaponics for the sustainable development of food production in urban. Chem Eng Trans 63:475–480. https://doi.org/10.3303/CET1863080
24. Conijn JG, Bindraban PS, Schröder JJ, Jongschaap REE (2018) Can our global food system meet food demand within planetary boundaries? Agric Ecosyst Environ 251:244–256. https://doi.org/10.1016/j.agee.2017.06.001
25. Turnsek M, Joly A, Thorarinsdottir R, Junge R (2020) Challenges of commercial aquaponics in Europe: beyond the hype. Water 12:306. https://doi.org/10.3390/w12010306
26. Körner O, Bisbis M, Baganz G, Baganz D, Staaks G, Monsees H, Goddek S, Keesman K (2021) Environmental impact assessment of local decoupled multi-loop aquaponics in an urban context. J Clean Prod 313:127735. https://doi.org/10.1016/j.jclepro.2021.127735
27. Proksch G, Horn E, Lee G (2022) Urban integration of aquaponics: advancing integrated food systems for the circular city. In: Droege P (ed) Urban Agriculture and Regional Food Systems. Elsevier, pp 403–430. https://doi.org/10.1016/B978-0-12-820286-9.00014-5
28. Borg M, Little D, Telfer TC, Price C (2014) Scoping the potential role of aquaponics in addressing challenges posed by the food-water-energy nexus using the maltese islands as a case-study. Acta Hortic 1034:163–168. https://doi.org/10.17660/ActaHortic.2014.1034.19
29. Greenfeld A, Becker N, Bornman JF, dos Santos MJ, Angel D (2020) Consumer preferences for aquaponics: a comparative analysis of Australia and Israel. J Environ Manage 257:109979. https://doi.org/10.1016/j.jenvman.2019.109979
30. Araújo L, Keesman K, Goddek S (2021) Making aquaponics a business: a framework. Water 13:2978. https://doi.org/10.3390/w13212978
31. Pattillo DA, Hager JV, Cline DJ, Roy LA, Hanson TR (2022) System design and production practices of aquaponic stakeholders. Plos One 17:e0266475. https://doi.org/10.1371/journal.pone.0266475
32. Kledal PR, Thorarinsdottir R (2018) Aquaponics: a commercial niche for sustainable modern aquaculture. In: Hai FI, Visvanathan C, Boopathy R (eds) Sustainable aquaculture. Springer International Publishing, Cham, pp 173–190
33. Love DC, Fry JP, Genello L, Hill ES, Frederick JA, Li X, Semmens K (2014) An international survey of aquaponics practitioners. Plos One 9:e102662. https://doi.org/10.1371/journal.pone.0102662
34. Love DC, Fry JP, Li X, Hill ES, Genello L, Semmens K, Thompson RE (2015) Commercial aquaponics production and profitability: findings from an international survey. Aquaculture 435:67–74. https://doi.org/10.1016/j.aquaculture.2014.09.023
35. Villarroel M, Junge R, Komives T, König B, Plaza I, Bittsánszky A, Joly A (2016) Survey of aquaponics in Europe. Water 8:468. https://doi.org/10.3390/w8100468
36. Engle CR (2015) Economics of aquaponics. SRAC. https://doi.org/10.1016/B978-0-12-820286-9.00014-5
37. Köhler J, Geels FW, Kern F, Markard J, Onsongo E, Wieczorek A, Alkemade F, Avelino F, Bergek A, Boons F, Fünfschilling L, Hess D, Holtz G, Hyysalo S, Jenkins K, Kivimaa P, Martiskainen M, McMeekin A, Mühlemeier MS et al (2019) An agenda for sustainability transitions research: state of the art and future directions. Environ Innov Soc Transit 31:1–32. https://doi.org/10.1016/j.eist.2019.01.004
38. Lewis M, Schweitzer J, Cunningham R, Jacobs B (2020) Navigating complex organisational change: putting sustainable transitions theory to practice. LUT Scientific and Expertise Publications. Virtual, In
39. Wiegand M (2019) Aquaponics development in the Netherlands: the role of the emerging aquaponics technology and the transition towards sustainable agriculture. Utrecht University
40. Geels FW (2004) From sectoral systems of innovation to socio-technical systems: insights about dynamics and change from sociology and institutional theory. Res Policy 33:897–920. https://doi.org/10.1016/j.respol.2004.01.015

