

Industrial Symbiosis for the Food-Water-Energy Nexus: Optimizing the Implementation of Circularity Frameworks and Aquaponic Systems

Erin Kelly Horn

A dissertation

submitted in partial fulfillment of the
requirements for the degree of

Doctor of Philosophy

University of Washington

2024

Reading Committee:

Gundula Proksch, Co-chair

Carrie Sturts Dossick, Co-chair

Carmel Lindkvist

Program Authorized to Offer Degree:

Department of Civil and Environmental Engineering

©Copyright 2024

Erin Kelly Horn

University of Washington

Abstract

Industrial Symbiosis for the Food-Water-Energy Nexus: Optimizing the Implementation of
Circularity Frameworks and Aquaponic Systems

Erin Kelly Horn

Chairs of the Supervisory Committee:

Gundula Proksch
Department of Architecture

Carrie Sturts Dossick
Department of Construction Management

Critical infrastructure sectors are integral to the functioning of civilizations, among which food, water, and energy systems interact closely. To proactively adapt and innovate these systems to mitigate further contributions to global climate change, sustainable and resilient solutions are needed in critical Food-Water-Energy-infrastructure and dedicated transdisciplinary efforts are crucial. Particularly, there is a need to consider and deconstruct practical implementation challenges to achieve feasibility and actualize intended impacts. Circular economy strategies are viewed with increasing promise and may be advanced through resource symbiosis measures within Food-Water-Energy systems. To support effective implementation, this work furthers theoretical frameworks and evaluates critical gaps and development needs to effectively operationalize resource circularity, focusing on the case typology of aquaponics. Aquaponics, the land-based symbiotic production of plants and fish, is a form of controlled-environment agriculture with high potential for sustainable food production. Key resources are recycled within the growing system itself and production can be further integrated with other renewable resources and industries in symbiotic partnerships. To support the application of industrial symbiosis measures toward circular economy in the Food-Water-Energy nexus, three investigations are advanced in this work. It first assesses relevant circular sustainability frameworks through systematic literature review, clarifying their ideological relationships and creating a centralized reference of framework definitions and implementation strategies to help streamline and support future research with circular and sustainable aims. It then considers the implementation strategy of aquaponics, evaluating the state of environmental efficiency in commercial aquaponics to identify development needs. Findings illuminate previously unexplored gaps between research and practice, advance a new aquaponic systems framework, and introduce a novel engineered-process analysis of nutrient recovery identifying inconsistent technology usage through interviews, qualitative thematic analysis, and engineered process analysis. Next considering a means of closing one of these identified gaps, this work then analyzes existing examples of industrial symbiosis with Controlled-Environment-Agriculture operations to identify key factors for successful implementation and symbiotic resource exchange through an exploratory cross-case synthesis utilizing interview and

document analysis and qualitative thematic analysis, documenting and advancing understanding of this emergent typology. This analysis identifies crucial material exchanges and organizational and institutional factors that impact existing cases, creating a conceptual platform for future research of industrial symbiosis implementation within the Food-Water-Energy nexus.

Keywords

Food-Water-Energy Nexus, Circular Economy, Aquaponics, Industrial Symbiosis, Critical Infrastructure, Controlled-Environment Agriculture, Case Study, Nutrient Recovery

Table of Contents

Industrial Symbiosis for the Food-Water-Energy Nexus: Optimizing the Implementation of Circularity Frameworks and Aquaponic Systems	1
Keywords.....	5
Table of Contents.....	5
List of Figures	9
List of Abbreviations	10
Chapter 1: Introduction	12
1.1 <i>Motivation of the Problem: Adaptation and Mitigation in Critical Food-Water-Energy Infrastructure</i>	12
1.1.1 Critical Infrastructure	12
1.1.2 Food-Water-Energy Nexus	12
1.1.3 Aquaponics: A circular technology at the intersection of the FWE-Nexus	15
1.2 Points of Departure.....	17
1.2.1 Operationalizing intersections: A role for circular frameworks.....	17
1.2.2 Implementing Aquaponics for Environmental Efficiency.....	19
1.2.3 Optimizing via Resource Integration: Industrial Symbiosis with Controlled-Environment Agriculture	21
1.3 Bridging the Gaps: Overview of Objectives.....	24

1.4 Methods	27
1.4.1 Research Perspective.....	27
1.4.2 Methodology Overview	27
1.5 Dissertation Structure and Nature	28
1.5.1 Arc of Development.....	28
1.5.2 Dissertation Structure	29
Chapter 1 References.....	30
Chapter 2: Symbiotic and Regenerative Sustainability Frameworks: Moving Towards Circular City Implementation	37
Abstract	37
Keywords.....	37
1. Introduction.....	37
2. Methods	38
3. Closing the Loop- Tracing and Defining Overlapping Concepts.....	41
3.1 Origins in Sustainable Development	43
3.2 Nexus Perspectives.....	44
3.3 Circular Economy.....	46
3.4 Biological and Ecosystem Driven Circularity	48
3.5 Symbiosis and Circularity in Industrial Systems	50
3.6 Conceptualizing Urban Circularity	51
3.7 Regenerative Built Environment Concepts.....	53
4. Implementing Circularity.....	55
4.1 Resource and Material Management.....	59
4.2 Systems Development and Integration.....	61

4.3 Bio-Based Solutions	64
4.4 Supporting Strategies	65
5 Conclusion and Future Research Directions	67
6 Author Contributions	68
7 Funding.....	68
8 Acknowledgements.....	68
Chapter 2 References.....	68
Chapter 3. A Mixed-Methods Assessment of Environmental Sustainability Gaps in Commercial Aquaponic Operations in North America	78
Keywords.....	78
Abstract	78
1. Introduction	78
2. Methodology	80
2.1 Sustainability Assessment of Aquaponics in Literature	80
2.2 Analytical framework.....	81
2.3 Interviews	84
2.4 Data analysis	85
3. Findings	85
3.1 Core Aquaponic System - Hydroponics and Recirculating Aquaculture Systems (Primary)	86
3.2 Infrastructure of Controlled Environment Agriculture (Secondary)	101
3.3 Integrative Context, Climate, and Regional Factors (Tertiary + Quaternary)	104
4.0 Discussion	105
4.1 Core Aquaponic System.....	106

4.2 CEA Built and Operational Infrastructure.....	106
4.3 Integrative Context.....	108
4.4 Future Research Directions	108
5.0 Conclusions.....	109
6. Funding.....	110
7. Acknowledgements.....	110
8. Chapter 3 References.....	110
Chapter 4- Industrial Symbiosis with Controlled Environment Agriculture: An Exploratory Multiple Case Study Analysis	116
Abstract	116
1. Introduction	116
2. Research Design & Methods.....	119
2.1 Case Study Methodology.....	119
2.2 Data collection.....	120
2.3 Data analysis.....	121
2.4 Validation.....	122
3. Results.....	122
3.1 Motivations for CEA-IS.....	122
3.2 Resource Exchanges in CEA-IS	126
3.3 Intra- and Inter- Organizational and Institutional Context and Trends in Emerging CEA-IS	131
4. Discussion.....	134
5. Conclusion	141
6. Funding.....	142

7. Acknowledgements	142
Chapter 4 References	142
Chapter 5. Conclusions	149
Chapter 5 References	154
Appendix A- Glossary	155
Glossary References	156

List of Figures

Figure 1.1- Aquaponics in the Food-Water-Energy Nexus	17
Figure 1.2- Overview of Chapter 2	19
Figure 1.3- Overview of Chapter 3	21
Figure 1.4- Overview of Chapter 4	23
Table 1.1- Overview of Objectives	24
Table 1.2- Overview of Methods	28
Figure 1.5- Overview of Core Dissertation Chapters	30
Figure 2.1- Literature Review Process	39
Table 2.1- Circular, regenerative, and symbiotic sustainability frameworks reviewed.	41
Table 2.2- Circular, regenerative, and symbiotic sustainability frameworks reviewed and prominent descriptions.....	46
Figure 2.2- Circular implementation strategies.....	57
Figure 2.3- Implementation strategies in circular city literature.....	58
Figure 2.4- Occurrence of thematic areas and strategies in key reviewed frameworks.....	61
Figure 3.1- Commercial Aquaponics Analytical Framework- System model of commercial scale aquaponic operations and resource flows	83

Figure 3.2- Overview of Aquaponics Operations Interviewed	85
Table 3.1: Core Aquaponic System Characteristics	88
Table 3.2- Inputs and Outputs of Core Aquaponics System	93
Figure 3.3- Engineered Process Analysis: Nutrient Reuse and Recovery Processes of Interviewed Operations	97
Table 3.3- Gaps for further exploration between potential and observed environmental sustainability practices in North American Commercial Aquaponics.....	106
Table 4.1- Overview of Selected Controlled Environment Agriculture- Industrial Symbiosis Case Studies.....	123
Figure 4.1- a) Agrotopia Rooftop Greenhouse and Façade (photographed by author during site visit).....	124
Figure 4.2- a) Agtira’s greenhouse, exterior view, b) Cucumber yield and greenhouse space at Agtira’s headquarters (photographed by author during site visit).....	125
Table 4.2- Symbiotic Linkages in CEA-IS.....	126
Figure 4.3a- Agrotopia Resource Exchanges.....	127
Figure 4.3b- Agtira Resource Exchanges, Boden	127
Figure 4.4a- Big Akwa Resource Exchanges, Sundsvall.....	130
Figure 4.4b- Big Akwa IS Network, Alby.....	130
Figure 4.5- Columbi Farms Resource Exchanges	131
Figure 4.6- Emergent Organizational and Institutional Themes in CEA-IS	134
Table 5.1- Overview of Key Contributions	152

List of Abbreviations

- **AES**- Agro-Ecological Symbiosis
- **CE**- Circular Economy
- **CEA**- Controlled-Environment Agriculture
- **CEA-IS**- Controlled-Environment Agriculture Industrial Symbiosis

- **CC**- Circular City
- **EU**- European Union
- **FWE**- Food-Water-Energy
- **IS**- Industrial Symbiosis
- **RAS**- Recirculating Aquaculture System

Chapter 1: Introduction

1.1 *Motivation of the Problem: Adaptation and Mitigation in Critical Food-Water-Energy Infrastructure*

1.1.1 Critical Infrastructure

Critical infrastructure forms a vital foundation for a functioning society, ensuring that essential services and supplies are available to the public (Forzieri et al., 2018; Stewart et al., 2009; Huddleston et al., 2022). These essential goods and services support the welfare and security of a population and are systems relied on for day-to-day life, including supply systems for energy, food, and water and services such as health care, communications networks, banking, public administration, emergency services, and transportation (Nan and Sansavini, 2017; Niall and Kallies, 2017). The impacts of climate change form an increasing threat to critical infrastructure (Huddleston et al., 2022) and compel both adaptation of critical infrastructure systems and their employment toward mitigation efforts as “the response of critical infrastructure to climate change is of utmost importance” (Huddleston et al., 2022). Critical infrastructure is “generally built to exist over long periods” (Huddleston et al., 2022) and will be therefore exposed and increasingly vulnerable to both rapid-onset (e.g. severe storm) and slow-onset (e.g. rising sea levels) events (Shakou et al., 2019). This has been reflected in the literature shift toward flexible adaptation strategies (Coaffee and Clarke, 2017) recognizing “the complexity and unpredictability of contemporary challenges” (Huddleston et al., 2022). Some authors warn that inadequate consideration and understanding of relationships between different infrastructure systems can hinder their adaptation (Pumpuni-Lenss et al., 2017). Solving the complex environmental challenges of our era necessitates understanding and leveraging interactions between key systems. Nexus frameworks, with origins in policy making environments (Horn and Proksch, 2022), offer a means to conceptualize and better address the complex interactions of critical infrastructure systems.

1.1.2 Food-Water-Energy Nexus

The United States documents sixteen critical infrastructure sectors, this work focuses in particular on three of these: “food and agriculture”, “energy,” and “water and wastewater” (CISA). Among the elements of critical infrastructure, food and water are some of the most vital to sustaining human life and are entwined closely with both one another and with energy, a sector deeply tied to the climate crisis. The conceptualization of this dynamic has been advanced as a Food-Water-Energy nexus (FWE) and has been introduced by political and academic actors as a means to better frame and confront the intersections and influences between food, water, and energy systems (Bazilian et al., 2011; Bizikova et al., 2013; Mukuve and Fenner, 2015; Newell, 2019). Regenerative approaches are needed to restructure many current value chains and market forces within the FWE-nexus which leave these critical infrastructure systems vulnerable to rapid and slow onset crisis events (Allan et al., 2015; Horn and Proksch 2022).

Among such potential events, extreme weather events, droughts, and seasonal variation can affect the ability to grow outdoors and impact the viability of land-based production (Campbell et al., 2018; Pais et al., 2020), while climate change also impacts natural ecosystems that may affect natural fisheries supply and health (Zou, 2021). Recently, it has been increasingly acknowledged that the globalized food system has allowed for large quantities of food production but is not sustainable and has fostered significant path dependencies to the detriment of long-term food security (Kennedy et al., 2004; Moragues-Faus et al., 2017; Skar et al., 2019). The disruption of global supply chains in the face of significant worldwide events such as the COVID-19 pandemic further demonstrates such instability (Pulighe & Lupia, 2020), suggesting that there is a need to greatly improve local resilience and essential supply chains in times of crisis and beyond. The advancement of chemical fertilizers, an energy intensive process, was key to agricultural revolutions and increased production capacity, but also introduced heightened spatial decoupling of agricultural production and consumption and generated environmental ecosystem harm, creating vulnerabilities to FWE-systems. Plant nutrients are vital to food production but may act as environmental pollutants when in excess in natural environments- a dynamic highlighted by the global phosphorus challenge which may increasingly impact most of the world (Cordell et al., 2011). Potential scarcity of rock phosphate looms, and these resources are located only within a handful of regions globally, forming potential geopolitical challenges (Cordell et al., 2011; Steen, 1998; Van Vuuren et al., 2010). Some have predicted global peak phosphorus production in the early 2030s (Cordell et al. 2009). Despite the potential for scarcity, as phosphorus (P) is an essential and non-substitutable nutrient element for plant growth, much of the excess P from chemical fertilizers applied to fields still ends up in natural waters which can lead to harmful levels of eutrophication (Goyette et al., 2018), in which high nutrient concentrations create dangerous imbalances to natural ecosystems. Natural and engineered water systems infrastructure, including wastewater treatment, seek to address issues caused by nutrients and other pollutants, but their ability to intervene has been traditionally limited to downstream processes rather than preventative measures.

Many of the challenges to contemporary FWE critical infrastructure, including climate change itself, reflect changes in the scale and directionality of resource use during historical periods of increasing industrialization and globalization of human systems as local economies shifted to larger extractive modes. While these changes have been part of, and key to enabling, vital societal advancements and population growth, and indeed created critical FWE infrastructures as we recognize them today, they have also generally turned out to be unsustainable in their linearity which has failed to recognize the reality of planetary boundaries and natural timescales of global biogeochemical cycles, which, unsurprisingly, cannot facilitate infinite growth on a finite planet.

Key among such historical transitions were the increasing use of fossil fuels, centralization of water distribution and treatment systems, and technological advancements of agriculture enabling its industrialization, including advancements in chemical fertilizers (James, 2018).

Centralized water systems were introduced in 1802, 1808, and 1856 in Paris, London, and Berlin, respectively, instigating “a complex sequence of developments which would take many decades to resolve” (Gandy 2004). As modern bathrooms were installed, the nitrogen and phosphorus value of human wastes for agriculture was diluted, and traditional “night soil collectors” were made increasingly irrelevant (Gandy 2004). This helped considerably to achieve intended sanitation and public health benefits, but simultaneously changed the scale and nature of nutrient cycles between cities and agricultural regions (Corbin 1986; Laporte, 2000). In other words “the economics of human manure was also progressively undermined by the development of synthetic fertilizers which began to play an ever greater role in agriculture,” (Gandy 2004) as concurrently, the interactions of cities and their surroundings shifted (Green, 1990; Gandy 2002) and “the last vestiges of any cyclical interaction with a rural hinterland were replaced by a metropolitan emphasis on nature as a source of leisure” (Gandy 2004). Moreover, while cities depend on FWE systems to function, these resources are now often produced externally, sometimes at great distance, (Skar et al., 2019), making urban FWE systems particularly vulnerable, especially in highly populated cities (Garcia and You, 2016; Tobosco-Chavero et al., 2018). To proactively adapt FWE critical infrastructures and innovate systems to mitigate further contributions to global climate change, sustainable FWE systems solutions are needed, including improved integration of food production and waste systems and more efficient energy, water, and nutrient processes, as an important aspect of cities’ adaptation to climate change (Corcelli et al., 2019).

Recent efforts to adapt critical FWE-infrastructure seek to increasingly reconnect and localize resource flows while leveraging technological advantages to maintain the health, safety, and stability provided by modern FWE-infrastructure (Horn and Proksch 2022). Circular economy (CE) is a guiding framework for such efforts and is a re-envisioned economic system replacing linear-extraction-to-waste processes with efforts to reuse, reduce, recycle and recover material resources (Kircherr et al., 2017). FWE systems interact especially strongly with the circular bioeconomy, a subcomponent of CE, which concerns the circular use of biological resources (Stegmann et al., 2020), traditionally an inherent part of agricultural production. Living and nature-based systems and materials (Ferrara and Squatrito 2022) are valuable means of advancing circularity in FWE infrastructure (Kallipoliti 2018; Shakou et al., 2019), “broaching the artificial divide between anthropogenic critical infrastructure systems and the natural environment” (Huddleston et al. 2022), and interest in biophilic and biomimetic approaches is on the rise (Langergraber et al. 2021; Horn and Proksch 2022; Scalisi and Ness 2022). Though strategies incorporating the diverse functional potential of living and biomimetic systems is broadly considered to have significant potential to achieve better equilibrium within planetary boundaries and revise and re-localize the interaction between FWE-systems and global biogeochemical cycles (Horn and Proksch 2022), there is the disconcerting possibility, and in many cases, reality, that if approached insincerely or ineffectively, such strategies can become merely tokenistic (IPCC 2022; Olson, 2021; Scalisi and Ness 2022). The clock is ticking on implementing effective adaptation and mitigation strategies in critical FWE-infrastructure, with no leeway for greenwashing for appearance alone over performance, and dedicated

transdisciplinary efforts are required for impactful implementation. Particularly, as technological innovation progresses and makes innovations in the FWE-nexus theoretically viable, there is a need to consider and deconstruct practical implementation challenges to achieve feasibility in applied contexts and actualize intended sustainability and resilience impacts within critical FWE-infrastructure.

1.1.3 Aquaponics: A circular technology at the intersection of the FWE-Nexus

Among research and development efforts at the nexus of critical FWE-infrastructure, aquaponics, the symbiotic co-production of fish and plants in a controlled-environment (Rakocy 2006), stands out for the considerable interest it has attracted and its strong interactions with all three of the FWE-systems (Figure 1.1) and its compatibility with CE paradigms and those of related frameworks such as Circular City, the FWE-Nexus, and Circular Bioeconomy (Carus and Dammer, 2018; Gregg et al. 2019; Baganz et al. 2021). Aquaponics is a type of controlled-environment agriculture (CEA). CEA is both a technology that can be integrated into the form and operation of built environments and, perhaps most centrally, a tool for resource efficient and resilient food production within the larger food system at a time when environmentally friendly and reliable food sources are vitally needed. Within CEA production, parameters such as light, temperature, humidity, and nutrients are controlled in an enclosed environment (Proksch et al. 2019). Controlling these factors helps to optimize production, often allowing more food to be produced with less space and resources, as well as shielding crops from external climatic challenges (e.g. drought, storms, poor air quality). Greenhouse production, especially utilizing hydroponics, where plants grow in nutrient rich water, is an example of CEA which many may be familiar with. Recirculating aquaculture systems (RAS) are a more recent form of CEA, utilizing controlled aquatic parameters to perform aquaculture on land, growing fish or other aquatic organisms in better-controlled conditions than possible in other forms of aquaculture, and offering the opportunity to curb pollution and other threats to natural environments (Hamilton et al. 2016). The contained nature of CEA also provides the opportunity to capture and recover resources from waste streams which are more physically concentrated and controlled than in conventional agriculture.

This dynamic is epitomized by the marriage of hydroponics and RAS systems, in the form of aquaponics, which has garnered considerable public and academic attention within recent decades, namely for the symbiotic resource usage of nutrients and water that it facilitates in the co-production of both vegetable and protein food sources, however its integration potential with other sustainable resources is also increasingly discussed in literature (Horn and Proksch 2020), painting an alluring picture of circular food production that leverages FWE-nexus interactions to contribute to the strengthening of critical FWE-infrastructure sustainability and resilience. Fish protein is well recognized as a healthy protein source compared to other meat options, and as an alternative pescatarian human diet has a reductive impact on GHG emissions (Baganz et al. 2021). Rather than via fisheries the majority of fish protein is now provided by aquaculture, which is a swiftly growing food production industry (Baganz et al., 2021; FAO,

2018; Joyce et al., 2019). While fish consumption per capita continues to rise, most of the world's fisheries are fully or over-exploited, as "overfishing" has increased (Baganz et al., 2021; Goddek et al., 2015; Joyce et al., 2019; Link & Watson, 2019). Likewise, while traditional aquaculture is a key solution, it has also been associated with environmental issues including degradation of natural ecosystems, water pollution, and waste management (Baganz et al., 2021; Chunjie Li et al., 2018; Cifuentes-Torres et al., 2021; Edwards et al., 2015; Hao et al., 2020; Ottinger et al., 2016). As aquaculture "must be able to simultaneously intensify its productivity and its environmental performance," CE strategies are needed to utilize fewer resources while producing less waste (Regueiro et al., 2021). There is accordingly a need for innovative forms of aquaculture which can increase sustainability and profitability and side-stream valorization, such as via aquaponics (Chunjie Li et al., 2018; Hao et al., 2020; Regueiro et al., 2021). Aquaponics combines RAS with hydroponics to optimize nutrient and water flows. Within aquaponic growing systems, wastewater from raising fish supplies nutrients for crops, which filter the water to a state where it can be returned to the fish tanks (Goddek et al. 2015). Furthermore, given the efficient use of nutrients within aquaponics, the phosphorus challenge may become a growing driver of implementation of aquaponic production. Improving the cycling of nutrients, especially fluxes of nitrogen and phosphorus, is crucial given the unsustainability of current land use practices in relation to planetary boundaries (Steffen et al. 2015, Campbell et al. 2018; Baganz et al. 2021b). The reduction of phosphorus and nitrogen emissions and agricultural runoff, as well as improving the capture and reuse of these nutrients, is key to transforming unsustainable nutrient cycling (Conijn et al. 2018; Joyce et al. 2019). Strategies to recover nutrients, especially phosphorus, are crucial to prevent global food shortages in the future (Asadullah et al., 2020). Particular attention has been called to phosphorus (P), a macronutrient needed for plant growth- essential to vegetative and flowering growth stages- which plants assimilate in ionic orthophosphate form ($H_2PO_4^-$, HPO_4^{2-} , PO_4^{3-}) (Goddek et al. 2015; López-Arredondo et al. 2013). Phosphate use in agriculture is part of a complex dilemma, mineral fertilizer use has supported intensified plant and food production, however agricultural runoff has also contributed to excess P-inputs natural environments and eutrophic conditions in aquatic ecosystems in many regions (Elser 2012, Weikard 2016, Huang et al. 2020, Baganz et al. 2021). Moreover, as mineral P is finite, and mine resources are decreasing with time, P-availability is expected to become a growing concern and continue to increase in price, making it all the more important to investigate and advance means of efficiently using P and recovering it from P-rich waste and effluent sources (Ragnarsdottir et al. 2011; Sverdrup & Ragnarsdottir 2011; Gilbert 2009; Cordell et al. 2011; Shu et al. 2006; Goddek et al. 2015). Aquaponics both minimizes nutrient-rich effluent emission to natural environments and converts aquaculture waste into vegetable biomass (Estim et al., 2019). This has the potential to make full use of nutrients in fish feed and waste and significantly reduce industrial fertilizer use (Joyce et al., 2019). Its efficiencies, especially of nutrient recycling, have thus made it a food production method with recognized potential to help address sustainable development goals, with its water efficiency especially suited for arid regions and energy and growth efficiencies of an enclosed growing environment offering a particular advantage in moderate climates (Conijn et al., 2018; Körner and Challa, 2003; Goddek and Körner 2019).

Danish et al. 2021 assert that the outcomes of aquaponics align with the United Nations Sustainable development goals (SDGs): 2. Zero hunger, 7. Clean energy for all, 8. economic growth and job satisfaction, 12. Responsible consumption and production, and 14. Protection of ocean ecosystems.

With such compelling drivers, research of aquaponics has expanded in recent decades, as technological development and integration efforts have garnered increasing attention. Among such efforts, international, transdisciplinary research consortiums, such as that of project CITYFOOD, have played an important role, and academic consideration of aquaponics has expanded to investigations of its potential for integration in urban environments as a form of FWE-infrastructure (Proksch and Baganz 2020), and increasingly as an implementation strategy of CE and related efforts such as the circular cities movement (Skar et al. 2019), increasing regenerative resource exchange and local resilience in FWE-infrastructure.

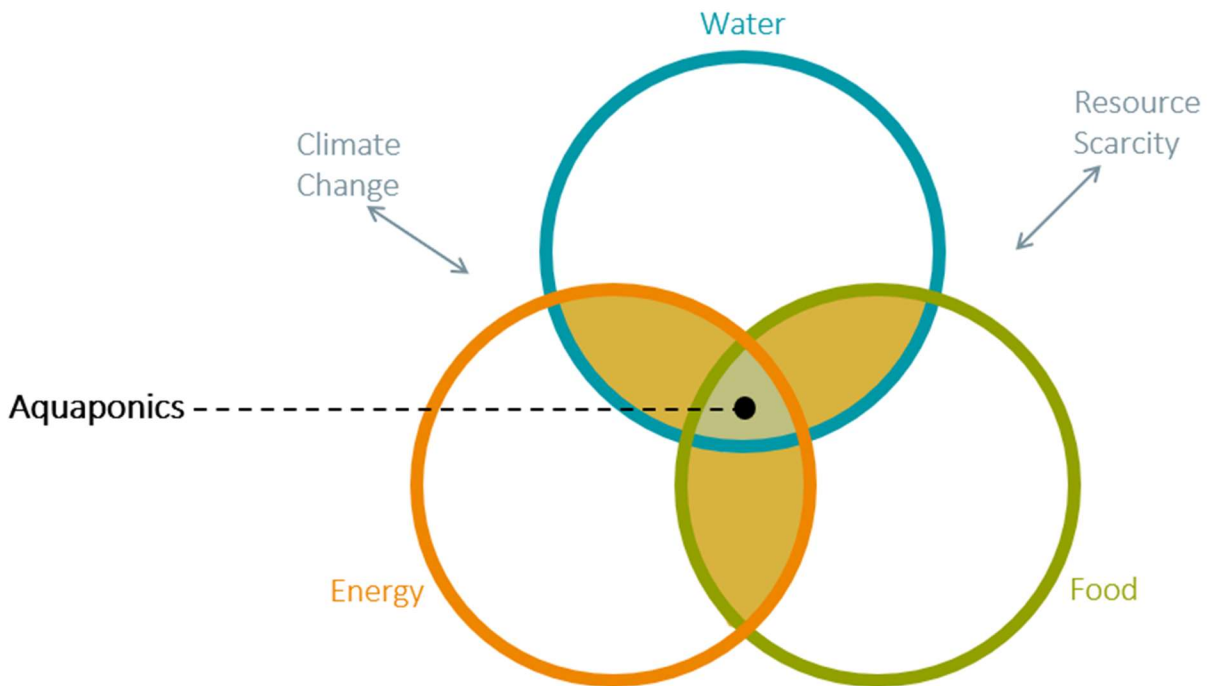


Figure 1.1- Aquaponics in the Food-Water-Energy Nexus

1.2 Points of Departure

1.2.1 Operationalizing intersections: A role for circular frameworks

The resource circularity of aquaponics, as well as its perceived multifaceted sustainability potential, has drawn research funding associated with conceptual frameworks of resource exchange and symbiosis, including the Sustainable Urbanisation Global Initiative (SUGI) Food-Water-Energy Nexus call, established by the Belmont Forum and Joint Programming Initiative

(JPI) Urban Europe in 2016, which led to the creation of research consortium CITYFOOD (Proksch and Baganz 2020). Regenerative resource exchanges for critical FWE-infrastructure have been thus far conceptualized through several prominent frameworks for human-built systems (Horn and Proksch 2022). Many of these frameworks are relevant to the assessment of aquaponics, such as the FWE-Nexus (Proksch and Baganz 2020), circular economy (CE) (Horn et al. 2023), and Circular City (CC) (Horn and Proksch 2022; Skar et al. 2019), as will be further discussed in *Chapter 2*. These “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” (Horn et al. 2023). The application of circularity frameworks to the consideration of aquaponics presented a more operationalizable means of conceptualizing symbiotic resource exchanges than the FWE-nexus alone, which is often used to describe broader system dynamics. Such frameworks are very interconnected, though not directly exchangeable, applicable to varying scales, among other subtleties to their definitions. Likewise, there is of course not just one way to situate a biocircular technology like aquaponics among broader sustainability dialogue and associated symbiotic, circular, and regenerative frameworks (Horn and Proksch 2022). However, as these frameworks proliferate, often in conjunction with new funding initiatives aligned with their research advancement, such as COST Action Circular City, in Europe, which also invokes the concept of nature-based solutions (NBS) (Action CA17133), selection and application of these frameworks for research or policy, let alone their implementation, can become murky. There is accordingly a need to dissect the relation of such frameworks and the overlaps and synergies in what they espouse. The prevention of repetitive research compels holistic review and discussion of these frameworks and the creation of a centralized resource for their definitions, contexts, and intersections. Moreover, the advancement of practical implementation strategies, even in the case of CE, remains in an emerging state (Korhonen et al., 2018; Suárez-Eiroa et al., 2019), emphasizing the need for more research supporting implementation strategies for circular, regenerative, and symbiotic frameworks. Considering the relationships between multiple frameworks enables the translation of implementation strategies and shared goals across frameworks for use in research, policy, and applied practice, all the better supported by the creation of a centralized resource cataloging implementation strategies. Addressing these gaps can help to clarify ideological relationships of circular, symbiotic, and regenerative frameworks and generate a centralized reference source for framework definitions and of implementation strategies, helping to operationalize understanding of critical FWE-infrastructure interactions into actionable implementation strategies (Figure 1.2).

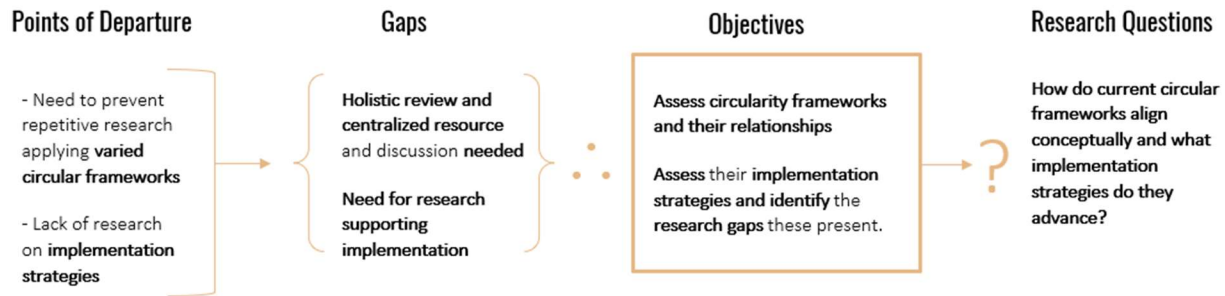


Figure 1.2- Overview of Chapter 2

1.2.2 Implementing Aquaponics for Environmental Efficiency

As technological innovation progresses and makes systems theoretically viable there is a need to consider and deconstruct implementation challenges to achieve feasibility in applied contexts and actualize intended sustainability impacts. The sustainability of aquaponics is widely discussed in literature and was expressed as a key motivation for entering the industry by commercial aquaponics practitioners (Horn et al. 2023). Economic feasibility and environmental performance of commercial aquaponics currently have an indirect relationship, as benefits including pollution prevention, efficient water use, local food production, and resilience to extreme climates, are external to producers (Greenfield et al. 2021; Horn et al. 2023). Moreover, “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” (Horn et al. 2023). An assessment of commercial aquaponics through a Technological Innovation System (TIS) framework identified the advancement of system designs and technology for the improvement of sustainability performance and economic feasibility to be a key strategy for the advancement of commercial aquaponics and realization of its potential sustainable impacts (Horn et al. 2023). Likewise, König et al. 2018 suggest that the direction of aquaponics development should be in the consideration of its sustainability impact and how it can help resolve sustainability challenges in hydroponics and aquaculture and make best use of their existing establishment to succeed in achieving the desired sustainability outcomes.

Resource efficiency aiming for the minimization of waste and maximization of production is a cornerstone of aquaponics (Estim et al. 2020; Danish et al. 2021). Sustainability benefits of aquaponics expressed in literature emphasize efficient use of water and nutrients (Joyce et al. 2019, Folorunso et al. 2021), including reduced wastewater discharge (Petrea et al. 2019, Danish et al. 2021), with potential for “near-zero” nutrient loss and reuse of water at sufficient pH levels in a cycle of recycled exchange between fish and crops (Danish et al. 2021). This helps to minimize of fertilizer and chemical inputs, external organics, pesticides, antibiotics (Rakocy 2006; Chunjie Li et al. 2018; Joyce et al. 2019; Danish et al. 2021; Folorunso et al. 2021) allowing for lessened emissions and little to no pollution (Goddek et al. 2015, Abusin & Mandikiana

2020, Wu & Song 2021, Folorunso et al. 2021). Other benefits are further discussed in *Chapter 3*. Aquaponics improves water efficiency over other methods by productively using wastewater from aquaculture production and, in doing so, avoiding the environmental pollution which RAS and traditional fisheries can create (Love et al. 2015; Hao et al. 2020). Depending on local climate conditions, aquaponics utilizes 10% or less of the water that conventional agriculture would (Danish et al. 2021; Goddek et al. 2015). Published efficiency values in literature have documented 95-99% water reuse and, more than 50% reduction in the need for synthetic fertilizers, eliminated pesticide use, no dependence on soil, and low waste outputs (Al-Hafedh et al., 2008; dos Santos, 2016; König et al., 2018; Maucieri et al., 2018; Cifuentes-Torres et al. 2021).

Whilst the potential of aquaponics is popularly discussed, the complexity of the growing system and its integration potential make the nuanced challenges of implementation unavoidable. For all the benefits of CEA, including to aquaponics, the additional infrastructure required for controlled conditions and full operational sustainability (Reyes-Lúa et al. 2021) compels the use of design and technical innovations as well as thorough, critical approaches to implementation. The most intrinsic symbiotic resource exchanges in aquaponics systems are those of nutrients and water, however other resources (e.g. heat, light, fish food, enclosure, etc.) are also needed for aquaponic production (Proksch et al. 2019). While these can be sourced and managed sustainably, this is not a given outcome and depends on complex dynamics (Chapter 3). Potential environmental “hotspots” noted thus far include equipment and structures, heat, electricity, and fish feed (Ghamkhar et al., 2020; Körner et al. 2021). Though the potential for renewable sources is often discussed in literature, whether such strategies are utilized in current commercial aquaponic farms has not yet been documented. Likewise, the degree of sophistication of nutrient recovery in practice is little documented despite its popularity as a topic of research and intrinsic vitality to the environmental efficiency of aquaponics. Previous study of commercial aquaponics practice has indicated the need for research to “to better elucidate the current sustainable performance and practices of commercial aquaponic operations in comparison to the possibilities for documented in literature” 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” (Horn et al. 2023). This understudied gap between theoretical potential and applied practice is the focus of *Chapter 3*, which seeks to characterize the disparity between academic discussions of potential and applied practice in commercial aquaponic operations and future directions to address these. This work accordingly also helps to address a noted gap in literature of the need for better strategic knowledge to support the successful development of sustainable food production approaches, like aquaponics, while “maintaining their promise of sustainability” and ability to act as the solutions they are set out to be (König et al. 2018). Moreover, it is important that claims “and supporting evidence of aquaponics’ sustainability are essential to securing legitimacy” (Horn et al. 2023) of aquaponics, while inaccurate assertions could hinder its advancement and ability to deliver on sustainability potential (König et al. 2018). As the alignment between theoretical (as expressed in literature) and applied (in the

commercial field) environmental sustainability of aquaponics is unsubstantiated, gaps between literature and practice should be identified to help support more effective real-world implementation. *Chapter 3* will accordingly seek to address this gap (Figure 1.3) by introducing and applying an analytical framework conceptualizing aquaponics systems through a material flow and engineering process lens to identify gaps between research and practice in North American aquaponics and potential means to close these, particularly by leveraging the intersections of aquaponic systems with other sustainable technologies and industries.

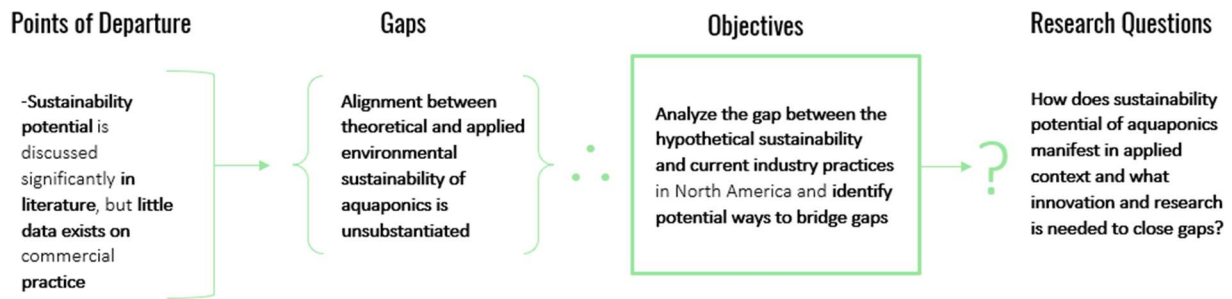


Figure 1.3- Overview of Chapter 3

1.2.3 Optimizing via Resource Integration: Industrial Symbiosis with Controlled-Environment Agriculture

Like other systems with living processes at their core, aquaponics includes inbuilt valorization of organic waste streams but can be augmented through additional enhancements to achieve greater efficiency and regenerative circularity, such as through integrations with buildings, industries, and urban environments (Horn and Proksch, 2020, Schneider et al., 2020; Horn and Proksch, 2022, Baganz et al. 2020, Estim et al. 2020). CE strategies of this nature have 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” (Horn et al. 2023). Assessment of commercial aquaponics has observed promise in “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” (Horn et al. 2023). Symbiotic resource exchanges offer a means of optimizing environmental performance, potentially helping to overcome many of the gaps observed in *Chapter 3*. This can include physical resource exchanges, but also shared use of space and organizational partnerships.