41. Baganz G, Schrenk M, Körner O, Baganz D, Keesman K, Goddek S, Siscan Z, Baganz E, Doernberg A, Monsees H, Nehls T, Kloas W, Lohrberg F (2021) Causal relations of upscaled urban aquaponics and the food-water-energy nexus—a Berlin case study. Water 13:2029. https://doi.org/10.3390/w13152029
42. Bergek A, Hekkert M, Jacobsson S, Markard J, Sandén B, Truffer B (2015) Technological innovation systems in contexts: conceptualizing contextual structures and interaction dynamics. Environ Innov Soc Transit 16:51–64. https://doi.org/10.1016/j.eist.2015.07.003
43. Geels FW, Schot J (2007) Typology of sociotechnical transition pathways. Res. Policy 36:399–417. https://doi.org/10.1016/j.respol.2007.01.003
44. Markard J, Truffer B (2008) Technological innovation systems and the multi-level perspective: towards an integrated framework. Res Policy 37:596–615. https://doi.org/10.1016/j.respol.2008.01.004
45. Walrave B, Raven R (2016) Modelling the dynamics of technological innovation systems. Res Policy 45:1833–1844. https://doi.org/10.1016/j.respol.2016.05.011
46. Asadullah M, Khan SN, Safdar HM, Aslam RA, Shaukat I (2020) Sustainability and development of aquaponics system: a review. Earth Sci Pak 4:78–80. https://doi.org/10.26480/esp.02.2020.78.80
47. Regueiro L, Newton R, Soula M, Méndez D, Kok B, Little DC, Pastres R, Johansen J, Ferreira M (2021) Opportunities and limitations for the introduction of circular economy principles in EU aquaculture based on the regulatory framework. J Ind Ecol:1–12. https://doi.org/10.1111/jiec.13188
48. Augenstein K, Bachmann B, Egermann M, Hermelingmeier V, Hilger A, Jaeger-Erben M, Kessler A, Lam DPM, Palzkill A, Suski P, von Wirth T (2020) From niche to mainstream: the dilemmas of scaling up sustainable alternatives. GAIA 29:143–148. https://doi.org/10.4512/gaia.29.3.3
49. Bergek A, Jacobsson S, Carlsson B, Lindmark S, Rickne A (2008) Analyzing the functional dynamics of technological innovation systems: a scheme of analysis. Res Policy 37:407–429. https://doi.org/10.1016/j.respol.2007.12.003
50. Markard J, Raven R, Truffer B (2012) Sustainability transitions: an emerging field of research and its prospects. Res Policy 41:955–967. https://doi.org/10.1016/j.respol.2012.02.013
51. Edsand H-E (2017) Identifying barriers to wind energy diffusion in Colombia: a function analysis of the technological innovation system and the wider context. Technol Soc 49:1–15. https://doi.org/10.1016/j.techsoc.2017.01.002
52. Hekkert MP, Suurs RAA, Negro SO, Kuhlmann S, Smits REHM (2007) Functions of innovation systems: a new approach for analysing technological change. Technol Forecast Soc Change 74:413–432. https://doi.org/10.1016/j.techfore.2006.03.002
53. Hebinck A, Klerkx L, Elzen B, Kok KPW, König B, Schiller K, Tschersich J, van Mierlo B, von Wirth T (2021) Beyond food for thought—directing sustainability transitions research to address fundamental change in agri-food systems. Environ Innov Soc Transit 41:81–85. https://doi.org/10.1016/j.eist.2021.10.003
54. Meelen T, Farla J (2013) Towards an integrated framework for analysing sustainable innovation policy. Technol Anal Strateg Manag 25:957–970. https://doi.org/10.1080/09537325.2013.823146
55. Deleye M, Van Poeck K, Block T (2019) Lock-ins and opportunities for sustainability transition. Int J Sustain High Educ 20:1109–1124. https://doi.org/10.1108/IJSHE-09-2018-0160
56. Hörisch J (2015) The role of sustainable entrepreneurship in sustainability transitions: a conceptual synthesis against the background of the multi-level perspective. Adm Sci 5:286–300. https://doi.org/10.3390/admsci5040286
57. Kemp R, Loorbach D (2003) Governance for sustainability through transition management. In: EAEPE 2003 Conference, Maastricht, the Netherlands
58. Frantzeskaki N, de Haan H (2009) Transitions: two steps from theory to policy. Futures 41:593–606. https://doi.org/10.1016/j.futures.2009.04.009
59. Jacobs B, Cordell D, Chin J, Rowe H (2017) Towards phosphorus sustainability in North America: a model for transformational change. Environ Sci Policy 77:151–159. https://doi.org/10.1016/j.envsci.2017.08.009