Opportunities for synergistic integration of FWE resources in aquaponics include integration with waste heat, district heating systems, other renewable energy systems, and wastewater resource flows for mutual benefit (Skar et al., 2019; Million et al., 2014, Asheim et al., 2011; Klerkx, 2020; Horn et al., 2023). A small minority of interviewed aquaponics industry members in North America were actively engaged in considering opportunities for CE-oriented business partnerships, suggesting an opportunity to expand awareness and accessibility of this route for

practitioners (Horn et al. 2023). One of these producers 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” but was ultimately hindered by “the lack of recognition of aquaponics as a viable high-output commercial industry by potential resource-sharing partners” at the time (Horn et al. 2023). Moreover, while industrial symbiosis and its scalar variations are a key infrastructural element of implementing CE and associated regenerative aims, its use is little researched in the context of controlled-environment agriculture (CEA) systems, particularly for aquaponic systems- and its component hydroponic and recirculating aquaculture systems. As more regions seek to bolster applications of industrial symbiosis with food production industries, particularly in industrial symbiosis networks as a type of Agro-Ecological Symbiosis (AES) (Helenius et al. 2020), there is a critical need to learn from existing examples. The potential for sustainable development of commercial aquaponics, as well as CEA more broadly, by increasing symbiotic resource use and recovery via the integration with urban and industrial resources could provide a notable means of closing additional resource loops (Horn and Proksch 2020), and is currently an expanding practice, particularly in Northern Europe where early examples can be found and “useful lessons may be learned” (Horn et al. 2023).

Moreover, “as resource sharing arrangements (e.g., industrial symbiosis networks) that include [CEA] 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” (Horn et al. 2023). Available data and industry discussion indicates that barriers to advancing industrial symbiosis partnerships are more often organizational (Hamam et al. 2022) and regulatory in nature than technical, but little research exists on the issue. Examples of CEA industrial symbiosis are popping up in Northern Europe, and their potential has been discussed in literature, particularly through a theoretical lens among CEA scholars, but not connected yet to existing industrial symbiosis literature, the framing of which is well suited to help document trends and uncover factors influencing implementation. While industrial symbiosis strategies are discussed in CEA literature, and greenhouses have been documented in previous industrial symbiosis networks, existing literature has not yet addressed the increasing implementation of industrial symbiosis with CEA organizations. Chapter 4 accordingly seeks to address this gap (Figure 1.4) for the context of industrial symbiosis with CEA operations that produce food using aquaponics and its related subsystems, helping to advance research supporting the successful implementation of such symbioses, and leveraging framework and aquaponic systems insights developed in both Chapter 2 and Chapter 3. This study will employ exploratory multiple case study methods to document and advance understanding of industrial symbiosis with CEA and identify emergent intra-organizational, inter-organizational, and institutional factors that affect their implementation, creating a conceptual platform for further research on this emergent typology to support their successful development and contributions to critical FWE-infrastructure resilience and sustainability.

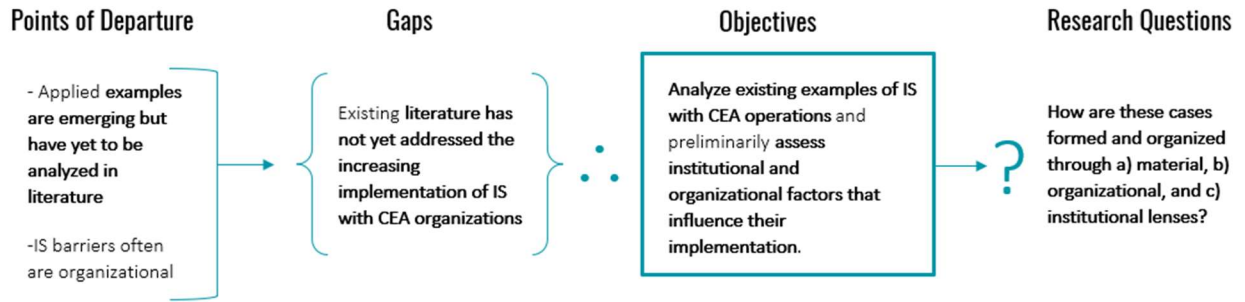


Figure 1.4- Overview of Chapter 4

1.3 Bridging the Gaps: Overview of Objectives

Supported by three investigations, this work considers the overarching question:

To achieve improved environmental efficiency and resilience, how can the implementation of circular economy in the Food-Water-Energy Nexus be advanced through industrial symbiosis strategies within these intersecting critical infrastructure sectors?

Table 1.1- Overview of Objectives

	Points of Departure	Gaps	Objectives	Research Questions	Primary Methods	Journal Audiences	Contributions
1	<ul style="list-style-type: none"> - Varied frameworks create confusion and inefficiency - Insufficient availability of resource cataloging implementation strategies 	<ul style="list-style-type: none"> Need for more research supporting implementation Avoidance of repetitive research compels holistic review and the creation of centralized resource and discussion 	<ul style="list-style-type: none"> Describe what different frameworks exist to conceptualize circular sustainability and the relationships, similarities, and differences between them. Assess the implementation strategies recommended by prominent regenerative, circular, and symbiotic sustainability 	<ul style="list-style-type: none"> How do current circular, regenerative, and symbiotic sustainability frameworks for the built environment align conceptually and what implementation strategies do they advance? 	<ul style="list-style-type: none"> Systematic literature review 	<ul style="list-style-type: none"> Published in <i>Frontiers in Built Environment</i>, which reaches an interdisciplinary sustainability audience, particularly those focused on urban and building scale research. 	<ul style="list-style-type: none"> Clarifies ideological relationships of circular, symbiotic, and regenerative frameworks Acts as a centralized reference of framework definitions and of implementation strategies they advance to bolster an integrated and

			frameworks in the context of circular city implementation, and the research gaps they present.				transdisciplinary approach
2	2- Literature describes thoroughly the theoretical sustainability potential of aquaponics production, however little data exists on the applied sustainability in contemporary commercial industry processes	The alignment between theoretical (as expressed in literature) and applied (in the commercial field) environmental sustainability of aquaponics is unsubstantiated. Gaps between literature and practice should be identified to help support more effective real-world implementation.	-Assess the alignment or differences between the hypothetical sustainability of commercial aquaponics and current industry practices in North America, the factors which shape these, and the resulting innovation and research needs to support the sustainability and success of commercial aquaponics.	How does the purported sustainability potential of aquaponics manifest in applied context in operating commercial aquaponics and what innovation and research is needed to close any gaps between theoretical and applied performance?	Semi-structured interviews, literature review, engineered process assessment, and qualitative coding	Intended audience with interest in sustainable technologies and production practices as well as aquaponics practitioners and researchers	Advances a framework conceptualizing aquaponics systems through a material flow and process lens Presents previously unexplored gaps between research and practice in North American aquaponics are identified and potential means to close these

3	<p>3- Examples of CEA-IS are emerging in Northern Europe, and their potential has been discussed in literature, particularly in CEA communities, but not connected yet to existing IS literature.</p> <p>General IS barriers are often organizational in nature.</p>	<p>While IS strategies are discussed in CEA literature, and greenhouses have been documented in previous ISNs, existing literature has not yet addressed the increasing implementation of industrial symbiosis with CEA organizations</p>	<p>-Describe and characterize existing examples of IS with CEA operations in Northern Europe and preliminarily assess institutional and organizational factors that influence their implementation.</p>	<p>How and why is CEA-IS pursued in these cases?</p> <p>How are these cases formed and organized through a) material, b) organizational, and c) institutional lenses? How and why do emergent trends in the dynamics of these categories influence the viability and success of CEA-IS?</p>	<p>Exploratory multiple case study, interview and document analysis, qualitative thematic coding</p>	<p>Intended audience with interest in industrial ecology and industrial symbiosis as well as CEA researchers, business owners, and policymakers</p>	<p>Documents and advances understanding of IS with CEA</p> <p>Identifies emergent intra-organizational, inter-organizational, and institutional factors that affect CEA-IS implementation</p> <p>Creates conceptual platform for further research of CEA-IS implementation</p>
---	--	---	---	---	--	---	--

1.4 Methods

1.4.1 Research Perspective

This work considers circular frameworks and industrial symbiosis strategies leveraging aquaponics growing systems through an environmental engineering lens, considering their relation to larger global biogeochemical cycles and advancement of adaptation and mitigation efforts through the built environment disciplines. There is a vital need to pair technological advancements with implementation science efforts, a task which engineers are especially well positioned to do within interdisciplinary research efforts by considering the intersection of engineered processes with larger social processes. In addition to traditional quantitative approaches, qualitative and mixed-methods research is increasingly needed to address implementation gaps that arise during translation into applied settings.

1.4.2 Methodology Overview

Assessment of circularity frameworks in *Chapter 2* (Table 1.2) is pursued through systematic literature review, a method for the identification and evaluation of all literature relevant to a given topic to support conclusions on a given consideration or research question (Booth et al., 2012). Literature review is also utilized in *Chapter 3*, forming a basis of comparison for interview and case analysis and an engineered process analysis. Case study methods are likewise applied in *Chapter 4*, which conducts an exploratory multiple case study, presenting a cross-case synthesis. A multiple case study approach is selected as these are considered “likely to be stronger than single-case studies” and apply a replication, rather than sampling, logic, yielding similar results across the cases to strengthen insights (Yin 2018). Accordingly, a cross-case synthesis utilizes a “case-based” approach instead of a “variable-based” one (Byrne 2009; Ragin and Becker 1992; Yin 2018), aiming to keep the integrity of the cases and “then to compare or synthesize any within-case patterns across the cases” rather than reduce them into a series of separate variables (Yin 2018). Case study analysis utilized triangulation, recognized as an element of good practice within case study research (Dubé & Paré 2003; Gibbert and Ruigrok 2010; Piekkari et al. 2009; Beverland and Lindgreen 2010; Eisenhardt 1989; Johnston et al. 1999; Piekkari et al. 2010; Farquhar et al. 2020), as a means to address validity and reliability (Beverland and Lockshin 2003; Yin, 2018; Jick 1979; Miles and Huberman 1994; Farquhar et al. 2020). According to Farquhar et al. 2020, “with its absorption into social sciences, triangulation serves as a metaphor for research that employs different methods, theories or data sources, as a means of capturing social reality in a comprehensive manner,” particularly that of a studied phenomenon (Bilandzic 2008, Wolfram Cox and Hassard 2005; Farquhar et al. 2020). Farquhar et al. 2020 considered and re-appraised the role of triangulation in the context of case study research, expanding beyond an emphasis on convergence to other capacities which have been discussed over time (Flick 1992; Wilson and Hutchinson 1991; Erzberger and Prein 1997; Richardson 1994) introducing a “a theoretical reframing of triangulation consisting of three modes - convergence, complementarity and divergence,” to better reflect its capacity to expose “analytic richness (Fielding 2009), through enhancing the evaluation of alternative

explanations (Patton 1999; Wallendorf and Belk 1989)” and to offer varied perspectives on a phenomenon (Dubé and Paré 2003; Silverman 2006; Farquhar et al. 2020). Moreover, they echo previous research in asserting that triangulation accordingly can stimulate the better definition and analysis of problems in organizational research (Jick 1979; Farquhar et al. 2020), as explored in *Chapter 4*.

Table 1.2- Overview of Methods

Ch.	Methods	Audience	Key Contributions
2	Systematic literature review	<i>Frontiers in Built Environment</i>	Clarifies ideological relationships of circular, symbiotic, and regenerative frameworks Centralized reference of framework definitions and of implementation strategies
3	Semi-structured interviews, literature review, qualitative thematic analysis, document and photographic analysis, engineered process assessment	Sustainability researchers, aquaponics practitioners and researchers	Advances new aquaponic systems framework Novel nutrient recovery engineered-process analysis identifies inconsistent technology usage Illuminates previously unexplored gaps between research and practice
4	Exploratory multiple case study, interview and document analysis, and qualitative thematic analysis	Industrial ecology researchers, CEA researchers & business owners, and policymakers	Documents and advances understanding of IS with CEA Identifies emergent intra-organizational, inter-organizational, and institutional factors that affect CEA-IS implementation Creates conceptual platform for further research of CEA-IS implementation

1.5 Dissertation Structure and Nature

1.5.1 Arc of Development

This work developed through Project CITYFOOD, an interdisciplinary consortium studying the urban integration of aquaponics, of which the Circular City & Living Systems Lab at the University of Washington (UW) was a core member together with five other international teams (Proksch and Baganz 2020). Emerging from earlier work on urban integration, including building (Horn and Proksch 2020; Harrel et al. 2020) and urban resource integration (Horn and Proksch, 2020b; Proksch et al. 2022), the variety and proliferation of potential circular frameworks that could be applied to aquaponics and increasing discussion of Circular City concepts among related research inspired a deeper dive into these framework meanings and implementation strategies as presented in *Chapter 2*, published as *Symbiotic and Regenerative Sustainability Frameworks: Moving Towards Circular City Implementation* in *Frontiers in Built Environment* (Horn and Proksch 2022). Following up CITYFOOD, teams from UW and the University of Gothenburg teamed up with new international research partners in the project *Resource Recovery in the Food-Water-Energy Nexus*, which sought to go deeper into topics of nutrient recovery (particularly phosphorus) and sustainable resource management and operations in aquaponics. Interviews with North American commercial aquaponics practitioners in this project supported the assessment of aquaponics as a Technological-Innovation-System

(TIS) incorporating Multi-Level Perspectives to identify a supportive niche for commercial aquaponics and pathways to get there (Horn et al. 2023) as well as an analysis of nutrient recovery approaches and environmental efficiency of commercial aquaponics operations, found in *Chapter 3* of this work- *A Mixed-Methods Assessment of Environmental Sustainability Gaps in Commercial Aquaponic Operations in North America*. Findings of Horn et al. 2023 and *Chapter 3* highlighted the importance of industrial symbiosis strategies for resource sharing to support the environmental efficiency and viability of commercial aquaponics, as well as the need to ease access to such strategies through organizational and institutional perspectives, leading to the investigation presented in *Chapter 4- Industrial Symbiosis with Controlled Environment Agriculture: An Exploratory Multiple Case Study Analysis*. This work was made possible through a Valle Exchange supporting research and case study visits in Norway, Sweden, and nearby regions, and analyzes emergent examples of CEA operations in Northern Europe to document and identify their motivations, contexts, material exchanges, and influential organizational and institutional factors to form a platform for further study to support implementation success.

1.5.2 Dissertation Structure

This dissertation follows a three-paper format, in which three journal articles (one published, two to be submitted) form the core of the work. These are chapters 2, 3, and 4 respectively (Figure 1.5).

Chapter 1 consists of an introduction and overview of the dissertation, including motivating context, points of departure, and supporting content.

Chapter 2 contains the first dissertation paper, *Symbiotic and Regenerative Sustainability Frameworks: Moving Towards Circular City Implementation*, as published in *Urban Science*, a section of the journal *Frontiers in Built Environment* in March of 2022. This is an open access piece with author-maintained copyright.

Chapter 3 contains a manuscript of the second dissertation paper, *A Mixed-Methods Assessment of Environmental Sustainability Gaps in Commercial Aquaponic Operations in North America*. This piece is intended for publication for an audience with interest in cleaner production approaches, aquaponics, and CEA sustainability.

Chapter 4 contains a manuscript of the third dissertation paper, *Industrial Symbiosis with Controlled Environment Agriculture: An Exploratory Multiple Case Study Analysis*, intended to reach audiences interested in industrial ecology, industrial symbiosis, CEA, and sustainable development policies.

Chapter 5 is a conclusion section, addressing contributions to knowledge, limitations, and future research directions.

References contain all references organized by respective chapter number.

Appendix A contains a Glossary of terms

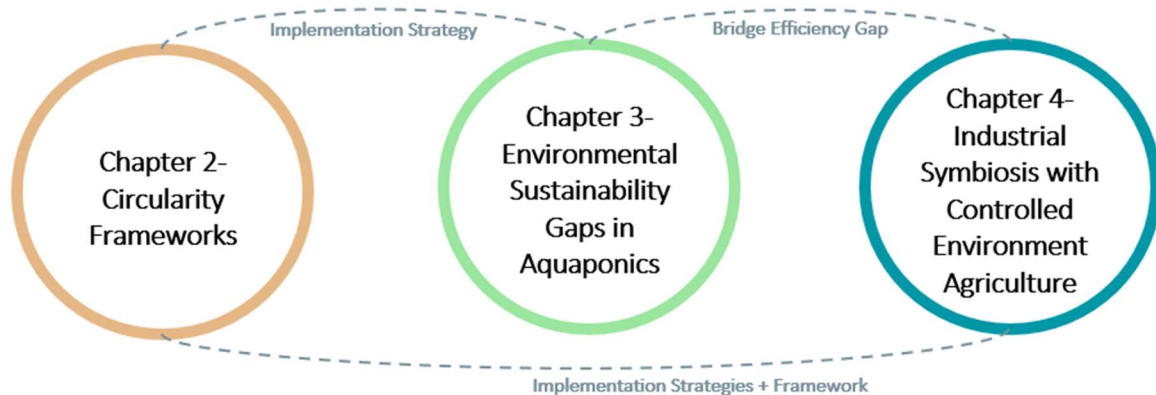


Figure 1.5- Overview of Core Dissertation Chapters

Chapter 1 References

- Abusin, S. A. A., & Mandikiana, B. W. (2020). Towards sustainable food production systems in Qatar: Assessment of the viability of aquaponics. *Global Food Security*, 100349. <https://doi.org/10.1016/j.gfs.2020.100349>
- Al-Hafedh, Y. S., Alam, A., & Beltagi, M. S. (2008). Food Production and Water Conservation in a Recirculating Aquaponic System in Saudi Arabia at Different Ratios of Fish Feed to Plants. *Journal of the World Aquaculture Society*, 39(4), 510–520. <https://doi.org/10.1111/j.1749-7345.2008.00181.x>
- Allan, T., Keulertz, M., and Woertz, E. (2015). The Water-Food-Energy Nexus: an Introduction to Nexus Concepts and Some Conceptual and Operational Problems. *Int. J. Water Resour. Develop.* 31 (3), 301–311. doi:10.1080/07900627.2015.1029118
- 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>
- Baganz, G., Proksch, G., Kloas, W., Lorleberg, W., Baganz, D., Staaks, G., & Lohrberg, F. (2020). Site Resource Inventories – a Missing Link in the Circular City’s Information Flow. *Advances in Geosciences*, 54, 23–32. <https://doi.org/10.5194/adgeo-54-23-2020>
- 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>
- Bazilian, M., Rogner, H., Howells, M., Hermann, S., Arent, D., Gielen, D., et al. (2011). Considering the Energy, Water and Food Nexus: Towards an Integrated Modelling Approach. *Energy Policy* 39 (12), 7896–7906. doi:10.1016/j.enpol.2011.09.039
- Beverland, M., & Lockshin, L. (2003). A longitudinal study of customers’ desired value change in business-to-business markets. *Industrial Marketing Management*, 32(8), 653–666. <https://doi.org/10.1016/j.indmarman.2003.06.006>
- Beverland, M., & Lindgreen, A. (2010). What makes a good case study? A positivist review of qualitative case research published in *Industrial Marketing Management*, 1971–2006. *Industrial Marketing Management*, 39(1), 56–63. <https://doi.org/10.1016/j.indmarman.2008.09.005>
- Bilandzic, H. (2008). Triangulation. In *The International Encyclopedia of Communication*. John Wiley & Sons, Ltd. <https://doi.org/10.1002/9781405186407.wbiect060>
- Bizikova, L., Roy, D., Swanson, D., Venema, H. D., and McCandless, M. (2013). *The Water–Energy–Food Security Nexus: Towards A Practical Planning and Decision Support Framework for Landscape Investment and Risk Management*. International Institute for Sustainable Development.

- Booth, A., Papaioannou, D., and Sutton, A. (2012) Systematic approaches to a successful literature review. London: Sage.
- Byrne, D. (2009). Introduction - Case-Based Methods: Why We Need Them; What They Are; How to Do Them. In *The SAGE Handbook of Case-Based Methods* (pp. 1–10). SAGE Publications, Limited.
<https://doi.org/10.4135/9781446249413.n1>
- Campbell, B. M., Hansen, J., Rioux, J., Stirling, C. M., Twomlow, S., & (Lini) Wollenberg, E. (2018). Urgent action to combat climate change and its impacts (SDG 13): Transforming agriculture and food systems. *Current Opinion in Environmental Sustainability*, 34, 13–20. <https://doi.org/10.1016/j.cosust.2018.06.005>
- Carus, M., & Dammer, L. (2018). The Circular Bioeconomy—Concepts, Opportunities, and Limitations. *Industrial Biotechnology*, 14(2), 83–91. <https://doi.org/10.1089/ind.2018.29121.mca>
- Chunjie Li, Chew Tin Lee, Yueshu Gao, Haslenda Hashim, Xiaojun Zhang, Wei-Min Wu, & Zhenjia Zhang. (2018). Prospect of aquaponics for the sustainable development of food production in urban. *Chemical Engineering Transactions*, 63, 475–480. <https://doi.org/10.3303/CET1863080>
- Cifuentes-Torres, L., Correa-Reyes, G., & Mendoza-Espinosa, L. G. (2021). Can Reclaimed Water Be Used for Sustainable Food Production in Aquaponics? *Frontiers in Plant Science*, 12, 669984–669984.
<https://doi.org/10.3389/fpls.2021.669984>
- CISA. (n.d.). Critical Infrastructure Sectors | CISA. Retrieved June 14, 2024, from <https://www.cisa.gov/topics/critical-infrastructure-security-and-resilience/critical-infrastructure-sectors>
- Coaffee, J., & Clarke, J. (2017). Critical infrastructure lifelines and the politics of anthropocentric resilience. *Resilience*, 5(3), 161–181. <https://doi.org/10.1080/21693293.2016.1241475>
- Conijn, J. G., Bindraban, P. S., Schröder, J. J., & Jongschaap, R. E. E. (2018). Can our global food system meet food demand within planetary boundaries? *Agriculture, Ecosystems & Environment*, 251, 244–256.
<https://doi.org/10.1016/j.agee.2017.06.001>
- Corbin, A. (1986). *The Foul and the Fragrant: Odor and the French Social Imagination*. Harvard University Press.
- Corcelli, F., Fiorentino, G., Petit-Boix, A., Rieradevall, J., & Gabarrell, X. (2019). Transforming rooftops into productive urban spaces in the Mediterranean. An LCA comparison of agri-urban production and photovoltaic energy generation. *Resources, Conservation and Recycling*, 144, 321–336. <https://doi.org/10.1016/j.resconrec.2019.01.040>
- Cordell, D., Drangert, J.-O., & White, S. (2009). The story of phosphorus: Global food security and food for thought. *Global Environmental Change*, 19(2), 292–305. <https://doi.org/10.1016/j.gloenvcha.2008.10.009>
- Cordell, D., Rosemarin, A., Schröder, J. J., & Smit, A. L. (2011). Towards global phosphorus security: A systems framework for phosphorus recovery and reuse options. *Chemosphere*, 84(6), 747–758.
<https://doi.org/10.1016/j.chemosphere.2011.02.032>
- Danish, M. S. S., Senjyu, T., Sabory, N. R., Khosravy, M., Grilli, M. L., Mikhaylov, A., & Majidi, H. (2021). A Forefront Framework for Sustainable Aquaponics Modeling and Design. *Sustainability*, 13(16), Article 16.
<https://doi.org/10.3390/su13169313>
- dos Santos, M. J. P. L. (2016). Smart cities and urban areas—Aquaponics as innovative urban agriculture. *Urban Forestry & Urban Greening*, 20, 402–406. <https://doi.org/10.1016/j.ufug.2016.10.004>
- Dubé, L., & Paré, G. (2003). Rigor in Information Systems Positivist Case Research: Current Practices, Trends, and Recommendations. *MIS Quarterly*, 27(4), 597–636. <https://doi.org/10.2307/30036550>
- Edwards, J., Othman, M., & Burn, S. (2015). A review of policy drivers and barriers for the use of anaerobic digestion in Europe, the United States and Australia. *Renewable and Sustainable Energy Reviews*, 52, 815–828.
<https://doi.org/10.1016/j.rser.2015.07.112>
- Eisenhardt, K. M. (1989). Building Theories from Case Study Research. *The Academy of Management Review*, 14(4), 532–550. <https://doi.org/10.2307/258557>
- Erzberger, C., & Prein, G. (1997). Triangulation: Validity and empirically-based hypothesis construction. *Quality & Quantity*, 31(2), 141–154. <https://doi.org/10.1023/A:1004249313062>
- Estim, A., Saufie, S., & Mustafa, S. (2019). Water quality remediation using aquaponics sub-systems as biological and mechanical filters in aquaculture. *Journal of Water Process Engineering*, 30, 100566.
<https://doi.org/10.1016/j.jwpe.2018.02.001>

- Estim, A., M. Shaleh, S. R., 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. *Aquaculture Studies*, 20(1). https://doi.org/10.4194/2618-6381-v20_1_08
- FAO, UN. (2018). *The State of World Fisheries and Aquaculture 2018—Meeting the Sustainable Development Goals*.
- Farquhar, J., Michels, N., & Robson, J. (2020). Triangulation in industrial qualitative case study research: Widening the scope. *Industrial Marketing Management*, 87, 160–170. <https://doi.org/10.1016/j.indmarman.2020.02.001>
- Ferrara, M., & Squatrito, A. (2022). Design-driven innovation of bio-based circular materials. Design strategies and skills. *AGATHÓN | International Journal of Architecture, Art and Design*, 11, 288–299. <https://doi.org/10.19229/2464-9309/11262022>
- Fielding, N. G. (2009). Going out on a Limb: Postmodernism and Multiple Method Research. *Current Sociology*, 57(3), 427–447. <https://doi.org/10.1177/0011392108101591>
- Flick, U. (1992). Triangulation Revisited: Strategy of Validation or Alternative? *Journal for the Theory of Social Behaviour*, 22(2), 175–197. <https://doi.org/10.1111/j.1468-5914.1992.tb00215.x>
- Folorunso, E. A., Roy, K., Gebauer, R., Bohatá, A., & Mraz, J. (2021). Integrated pest and disease management in aquaponics: A metadata-based review. *Reviews in Aquaculture*, 13(2), 971–995. <https://doi.org/10.1111/raq.12508>
- Forzieri, G., Bianchi, A., Silva, F. B. e., Marin Herrera, M. A., Leblois, A., Lavallo, C., Aerts, J. C. J. H., & Feyen, L. (2018). Escalating impacts of climate extremes on critical infrastructures in Europe. *Global Environmental Change*, 48, 97–107. <https://doi.org/10.1016/j.gloenvcha.2017.11.007>
- Gandy, M. (2002). *Concrete and clay: reworking nature in New York City*. Cambridge, MA: The MIT Press. <https://doi.org/10.7551/mitpress/2083.001.0001>
- Gandy, M. (2004). Rethinking urban metabolism: Water, space and the modern city. *City*, 8(3), 363–379. <https://doi.org/10.1080/1360481042000313509>
- Garcia, D. J., & You, F. (2016). The water-energy-food nexus and process systems engineering: A new focus. *Computers & Chemical Engineering*, 91, 49–67. <https://doi.org/10.1016/j.compchemeng.2016.03.003>
- Ghamkhar, R., Hartleb, C., Wu, F., & Hicks, A. (2019). Life cycle assessment of a cold weather aquaponic food production system. *Journal of Cleaner Production*, 118767. <https://doi.org/10.1016/j.jclepro.2019.118767>
- Gibbert, M., & Ruigrok, W. (2010). The “What” and “How” of Case Study Rigor: Three Strategies Based on Published Work. *Organizational Research Methods*, 13(4), 710–737. <https://doi.org/10.1177/1094428109351319>
- Gilbert, N. (2009). Environment: The disappearing nutrient. *Nature*, 461(7265), 716–718. <https://doi.org/10.1038/461716a>
- Goddek, S., Delaide, B., Mankasingh, U., Ragnarsdottir, K. V., Jijakli, H., & Thorarinsdottir, R. (2015). Challenges of Sustainable and Commercial Aquaponics. *Sustainability*, 7(4), 4199–4224. <https://doi.org/10.3390/su7044199>
- Goddek, S., & Körner, O. (2019). A fully integrated simulation model of multi-loop aquaponics: A case study for system sizing in different environments. *Agricultural Systems*, 171, 143–154. <https://doi.org/10.1016/j.agsy.2019.01.010>
- Goyette, J.-O., Bennett, E. M., & Maranger, R. (2018). Low buffering capacity and slow recovery of anthropogenic phosphorus pollution in watersheds. *Nature Geoscience*, 11(12), 921–925. <https://doi.org/10.1038/s41561-018-0238-x>
- Green, N. (1990). *The Spectacle of Nature: Landscape and Bourgeois Culture in Nineteenth-century France*. Manchester University Press.
- Greenfeld, A., Becker, N., Bornman, J. F., Spatari, S., & Angel, D. L. (2021). Monetizing environmental impact of integrated aquaponic farming compared to separate systems. *Science of The Total Environment*, 792, 148459. <https://doi.org/10.1016/j.scitotenv.2021.148459>
- Gregg, J. S., Jürgens, J., Sandvold, H. N., & Olsen, D. S. (2019). The transition to aquaponics in support of a circular bioeconomy: Policy recommendations to overcome geographical and scale barriers. 14.
- Hamilton, H. A., Brod, E., Hanserud, O. S., Gracey, E. O., Vestrum, M. I., Bøen, A., Steinhoff, F. S., Müller, D. B., & Brattebø, H. (2016). Investigating Cross-Sectoral Synergies through Integrated Aquaculture, Fisheries, and Agriculture Phosphorus Assessments: A Case Study of Norway. *Journal of Industrial Ecology*, 20(4), 867–881. <https://doi.org/10.1111/jiec.12324>
- Hamam, M., Spina, D., Raimondo, M., Di Vita, G., Zanchini, R., Chinnici, G., Tóth, J., & Mario, D. (2023). Industrial symbiosis and agri-food system: Themes, links, and relationships. *Frontiers in Sustainable Food Systems*. <https://doi.org/10.3389/fsufs.2022.1012436>

- Hao, Y., Ding, K., Xu, Y., Tang, Y., Liu, D., & Li, G. (2020). States, Trends, and Future of Aquaponics Research. *Sustainability*, 12(18), Article 18. <https://doi.org/10.3390/su12187783>
- Harrel, M., Horn, E., Koehn, J. A., Ianchenko, A., & Proksch, G. (2020). Adaptive Reuse as Carbon Adaptation: Urban Food Production in the under-used Parking Garages of the Future.
- Helenius, J., Hagolani-Albov, S. E., & Koppelmäki, K. (2020). Co-creating Agroecological Symbioses (AES) for Sustainable Food System Networks. *Frontiers in Sustainable Food Systems*, 4. <https://www.frontiersin.org/articles/10.3389/fsufs.2020.588715>
- Horn, E., & Proksch, G. (2020). Building an Ecosystem: Integrating Rooftop Aquaponics with a Brewery to Advance the Circular Economy.
- Horn, E., & Proksch, G. (2020b). Sourcing Energy from Waste in the Circular City: Integrated Anaerobic Digestion toward long term Decarbonization.
- Horn, E., & Proksch, G. (2022). Symbiotic and Regenerative Sustainability Frameworks: Moving Towards Circular City Implementation. *Frontiers in Built Environment*, 7. <https://www.frontiersin.org/article/10.3389/fbuil.2021.780478>
- Horn, E., Joyce, A., Chowdhury, R., Caputo, S., Jacobs, B., Winkler, M. & Proksch, G. (2023). Translating Environmental Potential to Economic Reality: Assessment of Commercial Aquaponics through Sustainability Transitions Theory. *Circular Economy and Sustainability*. <https://doi.org/10.1007/s43615-023-00291-0>
- Huddleston, P., Smith, T., White, I., & Elrick-Barr, C. (2022). Adapting critical infrastructure to climate change: A scoping review. *Environmental Science & Policy*, 135, 67–76. <https://doi.org/10.1016/j.envsci.2022.04.015>
- IPCC – Intergovernmental Panel on Climate Change (2022), *Climate Change 2022 – Impacts, Adaptation and Vulnerability – Summary for Policymakers*, Switzerland. [Online] Available at: [ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_FinalDraft_FullReport.pdf](https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_FinalDraft_FullReport.pdf) [Accessed 30 June 2022].
- James, D. (2018). The Novel as Encyclopedia. *Realising the Circular Bioeconomy 2018*, 74–90. doi:10.1017/9781316659694.006
- Jick, T. D. (1979). Mixing Qualitative and Quantitative Methods: Triangulation in Action. *Administrative Science Quarterly*, 24(4), 602–611. <https://doi.org/10.2307/2392366>
- Johnston, W. J., Leach, M. P., & Liu, A. H. (1999). Theory Testing Using Case Studies in Business-to-Business Research. *Industrial Marketing Management*, 28(3), 201–213. [https://doi.org/10.1016/S0019-8501\(98\)00040-6](https://doi.org/10.1016/S0019-8501(98)00040-6)
- Joyce, A., Goddek, S., Kotzen, B., & Wuertz, S. (2019). Aquaponics: Closing the Cycle on Limited Water, Land and Nutrient Resources. In *Aquaponics Food Production Systems* (pp. 19–34). https://doi.org/10.1007/978-3-030-15943-6_2
- Kallipoliti, L. (2018). History of Ecological Design. *Oxford Research Encyclopedia of Environmental Science*. https://www.academia.edu/36516131/History_of_Ecological_Design
- Kennedy, G., Nantel, G., & Shetty, P. (2004). Globalization of food systems in developing countries: Impact on food security and nutrition. *FAO Food and Nutrition Paper*, 83, 1–300.
- Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, 127, 221–232. <https://doi.org/10.1016/j.resconrec.2017.09.005>
- 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>
- Korhonen, J., Honkasalo, A., and Seppälä, J. (2018). Circular Economy: The Concept and its Limitations. *Ecol. Econ.* 143, 37–46. doi:10.1016/j.ecolecon.2017.06.041
- König, B., Janker, J., Reinhardt, T., Villarroel, M., & Junge, R. (2018). Analysis of aquaponics as an emerging technological innovation system. *Journal of Cleaner Production*, 180, 232–243. <https://doi.org/10.1016/j.jclepro.2018.01.037>
- Körner, O., & Challa, H. (2003). Design for an improved temperature integration concept in greenhouse cultivation. *Computers and Electronics in Agriculture*, 39(1), 39–59. [https://doi.org/10.1016/S0168-1699\(03\)00006-1](https://doi.org/10.1016/S0168-1699(03)00006-1)
- 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. *Journal of Cleaner Production*, 313, 127735. <https://doi.org/10.1016/j.jclepro.2021.127735>
- Langergraber, G., Castellar, J., Andersen, T., Andreucci, M., Baganz, G., Buttiglieri, G., Canet-Martí, A., Carvalho, P., Finger, D., Griessler Bulc, T., Junge, R., Megyesi, B., Milosevic, D., oral, hasan volkan, Pearlmutter, D., Pineda-Martos, R.,

- Pucher, B., van Hullebusch, E., Atanasova, N., & Sathasivan, A. (2021). Towards a Cross-Sectoral View of Nature-Based Solutions for Enabling Circular Cities. *Water*, 13, 2352. <https://doi.org/10.3390/w13172352>
- Laporte, D. (2000) History of shit. Trans. Nadia Benabid and Rodolphe el-Khoury. Cambridge, MA: The MIT Press.
- Link, J. S., & Watson, R. A. (2019). Global ecosystem overfishing: Clear delineation within real limits to production. *Science Advances*, 5(6), eaav0474–eaav0474. <https://doi.org/10.1126/sciadv.aav0474>
- Love, D. C., Uhl, M. S., & Genello, L. (2015). Energy and water use of a small-scale raft aquaponics system in Baltimore, Maryland, United States. *Aquacultural Engineering*, 68, 19–27. <https://doi.org/10.1016/j.aquaeng.2015.07.003>
- Maucieri, C., Nicoletto, C., Junge, R., Schmutz, Z., Sambo, P., & Borin, M. (2018). Hydroponic systems and water management in aquaponics: A review. *Italian Journal of Agronomy*, 13(1), 1–11. <http://dx.doi.org/10.4081/ija.2017.1012>
- Miles, M. & Huberman, A. (1994), *Qualitative Data Analysis* (2nd Edition), Thousand Oaks, Sage Publications.
- 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
- Moragues-Faus, A., Sonnino, R., & Marsden, T. (2017). Exploring European food system vulnerabilities: Towards integrated food security governance. *Environmental Science & Policy*, 75, 184–215. <https://doi.org/10.1016/j.envsci.2017.05.015>
- Mukuve, F. M., and Fenner, R. A. (2015). Scale Variability of Water, Land, and Energy Resource Interactions and Their Influence on the Food System in Uganda. *Sustainable Prod. Consumption* 2, 79–95. doi:10.1016/j.spc.2015.07.009
- Nan, C., & Sansavini, G. (2017). A quantitative method for assessing resilience of interdependent infrastructures. *Reliability Engineering & System Safety*, 157, 35–53. <https://doi.org/10.1016/j.res.2016.08.013>
- Newell, J. P., Goldstein, B., and Foster, A. (2019). A 40-year Review of FoodEnergy-Water Nexus Literature and its Application to the Urban Scale. *Environ. Res. Lett.* 14 (7), 073003. doi:10.1088/1748-9326/ab0767
- Niall, S., & Kallies, A. (2017). Electricity systems between climate mitigation and climate adaptation pressures: Can legal frameworks for resilience provide answers? *Environmental and Planning Law Journal*, 34(6), 488–502.
- Olson, E. (2021), “Plants on Rooftops – Greenwashing in Architecture”, in *The Climate Change Review*, 08/02/ 2021. [Online] Available at: ucsdclimaterewiew.org/post/plants-on-rooftops-greenwashing-in-architecture [Accessed 30 June 2022].
- Ottinger, M., Clauss, K., & Kuenzer, C. (2016). Aquaculture: Relevance, distribution, impacts and spatial assessments – A review. *Ocean & Coastal Management*, 119, 244–266. <https://doi.org/10.1016/j.ocecoaman.2015.10.015>
- Pais, I. P., Reboredo, F. H., Ramalho, J. C., Pessoa, M. F., Lidon, F. C., & Silva, M. M. (2020). Potential impacts of climate change on agriculture—A review. *Emirates Journal of Food and Agriculture*, 32(6), 397–407. <http://dx.doi.org/10.9755/ejfa.2020.v32.i6.2111>
- Patton, M. Q. (1999). Enhancing the quality and credibility of qualitative analysis. *Health Services Research*, 34(5 Pt 2), 1189–1189.
- Petrea, Ștefan-M., Bandi, A.-C., Cristea, D., & Neculiță, M. (2019). Cost-benefit analysis into integrated aquaponics systems. *Custos e Agronegocio*, 15(3), 31.
- Piekkari, R., Welch, C., & Paavilainen, E. (2009). The Case Study as Disciplinary Convention: Evidence From International Business Journals. *Organizational Research Methods*, 12(3), 567–589. <https://doi.org/10.1177/1094428108319905>
- Piekkari, R., Plakoyiannaki, E., & Welch, C. (2010). ‘Good’ case research in industrial marketing: Insights from research practice. *Industrial Marketing Management*, 39(1), 109–117. <https://doi.org/10.1016/j.indmarman.2008.04.017>
- Proksch, G., Ianchenko, A., & Kotzen, B. (2019). Aquaponics in the Built Environment. In S. Goddek, A. Joyce, B. Kotzen, & G. M. Burnell (Eds.), *Aquaponics Food Production Systems: Combined Aquaculture and Hydroponic Production Technologies for the Future* (pp. 523–558). Springer International Publishing. https://doi.org/10.1007/978-3-030-15943-6_21
- Proksch, G., & Baganz, D. (2020). CITYFOOD: Research Design for an International, Transdisciplinary Collaboration. *Technology|Architecture + Design*, 4(1), 35–43. <https://doi.org/10.1080/24751448.2020.1705714>
- Proksch, G., Horn, E., & Lee, G. (2022). Urban Aquaponics Integration. In *Urban Agriculture and Regional Food Systems*- ed. Peter Droege. Elsevier.

- Pulighe, G., & Lupia, F. (2020). Food First: COVID-19 Outbreak and Cities Lockdown a Booster for a Wider Vision on Urban Agriculture. *Sustainability (Basel, Switzerland)*, 12(12), 5012-. <https://doi.org/10.3390/su12125012>
- Pumpuni-Lenss, G., Blackburn, T., & Garstenauer, A. (2017). Resilience in Complex Systems: An Agent-Based Approach. *Systems Engineering*, 20(2), 158–172. <https://doi.org/10.1002/sys.21387>
- Ragin, C. C., & Becker, H. S. (1992). *What is a case?: Exploring the foundations of social inquiry*. Cambridge University Press.
- Ragnarsdottir, K. V., Sverdrup, H. U., & Koca, D. (2011). Challenging the planetary boundaries I: Basic principles of an integrated model for phosphorous supply dynamics and global population size. *Applied Geochemistry*, 26, S303–S306. <https://doi.org/10.1016/j.apgeochem.2011.03.088>
- Rakocy, J. E., Masser, M. P., & Losordo, T. M. (2006). *Recirculating Aquaculture Tank Production Systems: Aquaponics—Integrating Fish and Plant Culture*. 16.
- Regueiro, L., Newton, R., Soula, M., Méndez, D., Kok, B., Little, D. C., 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. *Journal of Industrial Ecology*, n/a(n/a), 1–12. <https://doi.org/10.1111/jiec.13188>
- Reyes-Lúa, A., Straus, J., Skjervold, V. T., Durakovic, G., & Nordtvedt, T. S. (2021). A Novel Concept for Sustainable Food Production Utilizing Low Temperature Industrial Surplus Heat. *Sustainability (Basel, Switzerland)*, 13(17), 9786. <https://doi.org/10.3390/su13179786>
- Richardson, L. (1994). Writing: A Method of Inquiry. In *HANDBOOK OF QUALITATIVE RESEARCH* (pp. 516–529).
- Scalisi, F., & Ness, D. (2022). Symbiosis of greenery with built form. A holistic, systems, multi-level approach. *AGATHÓN | International Journal of Architecture, Art and Design*, 11, 26–39. <https://doi.org/10.19229/2464-9309/1122022>
- Schneider, P., Meyer, A., & Plat, K. (2020). Potential of Bioeconomy in Urban Green Infrastructure. In C. Keswani (Ed.), *Bioeconomy for Sustainable Development* (pp. 251–276). Springer. https://doi.org/10.1007/978-981-13-9431-7_13
- Shakou, L. M., Wybo, J.-L., Reniers, G., & Boustras, G. (2019). Developing an innovative framework for enhancing the resilience of critical infrastructure to climate change. *Safety Science*, 118, 364–378. <https://doi.org/10.1016/j.ssci.2019.05.019>
- Shu, L., Schneider, P., Jegatheesan, V., & Johnson, J. (2006). An economic evaluation of phosphorus recovery as struvite from digester supernatant. *Bioresource Technology*, 97(17), 2211–2216. <https://doi.org/10.1016/j.biortech.2005.11.005>
- Silverman, D. (2006), *Interpreting Qualitative Data: Methods for Analysing Talk, Text and Interaction*, 3rd Edition. London: Sage.
- Skar, S. L. G., Pineda-Martos, R., Timpe, A., Pölling, B., Bohn, K., Kylvik, M., Delgado, C., Pedras, C. M. G., Paço, T. A., Čujić, 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 Systems*. <https://doi.org/10.2166/bgs.2019.931>
- Steen, I. (1998). Phosphorus availability in the 21st century: Management of a non-renewable resource. *Phosphorus & Potassium*, 217, 25–31.
- Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., de Vries, W., de Wit, C. A., Folke, C., Gerten, D., Heinke, J., Mace, G. M., Persson, L. M., Ramanathan, V., Reyers, B., & Sörlin, S. (2015). Planetary boundaries: Guiding human development on a changing planet. *Science*, 347(6223), 1259855. <https://doi.org/10.1126/science.1259855>
- Stegmann, P., Londo, M., & Junginger, M. (2020). The circular bioeconomy: Its elements and role in European bioeconomy clusters. *Resources, Conservation & Recycling: X*, 6, 100029. <https://doi.org/10.1016/j.rcrx.2019.100029>
- Stewart, G. T., Kolluru, R., & Smith, M. (2009). Leveraging public-private partnerships to improve community resilience in times of disaster. *International Journal of Physical Distribution & Logistics Management*, 39(5), 343–364. <https://doi.org/10.1108/09600030910973724>
- Suárez-Eiroa, B., Fernández, E., Méndez-Martínez, G., and Soto-Oñate, D. (2019). Operational Principles of Circular Economy for Sustainable Development: Linking Theory and Practice. *J. Clean. Prod.* 214, 952–961. [doi:10.1016/j.jclepro.2018.12.271](https://doi.org/10.1016/j.jclepro.2018.12.271)
- Sverdrup, H. U., & Ragnarsdottir, K. V. (2011). Challenging the planetary boundaries II: Assessing the sustainable global population and phosphate supply, using a systems dynamics assessment model. *Applied Geochemistry*, 26, S307–S310. <https://doi.org/10.1016/j.apgeochem.2011.03.089>

- Toboso-Chavero, S., Nadal, A., Petit-Boix, A., Pons, O., Villalba, G., Gabarrell, X., Josa, A., & Rieradevall, J. (2018). Towards Productive Cities: Environmental Assessment of the Food-Energy-Water Nexus of the Urban Roof Mosaic. *Journal of Industrial Ecology*. <https://doi.org/10.1111/jiec.12829>
- Van Vuuren, D. P., Bouwman, A. F., & Beusen, A. H. W. (2010). Phosphorus demand for the 1970–2100 period: A scenario analysis of resource depletion. *Global Environmental Change*, 20(3), 428–439. <https://doi.org/10.1016/j.gloenvcha.2010.04.004>
- Wallendorf, M. & Belk, R. (1989), Assessing Trustworthiness in Naturalistic Consumer Research. *Special Volumes- Interpretive Consumer Research*, Association for Consumer Research, 69-84.
- Wilson, H. S., & Hutchinson, S. A. (1991). Triangulation of Qualitative Methods: Heideggerian Hermeneutics and Grounded Theory. *Qualitative Health Research*, 1(2), 263–276. <https://doi.org/10.1177/104973239100100206>
- Wolfram Cox, J., & Hassard, J. (2005). Triangulation in Organizational Research: A Re-Presentation. *Organization*, 12(1), 109–133. <https://doi.org/10.1177/1350508405048579>
- Wu, Y., & Song, K. (2021). Source, Treatment, and Disposal of Aquaculture Solid Waste: A Review. *Journal of Environmental Engineering*, 147(3), 03120012. [https://doi.org/10.1061/\(ASCE\)EE.1943-7870.0001850](https://doi.org/10.1061/(ASCE)EE.1943-7870.0001850)
- Zou, K. (2021). Climate Change and Fisheries Regulation: What We Should Consider for the Future? *Sustainability*, 13(17), Article 17. <https://doi.org/10.3390/su13179735>

Chapter 2: Symbiotic and Regenerative Sustainability Frameworks: Moving Towards Circular City Implementation

Erin Horn and Gundula Proksch

Abstract

Growing in popularity, the circular city framework is at the leading-edge of a larger and older transitional dialogue which envisions regenerative, circular, and symbiotic systems as the future of urban sustainability. The need for more research supporting the implementation of such concepts has been often noted in literature. To help address this gap, this holistic review assesses a range of pertinent sustainability frameworks as a platform to identify actionable strategies which can be leveraged to support and implement circular city goals. This assessment is grounded in a holistic overview of related frameworks across interdisciplinary and scalar domains including circular city, the food-water-energy nexus, circular economy, bioeconomy, industrial symbiosis, regenerative design, and others. Building on these interrelationships, the applied strategies espoused within these publications are synthesized and assessed in the context of circular city implementation. From an initial 250 strategies identified in literature, thirty-four general implementation strategies across six thematic areas are distinguished and discussed, finding strong overlaps in implementation strategies between frameworks, and opportunities to further develop and harness these synergies to advance circular city toward sustainable urban futures.

Keywords

circular city, implementation strategies, literature review, circular economy, FWE-Nexus, regenerative design, systems integration

1. Introduction

With increasing urbanization, cities have become particularly dependent on imported flows of food, water, energy, and materials, which are brought into the urban system and consumed whilst ensuing waste streams are sent back out of the city to treatment, landfill, and as emissions and environmental contamination (Dzene et al., 2016). This linear model has allowed urban regions to develop environmental footprints which outweigh their natural bio-capacities and has weakened the resilience of cities (Doughty and Hammond, 2004; Corcelli et al., 2019). The impacts of consuming ever-dwindling raw materials at a rate outpacing nature's ability to replenish them and reach new equilibriums "is a matter of serious global concern," Katsou et al. (2020) assert. The intensity of human activities within cities, where socioeconomic systems and natural systems interact constantly, has considerable implications for natural environments (Meng et al., 2019). Cities vitally impact global water, energy, material, and nutrient cycles such that revising current paradigms will be essential to global sustainable development and climate

action (Kennedy and Hoornweg, 2012; Lenhart et al., 2015; UN, 2020). The circular city (CC) framework has become part of a larger transitional dialogue which envisions regenerative circularity and symbiotic resource flows across scales and contexts. Implementing circular principles in cities can involve actions such as scaling up integrated networks, retrofitting existing businesses, and creating new operational practices across scales. In doing so, challenges often exist, and there is a need for new tools, innovation, and approaches to future planning (Baganz et al., 2020). Even in the case of the more established framework of circular economy (CE), the development of scientific literature and discussion of concepts is ongoing, and the design and development of practical implementation strategies remains in an emerging state (Korhonen et al., 2018; Suárez-Eiroa et al., 2019).

Current deployment of CC strategies is often guided by a range of frameworks under various terms to describe sustainable future cities (Castán-Broto and Bulkeley, 2013; Petit-Boix and Leipold, 2018; Corcelli et al., 2019). Recognizing that the CC framework is a part of a lineage of circular, symbiotic, and regenerative theory, a critical approach to CC implementation must address both its ideological relationships to existing frameworks and investigate the range of implementation strategies which emerge from them and their role in enacting and operationalizing the CC. The varied array of circular frameworks and concepts across scales as a platform of insights and strategies can be leveraged to serve and help implement CC goals through recontextualization, and do not have to be seen merely as competing or confounding ideologies. This article therefore seeks to bolster the identification of implementation strategies for the CC by synthesizing the definitions and relationships of a selection of prominent circular, regenerative, and symbiotic frameworks and analyzing the applied strategies they espouse. The review first addresses a cross section of frameworks relevant to CC implementation from an interdisciplinary range of economic, industrial, urban, and built-environment sustainability concepts. Building on these interrelationships, and review of the applied strategies espoused within the reviewed publications, six thematic areas of thirty-four circular actions and supporting implementation strategies are identified across the spectrum of circular concepts and discussed. In doing so, opportunities to further develop and harness these synergies to advance CC are uncovered. Likewise, the under-expressed value of leveraging related sustainability frameworks toward of shared goals and actualization is brought into new light in pursuit of closing loops without reinventing wheels, as momentum to sustainable urban futures through the CC framework builds.

2. Methods

To address the research aims of this investigation within the large conceptual umbrella the frameworks occupy, two phases of review were conducted, the first of the conceptual characteristics of the frameworks, and the second of the implementation strategies they expressed (Figure 2.1). To gather pertinent conceptual descriptions of frameworks with relevance to circularity-oriented sustainability, articles on an array of frameworks were

collected and reviewed for conceptual descriptions (Table 2.1). The frameworks were selected for qualities they contained (circular, regenerative, and/or symbiotic) relating to aspects of CC.

This review was conducted via keyword searches of the framework names independently and paired with a selection of phrases aimed at finding implementation-oriented publications which included “applied,” “implementation,” “built environment,” “design,” “neighborhood,” “district,” “city,” and “eco-district.” The search was conducted in the university’s libraries catalogue, which consists of a selection of databases to which the libraries subscribe. Search results were filtered for peer-reviewed journal articles on these topics. The initial review pool based on the starting searches included 280 papers included based on abstract review. These were then filtered down via abstract and introduction review to a pool of 167 articles. Key internal citations within these papers were also added to the review pool at this point. From this narrowed pool, all articles were reviewed by a second close reading of the abstract and skimming of the entire paper for whether the paper offered or cited a definition of the given concept and/or whether they discussed implementation strategies for that concept, generating a pool of 84 core articles. These were included for review of framework definitions and implementation strategies and closely reviewed and coded for content pertaining to: definition of the concept/framework(s) discussed, scope of concept(s) described; scales of application inherent or described; implementation strategies presented; and references to other circular frameworks and conceptual relationships.

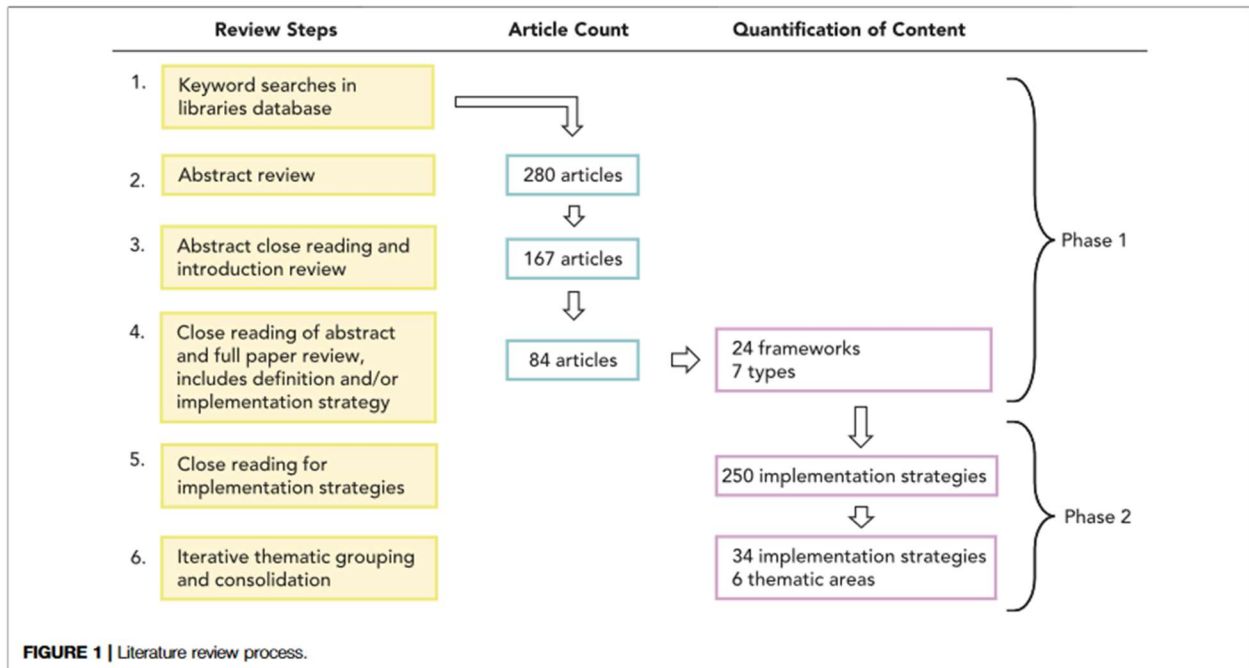


Figure 2.1- Literature Review Process

In the second phase of assessment, implementation strategies discussed in the core 84 papers were then reviewed and organized into a list of 250 identified implementation strategies and

associated circular concepts. Through an iterative review process of grouping and consolidating similar strategies, these were sorted by content type and consolidated by qualitative alignment and equivalencies into 34 general strategies within six thematic areas. These strategies were summarized in a review table which notes the relevant citations in our review for the approaches. CC literature within the review pool was also closely reviewed, and highlighted on its own, in addition to the overview, due to the centrality of CC in our review. Furthermore, the cooccurrences of implementation strategies in the reviewed literature were used to form a Sankey diagram of the relationship between the circular concepts reviewed and the six thematic groups and thirty-four strategies. Circular concepts for which we found less than three strategies were excluded from this analysis for additional clarity and emphasis on influential and more applied concepts. This reflects an expected literature bias, as the starting pools of literature on the different topics varied greatly, with discussion of CE, for instance, published at greater magnitudes than other frameworks reviewed. This meant that even if only a subset of publications on a given framework discussed implementation on that framework, this impacted the strategy counts more significantly than for less widely published frameworks. We likewise expect that different counts and expanded results for phase two could be found if the analysis is repeated to account for passing time, or if more databases and search terms were added to the initial literature collection phase. This factor was limited to scope the initial investigation within a large conceptual umbrella while addressing the core research questions, as to assess and address conceptual relationships of the frameworks first is a necessary component of analyzing their overlapping relevance and potential for the implementation of CC.

Table 2.1- Circular, regenerative, and symbiotic sustainability frameworks reviewed.

TABLE 1 | Circular, regenerative, and symbiotic sustainability frameworks reviewed.

Framework association	Framework name	Selected for the following CC related qualities
Sustainable Development	Sustainability Sustainable Development	Regenerative Regenerative
Nexus Perspectives	Food-Water-Energy Nexus (FWE) Water-Energy (WE) Energy-Water-Carbon (EWC) Land-Carbon (LC)	Symbiotic Symbiotic Symbiotic Symbiotic
Economy	Circular Economy (CE) Blue Economy	Circular, regenerative Regenerative
Biological Systems and Ecosystems	Bioeconomy (BE) Circular Bioeconomy (CBE) Eco-localism	Regenerative Circular, regenerative, symbiotic Regenerative, symbiotic
Industrial Systems	Industrial Ecology Industrial Metabolism Industrial Symbiosis	Circular, symbiotic Symbiotic Symbiotic
Urban Systems	Circular City (CC) Urban Environmentalism Urban Ecology Urban Symbiosis Urban Metabolism Biomimicry	Circular, regenerative, symbiotic Regenerative Regenerative, symbiotic Symbiotic Regenerative, symbiotic Circular, regenerative, symbiotic
Design	Green Infrastructure Net-zero design Regenerative Design Cradle-to-Cradle (C2C)	Regenerative Circular, regenerative Circular, regenerative Regenerative

3. Closing the Loop- Tracing and Defining Overlapping Concepts

There is general consensus that efficiently and synergistically closing resource cycles is vital to achieving sustainable urban futures (Hodson et al., 2012; Ranhagen and Groth, 2012; Lenhart et al., 2015; Dzene et al., 2016; Kujundzic and Vuckovic, 2019). Industrial ecology perspectives assert that the potential for symbiotic exchanges which are economically and environmentally advantageous is large, and that implementing circular transition requires identifying and supporting these types of synergies (Chertow, 2007). Such ideas are not entirely new, for instance, the need of innovations to create value from waste created by cities and large towns, like food by-products, was expressed as early as in 1862 (Simmonds, 1862). The larger scale perspective of planetary limits was advanced by Boulding in 1966, who highlighted the exhaustibility of natural resources on Earth (Boulding, 2017). Ensuing implications for an economy which could be shaped by labor-based loops were envisioned in 1976 by Stahel and Reday-Mulvey and the concept of CE has gained increasing dimension and attention in the following decades (Stahel and Reday-Mulvey, 1976). Today, the imperative for cities to transition to close resource loops in order to lessen global emissions and waste is becoming a cornerstone of urban sustainability discussions (Liang and Zhang, 2011; Williams, 2019). Counteracting wasteful linear models in cities through the implementation of circularity is accordingly receiving traction and attention from researchers, planners, and decision makers

(Petit-Boix and Leipold, 2018; Prendeville et al., 2018; Williams, 2019; Zeller et al., 2019; Katsou et al., 2020).

Scholarship and implementation is advancing on circular approaches to urban resource consumption and production to help balance global management of finite resources. It is increasingly recognized that in order for contemporary cities to become more sustainable, they must develop more circular metabolisms through resource recycling and reuse, localized resource loops, and clean energy scenarios. Despite this, the discussion of closed-loop practices and circularity at the urban scale has not been the dominant academic dialogue (Doughty and Hammond, 2004; Corcelli et al., 2019; Williams, 2019). Williams (2019) asserts that the “circularity debate” has thus far been dominated by discussions of CE and closed-loop industrial systems by industrial ecologists and economists, producing insufficient frameworks for the complexity of the city (Williams, 2019). The answer to this gap has been the CC framework, which seeks to provide an urban-responsive approach to resource management (Williams, 2019).

The CC concept envisions the city as a regenerative and restorative system (Baganz et al., 2020). Aiming to eliminate waste and keep resources functioning at a high utility over time, CC applies many of the principles and goals of CE to foster coupling of resource flows such that by-products of one process are the input for another process (Baganz et al., 2020; Katsou et al., 2020). Prendeville et al. (2018) define the CC as one which practices CE principles, partnering with city stakeholders including community members, businesses, and researchers to close resource loops and create “a future-proof city” (Prendeville et al., 2018). The Ellen MacArthur Foundation (EMF)’s description of CC is similar, describing a city embedding CE principles across its functions to establish an intentionally regenerative, abundant, and accessible urban system (EMF, 2017). Elements of the CC include the built environment, production systems, energy systems, urban transportation systems, and urban bioeconomy (EMF, 2017). Some also note the importance of digital technology to enable the CC (Baganz et al., 2020). The definition given by the European Investment Bank includes the conservation, sharing, and reuse of resources, increasing the use and usefulness of assets, and minimizing both consumption and waste of resources (European Investment Bank, 2018). Paiho et al. (2020) suggest a useful synthesized definition: “A circular city is based on closing, slowing and narrowing the resource loops as far as possible after the potential for conservation, efficiency improvements, resource sharing, servitization and virtualization has been exhausted, with remaining needs for fresh material and energy being covered as far as possible based on local production using renewable natural resources” (Paiho et al., 2020). Through its origins and place among a shared portfolio of theoretical and applied circular, regenerative, and symbiotic frameworks which seek to foster ways of living on Earth within planetary boundaries, CC shares characteristics and goals with other concepts (Table 2.2). Given these relationships, CC can benefit from a self-reflective process of building on the momentum of other synergetic ideas and bringing the strategies for real-world change and implementation that they have proposed into the fold of CC as a means of strengthening and hastening vital circular transitions in urban settings. In the following seven

sections, a review of the framing concepts of sustainability and relevant economic, industrial, urban, and built-environment frameworks with alignments to CC will formulate the ideological platform for a subsequent assessment of implementation strategies across multiple frameworks.

3.1 Origins in Sustainable Development

It is near impossible to discuss improving humanity's ability to use resources regeneratively while mitigating harmful impacts without using the eminent phrase-sustainability. While its definition varies contextually, an increasingly prevalent definition is well represented by Ghisellini et al. (2016) who "define sustainability as the balanced integration of economic performance, social inclusiveness, and environmental resilience, to the benefit of current and future generations" (Ghisellini et al., 2016; Prieto-Sandoval et al., 2018). The word sustainability has origins in the French verb for "to hold up or support," *soutenir* (Brown et al., 1987; Geissdoerfer et al., 2017). Our omnipresent, contemporary use of the term comes from its usage in forestry and silviculture, and the idea that the amount of wood being harvested should not outweigh the amount that can grow again (Geissdoerfer et al., 2017). This further evolved into ecological contexts as the recognition of nature's ability to regenerate itself, and the necessity of respecting this. There are several hundred definitions of sustainability today (Geissdoerfer et al., 2017). These range from conducting human activities in a manner conserving the functioning of Earth's ecosystems (ISO 15392, 2008), to the Brundtland Commission's influential definition of sustainability to mean "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, 1987). The triple bottom line, or three pillars of sustainability, which are reflected in Ghisellini's definition above, are a core aspect of recent interpretations of sustainability. The three pillars in this meaning are people, profit, and planet, or as a triple bottom line, sustainable economic, environmental, and social integration and performance (Elkington, 1997; Geissdoerfer et al., 2017; Rahbarianyazd, 2017). The three aspects in these interpretations "are systemically intertwined and continuously and cumulatively affect one another through mutual causality and positive feedback" (Mckelvey, 2002; Geissdoerfer et al., 2017). Interestingly, this description of interdependency among the three spheres, or pillars of sustainability, shares a common thread of the recognition of systems complexity and interconnectedness across scales which is echoed by CC and by many of the frameworks discussed in this review.

While sustainable development is rooted in an environmental perspective, it has been expanded to encompass an array of visions for global progress. This added complexity reflects the three pillars of sustainability and views of their interdependencies, a dynamic aptly addressed by Kates et al. who express that "the concrete challenges of sustainable development are at least as heterogeneous and complex as the diversity of human societies and natural ecosystems around the world" (Kates et al., 2005; Geissdoerfer et al., 2017). The seventeen 2030 United Nations Sustainable Development Goals (SDGs) are a leading example

of the range and complexity of topics which form a global vision for a sustainable future (UN, 2020). Circularity as a sustainable development strategy is most often broached in the context of urban developments, where action to improve environmental sustainability and resource efficiency is urgently needed (Mendoza et al., 2017; Gallego-Schmid et al., 2020). Accordingly, CE has been highlighted as a means to achieve SDG 12 of responsible production and consumption, and SDG 11, which seeks to “make cities and human settlements inclusive, safe, resilient and sustainable” (Huovila et al., 2020). CE principles are consequently viewed as essential to realize sustainable development, and several of the SDG targets can contribute to the actualization of a CE (Mendoza et al., 2017; Gallego-Schmid et al., 2020; Ddiba et al., 2021). The alignments between CC and sustainable development goals and efforts provide a ripe platform for coordinated efforts and sharing of implementation strategies. They also provide a reminder of the vitality of supporting regenerative sustainability transitions in developing urban settings and the consideration of context responsive implementation strategies for CC. Shared visions for more sustainable cities also gain valuable perspective and grounded approaches to implementation through the consideration of resource system nexuses.

3.2 Nexus Perspectives

Approaching sustainability and sustainable development across scales from global to local also necessitates nexus approaches, which recognize the interconnectedness and interdependence of multiple systems. For instance, the urban water-energy (WE) nexus is especially relevant for circular systems transitions in cities, as it describes the intersection of globally prevalent changes of urbanization, water scarcity, and energy transitions (De Stercke et al., 2020). Water and energy systems are interlinked, with bidirectional interactions, for instance, energy is required to treat and convey water to end users and water is needed in aspects of energy supply such as for cooling and hydropower (Gleick, 1994; De Stercke et al., 2020). Within cities, demand for energy and water services is concentrated, with urban settings accordingly forming a key reason for the way these systems are structured and the problems which have arisen within the nexus (De Stercke et al., 2020).

The conceptualization of this nexus can be further expanded to the food-water-energy nexus (FWE). A FWE nexus approach between the three sectors has been called for by academic and political communities in order to better understand and address synergies and impacts between food, water, and energy systems which are strongly interwoven beyond the acknowledgement shown through many current management approaches (Bazilian et al., 2011; Bizikova et al., 2013; Mukuve and Fenner, 2015; Newell, 2019). The FWE nexus is commanded largely by supply value chains and market mechanisms which are not yet capable of revealing societal and environmental risks and stands to benefit from regenerative approaches (Allan et al., 2015). As a result of the intense resource use of cities, FWE systems interactions in urban settings play a dominant role in driving global demand for all types of flows (Grimm et al., 2008; Cordell et al., 2009; McDonald et al., 2014; Kennedy et al., 2015; Ramaswami et al., 2017; Newell, 2019). Cities depend on FWE systems to function, though these resources are often

produced outside of urban confines (Skar et al., 2019). Urban regions are thus particularly vulnerable in their FWE systems, especially in highly populated cities (Garcia and You, 2016; Tobosco-Chavero et al., 2018). There is a need for sustainable FWE systems solutions, including integration of food transport and waste systems as an important aspect of cities' adaptation to climate change (Corcelli et al., 2019). Combining assessment of urban FWE nexus interactions with the implementation of more circular actions toward regenerative urban resource cycles may offer a means of advancing CC frameworks in application.

Carbon also plays an important part in urban nexuses, and the energy-water-carbon (EWC) nexus provides a valuable lens for CC transitions. Within urban economic supply chains, flows of energy, water, and carbon dioxide interact with complexity and interdependence (Meng et al., 2019). Energy and water security, as well as the need to reduce carbon dioxide emissions are core environmental issues affiliated with cities, and are receiving growing attention in research and practice (Meng et al., 2019). Emission reduction and resource efficiency are likewise a core aspect within CC perspectives. In cities, EWC systems are closely integrated with each other in product supply chains (Meng et al., 2019). For example, consumption of energy in cities contributes significantly to global CO₂ emissions (Meng et al., 2019). Meng et al. argue the importance of accurately describing and revealing the mechanisms of urban metabolism in order to achieve sustainability in urban management (Meng et al., 2019). The urban EWC nexus, like many of the other frameworks, is limited in its usefulness for studies due to “unclear system boundaries of a nexus or city and imprecise urban inner structures” (Meng et al., 2019). Carbon emissions are also tied to land use patterns, which can impact one another in processes of urban transitions (Xia and Chen, 2020). Nonetheless, these two factors have been often handled as isolated from one another in the consideration of urban carbon emission mitigation (Xia and Chen, 2020). A spatial land-carbon (LC) nexus framework has been proposed for investigating the interconnections of land-use changes and carbon emissions (Xia and Chen, 2020). The carbon balance of urban systems is significantly influenced by ranging intensities of land use, scales, and impacts which shape carbon stock and emission inputs and outputs (Xia and Chen, 2020). Magnitudes and scales of resource flows, their interactions and interconnections, and contexts as assessed through nexus perspectives including those of WE, FWE, EWC, and LC, are all deeply relevant to CC implementation. Assessment and coordination of larger systemic nexus frameworks can help navigate the invariable systems complexity at the urban scale which shapes potential routes for successful circular transitions.

Table 2.2- Circular, regenerative, and symbiotic sustainability frameworks reviewed and prominent descriptions

Framework	Description
Sustainability	"The balanced and systemic integration of intra and intergenerational economic, social, and environmental performance" (Geissdoerfer et al., 2017)
Sustainable Development	Global progress which reflects economic, environmental, and societal complexities and accounts for their complexities (UN, 2020)
Food-Water-Energy Nexus (FWE)	The intersections and interdependencies of food, water, and energy systems (Tien, 2018)
Circular Economy (CE)	"An economic system that is based on business models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes ... with the aim to accomplish sustainable development" (Kircherr et al., 2017)
Bioeconomy (BE)	"The production of renewable biological resources and the conversion of these resources and waste streams into value added products, such as food, feed, bio-based products and bioenergy" (European Commission, 2012; Carus, 2017; Stegmann et al., 2020)
Circular Bioeconomy (CBE)	"The sustainable, resource-efficient valorization of biomass in integrated, multi-output production chains (e.g. biorefineries) while also making use of residues and wastes and optimizing the value of biomass over time via cascading. Such an optimization can focus on economic, environmental or social aspects and ideally considers all three pillars of sustainability" (Stegmann et al., 2020)
Eco-localism	Creating self-reliant local or regional economies in order to secure economic sustainability including via prioritizing the local society and community in the economy including the goals of preserving natural ecosystems, supporting the health of the community, meeting economic needs, and supporting quality of life (Curtis, 2003)
Industrial Ecology	Optimizing use of energy and materials and reducing waste and pollution by transforming industrial waste and by-products into inputs for other processes as part of a transition to economically viable industrial systems which mimic the behavior of natural ecosystems (Beaulieu, 2015)
Industrial Metabolism	Transforming linear economic systems into integrated ecosystems of industries (Prendeville et al., 2018)
Industrial Symbiosis	Physical exchanges of materials and resources, including energy, water, and byproducts between businesses (Chertow, 2007)
Circular City	A city "based on closing, slowing and narrowing the resource loops as far as possible after the potential for conservation, efficiency improvements, resource sharing, servitization and virtualization has been exhausted, with remaining needs for fresh material and energy being covered as far as possible based on local production using renewable natural resources" (Paiho et al., 2020)
Urban Ecology	Envisions urban systems as metaphorical heterotrophic ecosystems which can be optimized (Odum, 1983)
Urban Symbiosis	Assesses how urban cycles of resource exchange and material flows, such as of food, water, and energy, can be made more closed-loop and regenerative to reform linear urban resource consumption (Lenhart et al., 2015)
Urban Metabolism	"The sum total of the technical and socioeconomic processes that occur in cities, resulting in growth, production of energy, and elimination of waste" (Kennedy et al., 2007)
Biomimicry	Echoing the natural environment to achieve sustainability and resolve human problems relating to climate, nutrients, society, time, and habitats, with the implication that human civilization should live within natural limits and is dependent on nature (Spiegelhalter, 2010)
Green Infrastructure	A re-envisionment of the linkages of cities and their implementation to the natural environment, the economy, society, technologies, and people (Ghaffarian et al., 2013)
Net-zero design	Meeting building needs for resources at the building scale through generation, treatment, and reuse (Crosson, 2018)
Regenerative Design	Design with the intent to produce projects within cities which generate positive impacts on ecological and social systems, often involving ecosystem biomimicry in order to support both urban development and ecosystem health (Blanco et al., 2021)
Cradle-to-Cradle (C2C)	Recovery and reuse of biological and technical materials in design and manufacturing (McDonough and Braungart, 2009)

3.3 Circular Economy

The framing of resource flows through an economic lens is also a core perspective which can bolster CC advancement. Arguably the most closely tied to the development of CC, CE is a concept for a rebalanced production and consumption cycle which aims to decouple economic growth from the degradation of the environment and depletion of natural resources (Jackson,

2009; Beaulieu, 2015; Williams, 2019). Prendeville et al. describe that while it has gained recent recognition, the concept of CE developed gradually and was influenced by seminal thinkers in ecology, environmental economics, and systems thinking to describe how resource flows in economies can become closed loop at different scales (Allenby and Graedel, 1993; Chertow, 2000; Prendeville et al., 2018). Early work in CE was discussed also as “closed-loop economy,” and was described by Boulding as the circular, closed-loops of the Earth and its systems and the resulting inference that the economy should exist in harmony within the boundaries of Earth’s natural systems and capacity (Boulding, 2017). Rachel Carson’s *Silent Spring* and Meadows et al.’s 1970s “Limits to Growth” have been suggested as having likely also played a role in shaping an early CE perspective (Carson, 1962; Meadows et al., 1972; Winans et al., 2017). CE was further developed by Stahel and Reday-Mulvey in the mid-70s, who described a looping economy with aspects of industrial scale waste prevention, regional labor economies, and resource efficiency (Stahel and Reday-Mulvey, 1976; Geissdoerfer et al., 2017). Conceptual frameworks were further developed by Pearce and Turner in 1990 who described the influence of natural resources on the economy and the openness of contemporary linear economic systems (Pearce and Turner, 1990; Geissdoerfer et al., 2017; Winans et al., 2017; Williams, 2019). They are sometimes attributed with the introduction of CE, such as by (Andersen, 2007; Su et al., 2013; Ghisellini et al., 2016; Geissdoerfer et al., 2017). Stahel and Reday-Mulvey’s (1976) work influenced economic policies in Japan and Germany in the 1980s and 90s, which in turn fostered the integration of CE concepts in industry (Moriguchi, 2007; Winkler and Bilitewski, 2007; Williams, 2019).

The recent growth of popularity of CE has been attributed by some to the last decade of efforts toward international sustainable development (Moriguchi, 2007). Whereas industrial processes in a linear economy are oriented around one-directional material flow in which raw materials are used to make a product and waste, and the product when its use is over, disposed of, CE features waste valorization and resource recovery which keep materials in the supply chain in order to decouple the growth of the economy and pressures on the natural environment (Ghisellini et al., 2016; Elia et al., 2017). Three principle aims of the CE approach include reducing consumption of resources and production of waste, preserving natural resources and ecosystem services, and designing out negative environmental, social, and economic externalities (Williams, 2019). Likewise, the CE approach is closely tied to the 3Rs—reduce, reuse, and recycle (Ginelli et al., 2020a; Ginelliet al., 2020b). Some also consider a fourth “R” for recovery, to represent recovering materials and energy from waste (Kirchherr et al., 2017; Joensuu et al., 2020). The Ellen MacArthur Foundation (EMF) is a prominent force in the popularization of CE, describing a vision for an economy which is by design, regenerative and restorative, and that keeps materials, products, and components at a high value and usability over time (EMF, 2017; Hart et al., 2019). The EMF’s work has been influenced by a variety of other frameworks. Blue Economy, for instance, proposes an economic system wherein multiple monetary flows close a waste to value loop as an alternative to linear value creating systems that deplete natural resources (Pauli, 2010; Prendeville et al., 2018).