60. Manente V, Caputo S (2022) The web community of soil-less farmers: a case study. In: Caputo S (ed) Small scale soil-less urban agriculture in Europe. Springer International Publishing, Cham, pp 151–165
61. Yep B, Zheng Y (2019) Aquaponic trends and challenges—a review. J Clean Prod 228:1586–1599. https://doi.org/10.1016/j.jclepro.2019.04.290
62. Goodman ER (2011) Aquaponics: community and economic development. Thesis, Massachusetts Institute of Technology
63. Junge R, Bulc TG, Anseeuw D, Yavuzcan Yildiz H, Milliken S (2019) Aquaponics as an educational tool. In: Goddek S, Joyce A, Kotzen B, Burnell GM (eds) Aquaponics food production systems:

combined aquaculture and hydroponic production technologies for the future. Springer International Publishing, Cham, pp 561–595
64. Metcalf SS, Widener MJ (2011) Growing buffalo's capacity for local food: a systems framework for sustainable agriculture. Appl Geogr (Sevenoaks) 31:1242–1251. https://doi.org/10.1016/j.apgeog.2011.01.008
65. Wardlow GW, Johnson DM, Mueller CL, Hilgenberg CE (2002) Enhancing student interest in the agricultural sciences through aquaponics. J Nat Resour Life Sci Educ; Madison 31:55
66. Wahl D, Ness B, Wamsler C (2021) Implementing the urban food–water–energy nexus through urban laboratories: a systematic literature review. Sustain Sci 16:663–676. https://doi.org/10.1007/s11625-020-00893-9
67. Cerozi BS, Fitzsimmons K (2017) Phosphorus dynamics modeling and mass balance in an aquaponics system. Agric Syst 153:94–100. https://doi.org/10.1016/j.agsy.2017.01.020
68. Diver S, Rinehart L (2010) Aquaponics—integration of hydroponics with aquaculture. Accessed at www.attra.ncat.org, National Sustainable Agriculture Information Service
69. Lobanov VP, Combot D, Pelissier P, Labbé L, Joyce A (2021) Improving plant health through nutrient remineralization in aquaponic systems. Front Plant Sci 12:683690. https://doi.org/10.3389/fpls.2021.683690
70. Manning C (2021) Gotham Greens' new era—produce grower. Produce grower, In https://www.producegrower.com/article/cover-story-gotham-greens-new-era/. Accessed 1 Aug 2021
71. Sorvino C (2020) With $87 million in fresh funding, lettuce grower Gotham Greens plots greenhouse expansion. Forbes https://www.forbes.com/sites/chloesorvino/2020/12/08/with-87-million-in-fresh-funding-lettuce-grower-gotham-greens-plots-greenhouse-expansion/. Accessed 1 Aug 2021
72. USDA (2013) 2013 Census of Aquaculture—Table 1212. Methods used for aquaculture production—United States and States [Washington, D.C.]: United States Department of Agriculture, National Agricultural Statistics Service. https://agcensus.library.cornell.edu/wp-content/uploads/2012-Census-of-Aquaculture-aqua_1_012_012.pdf. Accessed 13 May 2022
73. USDA 2018 Census of Aquaculture. https://www.nass.usda.gov/Publications/AgCensus/2017/Online_Resources/Aquaculture/index.php. Accessed 13 May 2022
74. Skar SLG, Pineda-Martos R, Timpe A, Pölling B, Bohn K, Külvik M, Delgado C, Pedras CMG, Paço TA, Ćujić M, Tzortzakis N, Chrysargyris A, Peticila A, Alencikiene G, Monsees H, Junge R (2019) Urban agriculture as a keystone contribution towards securing sustainable and healthy development for cities in the future. Blue-Green Syst. https://doi.org/10.2166/bgs.2019.931
75. Holliman JB, Adrian J, Chappell JA (2008) Integration of hydroponic tomato and indoor recirculating aquacultural production systems: an economic analysis. Auburn University
76. Tokunaga K, Tamaru C, Ako H, Leung P (2015) Economics of commercial aquaponics in Hawaii. J World Aquaculture Soc 46:20–32. https://doi.org/10.1111/jwas.12173
77. Proksch G, Ianchenko A (2022) Commercial rooftop greenhouses: technical requirements, operational strategies, economic considerations, and future opportunities. In: Droege P (ed) Urban Agriculture and Regional Food Systems. Elsevier, pp 503–528. https://doi.org/10.1016/B978-0-12-820286-9.00014-5