Peters et al. suggest that there are four key components to the definition of CE: The first is recirculating energy and resources, minimizing demand for resources, and valorising waste streams; the second is using a multilevel approach; the third is the importance of CE as a means to realize sustainable development; and the fourth is the importance of societal processes of innovation (Peters et al., 2007; Prieto-Sandoval et al., 2018). Karhu and Linkola expand upon this to describe CE in a three-aspect manner akin to a triple bottom line approach, which in addition to the creation of economic and environmental value, includes fostering social value such as preventing unhealthy and unethical labor conditions (Karhu and Linkola, 2019). Given that there is a certain ambiguity to the scale of economy in CE, interventions have been discussed to include three levels, micro (single companies, customers, products), meso (eco-industrial parks), and macro (cities, regions, and nations) (Ghisellini et al., 2016; Elia et al., 2017; Kirchherr et al., 2017; Prieto-Sandoval et al., 2018; Baganz et al., 2020). Geissdoerfer et al. describe the aim of these multiple levels of operations as accomplishing sustainable development by “creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations” (Geissdoerfer et al., 2017; Prieto-Sandoval et al., 2018; Thiriet et al., 2020). CE is thus intended to produce a regenerative system where emissions, resource input and waste, and energy inefficiencies are minimized via the reduction, integration, and refinement of material and energy loops (Bocken, 2016; Prieto-Sandoval et al., 2018; Paiho et al., 2020).

The application of CE to urban environments through urban mining approaches and the consideration of systems of anthropogenic urban resource management of food, water, energy, and waste is discussed often (Prendeville et al., 2018). Some have pointed out that there are challenges and limits to the environmental sustainability of CE, particularly in defining system boundaries of CE and managing flows between different actors (Korhonen et al., 2018; Baganz et al., 2020). A notable organizing principle of CE applications is based on material flow type, dividing CE into technical and biological cycles (Mendoza et al., 2017; Gallego-Schmidt et al., 2020). The technical cycle is made up of inorganic material flows, meaning that they are non-biodegradable such as metals, traditional plastics, and minerals (Joensuu et al., 2020). The CE biological cycle is made up of organic materials, which are biodegradable and contain biological nutrients which can reenter into the biosphere (Kirchherr et al., 2017; Joensuu et al., 2020). The consideration of both technical and biological flows is essential to CC implementation, as inorganic and organic resources flow through cities at high magnitudes, and the way that they are managed reflects evolving concepts and applications of urbanisms, which must shift towards increasing circularity and urban scaled regenerative practices to actualize CC transitions.

3.4 Biological and Ecosystem Driven Circularity

Biological cycles and resource recovery from organic waste streams has also been the focus of considerable research within the frameworks of bioeconomy (BE), circular bioeconomy (CBE), and urban bioeconomy (Ddiba et al., 2021). BE is less immediately concerned with circularity,

though due to the inherent regenerative cycles of organic flows, the connection is still significant. Historical BE reaches early into human history when the population lived primarily off of the land until the mid-1700s when the industrial revolution shaped changing paradigms (James, 2018). Population growth and industrial development make a return to regenerative BE a greater challenge than in the past, however, a transition is needed in the face of spiraling resource depletion and global climate change (James, 2018). Early formulations of BE are sometimes credited to Georgescu-Roegen's (1975) bioeconomics work advocating for a biophysical way of looking at the economy (Georgescu-Roegen, 1975; D'amato et al., 2017). More recently, BE was defined by the EU as "the production of renewable biological resources and the conversion of these resources and waste streams into value added products, such as food, feed, biobased products and bioenergy" (European Commission, 2012; Carus, 2017; Stegmann et al., 2020). Most conceptualizations of BE are based on the perspective that inputs for industrial activities, such as energy, material, and chemicals, should come from renewable biological resources, with necessary transformational processes supported by research and innovation (Bugge, 2016; Kleinschmit et al., 2014; Pfau et al., 2014; D'amato et al., 2017). Having bio-based alternatives to nonrenewable sources is a key aspect of BE, and thus industries like agriculture and forestry are vital to help fill this niche (Roos and Stendahl, 2015; D'amato et al., 2017). In this vein, Carraresi et al. (2018) describe the cross-industry nature of BE, in which a range of sectors, production systems, and technologies help shape renewable resource streams and by-product reuse. Cities can also foster unique opportunities for BE, and urban bioeconomy has been described "as a form of environmental value creation," a valuable perspective for inclusion in CC (Buck, 2017).

Bio-based industries and manufacturing already fit well in CE when they use organic residues and waste flows as biorefinery feedstocks, and given the circular cycles and metabolic pathways inherent in biology, however while the BE practices can be circular, they are not automatically so (James, 2018). Accordingly, the integration of CE principles in BE has been called for, including the assertion that this will be necessary for true resource efficiency from BE (D'amato et al., 2017). The intersection of BE and CE forms the concept of CBE (James, 2018). Stegmann et al. (2020) discuss a route for CBE optimization which is possible through cascading uses of biomass, meaning using resources sequentially for different purposes. They likewise define CBE as focusing on "the sustainable, resource-efficient valorization of biomass in integrated, multi-output production chains (e.g., biorefineries) while also making use of residues and wastes and optimizing the value of biomass over time" (Stegmann et al., 2020). Focus of optimization measures can be tailored to specific environmental, economic, or societal factors but in ideal scenarios should consider all of the three facets of sustainability (Stegmann et al., 2020).

Local scale circularity in the economy reoccurs in several sustainability frameworks and has been described in particular focus within the context of eco-localism. Eco-localism is centered around the idea of creating self-reliant local or regional economies in order to secure economic sustainability (Curtis, 2003). This involves prioritizing the local society and community in the economy by preserving natural ecosystems, supporting the health of the community, meeting

economic needs, and supporting quality of life (Curtis, 2003). Environmental geographies (e.g., bioregions) are often used to describe the natural limits and boundaries of eco-local economies (Sale, 1985; Curtis, 2003). The view of eco-localism is that ecological limits should shape the size of the economy, whose scale is vital to sustainability, and asserts that as ecosystems are heterogenous and symbiotic local capital unique, opportunities to replace natural capital with other types are limited (Curtis, 2003). Eco-local capital is made up of five forms of local scale capital-physical, financial, natural, social, and human, which interact symbiotically and reinforce one another (Curtis, 2003; Williams, 2019). For instance, local natural capital is reinforced by local social capital that guides preservation and restoration of ecosystems (Williams, 2005; Williams, 2019). Social capital also helps to make local resource sharing scenarios and loops more feasible and bolsters the outcomes of investing in human capital and physical infrastructure (Putnam, 1993; Williams, 2019). Physical capital, such as infrastructure and the built environment, can also help facilitate resource sharing and economic circularity in local economies; this is enhanced by physical proximity of those producing and utilizing resource flows such as utilities and industries (Williams, 2019). Several elements of eco-localism are particularly relevant for CC, especially as the idea of closing loops at the city scale anticipates some level of localization of resource flows and economic systems, within which the concept of local scale capital types becomes especially useful for development and assessment of implementation approaches for urban circularity.

3.5 Symbiosis and Circularity in Industrial Systems

One of the foundational precursors of CC, industrial ecology (IE) is a field of research and application focusing on creating and maintaining a closed-loop industrial ecosystem. As part of an envisioned transition to economically viable industrial systems which mimic the behavior of natural ecosystems, its aims include optimizing use of energy and materials and reducing waste and pollution by transforming industrial waste and by-products into inputs for other processes (Beaulieu, 2015). The perspective of IE frames industrial systems as part of a complex interrelated ecosystem-a view derived from the central concept that modeling human systems after natural systems is a path to greater sustainability (Spiegelhalter, 2010). A core aim in an urban context, therefore, is to holistically integrate technologies and processes which use energy and materials efficiently and with minimal greenhouse gas emissions (Spiegelhalter, 2010). A concept closely related to IE is industrial metabolism, which was described by Frosch and Gallopoulos (1989) as the concept of the transformation of a “linear economic system into an integrated industrial ecosystem” (Prendeville et al., 2018). Frosch and Gallapoulos’ influential article in *Scientific American* described a vision for industrial ecosystems wherein “the consumption of energy and materials is optimized and the effluents of one process...serve as the raw material for another process” (Frosch and Gallopoulos, 1989; Chertow, 2007). Industrial symbiosis (IS) is essential to this vision and requires close attention to material and energy flows through economies at a local and regional scale (Chertow, 2000).

IS is the concept of the physical exchanges of materials and resources, including energy, water, and byproducts between businesses (Chertow, 2007). This can involve the engagement of and interaction between industries that have been traditionally separate in order to arrive at an integrated, collective strategy to exchange resource flows and achieve a competitive advantage and resource efficiency (Chertow, 2000). Three main types of resource exchange are described by Chertow: by-product reuse, utility/infrastructure sharing, and joint provision of services (Chertow, 2007). By-product reuse is essentially exchange of industrial material flows between two or more businesses in which the excess material from one operation is used in the other in replacement of raw materials or commercial products (Chertow, 2007). Utility/infrastructure sharing is the shared organization and utilization of core resources like water, energy, and wastewater (Chertow, 2007). Similarly, joint provision of services is coordination such as shared arrangements of transportation, food supply, and other common needs across neighboring industries and businesses (Chertow, 2007). Types of physical manifestations of industrial symbiosis have been described as industrial ecosystems, eco-industrial networks, and eco-industrial parks. Eco-industrial park initiatives form around a close locational proximity between coordinating firms to exchange material and informational resources to reduce waste, curtail and optimize use of raw materials and energy, and foster multidimensional sustainable relationships between businesses and key actors (Winans et al., 2017). The same concept extends to industrial symbiosis networks and ecoindustrial networks where it is instead applied to a larger geographic region, even up to the scale of a state/province or country (Winans et al., 2017). Circularity in industrial systems is a necessary and influential piece of the transition to circularity in economies and cities, and can be integrated into other scalar perspectives and systems, even helping to provide examples and methods for CC via the existing lineage of industrial ecology thinking and development. Strides forward in CC transitions are increasingly seen taking effect in industrial economic sectors, with governance and programs promoting IS serving to also directly further key aspects of CC itself. Connecting and translating successful IE driven approaches to the full urban scale can leverage symbiotic industrial frameworks and be of great benefit, however also require further development to address and respond to the vast integrated systems of cities which among other differences include vital socio-political forces and actors.

3.6 Conceptualizing Urban Circularity

As discussed within CC perspectives, cities contain exceptionally complex interactions of resources flows, urban dwellers, and urban space. While many resources used in cities originate from nature, the reality still remains that within current modes most are utilized and then disposed of in a linear fashion (Skar et al., 2019). Circular approaches to urban resource use explore options for regenerative management of these flows through reduction, reuse, and recycling (Skar et al., 2019). This fosters the new formulations of the design and interrelationships of urban, peri-urban, and rural spaces, leading to closed-loop approaches such as localized food systems that take into account broader systems perspectives such as that of an urban/peri-urban FWE nexus (Skar et al., 2019). Unsurprisingly, the CC concept shares

modes of thought with several other urban scale metabolic conceptualizations of sustainability. Many of these metabolic, circular conceptions of the city take on aspects of biomimicry. Biomimicry (bios-life, mimesis-to imitate) seeks to echo the natural environment to achieve sustainability and resolve human problems relating to climate, nutrients, society, time, and habitats, with the implication that human civilization should live within natural limits and is dependent on nature (Spiegelhalter, 2010; Prendeville et al., 2018). These limits are perceived through the mediating systems of technology, culture, and socioeconomics (Spiegelhalter, 2010). Drawing on knowledge transfer and emulation of living organisms and ecosystems, biomimicry aims to foster greater sustainability (Blanco et al., 2021). Though biomimicry tends to imply the interpretation of nature-based ideas into physical designs, it can also prove a useful concept for other human systems like economies and cities (Pomponi and Moncaster, 2017). Spiegelhalter (2010) express that “it is almost an imperative attempt to biomimic natural processes towards a circular metabolism where city outputs seem to become resources for new inputs”. This can facilitate a strong conceptual starting point for urban environments; however, it has been argued that when biological analogies are applied to entire cities and regions, they need to be paired with other approaches and can otherwise lose usefulness and utility as an analytical lens for city functions (Gandy, 2004). Urban symbiosis, for instance, refashions the concepts of IS into the dimensions of a city (Lenhart et al., 2015). Urban symbiosis assesses how urban cycles of resource exchange and material flows, such as of food, water, and energy, can be made more closed-loop and regenerative to reform linear urban resource consumption (Lenhart et al., 2015). Consideration of governing and decision makers’ roles in shaping these dynamics is considered an important element of the framework, aligning strongly with CC (Lenhart et al., 2015).

Notably, the interconnected flows of modern cities are somewhat frequently referred to as a metabolism of integrated resource flows through urban space that rely on external energy, material, and information inputs (Gandy, 2004). Urban Metabolism (UM) accordingly describes cities as ecosystems under development which need resources and have metabolic flows of materials, nutrients and food, water, and energy (Kennedy et al., 2007; Gagliano et al., 2015; Paiho et al., 2020). Kennedy et al. define UM as “the sum total of the technical and socioeconomic processes that occur in cities, resulting in growth, production of energy, and elimination of waste” (Kennedy et al., 2007). In addition to quantification studies, UM can include assessment of application of circular metabolism in cities and application of biomimetic urban design strategies (Spiegelhalter and Arch, 2010; Buck, 2017; Prendeville et al., 2018). UM was developed in the context of environmental deterioration of water and air in the 1960s US and introduced the quantification of city resource fluxes (Wolman, 1965). Precursors and closely aligned conceptual antecedents to Wolman’s UM arguably emerged much earlier, particularly within the 1800s. For example, scientific developments in this period fostered a public health movement which promoted the hygienist city (Gandy, 2004). With the advancement of biological and physical sciences, sanitation systems and infrastructure were developed to control and separate resource flows in the city with the aims of better protecting human health. Along with these developments, recognizable linear flows in modern cities

became more established and thinking around urban conditions evolved, for example wastewater flows were viewed as a danger to be removed from urban cycles and sent out of cities, and their potential value as a nutrient source largely dismissed. UM can be a useful analogy and framework for analyzing the relationships between biophysical processes and societies, and it has been advocated that viewing it distinctly from its precursors is an important caveat to harnessing its usefulness (Gandy, 2004). Gandy describes that current day “urban metabolism can illuminate the circulatory processes that underpin the transformation of nature into essential commodities such as food, energy and potable water” and provide insights into “commodity chains, the particularities of local context and the fluidity of urban form” (Gandy, 2004). With its core qualities of conceptualizing resource flow dynamics and their assessment, UM fundamentally underpins CC perspectives and that of many related circular and sustainability frameworks including aspects of CE and urban symbiosis, further manifesting within the means of circular transitions that they espouse.

Urban Ecology likewise envisions urban systems as metaphorical heterotrophic ecosystems which can be optimized (Odum, 1983). Akin to complex living systems, cities metabolize resources and contain producers and consumers who interact to characterize resource flows and loops (Wolman, 1965; Kennedy et al., 2007; Williams, 2019). The urban ecosystem can be kept healthy through looping, or cycling, waste resources at various scales, which is further supplemented by the localization of resource cycles and the protection of natural ecosystem services (Orr, 1992; Williams, 2019). These actions align strongly with CC goals. McDonnell et al. describe such an urban ecosystem as containing distinct and integrated systems of the natural environment, the socioeconomic environment, and the built environment (McDonnell et al., 2009).

3.7 Regenerative Built Environment Concepts

The built environment will play a key role in the implementation of CC concepts. Indeed, some argue that the built environment is the sector that generates the most pressure on the natural environment (Pomponi and Moncaster, 2017). Pomponi and Moncaster critique CE’s lack of consideration of the built environment, describing that “in framing building research from a... [circular] perspective there is a lack of focus on buildings, with most research designed either around cities and neighbourhoods or construction materials” (Pomponi and Moncaster, 2017). According to the literature, assert Joensuu et al. (2020), the built environment should be understood to refer not only to buildings, infrastructure, and their construction, but also include their operation, maintenance, and use, which forms varying environmental impacts over a full life cycle. Several concepts in the built environment seek to facilitate greater circularity and regeneration in construction and operation of infrastructure and buildings.

At the infrastructural scale, Green Infrastructure has been described as a reenvisionment of the linkages of cities and their implementation to the natural environment, the economy, society, technologies, and people (Ghaffarian et al., 2013). Likewise, netzero design, which can focus on

specific resources at building or district scales, often features decentralized infrastructural approaches rather than conventional centralized infrastructure. Net zero water (NZW) is the concept of water independence, which can be achieved at building scales or district scale. To be net zero for water means that all of a building or district's water needs are met via localized capture, closed-loop systems, and reuse, including full management of storm water such that any discharged water is managed to benefit local ecology (Crosson, 2018). Net-zero energy (NZE) is similar, wherein site-based energy production and consumption sum to zero or even negatively such that production outweighs consumption. Some differences exist, however, as NZE can still include grid integration with centralized energy grids, while NZW exists independently from larger municipal systems (Crosson, 2018). Net-zero design relates strongly to the CC due to shared goals of closing resource loops, albeit at distinct, though potentially overlapping scales.

Buildings functioning with net-zero principles are sometimes referred to as “circular buildings.” Pomponi and Moncaster define the term as referring to “a building that is designed, planned, built, operated, maintained, and deconstructed in a manner consistent with CE principles” (Pomponi and Moncaster, 2017). The term living building has also been used to refer to highly sustainable, self-sufficient buildings, particularly in the context of the Living Building Challenge (ILFI, 2021). In this context, buildings and sites are also increasingly viewed as having the potential to be regenerative. Regenerative design aims to produce projects within cities which generate positive impacts on ecological and social systems, often involving ecosystem biomimicry in order to support both urban development and ecosystem health (Blanco et al., 2021). The regenerative design concept was proposed by John Tillman Lyle who described the possibility of building human systems and places “with a circular logic by reincorporating the essential elements of life, such as energy conversion, water treatment, and nutrient cycling in human designed urban spaces” (Lyle, 1994). Contemporary regenerative design practices espouse understanding urban systems through holistic and ecological lenses in order to achieve mutual benefit between ecological and social systems (Reed, 2007; Blanco et al., 2021).

Within the built environment, life cycle perspectives are seeing increasing uptake and usage. Consideration of the life cycle of materials from production and construction to disassembly further foster contemplation of circularity and opportunities for reuse. Braungart and McDonough's cradle-to-cradle (C2C) concept is an example of this perspective and promotes recovery and reuse of biological and technical materials (McDonough and Braungart, 2009). C2C has overlapping concepts with CE, but particular emphasis on reuse and recycling and further centers design as a means of closing material cycle loops (McDonough and Braungart, 2009; Joensuu et al., 2020). As the built environment disciplines strive for greater sustainability in design and practice, key opportunities to synergize efforts taking place under multiple certification systems and frameworks (e.g., C2C, LEED, Living Building Challenge, etc.) and influential concepts such as regenerative and net-zero design may exist as a means of furthering CC design and implementation and merit further consideration.

4. Implementing Circularity

Implementing CC concepts will require a multifaceted portfolio of strategies, many of which can be adopted from related frameworks. A range of approaches that bridge from theory to actualization have been suggested in literature. The similarities and variations of many of the frameworks discussed in section three are reflected in the strategies for implementing them. Within our selected literature pool, 250 individual strategies were identified which could be grouped into 34 general strategies within six thematic areas: *Resource and Material Management*, *Systems Development and Integration*, *Bio-based Solutions*, *Governance and Stakeholder Engagement*, *Data, Measurement, and Modeling*, and *Research and Education* (Figure 2.2). These implementation strategies vary from direct actions to supporting and regulatory approaches. The first three thematic areas include direct actions to advance circularity in practice. *Resource and Material Management* describes actions that involve the creation, transformation, and movement of urban resource flows such as through recycling, reuse, and construction. *Systems Development and Integration* strategies consist of actions to integrate systems of various types and scales and to develop new modes of operation, adapting and transitioning linear systems into regenerative ones. *Bio-based Solutions* are strategies fundamentally tied to living systems such as organic resource flows and processes, nature-based aspects of CC, and strategies involving the food system. The other three thematic areas of strategies which emerged through the review are supporting strategies, which help to advance, strategize, and enact CC goals. While less direct, these thematic areas are absolutely critical to CC implementation. For instance, *Governance and Stakeholder Engagement* strategies leverage policy and collaboration to foster CC transitions. Likewise, *Data, Measurement, and Modeling* strategies are essential to closing loops, supporting effective design and decision making, as is *Research and Education*, the sixth thematic area of strategies.

A noteworthy variation across the 34 strategies is the degree to which they rely on organic alliances and developments versus top-down approaches to circularity. This varies even within specific strategies such as in implementation strategy five, *Industrial Developments*. Figure 2.2 summarizes the strategies, with definitions and examples derived from the literature review. A literature review of implementation strategies documented in CC publications can be found in Figure 2.3.

There is significant overlap between strategies advocated under different frameworks particularly between CE, which included 33 of the 34 strategies, and CC, for which we identified 29 (Figure 2.4). Three strategies in particular saw strong occurrence in CC publications, 7. *Infrastructure developments and Infrasystems integration*, 8. *Circular business models*, and 22. *Developing and Leveraging datasets*. The other frameworks which included the most implementation strategies in literature include the FWE nexus, BE, IE, IS, CBE, and net-zero design (Figure 2.4). To rule out a bias of interpretation, we only attributed strategies to concepts for which journal articles specifically mentioned the implementation strategies in question. Despite strong theoretical overlaps between all concepts, a heavier emphasis on

application is observed in CC, CE, and FWE-Nexus publications, which included more strategies for implementation, pointing toward a tension and area of opportunity in the space between theoretical and applied circular sustainability.

Thematic Area	Strategy	Definition	Selected References
Resource and Material Management	1 Reduction, Reuse, and recycling of materials	Recycling and reusing materials and waste through means such as circular value chain innovation, and reducing the creation of waste where possible	Peñ-Boix and Lepold 2018; Gallego-Schmid et al. 2020; Iacovidou and Furnell 2016; Palho et al. 2020; Eia et al. 2017
	2 Localization	Connecting local material and monetary cycles and reducing distances between production and consumption while using locally appropriate methods and technologies	Carcassi et al. 2020; Chertow 2000; Lenhart et al. 2015; Williams 2019; Curtis 2003; Dipeolu et al. 2020; Corcelli et al. 2019
	3 Logistical Improvements	Improving waste flow identification, separation, collection, and distribution, developing cascading logistics	Giorgi et al. 2020; Gallego-Schmid et al. 2020; Williams 2019; Iacovidou and Furnell 2016; Glass et al. 2017
	4 Green Construction	Construction with holistic sustainability in mind including low carbon impacts, use of materials with recycled and reused inputs, consideration of deconstruction and component reuse	Corcelli et al. 2019; Gallego-Schmid et al. 2020; Ghaffarian et al. 2013; Iacovidou and Furnell 2016; Joensuu et al. 2020; Carcassi et al. 2020
Systems Development and Integration	5 Industrial developments	Developing symbiotic industrial networks and approaches to integration	Winans et al. 2017; Chertow 2007; Chertow 2000
	6 Building Integration	Integrating resource flow management and circularity at the building scale	Corcelli et al. 2019; Gehrike 2014; Tobesco-Chavero et al. 2018
	7 Infrastructure developments and infrasystems integration	Integration of infrastructural systems to foster circularity	Jonsson 2000; Lee et al. 2017; Williams 2019; Gentry 2019; Joensuu et al. 2020; Chertow 2007
	8 Circular business models	Systems thinking and institutional innovation around circular practices in business operation and associated material flows	Hart et al. 2019; Lewandowski 2016; Zaman et al. 2011; D'amato et al. 2017; Chertow 2000; Munaro et al. 2020
Bio-based solutions	9 Integrative & Eco-design	Incorporating circularity in design and manufacturing to close loops	Munaro et al. 2020; Campioli et al. 2020; Blanco et al. 2021; Ghaffarian et al. 2013
	10 Supporting sustainable local food production	Supporting local foodsheds and resource use	Skar et al. 2019; Moglia 2014; Ceron-Palma et al. 2012
	11 Controlled Environment Agriculture	Growing methods which control environmental conditions (light, temperature, etc.) in order to achieve high efficiency, resilient food production	Ceron-Palma et al. 2012; Ercila-Montserrat et al. 2017; Nadel et al. 2017; Pons et al. 2015; Sanjuan-Delmas et al. 2018
	12 Nature Based Solutions	Strategies that help protect, restore, and manage ecosystems sustainably while addressing human challenges	Skar et al. 2019; Langergraber et al. 2020; Katsou et al. 2020; Campioli et al. 2020; Fiori et al. 2020
Governance and Stakeholder Engagement	13 Valorization of organic waste streams	Recovering resources and value from sources such as wastewater, local food waste, and urban agriculture	Odiba et al. 2021; Wedner and Yang 2020; Gehrike 2014; Corcelli et al. 2019; Davidsson et al. 2007; Edwards et al. 2015; Thiriet et al. 2020
	14 Policy and Regulatory Changes	Utilizing policy and regulation (from local to national levels) to guide implementation of circularity and environmental practices	D'amato et al. 2017; Eia et al. 2017; Prieto-Sandoval et al. 2018; Curtis 2003; Dipeolu et al. 2020; Crosson 2018; Williams 2019
	15 Participatory Processes	Actively including communities and stakeholders in design solutions, research, and policy-making	Katsou et al. 2020; Xue et al. 2018; Joensuu et al. 2020; Jonsson 2000; Chertow 2007; Karhu and Linkola 2019
	16 Consideration of consumer behaviors	Incorporating context and current user interactions with resource flows in actionable solutions	Joensuu et al. 2020; Williams 2019; Hart et al. 2019
	17 Inclusive Communication	Communication key concepts and research findings in ways accessible to everyone	Kirchherr et al. 2017; Katsou et al. 2020; Joensuu et al. 2020
	18 Collaboration and Cooperation	Developing active partnerships between a wide range of industries, government, society, academic disciplines, and businesses	Eia et al. 2017; Katsou et al. 2020; Carcassi et al. 2020; Beaulieu et al. 2015; Prieto-Sandoval et al. 2018
	19 Decision Making	Taking critical analytical approaches to decision making	Katsou et al. 2020; Curtis 2003; Dipeolu et al. 2020
	20 Economic Incentives and Disincentives	Incentivizing circular practices and disincentivizing harmful linear modes	Eia et al. 2017; Giorgi et al. 2020; Ginelli et al. 2020; Carcassi et al. 2020; Prieto-Sandoval et al. 2018; Curtis 2003; Dipeolu et al. 2020
	21 Frameworks and Codes	Introducing circularity via building codes, performance standards, and certification systems	Giorgi et al. 2020; Carcassi et al. 2020; Crosson 2018
Data, Measurement, and Modelling	22 Developing and leveraging datasets	Creating and utilizing datasets, information models, and database resources for circularity	Baganz et al. 2020; Curtis 2003; Odiba et al. 2021; Prendeville et al. 2018
	23 Impacts Assessments	Assessment of impacts on environmental, economic and social systems, including benefits and trade-offs	Odiba et al. 2021; Corcelli et al. 2019; Katsou et al. 2020; Caputo et al. 2020; Eia et al. 2017
	24 Life Cycle Approaches	Considering the full life cycle of materials, products, and buildings through planning and evaluation	Beaulieu et al. 2015; Campioli et al. 2020; Carcassi et al. 2020; Gallego-Schmid et al. 2020; Joensuu et al. 2020; Katsou et al. 2020
	25 Flow and material analyses	Developing and utilizing frameworks to analyze material flows, value chains, and input-output matching	Chester 2020; Beaulieu et al. 2015; Chertow 2000; Carcassi et al. 2020; Eia et al. 2017
	26 Measurement of Performance	Evaluating performance of products, processes, and spaces	Campioli et al. 2020; Pomponi and Moncaster 2017; Katsou et al. 2020
	27 Forecasting and simulation	Using modeling tools to simulate and explore scenarios	Caputo et al. 2020; Katsou et al. 2020; Gallego-Schmid et al. 2020
	28 Systematic quantitative analysis	Using holistic systems assessment processes including developing and utilizing circularity indicators and accurately defining system boundaries for analysis	Dzeme et al. 2016; Joensuu et al. 2020; Stegmann et al. 2020; Gallego-Schmid et al. 2020
	29 Mapping	Utilizing various types of mapping and systematic approaches to assess current patterns, opportunities for integration, and future designs for circular implementation	Newell et al. 2019; Baganz et al. 2020
Research and Education	30 Assessment of emerging technologies	Research and assessments of technologies and strategies for circularity, critical evaluation of "hyped" solutions	Drodz-Szczybura 2015
	31 Methodology and Framework development	Developing methodologies and frameworks to implement circularity and support other strategies	Gallego-Schmid et al. 2020; Suarez-Eiroa et al. 2021
	32 Education	Educating communities and professionals to help foster new circular thinking, support emerging professional niches, and guide implementation	Folke et al. 1997; James; Suarez-Eiroa et al. 2019
	33 Use of transdisciplinary methods	Involving multiple disciplines, industries, and stakeholders in research	Giorgi et al. 2020; Carcassi et al. 2020; Blanco et al. 2021
	34 Applied Research Approaches	Researching implementation, human behaviors, and applied solutions	Kirchherr et al. 2017; Pomponi and Moncaster 2017

Figure 2.2- Circular implementation strategies.

References	Strategies																																				
	Resource and Material Management				Systems Development and Integration					Bio-based solutions				Governance and Stakeholder Engagement							Data, Measurement, and Modelling						Research and Education										
	1. Reduction, Reuse, & Recycling of materials	2. Localization	3. Logistical Improvements	4. Green Construction	5. Industrial Developments	6. Building Integration	7. Infrastructure developments and infrastructures integration	8. Circular business models	9. Integrative & Eco-design	10. Supporting sustainable local food production	11. Controlled Environment Agriculture	12. Nature Based Solutions	13. Valorization of organic waste streams	14. Policy & Regulatory Changes	15. Participatory Processes	16. Consideration of consumer behaviors	17. Inclusive communication	18. Collaboration & cooperation	19. Decision making	20. Economic Incentives & disincentives	21. Frameworks & codes	22. Developing & leveraging datasets	23. Impacts assessments	24. Life Cycle Approaches	25. Flow and material analyses	26. Measurement of performance	27. Forecasting & Simulation	28. Systematic quantitative analysis	29. Mapping	30. Assessment of emerging technologies	31. Methodology & Framework development	32. Education	33. Use of transdisciplinary methods	34. Applied Research Approaches			
Skar et al. 2019																																					
Baganz et al. 2020																																					
Katsou et al. 2020																																					
Prendeville et al. 2018																																					
Williams 2019																																					
Paiho et al. 2020																																					

Figure 2.3- Implementation strategies in circular city literature

4.1 Resource and Material Management

Managing resources and materials regeneratively is one of the most core functions of a CC. Circular actions of looping and adapting and supporting actions of localization and optimization are key to these implementation strategies (Williams, 2019; Figure 2.2). The first implementation strategy *Reduction, Reuse, and Recycling* of materials is by far one of the most central aspects of achieving circularity through CC, CE, and IE. Elia et al. note a growing interest in waste management, including reducing waste and increasing efficiency and sustainability of resources, which has progressed in US policy although CE and CC policy lags in the US compared to European efforts (Elia et al., 2017). *Logistical Improvements* comprise an essential aspect of a transition to greater circularity by shaping how flows and exchanges can occur in a more closed-loop manner. Strategy 2, *localization*, is also a core element across the frameworks, occurring in six of the eleven included in Figure 2.4. Of the frameworks reviewed, eco-localism perhaps most directly centers around the concept of localization, calling for decentralized sustainable technologies adapted to local environmental, cultural, community, and economic conditions (Curtis, 2003).

Green Construction, which forms an entire field of its own, is also a key strategy to implement urban circularity due to the fundamental role of the built environment in the city and in shaping how resources are used. There are opportunities to better integrate CC concepts into green construction. Munaro et al. (2020) note for instance, that attention to CE in the built environment has been growing in both theory and practice. They describe the need for more research on component reuse, the development of the secondary materials market, and more research and development of operating circular value models in the built environment (Munaro et al., 2020). They assert that “this is a critical gap because the role of managing and applying circular innovation in the built environment is often neglected” and describe that the implementation of circularity is held back by insufficient knowledge about the definitions of CE and similar frameworks, and about how to implement these within business models (Adams et al., 2017; Munaro et al., 2020). Karhu and Linkola (2019) also have discussed that approaches to implementing circularity in the built environment form an active topic of discussion and that understanding is under development as applied experiences grow. Gallego-Schmid et al. conducted a review which found that publication of research on CE in construction had not yet found a “home” and was published across a variety of journals and in conference proceedings, indicating “a new, growing area, with researchers first testing their ideas in a conference setting before publishing them as journal articles” (Gallego-Schmid et al., 2020). Building level considerations of CC, or CE, can view buildings as “material banks,” though building level circularity can also reflect further principles which bridge across scales (Cheshire, 2016; Geldermans, 2016; Giorgi et al., 2020). Giorgi et al. describe three areas of principles relevant to the building scale “design process aimed at adaptability and reversibility; resource/waste management aimed at reuse and recycling; [and] business models aimed at extending life and value of products while also changing the concept of ownership” (Giorgi et al., 2020). They express that waste prevention needs to be the first goal to use resources efficiently and

effectively, and that this can be achieved through a combination of strategies including extending building life, greater product durability, and repairing, reusing, and maintaining resources, such as in implementation strategy *one Reduction, Reuse, and Recycling* of materials (Giorgi et al., 2020). Green construction and building scale circularity intersect with several thematic areas and implementation strategies which emerged through our review. These include *Systems Development and Integration*, implementation strategy six *Building Integration*, and strategy eight *Circular Business models*, thematic area three *Bio-based solutions*, and thematic area five *Data, Measurement, and Modeling*, wherein many key supporting strategies and methodologies, such as LCA, increasingly used in green construction contexts, occur.

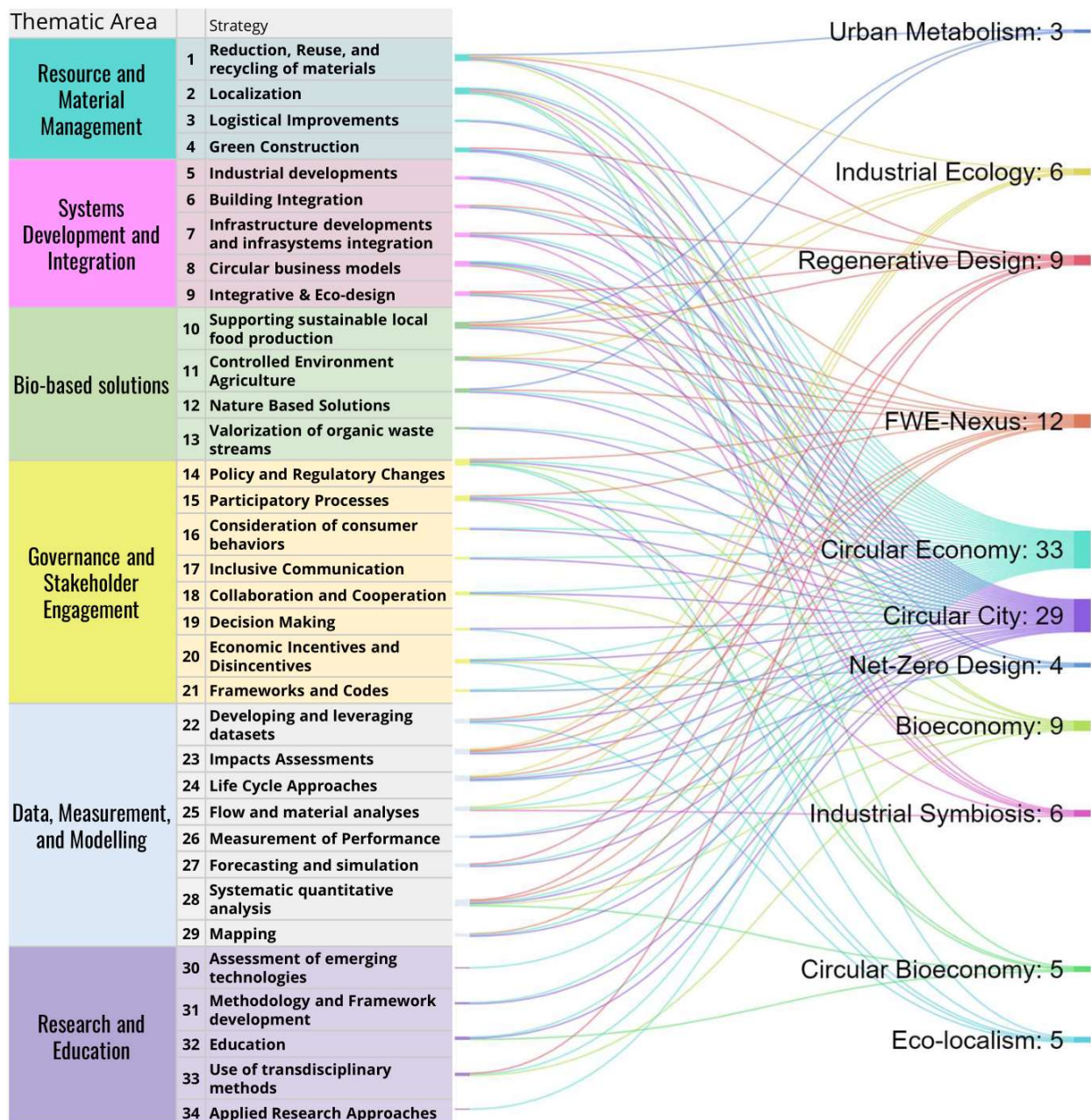


Figure 2.4- Occurrence of thematic areas and strategies in key reviewed frameworks.

4.2 Systems Development and Integration

The second thematic area which emerged is that of *Systems Development and Integration*, which is particularly relevant to the urban scale and context of CC. As sustainable urban developments proliferate globally, they will need to harness systems integration strategies, note Pandis-Iveroith et al. Systems integration approaches may include the generation of energy and transport fuels from domestic and organic waste streams, treatment of grey water for

irrigation or other secondary uses, fertilization of agricultural areas with treated sludge or various forms of recovered nutrients, and many more strategies, some of which we will discuss further below (Pandis-Iveroth et al., 2013). Integrated solutions advance circular urban metabolisms over linear processes, manifesting endeavors to close material flow and energy cycles in cities such that they take on ecosystem qualities (Pandis-Iveroth et al., 2013). A number of common strategies were advocated for by literature for CC and CE -which both mentioned all strategies in this thematic area-as well as by Industrial Symbiosis, the FEW Nexus, and Regenerative Design (Figure 2.4). BE literature called specifically for the implementation and development of strategy eight *Circular Business Models*, although the principles of BE align well with the other implementation strategies in this thematic area. The strategies identified within this thematic area include strategy five *Industrial Developments*, strategy six *Building Integration*, strategy seven *Infrastructure developments and infrasystems integration*, strategy eight *Circular Business Models*, and strategy nine *Integrative and Eco-Design*.