78. Hoevenaars K, Junge R, Bardocz T, Leskovec M (2018) EU policies: new opportunities for aquaponics. Ecocycles 4:10–15. https://doi.org/10.19040/ecocycles.v4i1.87
79. Reinhardt T, Hoevenaars K, Joyce A (2019) Regulatory frameworks for aquaponics within the EU. In: Goddek S, Joyce A, Kotzen B, Burnell GM (eds) Aquaponics food production systems: combined aquaculture and hydroponic production technologies for the future. Springer International Publishing, Cham, pp 501–522
80. Asheim BT, Lawton Smith H, Oughton C (2011) Regional innovation systems: theory, empirics and policy. Reg Stud 45:875–891. https://doi.org/10.1080/00343404.2011.596701
81. Klerkx L, Begemann S (2020) Supporting food systems transformation: the what, why, who, where and how of mission-oriented agricultural innovation systems. Agric Syst 184:102901–102901. https://doi.org/10.1016/j.agsy.2020.102901
82. FAO (2017) The future of food and agriculture—trends and challenges. Food and Agriculture Organization of the United Nations, Rome
83. Cifuentes-Torres L, Correa-Reyes G, Mendoza-Espinosa LG (2021) Can reclaimed water be used for sustainable food production in aquaponics? Front Plant Sci 12:669984–669984. https://doi.org/10.3389/fpls.2021.669984
84. Kledal PR, König B, Matulić D (2019) Aquaponics: the ugly duckling in organic regulation. In: Goddek S, Joyce A, Kotzen B, Burnell GM (eds) Aquaponics food production systems: combined aquaculture and hydroponic production technologies for the future. Springer International Publishing, Cham, pp 487–500

85. Dos-Santos MJ (2019) Sustainable and commercial development of aquaponics through the certification in Europe. Ecocycles 5:12–18. https://doi.org/10.19040/ecocycles.v5i2.140
86. Fruscella L, Kotzen B, Milliken S (2021) Organic aquaponics in the European Union: towards sustainable farming practices in the framework of the new EU regulation. Rev Aquac 13:1661–1682. https://doi.org/10.1111/raq.12539
87. Caputo S, Rumble H, Schaefer M (2020) "I like to get my hands stuck in the soil": a pilot study in the acceptance of soil-less methods of cultivation in community gardens. J Clean Prod 258:120585. https://doi.org/10.1016/j.jclepro.2020.120585
88. Specht K, Sanyé-Mengual E (2017) Risks in urban rooftop agriculture: assessing stakeholders' perceptions to ensure efficient policymaking. Environ Sci Policy 69:13–21. https://doi.org/10.1016/j.envsci.2016.12.001
89. Naspetti S, Zanoli R (2009) Organic food quality and safety perception throughout Europe. J Food Prod Mark 15:249–266. https://doi.org/10.1080/10454440902908019
90. Center for Food Safety and Applied Nutrition (2020) Full text of the Food Safety Modernization Act (FSMA). FDA
91. Joly A, Junge R, Bardocz T (2015) Aquaponics business in Europe: some legal obstacles and solutions. Ecocycles 1:3–5. https://doi.org/10.19040/ecocycles.v1i2.30
92. Gregg JS, Jürgens J (2019) The emerging regulatory landscape for aquaponics in Scandinavia—a case study for the transition to a circular economy. In: 14th Nordic Environmental Social Sciences Conference, Luleå, Sweden https://orbit.dtu.dk/en/publications/the-emerging-regulatory-landscape-for-aquaponics-in-scandinavia-a. Accessed 13 May 2022
93. Genello L, Fry JP, Frederick JA, Li X, Love DC (2015) Fish in the classroom: a survey of the use of aquaponics in education. Eur J Health Biol Educ 4:9–20. https://doi.org/10.20897/lectito.201502
94. Hart ER, Webb JB, Hollingsworth C, Danylchuk AJ (2014) Managing expectations for aquaponics in the classroom: enhancing academic learning and teaching an appreciation for aquatic resources. Fisheries 39:525–530. https://doi.org/10.1080/03632415.2014.966353
95. Hart ER, Webb JB, Danylchuk AJ (2013) Implementation of aquaponics in education: an assessment of challenges and solutions. Sci Educ Int 24:460–480. https://doi.org/10.1080/03632415.2014.966353
96. Junge R, Wilhelm S, Hofstetter U (2014) Aquaponic in classrooms as a tool to promote system thinking. In: Transmission of innovations, knowledge and practical experience into everyday practice. Naklo, Slovenia
97. Cammies C, Mytton D, Crichton R (2021) Exploring economic and legal barriers to commercial aquaponics in the EU through the lens of the UK and policy proposals to address them. Aquac Int 29:1245–1263. https://doi.org/10.1007/s10499-021-00690-w
98. Specht K, Siebert R, Hartmann I, Freisinger UB, Sawicka M, Werner A, Thomaier S, Henckel D, Walk H, Dierich A (2014) Urban agriculture of the future: an overview of sustainability aspects of food production in and on buildings. Agric Hum Values 31:33–51. https://doi.org/10.1007/s10460-013-9448-4
99. Caputo S (2022) Case Studies. In: Caputo S (ed) Small scale soil-less urban agriculture in Europe. Springer International Publishing, Cham, pp 95–150
100. Benis K, Ferrão P (2017) Potential mitigation of the environmental impacts of food systems through urban and peri-urban agriculture (UPA)—a life cycle assessment approach. J Clean Prod 140:784–795. https://doi.org/10.1016/j.jclepro.2016.05.176
101. Pulighe G, Lupia F (2020) Food first: COVID-19 outbreak and cities lockdown a booster for a wider vision on urban agriculture. Sustainability 12:5012. https://doi.org/10.3390/su12125012
102. Million A, Bürgow G, Steglich A, Raber W (2014) Roof water farm. Participatory and multifunctional infrastructures for urban neighborhoods. In: Finding spaces for productive cities. VHL University of Applied Sciences, Leeuwarden, Netherlands
103. Horn E, Proksch G (2022) Symbiotic and regenerative sustainability frameworks: moving towards circular city implementation. Front Built Environ 7:780478. https://doi.org/10.3389/fbuil.2021.780478
104. Sadhukhan J, Dugmore TIJ, Matharu A, Martinez-Hernandez E, Aburto J, Rahman PKSM, Lynch J (2020) Perspectives on "game changer" global challenges for sustainable 21st century: plant-based diet, unavoidable food waste biorefining, and circular economy. Sustainability 12:1976. https://doi.org/10.3390/su12051976
105. Goddek S, Körner O (2019) A fully integrated simulation model of multi-loop aquaponics: a case study for system sizing in different environments. Agric Syst 171:143–154. https://doi.org/10.1016/j.agsy.2019.01.010

106. Pollard G, Ward J, Koth B (2017) Aquaponics in urban agriculture: social acceptance and urban food planning. Horticulturae 3:39. https://doi.org/10.3390/horticulturae3020039
107. Jost JT, Banaji MR, Nosek BA (2004) A decade of system justification theory: accumulated evidence of conscious and unconscious bolstering of the status quo. Polit Psychol 25:881–919. https://doi.org/10.1111/j.1467-9221.2004.00402.x
108. Weikard HP (2016) Phosphorus recycling and food security in the long run: a conceptual modelling approach. Food Secur 8:405–414. https://doi.org/10.1007/s12571-016-0551-4
109. Chowdhury RB, Moore GA, Weatherley AJ, Arora M (2017) Key sustainability challenges for the global phosphorus resource, their implications for global food security, and options for mitigation. J Clean Prod 140:945–963. https://doi.org/10.1016/j.jclepro.2016.07.012
110. Miličić V, Thorarinsdottir R, Hančič MT, Hančič MT (2017) Commercial aquaponics approaching the European market: to consumers' perceptions of aquaponics products in Europe. Water 9:80. https://doi.org/10.3390/w9020080
111. Zech KM, Schneider UA (2019) Carbon leakage and limited efficiency of greenhouse gas taxes on food products. J Clean Prod 213:99–103. https://doi.org/10.1016/j.jclepro.2018.12.139
112. David L, Pinho S, Agostinho F, Costa J, Portella M, Keesman K, Garcia F (2021) Sustainability of urban aquaponics farms: an emergy point of view. J Clean Prod 331:129896. https://doi.org/10.1016/j.jclepro.2021.129896

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