The development of systems integration through industrial developments has been discussed for some time in the contexts of IS, IE, and CE, and has been more recently discussed with regard to CC and regenerative design. While industrial symbiosis and developments of integrated industrial networks are a key component of realizing the CC, it will be important to look to the previous observations of barriers and failures of industrial symbiotic partnerships which have been noted in industrial ecology and symbiosis literature so as to find successful supporting strategies and avoid repeating shortcomings in past implementation attempts (Chertow, 2007). Drivers of circular industrial developments range from social, environmental, and regulatory in nature, and manifest differently within different geographies and cultures (Chertow, 2007). Whilst there are many quantifiable benefits, Chertow argues the importance of asking why more cases of successful industrial symbiosis are not yet seen (Chertow, 2007). Gibbs et al. observed that difficulties in planning successful industrial ecosystems have been long noted by researchers and policymakers, leading to them to conclude that “initiatives based upon the interchange of wastes and cascading of energy are few in number and difficult to organize” (Gibbs et al., 2005; Chertow, 2007). Though this has begun to change in more recent years, contemporary efforts can benefit from considering past research of historical implementation failures. Literature identification and discussion of barriers to industrial symbiosis has noted these include typical business development challenges and other issues rooted in the operational, behavioral, and financial difficulties of working across organizations (Lowe et al., 1996; Chertow, 2000; Chertow, 2007).

Building Integration, strategy six, in some instances directly overlaps with symbiotic industrial development, though can also pertain to individual closed-loop systems at the building scale. This implementation strategy refers to the practice of integrating resource flow management and circularity at the building scale, which can occur through various means including building integrated water management, building scale energy production, integrated sustainable technologies or food production, and redistributing surpluses between buildings (Figure 2.2). The role of further research, which will reoccur in the context of thematic area six, is especially

relevant for the building level as there is currently a lack of research addressing the link between micro and macro levels of circularity which intersect at the building scale. Giorgi et al. describe “a link between...two levels [wherein] circular requirements (e.g., exchange and use of reused/recycled materials) at building level can activate circular practices on an urban level and with regards to materials’ composition” (Giorgi et al., 2020). Similar intersections exist between buildings and the FWE-Nexus. Tien (2018) describes the inextricable linkage of the two, especially in the case of water and energy systems, for which buildings often act as the end distribution points for municipal systems (Tien, 2018). Another form of building integration discussed by Tien is building integration of agriculture, which was mentioned in several articles of our literature review pool and is a means of FWE-Nexus implementation as well as of CE and CC. Building-integrated agriculture intersects with strategy eleven discussed below, *Controlled Environment Agriculture*. Agricultural systems and greenhouse structures can be integrated with buildings to produce benefits including synergetic use of heat and utilization of harvested rainwater (Delor, 2011; Proksch, 2016; Tien, 2018). Building resource flows and systems can also be integrated between buildings and in synergetic partnerships with productive and industrial processes, such as the building integration of aquaponics, and the building integration of aquaponics with a brewery (Proksch et al., 2019; Horn and Proksch, 2020a).

Strategy seven *Infrastructure developments and infrasystems integration* is an important means of resource and material management, particularly as a way of developing effective symbiotic urban systems for circular cities. Environmental benefits of infrasystem synergies include decreased energy and material usage and increased spatial concentration and use of secondary resources (Jonsson, 2000). Joensuu et al. (2020) note that urban symbiosis of infrasystems should apply cutting edge carbon neutral technological approaches to achieve greater benefit. Infrastructure developments and infrasystems integration and can also leverage frameworks such as C2C and the 3Rs, which align with implementation strategy one, *Reduction, Reuse, and Recycling* of materials, as well as industrial ecology approaches and integrated waste management (Kollikkathara et al., 2009; Joensuu et al., 2020). Joensuu et al. note that while an array of strategies to infrastructural integration can become a point of confusion to decision makers, approaches such as waste hierarchy can help to “prioritize the prevention of waste generation and to minimize processing which may provide costs savings opportunities” to material extraction and waste processing (Ribic et al., 2017; Joensuu et al., 2020). Decision making frameworks such as these can also be viewed as an implementation strategy themselves, a theme in literature which is synthesized via the supporting implementation strategy of *Decision Making* (strategy 19).

Considering infrasystems integration requires reflection on the relationships of urban and rural systems and resource exchanges, the dynamics of which need to be assessed and unraveled to facilitate efficient recovery of nutrients, energy, and materials in urban biotic cycles (Joensuu et al., 2020). Likewise, setting up effective working definitions and systems boundaries in applied contexts is a necessary step given the variability and overlap in conceptualizations of circularity. Continually asking what circular solutions make sense, where, and at what scales they are most

effective and efficient should become a recurring practice in both research and professional fields. At what scale should loops be closed? Net-zero buildings and building level circularity is such a scenario where this type of critical reflection can help achieve more efficient circular cities. In urban cases, it is reasonable to apply a critical lens to assess in which cases closing loops at the building scale is more sustainable than integrated grid-level solutions. However, many of the interests, goals, and quantitative approaches being used within the built environment's sustainability efforts are in clear alignment with circular goals, and if cutting edge approaches to circularity can be better integrated with conceptualizations of urban level system boundaries much stands to be gained. It is likely that a range of levels of integration with urban grids may form the most flexible and resilient scenario. More research is also needed on the connections of urban, peri-urban, and rural systems and what CC's impact on their interconnections may be. Opportunities can be explored to leverage historical relationships and potentials for synergy while reforming linear paradigms.

4.3 Bio-Based Solutions

Within thematic area three, Bio-Based Solutions, four general implementation strategies were identified- Supporting sustainable local food production, Controlled Environment Agriculture, Nature Based Solutions, and Valorization of organic waste streams. All can contain overlapping features, though are also distinct and received specific mentions as implementation strategies in the reviewed literature. Skar et al. (2019) describe that localizing urban food systems and narrowing of cities' foodsheds is vital to developing more healthy and sustainable cities. They express that this aligns "perfectly" with the CC concept, as organic waste flows can be processed to support other agricultural products, and that a more circular approach to food via systematic approaches is needed to combat contemporary linear models (Skar et al., 2019). Urban agriculture can be seen as a driving force behind new urban approaches to resource cycling and can particularly materialize CC principles via integrated solutions such as meeting water requirements from sources originating within the city's watershed rather than utilizing tap water (Fletcher et al., 2013; Tahir et al., 2018; Pratt et al., 2019; Skar et al., 2019). In addition to soil-based operations, a promising means of local food production in urban areas is found in Controlled Environment Agriculture (CEA), implementation strategy eleven. A field which has received increasing research interest and popularity in application, CEA consists of approaches to growing food wherein environmental conditions like light, water, temperature, and nutrients, are controlled, often through uses of technology like sensors, monitoring systems, and LEDs, to achieve highly efficient food production that is resilient to external environmental conditions. Several such growing typologies may sound familiar to many due to their growing popularity and media coverage and include aquaponics, hydroponics, vertical growing (often hydroponic), and building integrated agriculture such as integrated rooftop greenhouses (Ceron-Palma et al., 2012; Gehrke, 2014; Pons et al., 2015; Santos, 2016; Ercilla-Montserrat et al., 2017; Nadel et al., 2017; Stadler et al., 2017; Sanjuan-Delmas et al., 2018; Gentry, 2019; Baganz et al., 2020; Manriquez-Altamirano et al., 2020). Notable existing examples include ECF in Berlin, Germany, BIGH Ferme Abattoir in Brussels, Belgium, Gotham

Greens, in New York, United States, and Vertical Harvest Farms in Jackson, Wyoming, United States. Urban agriculture is sometimes seen as overlapping with a concept regularly mentioned in association with CC- Nature Based Solutions (strategy 12).

An emerging concept, *Nature-based solutions* (NBS) promote circular resource use of nutrients, water, and energy via the integration of ecosystem driven approaches like consideration of biodiversity, ecosystem services, green infrastructure, and enhancing natural capital (Katsou et al., 2020). Our review found NBS recommended as an implementation strategy under the umbrellas of CC, CE, the FWE-Nexus, and Urban Metabolism. Katsou et al. (2020) assert that NBS can be seen as an intermediate link between CE and CC as its enhancement of natural capital and efficient resource utilization enable transitioning from linear urban flows to circular cities (Katsou et al., 2020). Implementation strategy thirteen, the *Valorization of organic waste streams* is an important means of transitioning from linear to circular biotic flows. This refers to giving organic waste streams a higher inherent value by redirecting them into new uses and forms of societal, economic, and environmental value. This is a growing area of research and fundamentally emerges from BE and CBE. Organic waste streams in the city can include food waste, wastewater/human wastes, agricultural wastes such as animal manure, and certain industrial process wastes. Through technologies such as anaerobic digestion, organic waste can be processed into useful nutrients, heat, and gases (Horn and Proksch, 2020b). Various other methods exist to harvest these resources from organic waste streams, which are often closely tied to next uses in agricultural settings to produce food to the cities, and offer a means of actualizing food system circularity and organic flow regeneration in the CC.

4.4 Supporting Strategies

The final three thematic areas contain supporting strategies and actions, fundamental to successful CC transitions by guiding, bolstering, and driving changes. Thematic area four consists of approaches with qualities of shaping accountability and driving implementation through governance, regulation, and stakeholder engagement. This thematic area of *Governance and Stakeholder Engagement* was broadly advocated for and cited within literature across all frameworks and concepts reviewed in section two. A fundamental aspect of this is implementation strategy fourteen, *Policy and Regulatory Changes*, which are closely connected to strategies 19–21 *Decision Making, Economic Incentives and Disincentives*, and *Frameworks and Codes*. These are made more successful through implementation strategies 16–18, which ground such changes in societal realities and bring in key stakeholders and urban dwellers through Consideration of consumer behaviors, Inclusive Communication, and Collaboration and Cooperation. These social dimensions of implementation are vital not to overlook when shaping successful CC transitions, though in some similar cases this has been the case. Paiho et al. note, for instance, that prominent sustainable city examples such as the Hammarby Model focus on local stocks and flows while overlooking residential behavior and realities such as transportation, they therefore call for “broader and more holistic analyses” through which to assess “interdependencies and identify synergies between versatile urbanization challenges”

(Paiho et al., 2020). Effective CC implementation will include consideration of societal impacts and human health in addition to environmental and economic elements, as all are inextricably interconnected in application.

Data, Measurement, and Modeling, the fourth thematic area of implementation strategies is an essential component of actualizing circularity and realizing regenerative potentials in urban contexts. Accordingly, it was unsurprising to find that strategies in this genre were highly discussed across the range of reviewed frameworks (Figure 2.4). *Data, Measurement, and Modeling* acts as a mode of characterizing circularity and supporting optimization. Developing and leveraging data consists of approaches like creating and utilizing datasets, information models, and database resources for circularity (Figure 2.2). This allows for establishing baselines, keeping track of strategies, documenting resources and integration possibilities, and much more. Closely aligned is strategy 29, *Mapping*, which plays a similar role, with additional analytical potentials, in a spatial dimension. Strategies 23 and 24, *Impacts assessments*, and *Life Cycle Approaches* are closely aligned, and support effective decision making and design as well as evaluation of existing, potential, or new systems and strategies. Many methodologies exist and are under development to facilitate this and are necessary to implement CC effectively.

In our literature review, it is notable that LCA was one of the most frequently mentioned strategies, and *Life Cycle Approaches* received the most literature mentions of all 34 strategies. Ceron-Palma et al. describe the value of analysis and quantification of in-flows and outflows of cities including energy, materials and natural resources, water, and emissions (Ceron-Palma et al., 2012). This perspective was echoed within many of the reviewed publications which called for *systematic quantitative analysis* (strategy 28) as an approach to the implementation of circularity. Paiho et al. make a key point on this count with regard to the definition of system boundaries for analysis, noting that it “is an important issue as it defines the breadth and depth of the analysis required to assess the circularity of a city” but that the concept of CC itself can shape a direction for use of concrete boundaries, targets, and indicators for realization of circularity (Paiho et al., 2020). The development of such approaches to the implementation and measurement of CC performance, as well as all previously discussed implementation strategies, will be vitally supported through Research and Education, thematic area six, which plays a role in characterizing and optimizing circularity as well as shaping accountability. While perhaps less direct than other implementation strategies, these approaches account for the generation and dissemination of knowledge necessary to achieve successful circularity, including *Assessment of emerging technologies* (30), *Methodology and Framework development* (31), *Education* (32), *Use of transdisciplinary methods*, and *Applied Research Approaches* (34). All 34 strategies stand to benefit from further research and development and continued investigation of how they can be most effectively implemented in order to realize a more holistically sustainable and regenerative future via CC.

5 Conclusion and Future Research Directions

Envisioning and implementing regenerative, symbiotic, and circular cities of the future through the CC framework will ultimately require a complex assortment of context specific approaches and implementation strategies across all six thematic areas- *Resource and Material Management, Systems Development and Integration, Bio-based Solutions, Governance and Stakeholder Engagement, Data, Measurement, and Modeling, and Research and Education*. Given the many shared goals, conceptualizations, and strategies espoused under the array of circular sustainability frameworks reviewed above, there is reason to discern value in looking to foundational and parallel concepts as a resource for the strengthening and amplification of CC in applied urban settings. We found considerable overlap between the reviewed frameworks and strong alignments between aspects of all, pointing to the value of conducting this type of investigation to identify opportunities to leverage these relationships and to hasten the integration of CC frameworks across scales and sectors. Promise resides in further reflection and learning from successes and failures, as well as in pursuing partnership and collaboration where opportunities arise to align efforts in pursuit of common goals between synergetic schools of thought and disciplines pursuing circularity at differing scales. There is a need to expand insight and understanding of how different scales and sectors pursuing circular sustainability fit together and can partner to drive change and transformation. On this, and all aspects, from the technical, economic, societal, and to the logistical and political, and beyond, more research on implementation of CC is needed. Participation and perspectives from transdisciplinary researchers and stakeholders should comprise no small part in this effort. Even when technological solutions are impeccable, the realities of implementation can be fraught with strategical, social, and political difficulties, making the inclusion of supporting actions in addition to technical solutions all the more vital.

Achieving successful circular cities may be particularly contingent upon a successful transition toward reframing externalities to account for the true invaluable nature of ecosystems health and human wellbeing within economic and urban systems, something which has become all the more evident in light of the COVID-19 pandemic. Likewise, changing societal views and behaviors toward more sustainable practices, which are already in motion, are needed to strengthen a driving and supporting force for change. Accordingly, we will crucially need effective policy and governance formed in partnership with stakeholders. Cities just venturing into this realm should increasingly look to leading circular cities and regions which are already piloting such approaches. Gathering case studies of successful implementation strategies and circular business models to help with legitimation and proof of concept at scale could play an influential role in helping businesses and stakeholders garner support to instigate circular transitions. There may be potential in partnering with existing sustainability certification systems for products, services, and buildings to incorporate further CC concepts in professional approaches with existing notoriety and traction among practitioners. Likewise, assessing existing and emerging technical innovation systems and taking functional analysis and value engineering approaches to evaluate applied solutions for the CC remains an underexplored

niche which may offer new insights. Finally, education -both traditional and continuing-should not be overlooked as an invaluable part of larger social change and of forming new leaders, citizens, and innovators. In support of these outcomes, this review offers a new lens to the discussion of CC transitions and applied actions by revisiting the relationships of multiple synergetic sustainability frameworks and the coordination of the implementation strategies they advance to bolster an integrated and transdisciplinary approach. Further work may expand on this lens to find further synergies or deepen exploration of particular opportunities. Likewise, future investigations of particular implementation strategies and technologies can benefit from strategic reflection on the approach's situation within a coordinated conceptual range, for which this review can provide a starting tool. Through such approaches, the metaphor of not reinventing wheels can become a powerful channel for closing loops and strengthening pathways to achieve successful implementation of a new circular, regenerative, and symbiotic reality for urban sustainability.

6 Author Contributions

EH was responsible for literature review, figures, analysis, and writing of this publication. GP advised and supervised the research process, contributed to figure concepts and creation, and provided review and guidance.

7 Funding

The study originates from the project CITYFOOD, which is part of the Belmont Forum and JPI Urban Europe initiated Food-Water-Energy-Nexus/Sustainability Urbanization Global Initiative (SUGI) Collaborative Research Action. It received funding from the U.S. National Science Foundation (Award 1832213).

8 Acknowledgements

EH acknowledges, with much gratitude, JC, for proofreading, feedback, and invaluable support throughout the development of this paper.

Chapter 2 References

- Adams, Katherine Tebbatt, Mohamed Osmani, Tony Thorpe, and Jane Thornback. "Circular Economy in Construction: Current Awareness, Challenges and Enablers." *Proceedings of the Institution of Civil Engineers - Waste and Resource Management* 170, no. 1 (February 1, 2017): 15–24. <https://doi.org/10.1680/jwarm.16.00011>.
- Allan, Tony, Martin Keulertz, and Eckart Woertz. "The Water–Food–Energy Nexus: An Introduction to Nexus Concepts and Some Conceptual and Operational Problems." *International Journal of Water Resources Development* 31, no. 3 (July 3, 2015): 301–11. <https://doi.org/10.1080/07900627.2015.1029118>.
- Allenby, Braden R., and T. E. Graedel. "E05_0-13-046713-8_01.Pdf." *Industrial Ecology*, 1993. https://toc.library.ethz.ch/objects/pdf/e05_0-13-046713-8_01.pdf.
- Andersen, Mikael Skou. "An Introductory Note on the Environmental Economics of the Circular Economy." *Sustainability Science* 2, no. 1 (April 1, 2007): 133–40. <https://doi.org/10.1007/s11625-006-0013-6>.

- Baganz, Gösta, Gundula Proksch, Werner Kloas, Wolf Lorleberg, Daniela Baganz, Georg Staaks, and Frank Lohrberg. "Site Resource Inventories – a Missing Link in the Circular City's Information Flow." *Advances in Geosciences* 54 (October 1, 2020): 23–32. <https://doi.org/10.5194/adgeo-54-23-2020>.
- Barbier, Edward B. "The Green Economy Post Rio+20." *Science* 338, no. 6109 (November 16, 2012): 887–88. <https://doi.org/10.1126/science.1227360>.
- Bazilian, Morgan, Holger Rogner, Mark Howells, Sebastian Hermann, Douglas Arent, Dolf Gielen, Pasquale Steduto, et al. "Considering the Energy, Water and Food Nexus: Towards an Integrated Modelling Approach." *Energy Policy, Clean Cooking Fuels and Technologies in Developing Economies*, 39, no. 12 (December 1, 2011): 7896–7906. <https://doi.org/10.1016/j.enpol.2011.09.039>.
- Beaulieu, Luce. "Circular Economy: A Critical Literature Review of Concepts." Accessed October 6, 2020. https://www.academia.edu/20226696/Circular_Economy_a_Critical_Literature_Review_of_Concepts.
- Blanco, Eduardo, Maibritt Pedersen Zari, Kalina Raskin, and Philippe Clergeau. "Urban Ecosystem-Level Biomimicry and Regenerative Design: Linking Ecosystem Functioning and Urban Built Environments." *Sustainability* 13, no. 1 (January 2021): 404. <https://doi.org/10.3390/su13010404>.
- Bocken, Nancy M. P., Ingrid de Pauw, Conny Bakker, and Bram van der Grinten. "Product Design and Business Model Strategies for a Circular Economy." *Journal of Industrial and Production Engineering* 33, no. 5 (July 3, 2016): 308–20. <https://doi.org/10.1080/21681015.2016.1172124>.
- Boulding, Kenneth E. *The Economics of the Coming Spaceship Earth*. Environ. Qual. Issues Growing Econ., 2017.
- Brown, Becky J., Mark E. Hanson, Diana M. Liverman, and Robert W. Merideth. "Global Sustainability: Toward Definition." *Environmental Management* 11, no. 6 (November 1, 1987): 713–19. <https://doi.org/10.1007/BF01867238>.
- Brundtland. "The Brundtland Report: 'Our Common Future.'" *Medicine and War* 4, no. 1 (1987): 17–25. <https://doi.org/10.1080/07488008808408783>.
- Buck, Nick Taylor, and Aidan While. "The Urban Bioeconomy: Extracting Value from the Ecological and Biophysical." *Journal of Environmental Planning and Management* 0, no. 0 (July 13, 2020): 1–20. <https://doi.org/10.1080/09640568.2020.1763931>.
- . "The Urban Bioeconomy: Extracting Value from the Ecological and Biophysical." *Journal of Environmental Planning and Management* 64, no. 2 (January 28, 2021): 182–201. <https://doi.org/10.1080/09640568.2020.1763931>.
- Bugge, Markus M., Teis Hansen, and Antje Klitkou. "What Is the Bioeconomy? A Review of the Literature." *Sustainability* 8, no. 7 (July 2016): 691. <https://doi.org/10.3390/su8070691>.
- Campioli, Andrea, Elena Mussinelli, Monica Lavagna, and Andrea Tartaglia. "Design Strategies and LCA of Alternative Solutions for Resilient, Circular, and Zero-Carbon Urban Regeneration: A Case Study." In *Regeneration of the Built Environment from a Circular Economy Perspective*, edited by Stefano Della Torre, Sara Cattaneo, Camilla Lenzi, and Alessandra Zanelli, 205–15. Research for Development. Cham: Springer International Publishing, 2020. https://doi.org/10.1007/978-3-030-33256-3_20.
- Caputo, Paola, Simone Ferrari, and Federica Zagarella. "Urban Renovation: An Opportunity for Economic Development, Environmental Improvement, and Social Redemption." In *Regeneration of the Built Environment from a Circular Economy Perspective*, edited by Stefano Della Torre, Sara Cattaneo, Camilla Lenzi, and Alessandra Zanelli, 125–35. Research for Development. Cham: Springer International Publishing, 2020. https://doi.org/10.1007/978-3-030-33256-3_13.
- Carcassi, Olga Beatrice, Enrico De Angelis, Giuliana Iannaccone, Laura Elisabetta Malighetti, Gabriele Masera, and Francesco Pittau. "Bio-Based Materials for the Italian Construction Industry: Buildings as Carbon Sponges." In *Regeneration of the Built Environment from a Circular Economy Perspective*, edited by Stefano Della Torre, Sara Cattaneo, Camilla Lenzi, and Alessandra Zanelli, 237–47. Research for Development. Cham: Springer International Publishing, 2020. https://doi.org/10.1007/978-3-030-33256-3_23.
- Carlowitz, Hans Carl von. *Sylvicultura Oeconomica, oder hauswirthliche Nachricht und naturmässige Anweisung zur wilden Baumzucht ... zugleich eine gründliche Nachricht von den in Sächss. Landen gefundenen Turff, dessen Beschaffenheit, nutzen, etc.* Johann Friedrich Braun, 1713.
- Carraresi, Laura, Silvan Berg, and Stefanie Bröring. "Emerging Value Chains within the Bioeconomy: Structural Changes in the Case of Phosphate Recovery." *Journal of Cleaner Production* 183 (May 10, 2018): 87–101. <https://doi.org/10.1016/j.jclepro.2018.02.135>.

- Carson, Rachel. *Silent Spring*. Greenwich, CT: Fawcett Publications, 1962.
- Carus, Michael. "The Bioeconomy Is Much More than a Circular Economy." Text/html. BLICKWINKEL. BLICKWINKEL, August 30, 2017. <https://www.brain-biotech.com/blickwinkel/>. <https://www.brain-biotech.com/blickwinkel/circular/the-bioeconomy-is-much-more-than-a-circular-economy/>.
- Castán Broto, Vanesa, and Harriet Bulkeley. "A Survey of Urban Climate Change Experiments in 100 Cities." *Global Environmental Change* 23, no. 1 (February 1, 2013): 92–102. <https://doi.org/10.1016/j.gloenvcha.2012.07.005>.
- Ceron-Palma, Ileana, Esther Sanyé-Mengual, Jordi Oliver-Solà, and Joan Rieradevall. "Barriers and Opportunities Regarding the Implementation of Rooftop Eco.Greenhouses (RTEG) in Mediterranean Cities of Europe." *Journal of Urban Technology* 19 (November 1, 2012): 87–103. <https://doi.org/10.1080/10630732.2012.717685>.
- Chertow, Marian R. "INDUSTRIAL SYMBIOSIS: Literature and Taxonomy." *Annual Review of Energy & the Environment* 25, no. 1 (November 2000): 313. <https://doi.org/10.1146/annurev.energy.25.1.313>.
- . "'Uncovering' Industrial Symbiosis." *Journal of Industrial Ecology* 11, no. 1 (2007): 11–30. <https://doi.org/10.1162/jiec.2007.1110>.
- Cheshire, Dave. *Building Revolutions: Applying the Circular Economy to the Built Environment*. RIBA Publishing, 2016.
- Chester, Mikhail V. "Industrial Ecology in Support of Climate Change Adaptation." *Journal of Industrial Ecology* 24, no. 2 (2020): 271–75. <https://doi.org/10.1111/jiec.13006>.
- "China's Growing CO2 Emissions A Race between Increasing Consumption and Efficiency Gains | Environmental Science & Technology." Accessed September 20, 2021. <https://pubs.acs.org/doi/10.1021/es070108f>.
- Corcelli, F., G. Fiorentino, A. Petit-Boix, J. Rieradevall, and X. Gabarrell. "Transforming Rooftops into Productive Urban Spaces in the Mediterranean. An LCA Comparison of Agri-Urban Production and Photovoltaic Energy Generation." *Resources, Conservation and Recycling* 144 (May 1, 2019): 321–36. <https://doi.org/10.1016/j.resconrec.2019.01.040>.
- Cordell, Dana, Jan-Olof Drangert, and Stuart White. "The Story of Phosphorus: Global Food Security and Food for Thought." *Global Environmental Change, Traditional Peoples and Climate Change*, 19, no. 2 (May 1, 2009): 292–305. <https://doi.org/10.1016/j.gloenvcha.2008.10.009>.
- Cotana, Franco, Alessandro Petrozzi, Anna Laura Pisello, Valentina Coccia, Gianluca Cavalaglio, and Elisa Moretti. "An Innovative Small Sized Anaerobic Digester Integrated in Historic Building." *Energy Procedia* 45 (2014): 333–41. <https://doi.org/10.1016/j.egypro.2014.01.036>.
- Crosson, Courtney. "Innovating the Urban Water System: Achieving a Net Zero Water Future Beyond Current Regulation." *Technology/Architecture + Design* 2, no. 1 (January 2, 2018): 68–81. <https://doi.org/10.1080/24751448.2018.1420966>.
- Curtis, Fred. "Eco-Localism and Sustainability." *Ecological Economics* 46, no. 1 (August 1, 2003): 83–102. [https://doi.org/10.1016/S0921-8009\(03\)00102-2](https://doi.org/10.1016/S0921-8009(03)00102-2).
- D'Amato, D., N. Droste, B. Allen, M. Kettunen, K. Lähinen, J. Korhonen, P. Leskinen, B. D. Matthies, and A. Toppinen. "Green, Circular, Bio Economy: A Comparative Analysis of Sustainability Avenues." *Journal of Cleaner Production* 168 (December 1, 2017): 716–34. <https://doi.org/10.1016/j.jclepro.2017.09.053>.
- Davidsson, Asa, Jes la Cour Jansen, Björn Appelqvist, Christopher Gruvberger, and Martin Hallmer. "Anaerobic Digestion Potential of Urban Organic Waste: A Case Study in Malmö." *Waste Management & Research: The Journal of the International Solid Wastes and Public Cleansing Association, ISWA* 25, no. 2 (April 2007): 162–69. <https://doi.org/10.1177/0734242X07075635>.
- Ddiba, Daniel, Kim Andersson, Arno Rosemarin, Helfrid Schulte-Herbrüggen, and Sarah Dickin. "The Circular Economy Potential of Urban Organic Waste Streams in Low- and Middle-Income Countries." *Environment, Development and Sustainability*, May 22, 2021, 1–29. <https://doi.org/10.1007/s10668-021-01487-w>.
- Delor, Milan. "Current State of Building-Integrated Agriculture, Its Energy Benefits and Comparison with Green Roofs - Summary." University of Sheffield, February 2011.
- Dipeolu, Adedotun Ayodele, Onoja Matthew Akpa, and Akinlabi Joseph Fadamiro. "Mitigating Environmental Sustainability Challenges and Enhancing Health in Urban Communities: The Multi-Functionality of Green Infrastructure." *Journal of Contemporary Urban Affairs* 4, no. 1 (June 1, 2020): 33–46. <https://doi.org/10.25034/ijcua.2020.v4n1-4>.
- Doughty, Mark R. C., and Geoffrey P Hammond. "Sustainability and the Built Environment at and beyond the City Scale." *Building and Environment* 39, no. 10 (October 1, 2004): 1223–33. <https://doi.org/10.1016/j.buildenv.2004.03.008>.

- Drożdż-Szczybura, Małgorzata. "The architectural expression of buildings realising the ideas of urban agriculture." *Czasopismo Techniczne* 2015, no. Architektura Zeszyt 1-A (1) 2015 (December 4, 2015): 29–52. <https://doi.org/10.4467/2353737XCT.15.002.3747>.
- Dzene, Ilze, Aiga Barisa, Marika Rosa, and Kristine Dobraja. "A Conceptual Methodology for Waste-to-Biomethane Assessment in an Urban Environment." *Energy Procedia*, International Scientific Conference "Environmental and Climate Technologies", CONECT 2015, 95 (September 1, 2016): 3–10. <https://doi.org/10.1016/j.egypro.2016.09.002>.
- Edwards, Joel, Maazuz Othman, and Stewart Burn. "A Review of Policy Drivers and Barriers for the Use of Anaerobic Digestion in Europe, the United States and Australia." *Renewable and Sustainable Energy Reviews* 52 (December 1, 2015): 815–28. <https://doi.org/10.1016/j.rser.2015.07.112>.
- Elia, Valerio, Maria Grazia Gnoni, and Fabiana Tornese. "Measuring Circular Economy Strategies through Index Methods: A Critical Analysis." *Journal of Cleaner Production* 142 (January 20, 2017): 2741–51. <https://doi.org/10.1016/j.jclepro.2016.10.196>.
- Elkington, John. "Cannibals with Forks: The Triple Bottom Line of 21st Century Business." *Choice Reviews Online* 36, no. 07 (1997): 36-3997-36–3997. <https://doi.org/10.5860/CHOICE.36-3997>.
- Ellen MacArthur Foundation. "Cities in the Circular Economy: An Initial Exploration," 2017. <https://ellenmacarthurfoundation.org/cities-in-the-circular-economy-an-initial-exploration>.
- Ercilla-Montserrat, Mireia, Rebeca Izquierdo, Jordina Belmonte, Juan Ignacio Montero, Pere Muñoz, Concepción De Linares, and Joan Rieradevall. "Building-Integrated Agriculture: A First Assessment of Aerobiological Air Quality in Rooftop Greenhouses (i-RTGs)." *Science of The Total Environment* 598 (November 15, 2017): 109–20. <https://doi.org/10.1016/j.scitotenv.2017.04.099>.
- European Commission. *Innovating Sustainable Growth: A Bioeconomy for Europe* (2012).
- European Investment Bank, and Jonas Byström. *The 15 Circular Steps for Cities*. LU: Publications Office of the European Union, 2018. <https://data.europa.eu/doi/10.2867/39283>.
- Fiori, Matteo, Tiziana Poli, Andrea G. Mainini, Juan Diego Blanco Cadena, Alberto Speroni, and Daniele Bocchiola. "Assessing Water Demand of Green Roofs Under Variants of Climate Change Scenarios." In *Regeneration of the Built Environment from a Circular Economy Perspective*, edited by Stefano Della Torre, Sara Cattaneo, Camilla Lenzi, and Alessandra Zanelli, 375–80. Research for Development. Cham: Springer International Publishing, 2020. https://doi.org/10.1007/978-3-030-33256-3_35.
- Fletcher, T. D., H. Andrieu, and P. Hamel. "Understanding, Management and Modelling of Urban Hydrology and Its Consequences for Receiving Waters: A State of the Art." *Advances in Water Resources*, 35th Year Anniversary Issue, 51 (January 1, 2013): 261–79. <https://doi.org/10.1016/j.advwatres.2012.09.001>.
- Folke, Carl, Åsa Jansson, Jonas Larsson, and Robert Costanza. "Ecosystem Appropriation by Cities." *Ambio* 26, no. 3 (1997): 167–72.
- Frosch, Robert A., and Nicholas E. Gallopoulos. "Strategies for Manufacturing." *Scientific American* 261, no. 3 (1989): 144–52.
- Gagliano, Antonio, Francesco Nocera, Antonio D'Amico, and Catalina Spataru. "Geographical Information System as Support Tool for Sustainable Energy Action Plan." *Energy Procedia*, Sustainability in Energy and Buildings: Proceedings of the 7th International Conference SEB-15, 83 (December 1, 2015): 310–19. <https://doi.org/10.1016/j.egypro.2015.12.185>.
- Gallego-Schmid, Alejandro, Han-Mei Chen, Maria Sharmina, and Joan Manuel F. Mendoza. "Links between Circular Economy and Climate Change Mitigation in the Built Environment." *Journal of Cleaner Production* 260 (July 1, 2020): 121115. <https://doi.org/10.1016/j.jclepro.2020.121115>.
- Gandy, Matthew. "Rethinking Urban Metabolism: Water, Space and the Modern City." *City* 8, no. 3 (December 2004): 363–79. <https://doi.org/10.1080/1360481042000313509>.
- Garcia, Daniel J., and Fengqi You. "The Water-Energy-Food Nexus and Process Systems Engineering: A New Focus." *Computers and Chemical Engineering* 91 (September 29, 2016): 49–67. <https://doi.org/10.1016/j.compchemeng.2016.03.003>.
- Gehrke, I. "Building-Integrated Water Reuse in Combination with Urban Farming," 1603–7. Siena, Italy, 2014. <https://doi.org/10.2495/SC141362>.

- Geissdoerfer, Martin, Paulo Savaget, Nancy M. P. Bocken, and Erik Jan Hultink. "The Circular Economy – A New Sustainability Paradigm?" *Journal of Cleaner Production* 143 (February 1, 2017): 757–68. <https://doi.org/10.1016/j.jclepro.2016.12.048>.
- Geldermans, R. J. "Design for Change and Circularity – Accommodating Circular Material & Product Flows in Construction." *Energy Procedia*, Sustainable Built Environment Tallinn and Helsinki Conference SBE16, 96 (September 1, 2016): 301–11. <https://doi.org/10.1016/j.egypro.2016.09.153>.
- Gentry, Matthew. "Local Heat, Local Food: Integrating Vertical Hydroponic Farming with District Heating in Sweden." *Energy* 174 (May 1, 2019): 191–97. <https://doi.org/10.1016/j.energy.2019.02.119>.
- Georgescu-Roegen, Nicholas. "Energy and Economic Myths." *Southern Economic Journal* 41, no. 3 (1975): 347–81. <https://doi.org/10.2307/1056148>.
- GhaffarianHoseini, AmirHosein, Nur Dalilah Dahlan, Umberto Berardi, Ali GhaffarianHoseini, Nastaran Makaremi, and Mahdiar GhaffarianHoseini. "Sustainable Energy Performances of Green Buildings: A Review of Current Theories, Implementations and Challenges." *Renewable and Sustainable Energy Reviews* 25 (September 2013): 1–17. <https://doi.org/10.1016/j.rser.2013.01.010>.
- Ghisellini, Patrizia, Catia Cialani, and Sergio Ulgiati. "A Review on Circular Economy: The Expected Transition to a Balanced Interplay of Environmental and Economic Systems." *Journal of Cleaner Production*, Towards Post Fossil Carbon Societies: Regenerative and Preventative Eco-Industrial Development, 114 (February 15, 2016): 11–32. <https://doi.org/10.1016/j.jclepro.2015.09.007>.
- Gibbs, David, Pauline Deutz, and Amy Proctor. "Industrial Ecology and Eco-Industrial Development: A Potential Paradigm for Local and Regional Development?" *Regional Studies* 39 (April 1, 2005): 171–83. <https://doi.org/10.1080/003434005200059959>.
- Ginelli, Elisabetta, Claudio Chesi, Gianluca Pozzi, Giuditta Lazzati, Davide Pirillo, and Giulia Vignati. "Extra-Ordinary Solutions for Useful Smart Living." In *Regeneration of the Built Environment from a Circular Economy Perspective*, edited by Stefano Della Torre, Sara Cattaneo, Camilla Lenzi, and Alessandra Zanelli, 347–56. Research for Development. Cham: Springer International Publishing, 2020. https://doi.org/10.1007/978-3-030-33256-3_32.
- Ginelli, Elisabetta, Gianluca Pozzi, Giuditta Lazzati, Davide Pirillo, and Giulia Vignati. "Regenerative Urban Space: A Box for Public Space Use." In *Regeneration of the Built Environment from a Circular Economy Perspective*, edited by Stefano Della Torre, Sara Cattaneo, Camilla Lenzi, and Alessandra Zanelli, 137–47. Research for Development. Cham: Springer International Publishing, 2020. https://doi.org/10.1007/978-3-030-33256-3_14.
- Giorgi, Serena, Monica Lavagna, and Andrea Campioli. "Circular Economy and Regeneration of Building Stock: Policy Improvements, Stakeholder Networking and Life Cycle Tools." In *Regeneration of the Built Environment from a Circular Economy Perspective*, edited by Stefano Della Torre, Sara Cattaneo, Camilla Lenzi, and Alessandra Zanelli, 291–301. Research for Development. Cham: Springer International Publishing, 2020. https://doi.org/10.1007/978-3-030-33256-3_27.
- Glass, Jacqui, David Greenfield, and Phil Longhurst. "Editorial: Circular Economy in the Built Environment." *Proceedings of the Institution of Civil Engineers - Waste and Resource Management* 170, no. 1 (February 1, 2017): 1–2. <https://doi.org/10.1680/jwarm.2017.170.1.1>.
- Gleick, P H. "Water and Energy." *Annual Review of Energy and the Environment* 19, no. 1 (1994): 267–99. <https://doi.org/10.1146/annurev.eg.19.110194.001411>.
- "Green Economy | UNEP - UN Environment Programme." Accessed September 20, 2021. <https://www.unep.org/explore-topics/green-economy>.
- Grimm, Nancy B., Stanley H. Faeth, Nancy E. Golubiewski, Charles L. Redman, Jianguo Wu, Xuemei Bai, and John M. Briggs. "Global Change and the Ecology of Cities." *Science* 319, no. 5864 (February 8, 2008): 756–60. <https://doi.org/10.1126/science.1150195>.
- Hart, Jim, Katherine Adams, Jannik Gieseckam, Danielle Densley Tingley, and Francesco Pomponi. "Barriers and Drivers in a Circular Economy: The Case of the Built Environment." *Procedia CIRP* 80 (2019): 619–24. <https://doi.org/10.1016/j.procir.2018.12.015>.
- Hodson, Mike, Simon Marvin, Blake Robinson, and Mark Swilling. "Reshaping Urban Infrastructure." *Journal of Industrial Ecology* 16, no. 6 (2012): 789–800. <https://doi.org/10.1111/j.1530-9290.2012.00559.x>.

- Horn, Erin, and Gundula Proksch. Building an Ecosystem: Integrating Rooftop Aquaponics with a Brewery to Advance the Circular Economy, 2020.
- . Sourcing Energy from Waste in the Circular City: Integrated Anaerobic Digestion toward Long Term Decarbonization, 2020.
- Huovila, P, U Iyer-Raniga, and S Maity. "Circular Economy in the Built Environment: Supporting Emerging Concepts - IOPscience." Accessed December 8, 2020. <https://iopscience-iop-org.offcampus.lib.washington.edu/article/10.1088/1755-1315/297/1/012003>.
- Iacovidou, Eleni, and Phil Purnell. "Mining the Physical Infrastructure: Opportunities, Barriers and Interventions in Promoting Structural Components Reuse." *Science of The Total Environment* 557–558 (July 1, 2016): 791–807. <https://doi.org/10.1016/j.scitotenv.2016.03.098>.
- International Living Future Institute (ILFI). "Living Building Challenge | Living-Future.Org," February 19, 2020. <https://living-future.org/lbc/>.
- ISO 15392 (2008). 14:00-17:00. "ISO 15392:2008." ISO. Available at: <https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/04/04/40432.html> (Accessed September 20, 2021).
- Jackson, Tim. Prosperity without Growth: Economics for a Finite Planet. London ; Sterling, VA: Earthscan, 2009.
- James, PHILIP. "Realising the Circular Bioeconomy," n.d., 74.
- Jedelhauser, Michael, and Claudia R. Binder. "The Spatial Impact of Socio-Technical Transitions – The Case of Phosphorus Recycling as a Pilot of the Circular Economy." *Journal of Cleaner Production* 197 (2018): 856–69. <https://doi.org/10.1016/j.jclepro.2018.06.241>.
- Joensuu, Tuomo, Harry Edelman, and Arto Saari. "Circular Economy Practices in the Built Environment." *Journal of Cleaner Production* 276 (December 10, 2020): 124215. <https://doi.org/10.1016/j.jclepro.2020.124215>.
- Jonsson, Daniel. "Sustainable Infrasytem Synergies: A Conceptual Framework." *Journal of Urban Technology* 7, no. 3 (December 2000): 81–104. <https://doi.org/10.1080/713684136>.
- Karhu, J., and L. Linkola. "Circular Economy in the Built Environment in Finland - A Case Example of Collaboration." *IOP Conference Series: Earth and Environmental Science* 297 (September 2019): 012024. <https://doi.org/10.1088/1755-1315/297/1/012024>.
- Kates, R., T Parris, and A Leiserowitz. "What Is Sustainable Development? Goals, Indicators, Values and Practice," 2005. <https://climatecommunication.yale.edu/publications/what-is-sustainable-development/>.
- Katsou, Evina, Chrysanthi-Elisabeth Nika, Devi Buehler, Bruno Marić, Boldizsár Megyesi, Eric Mino, Javier Babí Almenar, et al. "Transformation Tools Enabling the Implementation of Nature-Based Solutions for Creating a Resourceful Circular City." *Blue-Green Systems* 2, no. 1 (January 1, 2020): 188–213. <https://doi.org/10.2166/bgs.2020.929>.
- Kennedy, Christopher A., Iain Stewart, Angelo Facchini, Igor Cersosimo, Renata Mele, Bin Chen, Mariko Uda, et al. "Energy and Material Flows of Megacities." *Proceedings of the National Academy of Sciences* 112, no. 19 (May 12, 2015): 5985–90. <https://doi.org/10.1073/pnas.1504315112>.
- Kennedy, Christopher, John Cuddihy, and Joshua Engel-Yan. "The Changing Metabolism of Cities." *Journal of Industrial Ecology* 11, no. 2 (2007): 43–59. <https://doi.org/10.1162/jie.2007.1107>.
- Kennedy, Christopher, and Daniel Hoorweg. "Mainstreaming Urban Metabolism." *Journal of Industrial Ecology* 16, no. 6 (2012): 780–82. <https://doi.org/10.1111/j.1530-9290.2012.00548.x>.
- Kirchherr, Julian, Denise Reike, and Marko Hekkert. "Conceptualizing the Circular Economy: An Analysis of 114 Definitions." *Resources, Conservation and Recycling* 127 (December 1, 2017): 221–32. <https://doi.org/10.1016/j.resconrec.2017.09.005>.
- Kleinschmit, Daniela, Berit Hauger Lindstad, Bo Jellesmark Thorsen, Anne Toppinen, Anders Roos, and Sjur Baardsen. "Shades of Green: A Social Scientific View on Bioeconomy in the Forest Sector." *Scandinavian Journal of Forest Research* 29, no. 4 (May 19, 2014): 402–10. <https://doi.org/10.1080/02827581.2014.921722>.
- Kollikkathara, Naushad, Huan Feng, and Eric Stern. "A Purview of Waste Management Evolution: Special Emphasis on USA." *Waste Management* 29, no. 2 (February 1, 2009): 974–85. <https://doi.org/10.1016/j.wasman.2008.06.032>.
- Korhonen, Jouni, Antero Honkasalo, and Jyri Seppälä. "Circular Economy: The Concept and Its Limitations." *Ecological Economics* 143 (January 2018): 37–46. <https://doi.org/10.1016/j.ecolecon.2017.06.041>.

- Kujundzic, Kosara, and Slavica Stamatovic Vuckovic. "Cultural Landscape Devastation as a Consequence of Poor Sustainable Urban Development Practice Case Study: Kostanjica, Boka Bay, Montenegro." *Journal of Contemporary Urban Affairs* 3, no. 1 (June 1, 2019): 121–31. <https://doi.org/10.25034/ijcua.2018.4689>.
- Langergraber, Guenter, Bernhard Pucher, Lena Simperler, Johannes Kisser, Evina Katsou, Devi Buehler, Mari Carmen Garcia Mateo, and Nataša Atanasova. "Implementing Nature-Based Solutions for Creating a Resourceful Circular City." *Blue-Green Systems* 2, no. 1 (January 1, 2020): 173–85. <https://doi.org/10.2166/bgs.2020.933>.
- Lee, Uisung, Jeongwoo Han, and Michael Wang. "Evaluation of Landfill Gas Emissions from Municipal Solid Waste Landfills for the Life-Cycle Analysis of Waste-to-Energy Pathways." *Journal of Cleaner Production* 166 (November 10, 2017): 335–42. <https://doi.org/10.1016/j.jclepro.2017.08.016>.
- Lenhart, Jennifer, Bas van Vliet, and Arthur P. J. Mol. "New Roles for Local Authorities in a Time of Climate Change: The Rotterdam Energy Approach and Planning as a Case of Urban Symbiosis." *Journal of Cleaner Production* 107 (November 16, 2015): 593–601. <https://doi.org/10.1016/j.jclepro.2015.05.026>.
- "Let's Build a Circular Economy." Accessed September 20, 2021. <https://ellenmacarthurfoundation.org/>.
- Lewandowski, Mateusz. "Designing the Business Models for Circular Economy—Towards the Conceptual Framework." *Sustainability* 8, no. 1 (January 2016): 43. <https://doi.org/10.3390/su8010043>.
- Liang, Sai, and Tianzhu Zhang. "Urban Metabolism in China Achieving Dematerialization and Decarbonization in Suzhou." *Journal of Industrial Ecology* 15, no. 3 (2011): 420–34. <https://doi.org/10.1111/j.1530-9290.2011.00343.x>.
- Lowe, Ernest A., Stephen R. Moran, Douglas B. Holmes, Eco-industrial Parks, Brendan Doyle, Ernest A. Lowe, Stephen R. Moran, et al. "A Fieldbook for the Development of Eco-Industrial Parks," 1996.
- Lyle, John Tillman. *Regenerative Design for Sustainable Development*. New York: John Wiley, 1994. <https://archive.org/details/regenerativedesi0000lyle>.
- Manríquez-Altamirano, Ana, Jorge Sierra-Pérez, Pere Muñoz, and Xavier Gabarrell Durany. "Analysis of Urban Agriculture Solid Waste in the Frame of Circular Economy: Case Study of Tomato Crop in Integrated Rooftop Greenhouse." *Science of The Total Environment*, May 1, 2020, 139375. <https://doi.org/10.1016/j.scitotenv.2020.139375>.
- McDonald, Robert I., Katherine Weber, Julie Padowski, Martina Flörke, Christof Schneider, Pamela A. Green, Thomas Gleeson, et al. "Water on an Urban Planet: Urbanization and the Reach of Urban Water Infrastructure." *Global Environmental Change* 27 (July 1, 2014): 96–105. <https://doi.org/10.1016/j.gloenvcha.2014.04.022>.
- McDonnell, Mark, Amy Hahs, and J Brueste. *Ecology of Cities and Towns: A Comparative Approach*. *Ecology of Cities and Towns: A Comparative Approach*, 2009. <https://doi.org/10.1017/CBO9780511609763>.
- McDonough, William, and Michael Braungart. *Cradle to Cradle: Remaking the Way We Make Things*. Vintage, 2009.
- Mckelvey, Bill. "Managing Coevolutionary Dynamics," September 20, 2021.
- Meadows, Donella, Dennis Meadows, Jorgen Randers, and William Behrens. *The Limits to Growth*, 1972. <https://www.clubofrome.org/publication/the-limits-to-growth/>.
- Mendoza, Joan Manuel F., Maria Sharmina, Alejandro Gallego-Schmid, Graeme Heyes, and Adisa Azapagic. "Integrating Backcasting and Eco-Design for the Circular Economy: The BECE Framework." *Journal of Industrial Ecology* 21, no. 3 (2017): 526–44. <https://doi.org/10.1111/jiec.12590>.
- Merli, Roberto, Michele Preziosi, and Alessia Acampora. "How Do Scholars Approach the Circular Economy? A Systematic Literature Review." *Journal of Cleaner Production* 178 (March 20, 2018): 703–22. <https://doi.org/10.1016/j.jclepro.2017.12.112>.
- Moglia, Magnus. "Urban Agriculture and Related Water Supply: Explorations and Discussion." *Habitat International* 42 (April 1, 2014): 273–80. <https://doi.org/10.1016/j.habitatint.2014.01.008>.
- Moriguchi, Yuichi. "Material Flow Indicators to Measure Progress toward a Sound Material-Cycle Society." *Journal of Material Cycles and Waste Management* 9, no. 2 (September 1, 2007): 112–20. <https://doi.org/10.1007/s10163-007-0182-0>.
- Mukuve, Feriha Mugisha, and Richard A. Fenner. "Scale Variability of Water, Land, and Energy Resource Interactions and Their Influence on the Food System in Uganda." *Sustainable Production and Consumption*, Sustainability issues in the food–energy–water nexus, 2 (April 1, 2015): 79–95. <https://doi.org/10.1016/j.spc.2015.07.009>.
- Munaro, Mayara Regina, Sérgio Fernando Tavares, and Luís Bragança. "Towards Circular and More Sustainable Buildings: A Systematic Literature Review on the Circular Economy in the Built Environment." *Journal of Cleaner Production* 260 (July 1, 2020): 121134. <https://doi.org/10.1016/j.jclepro.2020.121134>.

- Nadal, Ana, Pere Llorach-Massana, Eva Cuerva, Elisa López-Capel, Juan Ignacio Montero, Alejandro Josa, Joan Rieradevall, and Mohammad Royapoor. "Building-Integrated Rooftop Greenhouses: An Energy and Environmental Assessment in the Mediterranean Context." *Applied Energy* 187 (February 1, 2017): 338–51. <https://doi.org/10.1016/j.apenergy.2016.11.051>.
- Newell, Joshua P., Benjamin Goldstein, and Alec Foster. "A 40-Year Review of Food–Energy–Water Nexus Literature and Its Application to the Urban Scale." *Environmental Research Letters* 14, no. 7 (July 2019): 073003. <https://doi.org/10.1088/1748-9326/ab0767>.
- Odum, Eugene P. *Basic Ecology*, 1983.
- Oxford Languages. "Oxford Languages and Google - English | Oxford Languages," 2021. <https://languages.oup.com/google-dictionary-en/>.
- Paiho, Satu, Elina Mäki, Nina Wessberg, Martta Paavola, Pekka Tuominen, Maria Antikainen, Jouko Heikkilä, Carmen Antuña Rozado, and Nusrat Jung. "Towards Circular Cities—Conceptualizing Core Aspects." *Sustainable Cities and Society* 59 (August 1, 2020): 102143. <https://doi.org/10.1016/j.scs.2020.102143>.
- Pandis Iveroth, Sofie, Anne-Lorène Vernay, Karel F. Mulder, and Nils Brandt. "Implications of Systems Integration at the Urban Level: The Case of Hammarby Sjöstad, Stockholm." *Journal of Cleaner Production*, Environmental Management for Sustainable Universities (EMSU) 2010, 48 (June 1, 2013): 220–31. <https://doi.org/10.1016/j.jclepro.2012.09.012>.
- Pauli, Gunter A. *The Blue Economy: 10 Years, 100 Innovations, 100 Million Jobs*. Paradigm Publications, 2010.
- Pearce, David William, and R. Kerry Turner. *Economics of Natural Resources and the Environment*. JHU Press, 1990.
- Petit-Boix, Anna, and Sina Leipold. "Circular Economy in Cities: Reviewing How Environmental Research Aligns with Local Practices." *Journal of Cleaner Production* 195 (September 10, 2018): 1270–81. <https://doi.org/10.1016/j.jclepro.2018.05.281>.
- Pfau, Swinda F., Janneke E. Hagens, Ben Dankbaar, and Antoine J. M. Smits. "Visions of Sustainability in Bioeconomy Research." *Sustainability* 6, no. 3 (March 2014): 1222–49. <https://doi.org/10.3390/su6031222>.
- Pomponi, Francesco, and Alice Moncaster. "Circular Economy for the Built Environment: A Research Framework." *Journal of Cleaner Production* 143 (February 1, 2017): 710–18. <https://doi.org/10.1016/j.jclepro.2016.12.055>.
- Pons, Oriol, Ana Nadal, Esther Sanyé-Mengual, Pere Llorach-Massana, Eva Cuerva, David Sanjuan-Delmàs, Pere Muñoz, Jordi Oliver-Solà, Carla Planas, and Maria Rosa Rovira. "Roofs of the Future: Rooftop Greenhouses to Improve Buildings Metabolism." In *Procedia Engineering*, 123:441–48. Selected Papers from Creative Construction Conference 2015, 2015. <https://doi.org/10.1016/j.proeng.2015.10.084>.
- Pratt, Tyler, L. Niel Allen, David E. Rosenberg, Andrew A. Keller, and Kelly Kopp. "Urban Agriculture and Small Farm Water Use: Case Studies and Trends from Cache Valley, Utah." *Agricultural Water Management* 213 (March 1, 2019): 24–35. <https://doi.org/10.1016/j.agwat.2018.09.034>.
- Prendeville, Sharon, Emma Cherim, and Nancy Bocken. "Circular Cities: Mapping Six Cities in Transition." *Environmental Innovation and Societal Transitions* 26 (March 1, 2018): 171–94. <https://doi.org/10.1016/j.eist.2017.03.002>.
- Prieto-Sandoval, Vanessa, Carmen Jaca, and Marta Ormazabal. "Towards a Consensus on the Circular Economy." *Journal of Cleaner Production* 179 (April 1, 2018): 605–15. <https://doi.org/10.1016/j.jclepro.2017.12.224>.
- Proksch, Gundula. *Creating Urban Agricultural Systems : An Integrated Approach to Design*. 1st ed. New York: Routledge, 2016. <https://search.proquest.com/agricenvironm/docview/1999775647/6BCE38C1DCA448F7PQ/1>.
- Proksch, Gundula, Alex Ianchenko, and Benz Kotzen. "Aquaponics in the Built Environment," 523–58, 2019. https://doi.org/10.1007/978-3-030-15943-6_21.
- Putnam, Robert. "The Prosperous Community: Social Capital and Public Life." *The American Prospect*, no. 13 (1993): 35–42.
- Rahbarianyazd, Rokhsaneh. "Sustainability in Historic Urban Environments: Effect of Gentrification in the Process of Sustainable Urban Revitalization." *Journal of Contemporary Urban Affairs* 1, no. 1 (June 1, 2017): 1–9. [https://doi.org/10.25034/1761.1\(1\)1-9](https://doi.org/10.25034/1761.1(1)1-9).
- Ramaswami, Anu, Dana Boyer, Ajay Singh Nagpure, Andrew Fang, Shelly Bogra, Bhavik Bakshi, Elliot Cohen, and Ashish Rao-Ghorpade. "An Urban Systems Framework to Assess the Trans-Boundary Food-Energy-Water Nexus: Implementation in Delhi, India." *Environmental Research Letters* 12, no. 2 (February 2017): 025008. <https://doi.org/10.1088/1748-9326/aa5556>.

- Ranhagen, Ulf, and Klas Groth. *The Symbiocity Approach : A Conceptual Framework for Sustainable Urban Development*. SKL International, 2012. <http://urn.kb.se/resolve?urn=urn:nbn:se:du-34271>.
- Reed, Bill. "Shifting from 'Sustainability' to Regeneration." *Building Research & Information* 35, no. 6 (November 1, 2007): 674–80. <https://doi.org/10.1080/09613210701475753>.
- Ribić, Bojan, Neven Voća, and Branka Ilakovac. "Concept of Sustainable Waste Management in the City of Zagreb: Towards the Implementation of Circular Economy Approach." *Journal of the Air & Waste Management Association* 67, no. 2 (February 1, 2017): 241–59. <https://doi.org/10.1080/10962247.2016.1229700>.
- ROOS, ANDERS, and MATTI STENDAHL. "The Emerging Bio-Economy and the Forest Sector." In *Forests, Business and Sustainability*. Routledge, 2015.
- Sale, Kirkpatrick. *Dwellers in the Land: The Bioregional Vision*. University of Georgia Press, 1985.
- Sanjuan-Delmás, David, Pere Llorach-Massana, Ana Nadal, Mireia Ercilla-Montserrat, Pere Muñoz, Juan Ignacio Montero, Alejandro Josa, Xavier Gabarrell, and Joan Rieradevall. "Environmental Assessment of an Integrated Rooftop Greenhouse for Food Production in Cities." *Journal of Cleaner Production* 177 (March 10, 2018): 326–37. <https://doi.org/10.1016/j.jclepro.2017.12.147>.
- Santos, Maria José Palma Lampreia dos. "Smart Cities and Urban Areas—Aquaponics as Innovative Urban Agriculture." *Urban Forestry & Urban Greening* 20 (December 1, 2016): 402–6. <https://doi.org/10.1016/j.ufug.2016.10.004>.
- Sauvé, Sébastien, Sophie Bernard, and Pamela Sloan. "Environmental Sciences, Sustainable Development and Circular Economy: Alternative Concepts for Trans-Disciplinary Research." *Environmental Development* 17 (January 1, 2016): 48–56. <https://doi.org/10.1016/j.envdev.2015.09.002>.
- Simmonds, Peter Lund. *Waste Products and Undeveloped Substances: Or, Hints for Enterprise in Neglected Fields*. R. Hardwicke, 1862.
- Skar, Siv Lene, Rocío Pineda-Martos, Axel Timpe, Bernd Pölling, Katrin Bohn, Mart Külvik, Cecília Delgado, et al. "Urban Agriculture as a Keystone Contribution towards Securing Sustainable and Healthy Development for Cities in the Future." *Blue-Green Systems*, December 2, 2019. <https://doi.org/10.2166/bgs.2019.931>.
- Smith, Carla. "Processing London's Local Food Waste in an Anaerobic Digester Avoids 3.9 Tonnes of GHG Emissions." *Waste Management*, no. 503 (2018): 2.
- Spiegelhalter, T., and R. A. Arch. "Biomimicry and Circular Metabolism for the Cities of the Future," 215–26. La Coruna, Spain, 2010. <https://doi.org/10.2495/SC100191>.
- Spiegelhalter, Thomas. "Designing Cities of the Future with the Principles of Biomimicry and Circular Metabolism." *Design Principles & Practice: An International Journal* 4, no. 2 (February 2010): 267–79. <https://doi.org/10.18848/1833-1874/CGP/v04i02/37857>.
- Stadler, M. M., D. Baganz, T. Vermeulen, and K. J. Keesman. "Circular Economy and Economic Viability of Aquaponic Systems: Comparing Urban, Rural and Peri-Urban Scenarios under Dutch Conditions," 2017. <https://pubag.nal.usda.gov/catalog/5897744>.
- Stahel, Walter R. "The Circular Economy." *Nature* 531, no. 7595 (March 2016): 435–38. <https://doi.org/10.1038/531435a>.
- Stahel, Walter, and Geneviève Reday-Mulvey. "Jobs for Tomorrow: The Potential for Substituting Manpower for Energy," January 1, 1981.
- Stegmann, Paul, Marc Londo, and Martin Junginger. "The Circular Bioeconomy: Its Elements and Role in European Bioeconomy Clusters." *Resources, Conservation & Recycling: X* 6 (May 1, 2020): 100029. <https://doi.org/10.1016/j.rcrx.2019.100029>.
- Su, Biwei, Almas Heshmati, Yong Geng, and Xiaoman Yu. "A Review of the Circular Economy in China: Moving from Rhetoric to Implementation." *Journal of Cleaner Production* 42 (March 1, 2013): 215–27. <https://doi.org/10.1016/j.jclepro.2012.11.020>.
- Suárez-Eiroa, Brais, Emilio Fernández, Gonzalo Méndez-Martínez, and David Soto-Oñate. "Operational Principles of Circular Economy for Sustainable Development: Linking Theory and Practice." *Journal of Cleaner Production* 214 (March 20, 2019): 952–61. <https://doi.org/10.1016/j.jclepro.2018.12.271>.
- Taylor Buck, Nick. "The Art of Imitating Life: The Potential Contribution of Biomimicry in Shaping the Future of Our Cities." *Environment and Planning B: Urban Analytics and City Science* 44, no. 1 (January 1, 2017): 120–40. <https://doi.org/10.1177/0265813515611417>.

- International Institute for Sustainable Development. "The Water-Energy-Food Security Nexus: Towards A Practical Planning and Decision Support Framework for Landscape Investment and Risk Management." Accessed September 20, 2021. <https://www.iisd.org/publications/water-energy-food-security-nexus-towards-practical-planning-and-decision-support>.
- Thiriet, Pierre, Thierry Bioteau, and Anne Tremier. "Optimization Method to Construct Micro-Anaerobic Digesters Networks for Decentralized Biowaste Treatment in Urban and Peri-Urban Areas." *Journal of Cleaner Production* 243 (January 10, 2020): 118478. <https://doi.org/10.1016/j.jclepro.2019.118478>.
- Tien, Iris. "Resilient by Design: The Case for Increasing Resilience of Buildings and Their Linked Food-Energy-Water Systems." *Elem Sci Anth* 6, no. 1 (February 21, 2018). <https://doi.org/10.1525/elementa.142>.
- Toboso-Chavero, Susana, Ana Nadal, Anna Petit-Boix, Oriol Pons, Gara Villalba, Xavier Gabarrell, Alejandro Josa, and Joan Rieradevall. "Towards Productive Cities: Environmental Assessment of the Food-Energy-Water Nexus of the Urban Roof Mosaic." *Journal of Industrial Ecology*, November 26, 2018. <https://doi.org/10.1111/jiec.12829>.
- United Nations (UN). "Sustainable Development Goals." unfoundation.org. Accessed September 20, 2021. <https://unfoundation.org/what-we-do/issues/sustainable-development-goals/>.
- Wästfelt, Anders, and Qian Zhang. "Reclaiming Localisation for Revitalising Agriculture: A Case Study of Peri-Urban Agricultural Change in Gothenburg, Sweden." *Journal of Rural Studies* 47 (October 1, 2016): 172–85. <https://doi.org/10.1016/j.jrurstud.2016.07.013>.
- Weidner, Till, and Aidong Yang. "The Potential of Urban Agriculture in Combination with Organic Waste Valorization: Assessment of Resource Flows and Emissions for Two European Cities." *Journal of Cleaner Production* 244 (January 20, 2020): 118490. <https://doi.org/10.1016/j.jclepro.2019.118490>.
- Williams, Jo. "Sun, Surf and Sustainable Housing—Cohousing, the Californian Experience." *International Planning Studies* 10, no. 2 (May 1, 2005): 145–77. <https://doi.org/10.1080/13563470500258824>.
- Williams, Joanna. "Circular Cities." *Urban Studies* 56, no. 13 (October 1, 2019): 2746–62. <https://doi.org/10.1177/0042098018806133>.
- Winans, K., A. Kendall, and H. Deng. "The History and Current Applications of the Circular Economy Concept." *Renewable and Sustainable Energy Reviews* 68 (February 1, 2017): 825–33. <https://doi.org/10.1016/j.rser.2016.09.123>.
- Wise, Nicholas. "Outlining Triple Bottom Line Contexts in Urban Tourism Regeneration." *Cities* 53 (April 1, 2016): 30–34. <https://doi.org/10.1016/j.cities.2016.01.003>.
- Wolman, Abel. "The Metabolism of Cities." *Scientific American* 213, no. 3 (September 1965): 178–90. <https://doi.org/10.1038/scientificamerican0965-178>.
- Xue, Jingyan, Gengyuan Liu, Marco Casazza, and Sergio Ulgiati. "Development of an Urban FEW Nexus Online Analyzer to Support Urban Circular Economy Strategy Planning." *Energy* 164 (December 1, 2018): 475–95. <https://doi.org/10.1016/j.energy.2018.08.198>.
- Zaman, Atiq Uz, and Steffen Lehmann. "Challenges and Opportunities in Transforming a City into a 'Zero Waste City.'" *Challenges* 2, no. 4 (December 2011): 73–93. <https://doi.org/10.3390/challe2040073>.
- Zeller, Vanessa, Edgar Towa, Marc Degrez, and Wouter M. J. Achten. "Urban Waste Flows and Their Potential for a Circular Economy Model at City-Region Level." *Waste Management* 83 (January 1, 2019): 83–94. <https://doi.org/10.1016/j.wasman.2018.10.034>.

Chapter 3. A Mixed-Methods Assessment of Environmental Sustainability Gaps in Commercial Aquaponic Operations in North America

Erin Horn, Michael Schoemaker, Calvin Turek, and Gundula Proksch

Keywords

Aquaponics, Environmental Performance, Nutrient Recovery, Mixed-Methods Assessment, Process Engineering, Commercial Aquaponics, Wastewater Process Analysis, Comparative Analysis

Abstract

The sustainability potential of aquaponic production methods to grow produce and fish efficiently is widely discussed in literature and public discourse. Commercial aquaponics aims to scale these approaches up and increase integration with the larger food system. A potential trade-off of the space and resource efficiency of controlled environment agriculture approaches used in commercial aquaponic production is the additional built infrastructure and energy needed to maintain growing conditions. Additionally, internal nutrient recovery efficiency in operation is dependent on system process design. While literature assures that many resources required for aquaponics could be supplied through renewable and sustainable means, whether this is yet taking place in current commercial practice is less well documented, and to what degree academic literature and industry approaches to environmental sustainability align has not yet been studied. To address this gap, this paper analyzes the current technical, operational, and management environmental sustainability and efficiency practices of commercial aquaponics operations in North America to develop insights into how these align with the potential and intended sustainability outcomes of the field and to identify gaps between research and practice. This investigation accordingly utilizes a mixed-methods approach merging qualitative and quantitative data through case study analysis, semi-structured interviews (n=26) with a representative sub-section of commercial aquaponics practitioners in North America, literature review, wastewater process analysis, and content analysis. Findings shed light onto the recent status of implementation of resource efficiency measures within commercial aquaponic production in North America. Accordingly, it identifies areas of opportunity for further research and innovation to support the applied success of environmental sustainability within commercial aquaponics.

1. Introduction

The efficiency and sustainability of aquaponics, the integration of both hydroponics and aquaculture via water and nutrient exchange, has led many to view it as an environment-forward method of food production which makes use of the best qualities of both subsystems, especially by simultaneously solving the challenges of fish waste management in aquaculture

and need for essential nutrient input in hydroponics (Chunjie Li et al. 2018; Abusin & Mandikiana 2020). Aquaponics has accordingly been considered a promising system with which to help meet food production needs efficiently by utilizing circular, symbiotic, and regenerative practices that align with the aims of Circular Economy and related frameworks (Horn and Proksch 2022). Reusing nutrients and water while minimizing external material inputs is described by Estim et al. as the principle upon which aquaponic systems function and what most fundamentally creates its widely esteemed sustainability potential (Estim et al. 2020). Notably, Danish et al. 2021 describe nutrients, water, and energy as the three main areas of technical and scientific importance in contemporary aquaponics systems. It has been claimed that aquaponics uses less energy than conventional agriculture as it reduces need of energy intensive inputs (such as synthetic fertilizers) and can make use of renewable inputs (Chunjie Li et al. 2018; Joyce et al. 2019, Reyes-Lúa et al. 2021). Aquaponics can concurrently minimize fertilizer and chemical inputs, external organics, pesticides, antibiotics (Rakocy 2006; Chunjie Li et al. 2018; Joyce et al. 2019; Danish et al. 2021; Folorunso et al. 2021) as well as lessening emissions, creating little to no pollution (Goddek et al. 2015, Abusin & Mandikiana 2020, Wu & Song 2021, Folorunso et al. 2021), this in turn considerably abates impacts on natural systems and ecosystems (Danish et al. 2021). The reduction of synthetic and mineral fertilizer inputs may prove increasingly crucial, particularly noting the recycling of phosphorus in aquaponics and its potential to help mitigate phosphorus depletion (Baganz et al. 2021), as phosphorus rock sources are mined fully, and pollution issues due to fertilizer over application and runoff. Likewise, aquaponics can enable efficient land use (Danish et al. 2021; Joyce et al. 2019), reduce labor demands (Chunje Li et al. 2018); produce of high-quality vegetables and fish protein (Chunjie Li et al. 2018; Joyce et al. 2019), supporting sustainable protein shift. Food systems resilience is also supported, as controlled environment growing reduces production seasonality and supports year-round food production, helping aquaponics to offer consistent outputs and contribute to food security and diversity of local produce options (Pinstrup-Andersen, 2018; Abusin & Mandikiana 2020). The controlled nature of the aquaponics system likewise provides higher biosecurity, reducing contamination and disease risks (Chunjie Li et al. 2018). Furthermore, growth rates can be optimized by controlled conditions including increased CO₂ levels in the greenhouse (Körner and Challa, 2003; Aaslyng et al., 2003; Goddek and Körner 2019). However, achieving these ample sustainability and resilience benefits can also come along with additional infrastructure needs for commercial aquaponics, with potential environmental impact “hotspots” that can include equipment and structures, heat, electricity, and fish feed (Ghamkhar et al., 2020; Körner et al. 2021).

Maximizing sustainable potential while minimizing environmental impact is key to fully realizing the promise of aquaponics, and requires effective operational practices, business models, and use of technology to further the industry and foster innovation. It can prove challenging to investigate the realities of commercial aquaponics in applied context and not many (Love et al. 2014, 2015; Short et al. 2017; Mchunu et al. 2018) have sought to do so (Monsees et al. 2017; Folorunso et al. 2021). Moreover, Chunjie Li et al., who utilized a triple bottom line approach (environment, economics, social aspects) to assess the sustainability of aquaponics operational

practices, note that systematic modeling and research of aquaponics, especially of environmental aspects, is still lacking (Chunjie Li et al. 2018). As a complex food production system wherein sustainability benefits are shaped by multiple layers of the system and its integrative context- from the water and nutrient symbiosis of the core aquaponics system, the energy use and potential for resilience of Controlled Environment Agriculture (CEA) practices, the role of site and resource integration of operations, and the forces of larger regional climates and context- commercial aquaponic systems' environmental sustainability and performance stands to benefit from analysis through a systems process lens. While literature assures that many resources required for aquaponics could be supplied through renewable and sustainable means, whether this is yet taking place in current commercial practice is less well documented, and to what degree academic literature and industry approaches to environmental sustainability align has not yet been studied.

This investigation therefore seeks to analyze the current technical and operational practices of commercial farm systems in North America relating to environmental sustainability and efficiency, asking: *How does the purported sustainability potential of aquaponics manifest in applied context in operating commercial aquaponics and what innovation and research is needed to close any gaps between theoretical and applied performance?* This is pursued through a mixed-methods approach utilizing qualitative interviews with commercial aquaponics owner/operators, case study research methods, and literature review to develop insights into how recent practices and challenges shape current manifestations of the intended sustainability outcomes of the field and to identify gaps between research and practice to support further optimization of environmental sustainability within commercial aquaponic food production.

2. Methodology

2.1 Sustainability Assessment of Aquaponics in Literature

It can be challenging to meaningfully assess the sustainability benefits of aquaponics due to wide variation in system design, performance, and environmental context (König et al. 2018, 2016; Greenfeld et al. 2021). Means of evaluating sustainability in aquaponics include system technical and performance data evaluation, ecosystem services, environmental footprint analysis, life cycle assessment, material flow analysis, emergy analysis (David et al. 2021), qualitative analysis, comparisons to other systems, and case study approaches. LCA has been pursued to assess sustainability in aquaponics (Forchino et al., 2017; Maucieri et al., 2018; Chen et al., 2020), though not many exist (Greenfeld et al. 2021). These studies are not directly comparable, as they utilize differing methods of allocating environmental impacts and they assess systems of differing scales (Wu et al. 2019; Greenfeld et al, 2021). Results of these studies have varied, Greenfeld et al. 2021 describe that the environmental cost of the infrastructure of an aquaponic system was smaller than other compared systems that produced only one food product (Jaeger et al., 2019; Maucieri et al., 2019; Nicoletto et al., 2018; Ru et al., 2017; Yacout et al., 2016; Greenfeld et al. 2021).

A limitation of many existing studies is created by the challenge of assessing the sustainability of aquaponics as a system with environmental impacts shaped by both material elements of its infrastructure and operational resource flows determined by various biological processes. Commercial aquaponics is in many ways more comparable to water treatment systems than a building or traditional farm alone and is an example of a typological fusion between a productive biological system and a built environment. Due to this unique dynamic relationship between the structural, operational, and living components of an aquaponic system, sustainability analysis and comparison of multiple commercial operations may benefit from purposeful analytical methodologies that account for the process relationships of all components and their role in shaping the resource efficiency of commercial aquaponic operations.

2.2 Analytical framework

While there are other key tenets of sustainability (e.g. social and economic), the environmental sustainability of aquaponic production is the particular aspect under scrutiny within this study, as it is one of the most purported benefits of commercial aquaponics. As this form of agriculture is a technological production system utilizing biological components to yield food crops, we will introduce a novel analytical framework to analyze aquaponics through an operational process lens in which environmental sustainability is conceptualized as the resource flows and resource-use efficiency through the cradle-to-consumer lifecycle of resources utilized and produced within the system. These resource flows are mediated through multiple levels of the aquaponic production system (Figure 3.1), in which its core components, a hydroponics system and a linked recirculating aquaculture system (RAS), are nested within the larger CEA system, within the integrative context of the farm site, which is situated within a broader local and regional context, all layers of which play a role in shaping the environmental sustainability performance of a given commercial aquaponic production system. This conceptualization of the system is influenced by industrial ecology and urban metabolism approaches, as well as environmental engineering. It utilizes life cycle and resource perspectives often applied to carbon accounting increasingly applied in the built environment disciplines including architecture, engineering, and the broader sustainability science community. We will differentiate between resources flowing within the operating aquaponic production system, and the resources required for its built infrastructure. The inclusion and movement of various resource flows will be analyzed through the system model (Figure 3.1) to facilitate a comparison of processes and their environmental sustainability impacts between commercial aquaponics operations in North America. For a given resource, we will compare how it enters and exits the system as well as its use or transformation within the aquaponic system. This analysis will include an overview and comparison of processes used among interviewed farms, particularly delving into water and nutrient recovery processes (3.1), and materials and operational needs (e.g. energy) associated with CEA production (3.2), within their larger context

(3.3). Trends among operating farms will also be compared with state-of-the-art descriptions of aquaponic system environmental sustainability in literature, querying the baseline and potential gaps where optimization in the field or further research support is needed.

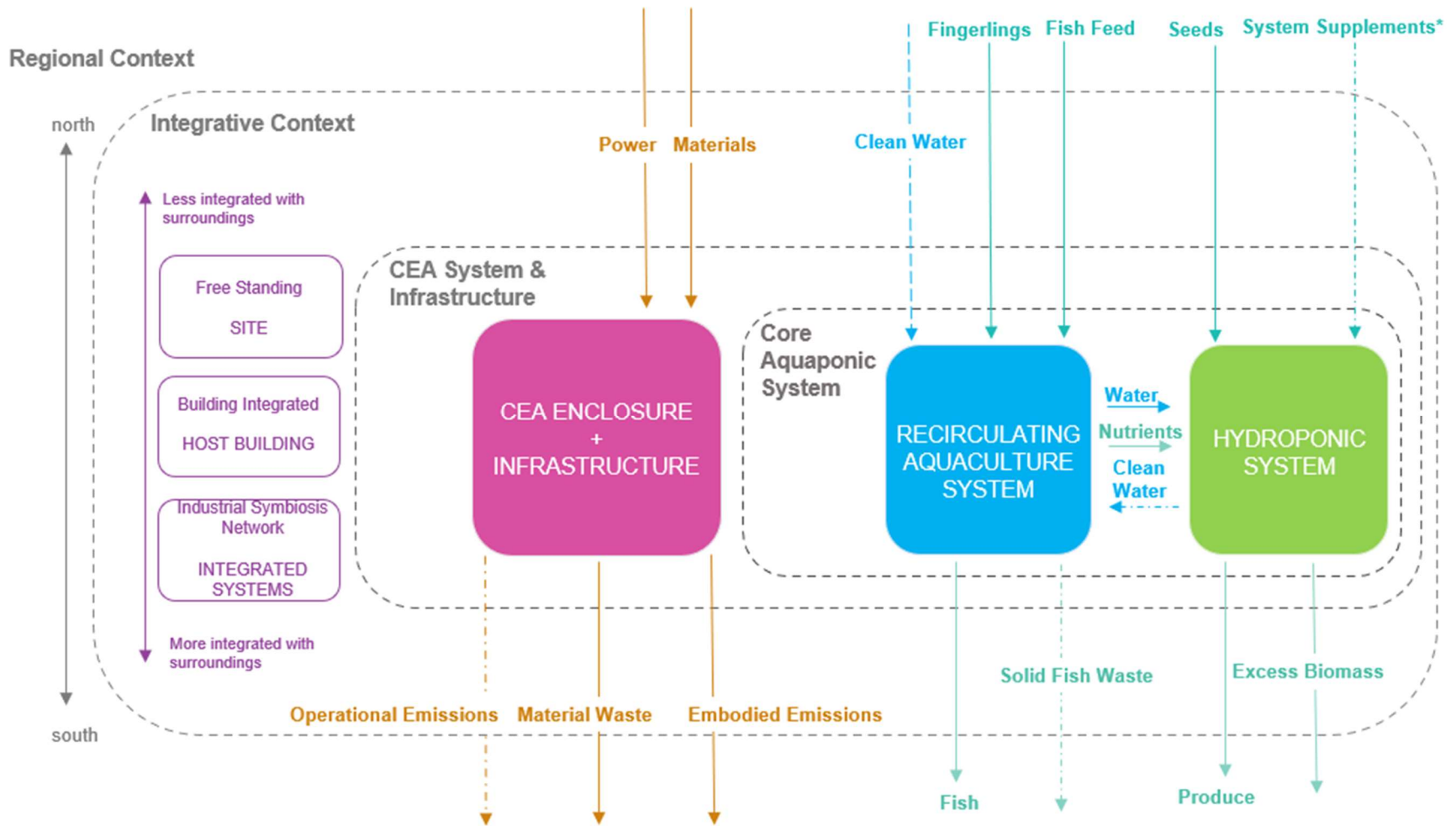
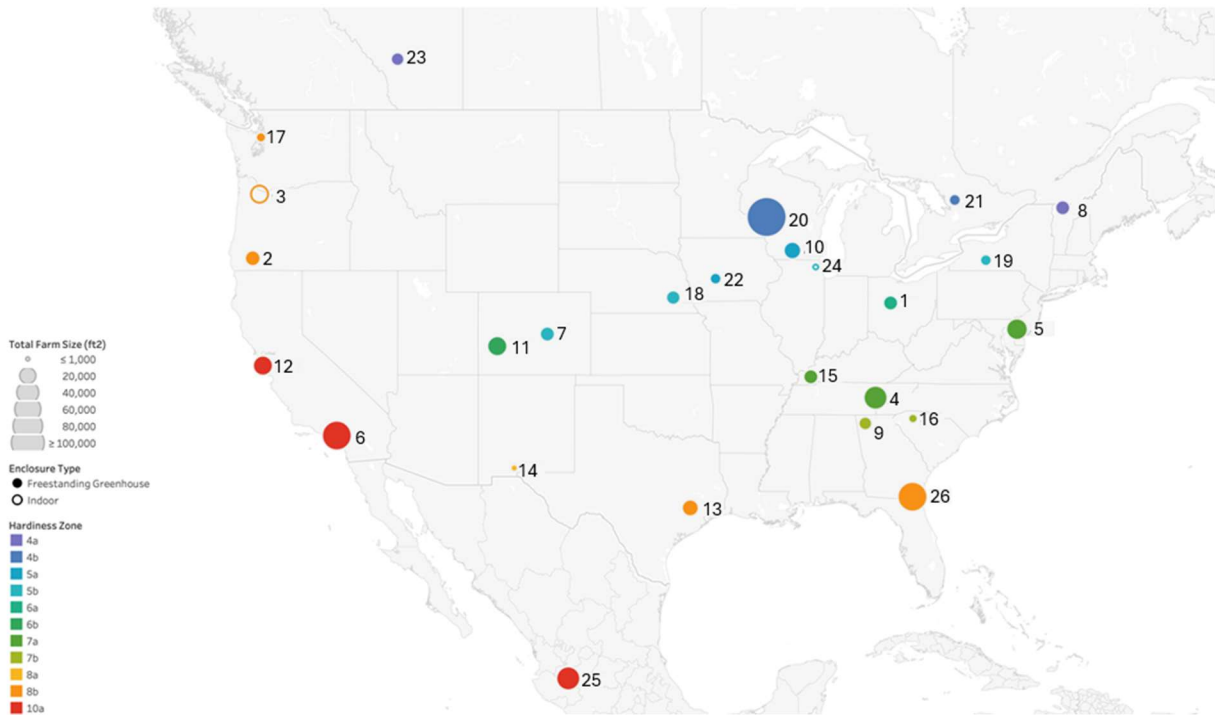


Figure 3.1- Commercial Aquaponics Analytical Framework- System model of commercial scale aquaponic operations and resource flows

2.3 Interviews

Participants were recruited from a database of n~152 aquaponic producers in North America created by Proksch’s Circular Cities + Living Systems Lab (Horn et al. 2023). Interviews were arranged with 26 participants and took place between May and July 2021. The interview guide and process of these interviews was reviewed internally as well deemed exempt from additional oversight by the University of Washington Institutional Review Board (IRB Exempt: STUDY00013037). Interviews were semi-structured and followed a set of prepared questions posed to all participants. Interviewed operations varied in size and were located across North America in a range of hardiness zones, allowing for a wide-ranging representation of characteristics and operations of commercial aquaponics to be considered (Figure 3.2).



ID	Hardiness zone	Size (sqft)	Year started	Enclosure type	Structure type	Primary Revenue Generating Service
1	6a	6,500	2011	Greenhouse (GH)	Hoop House	Produce
2	8b	10890	2011	GH	Hoop House	Produce
3	8b	15,000	2014	Indoor	warehouse	Produce
4	7a	26260	2013	GH	Medium Tech GH (new)	Consulting+ System Supplier
5	7a	20000	2018	GH	Medium Tech GH (new)	Produce
6	10a	50,000	2010	GH	Hoop Houses	Produce
7	5b	22,000	2010	GH	Medium Tech. (film)	Produce
8	4a	6,500	2016	GH	Passive Solar (custom)	Produce
9	7b	4,700	2014	GH	Hoop House	Produce

10	5a	9000	2013	GH	Medium Tech GH (new)	Produce
11	6b	14,000	2017	GH	Medium Tech GH (new)	Produce
12	10a	26,000	2014	GH	Medium Tech GH	Produce
13	8b	20000	2012	GH	Medium Tech. (film)	Produce
14	8a	200	2017	GH	DIY w/ plastic siding	
15	7a	8000	2018	GH	Medium Tech GH (new)	Produce
16	7b	1350	2016	GH	Hoop House	Produce
17	8b	1800	2018	GH	Medium Tech GH	Produce
18	5b	5760	2013	GH	Hoop House; Medium Tech GH	Cut Flowers
19	5b	2800	2013	GH	Hoop House + Attached Metal Fish House	Fish
20	4b	675,180	2017	GH	High Tech. GH	Produce
21	4b	3000	2016	GH	Cold-Adapted Hoop House	Produce
22	5a	5600	2013	GH	Hoop House	Produce
23	4a	4200	2016	GH	High Tech. (film); Passive Solar	Consulting+ System Supplier
24	5b	<1000*	2015	Indoor	Within home	Produce
25	10a	27000*	2006	GH	High Tech. GH	Produce
26	8b	10000*	2013	GH	High Tech. GH	Produce

Figure 3.2- Overview of Aquaponics Operations Interviewed

2.4 Data analysis

Both interview and literature data were preliminarily content coded with the environmental sustainability subtopics they discussed where mentioned, and codes organized through the system model analytical framework. Comprehensive documentation of operating farms in North America form core data tables supporting the analysis through the *Commercial Aquaponics Analytical Framework* advanced in this work. Interview thematic coding was repeated twice by separate individuals, and then iteratively coded once more in Atlas.ti. Water circulation and nutrient recovery and use practices discussed in interviews were analyzed through a process engineering lens to identify the approximate system components and practices used by interviewed operations, and generalized into appropriate process subcategories for better comparability (e.g. varied types of digester designs are referred to as mineralization units in diagrams), supplemental data from publicly available farm tour videos and websites were also consulted when needed to better elucidate system designs, as presented in Figure 3.3- *Engineered Process Analysis*. Figure 3.3 presents this process engineering analysis, comparing nutrient recovery practices across the cases, as has never been previously documented for commercial aquaponics within academic literature.

3. Findings

The aquaponic operations interviewed varied in age, though most were started since 2010, with one outlier dating to 2006, indicative of the relative youth of the industry (Figure 3.2). Most

operations were located within greenhouses, with a small minority utilizing indoor growing spaces and relying on grow lighting alone. Most generated their primary revenue through the sale of produce grown within their systems, and more than half also had additional types of agriculture on site. System characteristics and operational practices varied across the interviewed farms and are assessed through the system analytical model (Figure 3.1). In the following subsections, they are contextualized and compared with literature on the same system aspects to reveal emergent patterns and gaps between theory and practice of aquaponic production at commercial scale.

3.1 Core Aquaponic System - Hydroponics and Recirculating Aquaculture Systems (Primary)

3.1.1 Water Efficiency and Circulation

The recirculation of water within aquaponic systems enables its high degree of **water efficiency**, allowing farms to reuse nearly all of their water, typically only necessitating the replacement of water lost due to evaporation and transpiration (Forchino et al., 2017; Greenfeld et al. 2020; Tyson et al., 2011). Interviewee estimates of water reuse ranged from 90 to 100%. In alignment with literature, participants regularly stated that they just had to replace water to account for evaporation and normal losses via plants (e.g. transpiration). Several also stated that some water was removed from the system during solids removal (see section 3.1.2) or cleaning of the system on an occasional basis. To reduce the need for additional input water, it is possible to offset this by recapturing humidity within the system (Goddek et al. 2015) or rooftop rainwater harvesting (Ackerman et al., 2013). However, most interviewees did not take this approach, instead using their local municipal or well water sources to top off losses.

Classification of **aquaponic system types** includes the form of hydroponics utilized and the degree of closure of the water cycle in the system (Hao et al. 2020). Three typical hydroponics forms include Deep Water Culture (DWC), Nutrient Film Technique (NFT), and Media-Based Growing Bed (MBGB) (Goddek et al. 2015; Hao et al. 2020). Hao et al. note some of the advantages and drawbacks of each: “MBGB is space-saving but difficult to maintain and clean. DWC is easier to clean and has a higher removal rate of nitrate, but it requires extra biofilters, aeration devices, and a larger volume of water. NFT has higher efficiency for water use but lower yield” (Hao et al. 2020; Goddek et al. 2015). All of these methods were utilized by interviewees, many of which utilized multiple types of hydroponic system components in their operations, 21 or 80% made use of DWC systems, 14 or 54% utilized NFT systems, and 12 or 46% had MBGB. Additionally, seven (27%) utilized vertical growing configurations of their hydroponic components, a space saving practice with growing adoption in CEA operations. Interest in expanding to or retrofitting to NFT use was mentioned among participants as a desired pathway because it could further reduce their water use (21), while several valued MBGB as a means of fully utilizing nutrients in solids produced within the system, an approach akin to Nelson & Pade’s z-dep system.

There are varying approaches to the **degree of water circulation** between plant and fish production systems in aquaponics. Traditional systems utilize a single loop, growing both produce and fish at the same pH, nutrient concentrations, and temperature that is shared between the two systems, but often not optimal for either, creating trade-offs for the management of microorganisms, fish, and plants (Delaide et al. 2019; Goddek et al. 2015; Abusin & Mandikiana 2020). This is sometimes referred to as a “coupled” system (Hao et al. 2020; Baganz et al. 2021). To overcome associated trade-offs, the concept of decoupled aquaponics systems- which separate direct water exchange between hydroponic and aquaculture units and allow some or all water to exit the system (Hao et al. 2020) to moderate and more finely control water quality and resource content, has been advanced and implemented in some farms (Goddek et al., 2016; Goddek and Keesman, 2018; Suhl et al., 2016; Abusin & Mandikiana 2020, Hao et al. 2020). This approach requires more water input, but optimized water conditions improve produce yields (Gibbons 2020; Hao et al. 2020). However, a large majority of interviewees described their systems as coupled when asked, as most recirculated over 90% of their water between their hydroponic and RAS systems. Few, though, were familiar with the terminology of coupled and decoupled systems as utilized in literature and asked for clarification, potentially limiting the meaningfulness of their respective responses. The infrequent use of decoupled systems among interviewees may reflect their economic models shaped by current realities in which making a profit on fish sales is generally more difficult than with aquaponic produce (Horn et al. 2023). Notably, most interviewees did not sell their fish, and those that did were not utilizing it as a primary source of profit, perhaps limiting the imperative of operating aquaculture conditions beyond the sufficient wellbeing of the fish to supply a reliable nutrient source to hydroponic components, and accordingly disincentivizing retrofits from traditional single loop approaches to more decoupled models.

Estim et al. assert that **water quality management** across the production system is a necessary prerequisite for successful aquaponics outcomes, noting the need for research “to be carried out for confirming the sustainability in all its dimensions” of aquaponics “if this requires a structural design modification that envisages multi-loop decoupled arrangements for independent recirculating loops for fish and plants, and maybe for metabolic waste neutralization, through independent recirculating loops” (Estim et al. 2020). Baganz et al. 2021 add that a multiple loop system could also result from the incorporation of evaporated water recapture technologies and treatment systems, with additional loops added via remineralization steps, concentration units, and other processes. Despite self-characterization as single loop systems, interviews seemed to reflect a growing reality within North American commercial aquaponics wherein optimization steps were undertaken to improve water and nutrient conditions for better yields. Many of the systems described by the interviewed practitioners use intervening steps to optimize nutrient recovery from fish to plants, especially given the profit priority of produce sales, while generally returning water from the plants to the fish. Rather than oversimplifying into typologies or inventing new terminology to talk about processes which are largely well established in environmental engineering contexts, it is

beneficial to consider these steps through a process engineering lens. In this manner, the nutrient recovery aspect of aquaponics will be further explored in the following section.

Table 3.1: Core Aquaponic System Characteristics

ID	RAS Tank Sizes	RAS Vol. (gal.)	Hydroponic Component System Type	pH Aq	pH Hyd	Coupled or Decoupled	Use of digestion	Use of composting
1	----	----	DWC	----	----	----	N	N
2	----	----	DWC	6.5		Coupled	N	Y
3	----	----	Media Beds	6-6.5		Coupled	Y	N
4	8x 1,200 gal. 4x 400 gal. 16x 300 gal. 1x 24,000 gal.	4000 0	DWC, NFT, Media Beds	7.4		Decoupled	N	N
5	12x 800 gal.	9600	NFT, DWC, Media Beds	6-7 ("usually 6.5")		Coupled	N	N
6	----	----	NFT, DWC, Vertical	7		Coupled	N	Y
7	3x 1800 gal.	5400	DWC, Media Beds (IBC)	6.8-7		Coupled	N	Y
8	4x 4,500 gal.	1800 0	NFT, Media Beds (Bato Buckets)	----	----	Decoupled	Y	N
9	1x 1,200 gal.	1200	DWC	6.5-7		Coupled	N	N
10	12x 1,200 gal. (uses 6)	7200	DWC	6.8-7.8		Coupled	N	N
11	6x 1,500 gal.	9000	NFT, DWC, Vertical	5.8-6.5		Coupled	Y	N
12	2x 5,000 gal.	1000 0	DWC, Media Beds	6.4-6.6		Coupled	Y	Y
13	3x (2x 1500) gal. 2x150 gal.	9300	DWC	7.5		Coupled	N	Y
14	2x275 gal.	550	NFT, Media Beds	7-7.5		Coupled	N	N
15	6x 500 gal. 6x 50 gal.	3300	NFT, DWC, Media Beds	7.1		Coupled	Y	N
16	----	----	DWC, Media Beds	----	----	Coupled	N	N
17	1x 1000 gal.	1000	NFT	6.8	6.8	Decoupled	Y	N
18	2x 3000 gal. 1x 10000 gal.	1600 0	NFT, DWC, Media Beds, Vertical	8		Coupled	N	N
19	1x 2500 gal. 1x 6500 gal.	9000	DWC, Media Beds, Vertical	----	----	Coupled	Y	N
20	----	----	DWC, Vertical	----	----	Decoupled	Y	N

21	----	6,500	NFT, DWC, Vertical	"Low 6's"	"High 5's to low 6"	Decoupled	N	N
22	----	----	NFT	6.8		Coupled	Y	N
23	----	2400	DWC, NFT, Vertical, Media Beds	----	----	----	N	Y
24	2x 250 gal.	500	DWC	7	7	Coupled	N	N
25	----	----	NFT, DWC	----	----	Both	----	----
26	----	----	DWC, NFT	----	----	----	N	N

3.1.2 Nutrient Inputs and Recovery Processes in Aquaponics

Nutrient inputs, in the purest form of aquaponics, derive from fish feed and have been described as “the most important input” for aquaponics systems (Petrea et al. 2019). As a primary input to aquaponics, the sourcing and production of fish feed is a key area of sustainability concern among producers, several of whom expressed interest in optimizing the sustainability of their fish feed sources. Interests in efforts by a major fish feed producer to invest in atmospheric carbon removal as an ingredient for fish food (6) and in self-produced feed sources (6, 25) were among the potential solutions mentioned by interviewees. The importance of how to use solids from fish waste was emphasized by producers, including 26, who like many other interviewees, incorporates additional processing steps to make nutrients within the system- including in solids- more available for uptake by plants in their aquaponics systems. Fish feed composition affects the chemical composition of fish waste and conditions within the system, while the amount impacts nutrient load generation of both excreted metabolic waste and any unconsumed food waste (Estim et. al 2020). Fish feed introduced into the system is divisible “into assimilated feed, uneaten feed, and soluble and solid fish excrete” (Goddek et al. 2015; Neto et al. 2013). The soluble excreta mostly are made up of ammonia which is processed by nitrifying bacteria into nitrite and nitrate (Chen et al. 2006; Lekang & Kleppe 2000; Goddek et al. 2015). For unconsumed food and solid fish waste to be used, these need to be solubilized into ionic mineral forms which plants can assimilate (Goddek et al. 2015).

Microbes within aquaponic systems are vital to **make dissolved nutrients more bioavailable for plants**. Many commercial scale aquaponic systems make use of biofilters to help optimize this process. They are a standard component of RAS systems to maintain water quality parameters necessary for fish production (such as by facilitating denitrification), however are also very effective to process and remineralize dissolved nutrients into forms that plants in hydroponic systems can use. Solid waste is typically separated mechanically prior to biofiltration. Solids contain a minor fraction of total nutrients within aquaponics systems but contain many trace nutrients. Without additional process steps in aquaponics, solid waste is not fully recovered as soluble nutrients and is regularly settled out or filtered out mechanically (Cripps & Bergheim 2000; Goddek et al. 2015). Moreover, from 30-65% of phosphorus (P) input to RAS systems as

fish feed is lost as solid fish excreta which, along with uneaten food, comprises a significant nutrient reservoir that is removed from the system through settling or mechanical filtration systems (Neori et al. 2007; Goddek et al. 2015; Seawright et al. 1998; Schneider et al. 2005). Additionally, solubilized orthophosphate can become less available in solution, and thus less available to plants, as it can precipitate with calcium (Seawright et al. 1998; Krom et al. 2014; Goddek et al. 2015). Goddek et al. accordingly note that “aquaponic experiments report a range of 1–17 mg L⁻¹ PO₄-P” (Goddek et al. 2015; Endut et al. 2010; Lennard & Leonard 2006; Al-Hafedh et al. 2008; Villarroell et al. 2011). Concentrations recommended for hydroponics are however in the range of 40-60 mg L⁻¹ PO₄-P, suggesting a need to add or make available additional soluble phosphate for optimal plant growth (Sonneveld & Voogt 2009; Sikawa & Yakupitiyage 2010; Goddek et al. 2015). The recovery of P from RAS effluent within aquaponics systems is a means of closing the gap and optimizing system performance. These processes also help to prevent the discharge of effluent from aquaponics systems to the natural environment and lessen the pressures of filter cleaning and sludge disposal (David et al. 2021; Yogev et al. 2016). Moreover, improving nutrient recovery and water quality management can reduce the need for additional system supplements, particularly of micronutrients, a practice mentioned by ~10 of the interviewed operations (Table 3.2). To optimize operation and performance of an aquaponics system, understanding nutrient conversion and exchange between aquaculture and hydroponic components is essential (Chunjie Li et al. 2018), making the nutrient recovery processes of aquaponic operations an important determinant of environmental performance.

Although a certain degree of nutrient recovery is a core tenant of aquaponics, the potential losses of valuable nutrients in solids and need to optimize available soluble nutrients benefit from additional recovery steps to make use of nutrients derived from the system toward further productive means. Productive uses could be 1) as a fertilizer applicable outside of the core aquaponic system, such as to traditional fields on site or 2) within the aquaponics system. Various forms of these two general approaches emerged among the interviewed farms. The simpler approach to utilizing all nutrients is to remove solids for use as fertilizer in land-based traditional agriculture, akin to manure, compost, or liquid fertilizer. This was the general strategy of 17 or approximately 65% of the interviewed operations (group 1-Figure 3.3). Among these, three subgroups emerge, 6 utilized sludge removed from the system for direct use as fertilizer with no further processing after it was settled out of the system (1, 4, 10, 16, 21, 26). The second subgroup (2, 6, 7, 13, 18, 23) removed solids by settling (n=4) or mechanical filtration (n=2), and further composted the removed solids prior to utilization as fertilizer. The third subgroup (n=5) also further processed removed solids prior to use as fertilizer in external systems by mineralizing removed sludge, following the use of MBBR and/or sludge thickening steps, settling, or mechanical filtration steps (8, 11, 19, 20, 22).

Introducing remineralization processes, which close nutrient loops in the system by processing solid wastes into soluble forms that plant can assimilate, is an emerging technical solution (Goddek et al., 2016; Goddek et al., 2018; Yogev et al., 2016; Abusin & Mandikiana 2020). This makes use of processes and technologies established in environmental engineering, in

particular resembling wastewater treatment for a different aim, making nutrients bioavailable in solution instead of removing them. Digestion processes- aerobic, anaerobic, or in alternating cycles- are a key means of achieving this.

One approach is through sludge digestion, especially with P-solubilizing microorganisms to make leachate with accessible nutrients for uptake by plants and contribute to better produce yields (Emerenciano et al., 2017; Goddek et al., 2018; Abusin & Mandikiana 2020; Goddek et al. 2015). This can be facilitated by technologies such as biodigesters and bioreactors (Khiari et al., 2020; David et al. 2021; Wu & Song 2021; Reyes-Lúa et al. 2021), which can be generally referred to as mineralization tanks. These were also utilized by several (n=3) of the operations in group 2 (3, 12, 17), who reused solids entirely within their aquaponic systems (Figure 3.3- group 2). Another three circumvented the need to completely remineralize solids by incorporating living/media bed systems (5, 9, 14), while one system combined both approaches by utilizing mineralized nutrients as an input source for flood and drain style media beds (15). While general trends are reflected by these subgroups, all operations represent individualized set sub-processes (see process diagrams in Figure 3.3) designed to meet their water quality and nutrient recovery needs, often within an ongoing effort to further optimize the core aquaponic system as resources allow.

All but one small, interviewed operation (which is excluded from Figure 3.3), who disposed of excess solids to the sewer during cleaning, made further use of all nutrients generated in the system in some manner. Most (n=23) of the operations reused nutrients from solids on site, either within their aquaponic systems and/or for application to soil based crops. Only three operations did not use nutrients from solids on site. Besides the farm that disposed of theirs, another two produced fertilizer that was not used on site, all three were smaller than 15,000 sq ft. Reuse of all nutrients on site, whether or not within hydroponic production, represents a certain degree of localized circular economy of nutrient use. Notably, all operations that had additional agricultural activities on site (primarily field agriculture, some livestock or regenerative agriculture) utilized nutrients from solids on their property. Interestingly though, all operations in group 2, which were reusing and processing solids within their aquaponic system were started in 2014 or later: 4 in 2014, 1 in 2017, and all 3 from 2018 (*which are the newest operations in the group; in comparison, the oldest case study of the full group of n=26 dates to 2006). This may reflect recent increases in the availability of technology and informational resources relating to nutrient recovery technologies for aquaponics. Approaches to the end-use of solids by aquaponics operations may also reflect location and climate factors. Interestingly, all operations which reuse and recover all nutrients from solids within their aquaponics system are in hardiness zones 7a-10a only, though no pattern emerges for operations producing fertilizer. Perhaps reflecting a similar correlation, an intriguing pattern emerges around regionality of solids reuse wherein operations in the west and south census regions encompass all examples using reuse *in system* and other regions where interviews were conducted do not contain operations using reuse within system (US Midwest, US Northeast, Canada), this regional pattern seems to be in-line with the observation of hardiness zone

correlation above. This may reflect limitations or incentives to repurpose nutrients from solids within the core aquaponic system in different climates, or, particularly noting the consistent reuse practices among operations located in warmer climate zones, may reflect concern for water efficiency.

Table 3.2- Inputs and Outputs of Core Aquaponics System

ID	INPUTS				OUTPUTS								
	Water	Nutrients & Supplements			Fish			Plants		Fish Wastes			
	% water recirculated	Supplementation (Y/N)	System Supplements	Fish Feed	Fish Raised (Type)	Quantity (if known)	Sold (Y/N)	Produce Grown	Quantity	End-use of solids	On site	Sold	Specific use
1	----	----	----	----	Yellow Perch	4,000/Yr.	Y	Lettuce, Kale	----	Fertilizer	Y	N	Yard Fertilizer
2	----	Y	Iron (Norwegian Seaweed Foliar Spray)	Aquamax (by Purina)	Tilapia	----	Y	Basil	----	Fertilizer	Y	N	Row Crops
3	99-100%	Y	----	Optimal	Tilapia	----	Y	Living Herbs, Living Lettuce	----	Used in System	Y	N	Hydroponic Component
4	----	Y	Epson salts (for Mg), Calcium, Citric Acid, NH3, others implied	----	Tilapia, Catfish, koi, bass, bluegill	----	Y	Lettuce	6,000 Heads / Wk.	Fertilizer	Y	N	Field Crops (Blackberries)
5	90% recirculated - 10% to MB	N	N/A	----	Tilapia	500 Fish / Mo.	Y	Lettuce	4,900 Heads / Wk.	Used in System	Y	N	Living Beds
6	----	N	N/A	Aquastar /Lake Paris, water lettuce, duckweed	Tilapia	1000 / Yr.	Y	Basil, Lettuce	30,000 - 40,000 Heads / Mo.	Fertilizer	----	----	----
7	99-100%	Y	----	----	Tilapia	N/A	N	Lettuce, Bok Choy, Swiss Chard	----	Fertilizer	Y	N	Compost

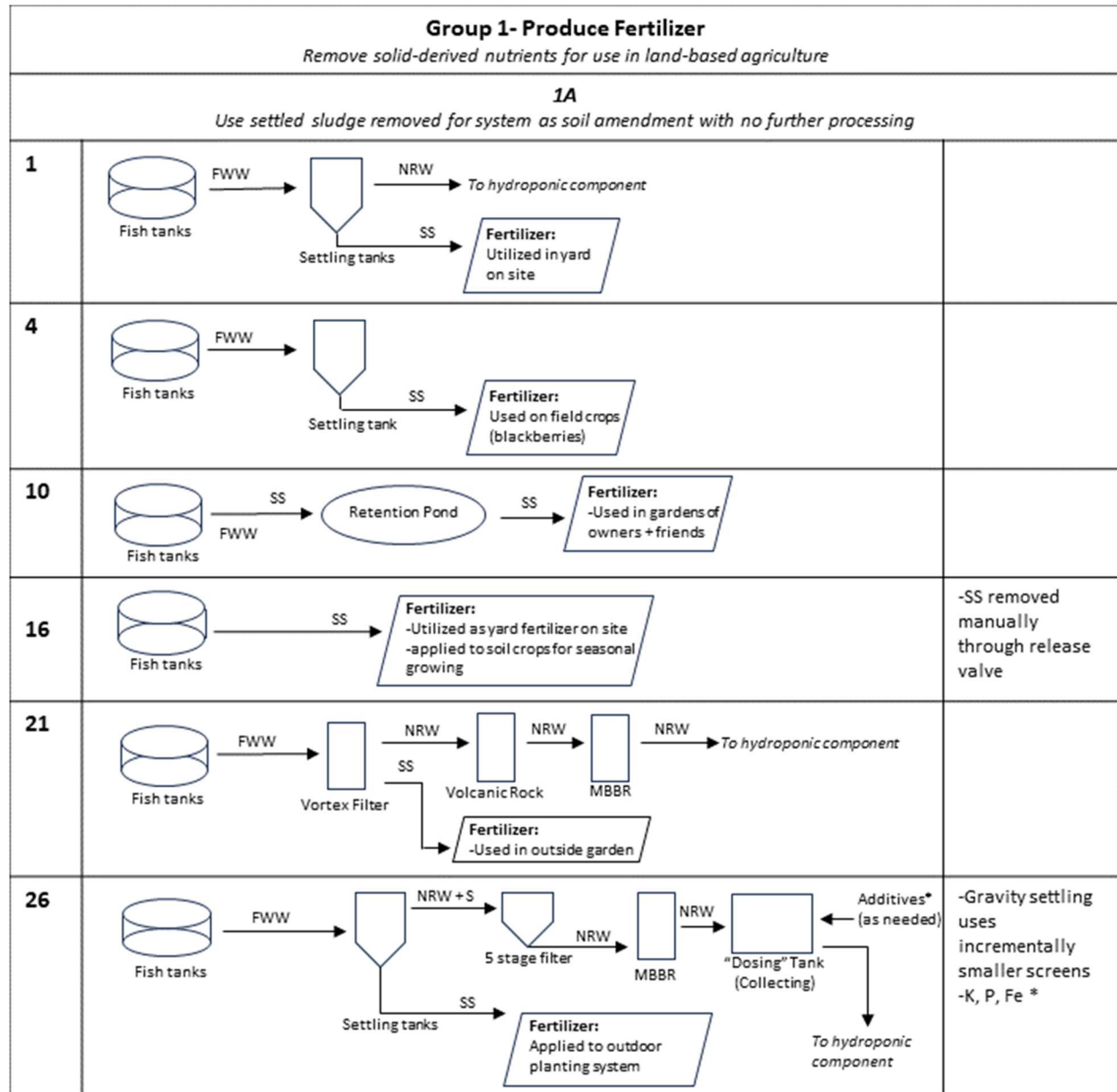
8	----	Y	----	"corn and soy free non-GMO food"	Tilapia	N/A	N	Mixed Greens, Basil, Cucumber, Microgreens, Tomatoes	----	Fertilizer	Y	Y	Used in orchard and vineyard; sold to customers
9	99-100%	Y	Chelated Iron, Mangeseum Sulfate, Oyster shells (for pH), Kelp	Perpetu-ATE by Perpetual Food Company	Tilapia, Goldfish	N/A	N	Lettuce, Garlic Chives	----	Used in System	Y	N	To media bucket system (tomatoes)
10	99%	N	N/A	Optimal	Tilapia Blue Gill Prawns Crawfish	approx. 3600 fish total	Y	Leafy Greens, Lettuce, Herbs, Spices, Hemp starters (previously), Flowers (incl. water hyacinth, sunflowers), Peppers (bell, habanero, jalapeños)	12,000 heads lettuce/Mo.	Fertilizer	Y	N	Garden use
11	99%	Y	Foliar Sprays (for micronutrients)	Skretting? ("based put of Utah")	Tilapia, Barramundi*, Crawfish Fresh water Lobster	N/A	N	Leafy greens, herbs, oyster, king and shiitake mushrooms, Hemp		Fertilizer	N	Y	(Planned) sale to customers as compost tea
12	99%	N	----	Optimal / Aquaponic specific feed	Rainbow Trout, Koi	Yes they sell fish	Y	Lettuce	2,000-4,000 units/Wk.	Used in System; Fertilizer	Y	Y	Used in hydroponic until vermicomposted for on-site use; sold as liquid and solid fertilizer

13	90%	N	----	----	Tilapia	----	Y	Leafy Greens (12 varieties), celery, Green onions, onions, tomatoes, cucumbers, kale, Swiss chard, edible flowers	10,000 heads/Wk.	Fertilizer	Y	N	Used on cover and experimental crops fed to animals on farm
14	----	----	----		Koi, Goldfish	N/A	N	Leafy Greens	----	Used in System	Y	N	Vermiculture within system (red wigglers)
15	100%*	N	----	Purina	Tilapia	Yes they sell fish	Y	Lettuce (butterhead, romaine), mint, tomatoes, Swiss chard, rosemary	----	Used in System	Y	N	Used in media beds
16	----	----	----	----	Tilapia	N/A	N	Kale, Butterhead Lettuce	250 Heads / Wk.	Fertilizer	Y	N	Yard Fertilizer; Soil Crops
17	----	Y	Kelp Powder (micronutrients, K, Mg); Chelated Iron	----	Koi, Goldfish, Bluegill	280 in system	N	Leafy Greens	----	Used in System; Fertilizer	Y	N	Excess NRW used in outside garden
18	100%	----	----	Sporting fish food (28%prot.)	Goldfish	N/A	N	Cut flowers(dahlias + others), Live Plants, leafy greens	----	Fertilizer	Y	N	On field crops, used to grow potted plants for sale
19	99%	----	----	Zigglers, Purina (Aquamax 400)	Tilapia, Red Claw Crayfish, Freshwater Prawns	7000 total (fish)	Y	Produce including lettuce, cucumbers, garlic, celery, onions, Bok Choy	----	Fertilizer	Y	N	Field Crops (Alfalfa)
20	99.90%	Y	Limited micronutrients (organic)	"Organic, non-GMO fishmeal	Atlantic Salmon,	~400/week	Y	Leafy greens	>3 million	Fertilizer	Y	N	Regenerative Agriculture

				and fish oil"					pounds/year*				
21	----	Y	Kelp Powder	----	Tilapia	N/A	N	7 var. lettuce, microgreens, Sprouts. beet greens, Swiss chard, red veined sorrel, kale	----	Fertilizer	Y	N	Outside Garden
22	98.00%	Y	calcium hydroxide, potassium, hydroxide, phosphoric acid, iron, Multivitamin, kelp	Purina	Tilapia	N/A	N	Kale, chard, lettuce, tomatoes, peppers, eggplant, okra, herbs, collard greens	----	Fertilizer	Y	N	Field crops, high-tunnel soil crops
23	98%	----	----	----	Koi, Rainbow trout	N/A	N	Lettuce, Kale	----	Fertilizer	T	N	Soil crops in green house
24	100%	Y	Chelated Iron	Aquamax (by Purina)	Yellow Perch	800 total	N	Lettuce, leafy greens, micro greens	----	Disposed	N	N/A	To sewer
25	----	N	----	Local Companies & produce their own	Tilapia, Brine Shrimp, trout	30 Tons tilapia 10 Tons Brine Shrimp	Y	Basil, Lettuce, chard	1500/week basil	Used in System	Y	N	----
26	----	Y	chelated iron	----	Hybird Striped Bass	----	Y	Leafy Greens, Herbs, beets, radish, carrots (+31 vegetable varieties)	----	Fertilizer	Y	N	Used on outdoor planting ("heavy" solids only)

Figure 3.3- Engineered Process Analysis: Nutrient Reuse and Recovery Processes of Interviewed Operations

FWW- Fish Wastewater; MBBR- moving bed biofilm reactor; NRW- Nutrient Rich Water; S- solids; SS- settled sludge.
 *Solids collected/ removed from hydroponic units (e.g. roots) not depicted



1B <i>Compost solids collected via settling or mechanical filtration prior to use as fertilizer</i>		
2	<p>Fish tanks → Screening → NRW → Wet-Dry Filter → NRW → To hydroponic component Screening → Screened Solids → Traditional Composting → Compost → Fertilizer: Used on row crops</p>	<p>-Described aquarium hobby based Japanese wet-dry filter utilizing lava rock in a partially submerged bag</p>
6	<p>Fish tanks → FWW → Settling tanks → NRW → Biofiltration → NRW → To hydroponic component Settling tanks → SS → Rotary Drum Filter → Thickened Sludge → Vermicomposting → Fertilizer: Planned use unspecified</p>	
7	<p>Fish tanks → SS → Traditional Composting → Fertilizer: Planned use on farm for soil crops</p>	
13	<p>Fish tanks → FWW → Filter tank → NRW → To hydroponic component Filter tank → S → Wicking Compost Beds → Compost → Fertilizer: Used on cover and experimental crops Compost → Yield fed to animals on farm</p>	
18	<p>Fish tanks → SS → Dilution tank → NRW → Fertilizer: -Used in traditional field agriculture -Used to grow potted live plants sold commercially</p>	<p>-soil-grown plants sold to customers so they can be planted, were in demand</p>
23	<p>Fish tanks → SS → Traditional Composting → Fertilizer: Applied to soil crops in greenhouse</p>	<p>-solids removed manually</p>

1C

Further process removed solids for use as fertilizer via mineralization steps

<p>8</p>		<p>-MBBR: interviewee described two 1,000 gal tanks with 9 in air stones in each</p>
<p>11</p>		<p>~500 gal underground holding tank (aerated)</p>
<p>19</p>		
<p>20</p>		<p>-Specific filtration systems and additional process details largely unspecified in available sources -*presumed</p>
<p>22</p>		

<p align="center">Group 2- Reuse within System <i>Use solid-derived nutrients within aquaponics system</i></p>		
<p align="center">2A <i>Use mineralization steps in processing</i></p>		
3		<ul style="list-style-type: none"> -Min. tank runs on 5 days aerobic, 2 days anaerobic cycle -Bag Filter is a fabric filter
12		<ul style="list-style-type: none"> -Mineralization tank is aerobic -Dried fertilizer price shared as 20\$/lb. or 5\$ for small bags (vol. unspecified)
17		
<p align="center">2B <i>Use living bed/media bed systems to make use of nutrients from solids within system</i></p>		
5		<ul style="list-style-type: none"> -Static biofilter composed of fishnets as bacterial surface
9		<ul style="list-style-type: none"> *interviewee described minimized solids due to fish food choice
14		<ul style="list-style-type: none"> -vermiculture within coupled system
<p align="center">2C <i>Combined both in flood-drain style media beds</i></p>		
15		<ul style="list-style-type: none"> -sprinkler system utilized to distribute to flood + drain style media beds

3.2 Infrastructure of Controlled Environment Agriculture (Secondary)

3.2.1 - Physical Infrastructure

In most climates, and to facilitate CEA conditions for commercial aquaponics, some form of structure or enclosure is needed to maintain appropriate growing conditions (Proksch et al. 2019). Among interviewed farms, enclosures varied from (1) simple hoop house style greenhouses to custom DIY variations (used by ten operations), indoor (used by two: one small (24) + one warehouse (3)), medium to high tech variants of film (used by three) or glass or other material new greenhouses (used by nine), two additional high-tech variants, and two passive solar approaches (8+23). The enclosures and necessary growing infrastructure comprise embodied material inputs to these aquaponic farms, including structural materials like steel or aluminum, glazing composed of glass or plastic variants, electrical components, shade materials, concrete and more (interviews). The lifespan of materials used varies, and several interviewees discussed material degradation issues due to exposure to sun and water (9). It was noted that materials associated with higher performance and lifespan also required higher investment, and some operators mentioned the barriers of high concrete and steel costs, particularly during the COVID-19 pandemic period (4).

3.2.2 Operational Inputs: CEA and Power

In keeping with infrastructure and technology needs for CEA, several LCA studies of aquaponics have indicated that its primary environmental issues pertain to high electricity demand and significant infrastructure and equipment needs (Forchino et al., 2017; Maucieri et al., 2018; Chen et al., 2020; David et al. 2021). Aspects of CEA such as the control of light and nutrient availability possible in greenhouses can be a potential source of increase to electricity demand (Reyes-Lúa et al. 2021). Operational demands described by interviewees include air circulation, lighting, air and water heating and cooling. Air circulation strategies utilized by the operations included mechanical and passive means, with fans mentioned by (1, 3, 4, 5, 8, 13, 14, 15, 18, 19, 22), both automatic and manual venting strategies by (1, 4, 5, 7, 9, 11, 15, 16, 22), and an additional passive strategy to help plants utilizing CO₂ from mushroom co-production (11). Use of supplemental lighting varied among interviewed operations, some primarily relied on natural lighting (1, 12, 16), while many, including (10, 18, 21) used LED lights, or wanted to improve or replace lights (1,8). Among those who didn't use LED lights beyond the germination room, a concern that held them back from broad use of LEDs was the potential of light pollution to the surrounding area (12). While some did not utilize heating (12), others had both air and water heaters (4, 21), or boiler heating such as (19). Some expressed the need for the addition of more heating (18). Water heating and cooling needs varied, with some, such as (4) using both. Some operations like (5) mentioned that an electric water heater had been insufficient, so they utilized a pool exchanger to heat or chill water as needed. Others used water chillers only in harvest tanks (15). When it came to keeping growing areas cool, evaporative cooling systems

were a popular strategy, mentioned by farms including (7, 9, 11, 12, 13, 23). Some just relied on air circulation with fans to help maintain sufficient indoor temperatures during the summer.

Optimization of energy use in aquaponics is impacted by location, system design and efficiency, and use of clean energy sources and integration measures. The model simulations of Goddek and Körner 2019 revealed that availability of energy is important to maintaining consistency of greenhouse conditions as “external seasonal light and temperature fluctuations have a direct impact on the system's energy input in order to grow food efficiently” (Goddek and Körner 2019). Securing appropriate water temperatures, filtration, oxygenation, circulation, and growing conditions requires input of energy, for which Danish et al. 2021 assert “clean and green power supply remains the core of the entire operation.” Aquaponics can be integrated with renewable and clean energy resources including solar power, wind, and biogas (Joyce et al. 2019; De Graaf and Goddek, 2019; Delaide et al., 2019; Abusin & Mandikiana 2020; Chen et al. 2020). However, as aquaponics thus can be very dependent on electricity, and despite sustainability ideals and potential- including the widely published potential to integrate with renewable power sources- in reality this energy input can also be comprised of non-renewable sources to support growing conditions (Baganz et al., 2020) and therefore the actual use of clean energy sources in operating commercial aquaponics farms interviewed did not consistently meet envisioned sustainability standards yet (interviews). For heating, natural gas heaters were a common approach, used by operations including (3, 6, 11, 15). Another widely used approach was propane heating systems, including (6, 8, 9, 16, 17, 18). Another operation expressed that the use of a wood-coal burning system (1) with a heat exchanger had been a great operational cost saving decision. Still, promise for the further sustainable development of the industry was evident throughout the interviews. Use of efficient technologies and clean energy sources not only has potential to improve environmental sustainability of aquaponics, but also economic sustainability, feasibility, and competitiveness, which is vital component for successful commercial aquaponics and thus a necessary prerequisite for optimal environmental performance, proliferation of the industry, and the potential sustainability outcomes which could stem from broader practice of aquaponics (Love et al. 2014; Petrea et al. 2019). Some interviewees mentioned interest in forming partnerships or experimenting with sustainable energy (21) and were utilizing or considering methods including geothermal, solar, and biomass-based heating and/or energy systems. One farm (7) currently uses a geothermal system, and another was enthusiastically planning a move to a property with geothermal heat (2), while others wanted to try geothermal systems (6, 12). When it came to solar, one farm was using a solar power and battery storage system (21), another supplemental solar panels (17), while two others wanted to implement solar energy or heating systems (22, 11). One of these (11) had tried to do so in the past but found regulations to be a barrier. Biomass and biofuel heating and energy systems were discussed by several participants, potentially reflecting a broader trend among agricultural industries, or the nature of questions in the interview pertaining to nutrient recovery processes. Interest in installing a biodigester (6), adding a compost heat system (17), actively setting up a heating composting system (21) and current use of one (23) were discussed. Another operator wanted to switch to a woodchip

boiler system instead of propane (4). One was currently using a wood boiler for radiant floor heating (8), but another operator using wood harvested on site in a wood furnace (10) was finding it to be costly and time consuming. Furthermore, use of electricity on site, when grid connected, like (21), which was typical, can benefit from potential broader shifts to renewable energy within public utilities. For instance, one operation (6) was benefitting from a neighboring landfill that generated electricity running through their property, and others (2) had sought similar arrangements.

3.2.3 Energy Efficiency Measures

Advances in technology are allowing aquaponics operations to progress toward energy efficiency and use of renewable energy to reduce carbon impacts from necessary use of filtration, pumps, heating, and cooling systems (Joyce et al. 2019). Means of optimizing the efficiency and use of heat and energy can include thermal energy storage solutions, heat pumps, combined heat and power units, decision support systems, use of LEDs, and model-based climate control systems (Reyes-Lúa et al. 2021; Baganz et al. 2021b; Cuce et al., 2016; Gruda et al., 2019; Körner et al. 2021; Petrea et al. 2019). Körner et al. 2021 further describe that “modern and highly insulated greenhouse systems have greatly reduced the environmental impact of fossil energy consumption” (Körner et al. 2021; Cuce et al., 2016). The overall heat requirement of an aquaponics system depends on its design (Reyes-Lúa et al. 2021). A component of this is that heat demand for RAS water heating varies relative to the recirculation of water and degree and directness of integration between hydroponic and aquaculture components (Reyes-Lúa et al. 2021). Additional heat is also needed if a distillation step is used to adjust nutrient concentrations (Goddek et al. 2019; Reyes-Lúa et al. 2021). Seasonal heat demand can vary, depending on water source and whether both water and space heating are required; these demands can both be larger in the winter and lower in warmer seasons depending on outside temperature conditions (Reyes-Lúa et al. 2021). Overall, for both RAS and greenhouses, “heating requirements are tightly determined by the outside temperature, which is more or less cyclical” (Reyes-Lúa et al. 2021). Interviewees described several energy efficiency considerations which impacted their operations. Whether fish and plants were kept within the same space impacted indoor environmental regulation needs, as often there are different temperature ideals for each production subsystem (2, 15, 17, 22), several interviewees expressed that there were advantages to separating the two to better facilitate growing environments and reduce energy demands to each. Fish species selection plays a big role in determining water heating and cooling needs, and was commonly mentioned as a factor in heating, cooling, and related energy use decisions. For example, one operation (1) uses yellow perch so they don’t have to heat water, while another who (2) raises tilapia expressed that “our greatest expense next to labor is heating cost” and separate fish in another room to let them be warmer and save money. Taking a different approach to this dilemma, another (12) chose a fish that allowed them to not to heat or cool water because it wouldn’t be cost effective for them to do so. Several chose fish types for this reason, even if it also meant they could not utilize fish as an income source, including (14) who raises koi and goldfish

because they're resilient to the extreme heat and cold, tanks have frozen before and they didn't lose fish, another operation (18) also raises goldfish for this reason. While some operations raised tropical species, because they found it easier to only have to heat water in winter but not have to cool it in the summer (21), others instead opted to cool water for species like rainbow trout (23). Water itself, when tanks are kept in the greenhouse, acted for several operations as a thermal mass to retain heat or cold respectively from day to night and regulate overall inside temperatures (2, 13). An additional passive cooling strategy is to lower systems further into the ground (14), which one farm was pursuing by digging trenches and lowering their system by 5 ft. Several interviewees also expressed that automation of various subsystems to maintain good growing conditions can be useful and help with energy efficiency (4, 7, 8, 10, 12, 18, 24) but can sometimes be unreliable (2, 5, 6).

3.3 Integrative Context, Climate, and Regional Factors (Tertiary + Quaternary)

The location of an aquaponics farm plays a significant role in determining how sustainable it is in context, with local climate and grid energy supply comprising two notable factors of place-based variability. Selection of a fitting location is considered an important condition, moreover, as aquaponics systems advantageously manage agricultural waste, it has been suggested that producing food with aquaponics is an ideal fit in locations where there are notable costs of nutrient emission and waste disposal (Monsees et al., 2017; Abusin & Mandikiana 2020). Aquaponics systems are highly adaptable to different environments, with the ability to address place-based challenges such as poor soil quality, water scarcity, and extremes of climate (Danish et al. 2021; Chunjie Li et al. 2018). Chunjie Li et al. noted locations where aquaponics fills a necessary niche for food production including arid regions, low-lying islands, and cities (Chunjie Li et al. 2018). Depending on the location, "different measures are needed in order to ensure that each system will have a suitable sustainable energy source all year round to provide stable conditions for fish and plants" (Goddek et al. 2015). In this vein, integrative context, location, and climate play a key role in shaping what infrastructural and operational decisions are most environmentally sustainable for a given commercial aquaponic operation. Some of the interviewed operations faced more challenges than others due to their local climate, including several (4,6,18) that had temperature swings with both significant high and low temperatures; some were challenged by winter storms and extreme temperatures (1, 21); several were challenged by humidity with heat (5,13,14) and with cold (6,16) impacting growing and nurturing mildew or frost respectively. Local land availability, land type, and land use restrictions also play a role in the commercial viability and environmental parameters of aquaponic production. One of the interviewed farms was closing because the land they were renting had been purchased (6), noting that land was becoming generally more difficult to access as cities expand into surrounding farmlands, and restrictions caused by zoning laws preventing agriculture in commercial zones in their region. They also noted growing motivations to move growing indoors, and into repurposed spaces, particularly in urban regions, expressing "I think that... we're going to be taking old buildings and taking

warehouses... and turning them into farms... [and] utilizing space, along rivers, waterways... a lot of great places where food can be grown [in] brown spaces” (6).

Innovation around space use and resource integration to deepen the environmental performance and sustainability of commercial aquaponics has been discussed frequently in literature, is being advanced in practice, and was mentioned by several practitioners in the interviews. These types of approaches can also help make aquaponics more viable in places with challenging climates for growing, for instance by combining combined heat and power units with waste heat resources like agricultural biogas to heat or cool growing spaces when the external climate is unfavorable (Goddek et al. 2015). Similar concepts have been considered for resource integration with other food industries e.g. breweries (Horn and Proksch 2020), urban resources (Baganz et al. 2020), and other typologies. A few potential resource integration pairings were mentioned by interviewees, including partnering with a lumber mill to use excess heat to heat water, heat from commercial composting operations, heat from compressors in commercial refrigeration facilities, or digester byproducts dairy, biogas plants, and/or landfill gas (2). The aquaponics operation of the primary interviewee that had considered these resource pairings had previously tried to form a partnership with a nearby landfill and run on landfill gas via a bio generator (2) as an energy pairing, but it unfortunately did not pan out due to landfill management’s concerns about the scale match of resources and the youth of aquaponics industry. Other forms of resource sharing were also discussed including interest in creating sharing economies, such as a van share system among multiple businesses (14) and allowing greenhouse growing spaces to be rented to multiple growers that could all then access byproduct nutrients created by fish production on site (17).

4.0 Discussion

Although the potential environmental sustainability of aquaponics is well described, the degree of realization of environmental performance in applied operational context has been less well established thus far. This investigation takes an introductory step to gauge current gaps between known theoretical potential and observed recent operational practices through the lens of interviewees running commercial aquaponic farms in North America. Documentation and analysis of the operational practices and system processes of a cross-sectional range of real commercial aquaponic systems in this manner has been previously underexplored despite the vitality of applied operational and qualitative data to support intended environmental sustainability outcomes. While literature is not necessarily overstating environmental potential, there is also a need to recognize that current manifestations of commercial aquaponics are not yet in full alignment with the ideals of multi-resource circularity often espoused in discussion of aquaponics. Though there is an unsurprising need for further technological innovation and cost-reduction measures, access hurdles to existing innovations and potential resource integration opportunities and organizational barriers, exacerbated by the inherent complexity of these systems, largely define the current gap between potential and observed practices. Some of these are highlighted through the system model analytical framework in Table 3.3.

4.1 Core Aquaponic System

At the primary level of a commercial aquaponics system- the core aquaponics system- there is necessary nuance to water recovery and nutrient recovery which motivates intermediary processes when scaling up aquaponics systems to commercial production scale. The gap identified within this work aligns strongly with view expressed in Estim et al. 2020, which stressed the importance of nutrient recovery and bioavailability of nutrients in aquaponics, explaining that as both profitability and “operational convenience” impact the adoption and success of commercial aquaponics “it is pertinent to invest more research efforts in multi-loop designs of aquaponic systems and to quantitatively evaluate the gains in terms of production efficiency (economic aspect), nutrient cascading and water conservation (environmental compatibility) and harvest quality (consumer interest)” (Estim et al. 2020).

4.2 CEA Built and Operational Infrastructure

Moreover, at the secondary level- CEA system and infrastructure- cost was the primary barrier to further environmental optimization in applied context. Interviewees expressed the reality that CEA and building high performing greenhouses is expensive (18, 19, 4, 8, 12, 14); though some (18,19) were actively planning to build more and considering upgrading their systems (2, 18). Solutions to improve CEA technology and access stand to benefit from advances in other sectors. As high performing CEA for aquaponics can call for considerable physical and technological infrastructure, and the power and heat needed to operate it, efforts to increase energy efficiency whilst also turning to renewable energy resources are indispensable to optimal environmental performance of commercial aquaponics. It is critical to note that most commercial operations interviewed were not yet utilizing renewable resources for heat and power, though there was a marked interest and movement toward doing so among the practitioners. The discrepancy between sustainable potential discussed in literature and observed practices is an important reminder to researchers of aquaponics, and of technologies with similar environmental aims, that although such technologies could be rendered more sustainable by fulfilling power needs with renewable sources, one should not assume that this will automatically be the case in practice. As such, proactive efforts to both reduce energy demands through design and ease access to both grid level and decentralized renewable energy resources must be pursued in concert with the development of the commercial aquaponics industry.

Table 3.3- Gaps for further exploration between potential and observed environmental sustainability practices in North American Commercial Aquaponics

System Level	Sustainability potential	Observed recent operational practices	Potential ways to bridge the gap
<i>Primary- Core Aquaponic System</i>	-Water can be recaptured to offset evaporation losses or harvested from	-Farms currently replace losses using municipal or well sources	-Further investigation is needed of the viability and cost-benefits of evaporation recovery technologies for

	rooftop rainwater collection		commercial aquaponic production in a variety of climates
	-Decoupled + multi loop systems optimize growing conditions for fish and plants respectively	-Most operators used fully coupled systems; many did not focus on selling fish	-Environmental implications of selling both fish and produce or just produce vs. running more complex vs. simple aquaponics systems should be assessed
	-Reuse of nutrients in system is optimized, this prevents discharge to the natural environment	-Most operations did not optimize nutrient recovery and technology application and use of nutrients recovered from solids do not align. Many operations utilize nutrients from solids for land-based agriculture, but some reuse all within the system by adopting additional technical recovery processes	Further investigation of recovery process efficiency and economic drivers thereof may add greater clarity to a nuanced aspect of process decision, which varies under disparate goals, climate, business models
Secondary-CEA	-An advantage of CEA is that growing parameters can be optimally regulated	-Not all commercial aquaponic farms control for all the factors	-Technology and infrastructure costs can form a barrier, as well as inconsistent performance results of automated systems. These may be addressed through further innovation and improved dissemination of best practices.
	-The physical infrastructure of CEA for aquaponics contributes to an embodied carbon footprint, but still seems worthwhile	-Operators are primarily considering cost, performance, and lifespan of materials and are not yet able to weigh carbon footprint heavily in materials selection due to economic constraints	-Commercial aquaponics can benefit from the growing development and expertise of built environment disciplines in materials assessment and energy efficiency modeling to reduce embodied carbon in design decisions. Interdisciplinary collaboration should be expanded.
	-Electricity and operational infrastructure needs can be met with renewable power sources	-Many commercial aquaponics farms were using natural gas and propane, a few were foraying into renewables, and more were interested but held back by cost and access barriers.	-Further efforts to lower the price and regulatory ease of access to decentralized renewable energy technologies are needed, as well as additional research and development of energy efficiency measures.
Tertiary-Integrative Context	-Resource integration with other industries or resource flows can be beneficial and is technologically possible	-Interest in these approaches is growing, but they haven't taken off yet within the North American commercial aquaponics industry	-Analysis of existing and nascent industrial symbiosis partnerships with food production industries, including aquaponics and related growing methods, and research on organizational barriers to symbiotic resource sharing is needed.

<i>Quaternary-</i> Location + Region	-Aquaponics can benefit food systems with locations in proximities to cities	-Land use regulations can be a barrier and limit potential sites for aquaponics.	-Further efforts to educate policymakers and planners about commercial aquaponics are needed.
--	--	--	---

4.3 Integrative Context

Among the potential solutions and innovations to improve energy and operational efficiency of commercial aquaponics is symbiotic resource sharing and exchanges, a sustainable performance modifier at the tertiary level of integrative context. This is something that can be pursued at building, urban, or industrial scales, and has been discussed and preliminarily explored in literature as a promising avenue for deepened resource circularity, including by the authors, but has yet to be significantly implemented within a North American context. Moreover, the added complexity of further resource integration is not without consequence to feasibility. There is still much to be researched and understood about the viability of the new realm of industrial symbiosis processes with controlled environment food production systems like aquaponics. The recent developments of such typologies in northern Europe may serve as valuable early examples and offer insights into possibilities and barriers. Organizational and political barriers appear to play a key role in hindering the development of commercial aquaponics and related variants of resource integrated symbioses and merit further assessment. The availability of land itself for aquaponic operations can form a hindrance, while location plays a key role in defining the climatic and regional factors that moderate what environmental sustainability looks like for a given application of aquaponic production.

4.4 Future Research Directions

Further analyses, particularly attempts to calculate and model the environmental sustainability of aquaponics, should accordingly seek to holistically factor in the role of locationally and regionally determined factors like climate in moderating environmental performance parameters. Similar work should take the pulse of the commercial aquaponics industry on a recurrent basis, noting the ongoing development and shifts that shape a dynamic industry. There are likely to be further developments since the study period considered in this investigation, a noted limitation, and it would be valuable to continually reevaluate how gaps between theoretical potential and applied practice shift over time. An additional potential limitation to note is that this investigation has intentionally focused solely on environmental aspects of sustainability, and thus cannot fully speak to more holistic sustainability alone and should be considered in conjunction with existing work on economic factors and dimensions of social sustainability in aquaponics which are invaluable to the potential contributions of the larger field to crucial global sustainability objectives. Further research can also benefit from considering other study regions where findings are likely to reflect a somewhat different reality. Ultimately there is likely to be a vital ongoing need for research on the applied implementation of aquaponics, especially as some initial economic challenges (even some interviewed farms have since closed) could hinder the development of a potentially crucial industry to sustainable

and resilient food systems. Large scale societal environmental, economic, and political drivers for CEA, and particularly aquaponic production (Horn et al. 2023), are highly likely to increase in strength over coming years. To truncate the growth of commercial aquaponics in the face of immediate economic conditions alone and not invest in promising ventures and seek to troubleshoot performance gaps between theoretical potential and the present reality would be shortsighted indeed. Intentional efforts to identify and dismantle barriers can benefit greatly from interdisciplinary, and vitally, transdisciplinary research and communication efforts to build valuable understanding, generate collaborative insights, and fully operationalize the environmental sustainability potential of aquaponics.

5.0 Conclusions

This work has analyzed the recent technical and operational environmental practices of commercial aquaponics in North America, comparing the current alignment of practice with potential sustainability outcomes as expressed in literature. A mixed-methods approach combined literature review, case study system process analysis, and content analysis of qualitative data from semi-structured interviews (n=26) with a representative sub-section of commercial aquaponics practitioners in North America. Findings brought to light the recent status of implementation of environmental resource use efficiency measures within commercial aquaponic production in North America and identified areas of opportunity for further research and innovation to support the applied success of environmental sustainability within commercial aquaponics. An analytical framework was shaped by the development of a system model of commercial aquaponics which delineates the interactions of the primary, or core elements of aquaponics systems, secondary CEA infrastructure, tertiary integration context, and quaternary location and regional context, which all interact with one another and shape what environmental performance looks like for a given commercial aquaponic system (see Figure 3.1). This novel differentiation supports more specific discussion of commercial aquaponic systems and allows for analysis which considers how intrinsic a given process within commercial aquaponics is to aquaponics itself and better identification of where there are technological overlaps with other industries and processes that can be bolstered by synergetic innovation. Particularly noting these overlaps, a process engineering lens is valuable to the analysis of aquaponic systems and could be used more often among aquaponics research efforts. It is useful to consider aquaponics, especially when adapted to commercial scale, as a series of processes and nested system components, many of which contain integrated biological systems, and in this regard little in aquaponic systems is wholly unshared with other industries. Innovation opportunities are thus forestalled unnecessarily when knowledge and engineering approaches are siloed without cause. While noting that systems integration itself and operation of aquaponics is a unique expertise, viewing aquaponics in a void, e.g. as an entirely new set of technologies, could shape consequential inefficiencies. Technological overlaps with other systems including different forms of CEA, hydroponics, aquaculture, wastewater treatment, engineering, microbiology, and the built environment disciplines, can ultimately provide a net-benefit and advantage to the sustainable development of commercial

aquaponics. Indeed, closing the gaps observed in this paper calls for innovation, research, and advocacy to improve technologies, lower costs, and advance successful implementation, wherein there are numerous opportunities to leverage the many overlaps of aquaponics with other industries and technologies, and much promise to materialize potential environmental sustainability outcomes to their full potential.

6. Funding

NSF- Project CITYFOOD.; Future Earth- Resource Recovery in the Food-Water-Energy Nexus

7. Acknowledgements

With thanks to JC for process diagram review and consulting and much appreciation to interview participants.

8. Chapter 3 References

- Abusin, S. A. A., & Mandikiana, B. W. (2020). Towards sustainable food production systems in Qatar: Assessment of the viability of aquaponics. *Global Food Security*, 100349. <https://doi.org/10.1016/j.gfs.2020.100349>
- Ackerman, K., Dahlgren, E., & Xu, X. (2013). Sustainable Urban Agriculture: Confirming Viable Scenarios for Production (13–07; p. 106).
- Al-Hafedh, Y. S., Alam, A., & Beltagi, M. S. (2008). Food Production and Water Conservation in a Recirculating Aquaponic System in Saudi Arabia at Different Ratios of Fish Feed to Plants. *Journal of the World Aquaculture Society*, 39(4), 510–520. <https://doi.org/10.1111/j.1749-7345.2008.00181.x>
- Baganz, G., Junge, R., Portella, M., Goddek, S., Keesman, K., Baganz, D., Staaks, G., Shaw, C., Lohrberg, F., & Kloas, W. (2021). The aquaponic principle—It is all about coupling. *Reviews in Aquaculture*. <https://doi.org/10.1111/raq.12596>
- Baganz, G., Proksch, G., Kloas, W., Lorleberg, W., Baganz, D., Staaks, G., & Lohrberg, F. (2020). Site Resource Inventories – a Missing Link in the Circular City’s Information Flow. *Advances in Geosciences*, 54, 23–32. <https://doi.org/10.5194/adgeo-54-23-2020>
- 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>
- Campbell, B. M., Hansen, J., Rioux, J., Stirling, C. M., Twomlow, S., & (Lini) Wollenberg, E. (2018). Urgent action to combat climate change and its impacts (SDG 13): Transforming agriculture and food systems. *Current Opinion in Environmental Sustainability*, 34, 13–20. <https://doi.org/10.1016/j.cosust.2018.06.005>
- Carus, M., & Dammer, L. (2018). The Circular Bioeconomy—Concepts, Opportunities, and Limitations. *Industrial Biotechnology*, 14(2), 83–91. <https://doi.org/10.1089/ind.2018.29121.mca>
- Chen, P., Zhu, G., Kim, H.-J., Brown, P. B., & Huang, J.-Y. (2020). Comparative Life Cycle Assessment of Aquaponics and Hydroponics in the Midwestern United States. *Journal of Cleaner Production*, 122888. <https://doi.org/10.1016/j.jclepro.2020.122888>
- Chen, S., Ling, J., & Blancheton, J.-P. (2006). Nitrification kinetics of biofilm as affected by water quality factors. *Aquacultural Engineering*, 34(3), 179–197. <https://doi.org/10.1016/j.aquaeng.2005.09.004>
- Chunjie Li, Chew Tin Lee, Yueshu Gao, Haslenda Hashim, Xiaojun Zhang, Wei-Min Wu, & Zhenjia Zhang. (2018). Prospect of aquaponics for the sustainable development of food production in urban. *Chemical Engineering Transactions*, 63, 475–480. <https://doi.org/10.3303/CET1863080>
- Cifuentes-Torres, L., Correa-Reyes, G., & Mendoza-Espinosa, L. G. (2021). Can Reclaimed Water Be Used for Sustainable Food Production in Aquaponics? *Frontiers in Plant Science*, 12, 669984–669984. <https://doi.org/10.3389/fpls.2021.669984>

- Conijn, J. G., Bindraban, P. S., Schröder, J. J., & Jongschaap, R. E. E. (2018). Can our global food system meet food demand within planetary boundaries? *Agriculture, Ecosystems & Environment*, 251, 244–256. <https://doi.org/10.1016/j.agee.2017.06.001>
- Cordell, D., Rosemarin, A., Schröder, J. J., & Smit, A. L. (2011). Towards global phosphorus security: A systems framework for phosphorus recovery and reuse options. *Chemosphere*, 84(6), 747–758. <https://doi.org/10.1016/j.chemosphere.2011.02.032>
- Cripps, S. J., & Bergheim, A. (2000). Solids management and removal for intensive land-based aquaculture production systems. *Aquacultural Engineering*, 22(1), 33–56. [https://doi.org/10.1016/S0144-8609\(00\)00031-5](https://doi.org/10.1016/S0144-8609(00)00031-5)
- Cuce, E., Harjunowibowo, D., & Cuce, P. M. (2016). Renewable and sustainable energy saving strategies for greenhouse systems: A comprehensive review. *Renewable and Sustainable Energy Reviews*, 64, 34–59. <https://doi.org/10.1016/j.rser.2016.05.077>
- Danish, M. S. S., Senjyu, T., Sabory, N. R., Khosravy, M., Grilli, M. L., Mikhaylov, A., & Majidi, H. (2021). A Forefront Framework for Sustainable Aquaponics Modeling and Design. *Sustainability*, 13(16), Article 16. <https://doi.org/10.3390/su13169313>
- 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. *Journal of Cleaner Production*, 331, 129896. <https://doi.org/10.1016/j.jclepro.2021.129896>
- de Graaf, F., & Goddek, S. (2019). Smarthoods: Aquaponics Integrated Microgrids. In S. Goddek, A. Joyce, B. Kotzen, & G. M. Burnell (Eds.), *Aquaponics Food Production Systems: Combined Aquaculture and Hydroponic Production Technologies for the Future* (pp. 379–392). Springer International Publishing. https://doi.org/10.1007/978-3-030-15943-6_15
- Delaide, B., Monsees, H., Gross, A., & Goddek, S. (2019). Aerobic and Anaerobic Treatments for Aquaponic Sludge Reduction and Mineralisation. In S. Goddek, A. Joyce, B. Kotzen, & G. M. Burnell (Eds.), *Aquaponics Food Production Systems: Combined Aquaculture and Hydroponic Production Technologies for the Future* (pp. 247–266). Springer International Publishing. https://doi.org/10.1007/978-3-030-15943-6_10
- dos Santos, M. J. P. L. (2016). Smart cities and urban areas—Aquaponics as innovative urban agriculture. *Urban Forestry & Urban Greening*, 20, 402–406. <https://doi.org/10.1016/j.ufug.2016.10.004>
- Elser, J. J. (2012). Phosphorus: A limiting nutrient for humanity? *Current Opinion in Biotechnology*, 23(6), 833–838. <https://doi.org/10.1016/j.copbio.2012.03.001>
- Emerenciano, M. G. C., Martínez-Córdova, L. R., Martínez-Porchas, M., & Miranda-Baeza, A. (2017). *Biofloc Technology (BFT): A Tool for Water Quality Management in Aquaculture* (H. Tutu, Ed.). InTech. <https://doi.org/10.5772/66416>
- Endut, A., Jusoh, A., Ali, N., & Wan Nik, W. B. (2011). Nutrient removal from aquaculture wastewater by vegetable production in aquaponics recirculation system. *Desalination and Water Treatment*, 32(1–3), 422–430. <https://doi.org/10.5004/dwt.2011.2761>
- Endut, A., Jusoh, A., Ali, N., Wan Nik, W. B., & Hassan, A. (2010). A study on the optimal hydraulic loading rate and plant ratios in recirculation aquaponic system. *Bioresource Technology*, 101(5), 1511–1517. <https://doi.org/10.1016/j.biortech.2009.09.040>
- Estim, A., M. Shaleh, S. R., 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. *Aquaculture Studies*, 20(1). https://doi.org/10.4194/2618-6381-v20_1_08
- Folorunso, E. A., Roy, K., Gebauer, R., Bohatá, A., & Mraz, J. (2021). Integrated pest and disease management in aquaponics: A metadata-based review. *Reviews in Aquaculture*, 13(2), 971–995. <https://doi.org/10.1111/raq.12508>
- Forchino, A. A., Lourguioui, H., Brigolin, D., & Pastres, R. (2017). Aquaponics and sustainability: The comparison of two different aquaponic techniques using the Life Cycle Assessment (LCA). *Aquacultural Engineering*, 77, 80–88. <https://doi.org/10.1016/j.aquaeng.2017.03.002>
- Ghamkhar, R., Hartleb, C., Wu, F., & Hicks, A. (2019). Life cycle assessment of a cold weather aquaponic food production system. *Journal of Cleaner Production*, 118767. <https://doi.org/10.1016/j.jclepro.2019.118767>
- Gibbons, G. (2020). An Economic Comparison of Two Leading Aquaponic Technologies Using Cost Benefit Analysis: The Coupled and Decoupled Systems. *All Graduate Theses and Dissertations, Spring 1920 to Summer 2023*. <https://doi.org/10.26076/2e92-2248>

- Gilbert, N. (2009). Environment: The disappearing nutrient. *Nature*, 461(7265), 716–718. <https://doi.org/10.1038/461716a>
- Goddek, S., Delaide, B., Mankasingh, U., Ragnarsdottir, K. V., Jijakli, H., & Thorarinsdottir, R. (2015). Challenges of Sustainable and Commercial Aquaponics. *Sustainability*, 7(4), 4199–4224. <https://doi.org/10.3390/su7044199>
- Goddek, S., Espinal, C. A., Delaide, B., Jijakli, M. H., Schmutz, Z., Wuertz, S., & Keesman, K. J. (2016). Navigating towards Decoupled Aquaponic Systems: A System Dynamics Design Approach. *Water*, 8(7), 303. <https://doi.org/10.3390/w8070303>
- Goddek, S., Joyce, A., Gross, A., Delaide, B. P. L., Eding, E. H., Bläser, I., Verreth, J., Keesman, K. J., Keizer, L. C. P., Jijakli, M. H., Reuter, M., Körner, O., Morgenstern, R., & Wuertz, S. (2018). Nutrient mineralization and organic matter reduction performance of RAS-based sludge in sequential UASB-EGSB reactors. *Aquacultural Engineering*, 83, 10–19. <http://dx.doi.org/10.1016/j.aquaeng.2018.07.003>
- Goddek, S., & Keesman, K. J. (2018). The necessity of desalination technology for designing and sizing multi-loop aquaponics systems. *Desalination*, 428, 76–85. <https://doi.org/10.1016/j.desal.2017.11.024>
- Goddek, S., & Körner, O. (2019). A fully integrated simulation model of multi-loop aquaponics: A case study for system sizing in different environments. *Agricultural Systems*, 171, 143–154. <https://doi.org/10.1016/j.agsy.2019.01.010>
- Greenfeld, A., Becker, N., Bornman, J. F., dos Santos, M. J., & Angel, D. (2020). Consumer preferences for aquaponics: A comparative analysis of Australia and Israel. *Journal of Environmental Management*, 257, 109979. <https://doi.org/10.1016/j.jenvman.2019.109979>
- Greenfeld, A., Becker, N., Bornman, J. F., Spataro, S., & Angel, D. L. (2021). Monetizing environmental impact of integrated aquaponic farming compared to separate systems. *Science of The Total Environment*, 792, 148459. <https://doi.org/10.1016/j.scitotenv.2021.148459>
- Gregg, J. S., Jürgens, J., Sandvold, H. N., & Olsen, D. S. (2019). The transition to aquaponics in support of a circular bioeconomy: Policy recommendations to overcome geographical and scale barriers. 14.
- Gruda, N., Bisbis, M., & Tanny, J. (2019). Impacts of protected vegetable cultivation on climate change and adaptation strategies for cleaner production – A review. *Journal of Cleaner Production*, 225, 324–339. <https://doi.org/10.1016/j.jclepro.2019.03.295>
- Hao, Y., Ding, K., Xu, Y., Tang, Y., Liu, D., & Li, G. (2020). States, Trends, and Future of Aquaponics Research. *Sustainability*, 12(18), Article 18. <https://doi.org/10.3390/su12187783>
- Horn, E., Joyce, A., Chowdhury, R., Caputo, S., Jacobs, B., & Winkler, M. (2023). Translating Environmental Potential to Economic Reality: Assessment of Commercial Aquaponics through Sustainability Transitions Theory. *Circular Economy and Sustainability*. <https://doi.org/10.1007/s43615-023-00291-0>
- Horn, E., & Proksch, G. (2020). Building an Ecosystem: Integrating Rooftop Aquaponics with a Brewery to Advance the Circular Economy.
- Horn, E., & Proksch, G. (2022). Symbiotic and Regenerative Sustainability Frameworks: Moving Towards Circular City Implementation. *Frontiers in Built Environment*, 7. <https://www.frontiersin.org/article/10.3389/fbuil.2021.780478>
- Huang, C.-L., Gao, B., Xu, S., Huang, Y., Yan, X., & Cui, S. (2019). Changing phosphorus metabolism of a global aquaculture city. *Journal of Cleaner Production*, 225, 1118–1133. <https://doi.org/10.1016/j.jclepro.2019.03.298>
- Jaeger, C., Foucard, P., Tocqueville, A., Nahon, S., & Aubin, J. (2019). Mass balanced based LCA of a common carp-lettuce aquaponics system. *Aquacultural Engineering*, 84, 29–41. <https://doi.org/10.1016/j.aquaeng.2018.11.003>
- Joyce, A., Goddek, S., Kotzen, B., & Wuertz, S. (2019). Aquaponics: Closing the Cycle on Limited Water, Land and Nutrient Resources. In *Aquaponics Food Production Systems* (pp. 19–34). Springer, Cham. https://doi.org/10.1007/978-3-030-15943-6_2
- Khiari, Z., Alka, K., Kelloway, S., Mason, B., & Savidov, N. (2020). Integration of Biochar Filtration into Aquaponics: Effects on Particle Size Distribution and Turbidity Removal. *Agricultural Water Management*, 229, 105874. <https://doi.org/10.1016/j.agwat.2019.105874>
- König, B., Janker, J., Reinhardt, T., Villarroel, M., & Junge, R. (2018). Analysis of aquaponics as an emerging technological innovation system. *Journal of Cleaner Production*, 180, 232–243. <https://doi.org/10.1016/j.jclepro.2018.01.037>
- König, B., Junge, R., Bittsanszky, A., Villarroel, M., & Komives, T. (2016). On the sustainability of aquaponics. *Ecocycles*, 2(1), 26–32. <https://doi.org/10.19040/ecocycles.v2i1.50>

- 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. *Journal of Cleaner Production*, 313, 127735. <https://doi.org/10.1016/j.jclepro.2021.127735>
- Krom, M. D., David, A. B., Ingall, E. D., Benning, L. G., Clerici, S., Bottrell, S., Davies, C., Potts, N. J., Mortimer, R. J. G., & Rijn, J. van. (2014). Bacterially mediated removal of phosphorus and cycling of nitrate and sulfate in the waste stream of a “zero-discharge” recirculating mariculture system. *Water Research*, 56, 109–121. <https://doi.org/10.1016/j.watres.2014.02.049>
- Lekang, O.-I., & Kleppe, H. (2000). Efficiency of nitrification in trickling filters using different filter media. *Aquacultural Engineering*, 21(3), 181–199. [https://doi.org/10.1016/S0144-8609\(99\)00032-1](https://doi.org/10.1016/S0144-8609(99)00032-1)
- Lennard, W. A., & Leonard, B. V. (2006). A Comparison of Three Different Hydroponic Sub-systems (gravel bed, floating and nutrient film technique) in an Aquaponic Test System. *Aquaculture International*, 14(6), 539–550. <https://doi.org/10.1007/s10499-006-9053-2>
- López-Arredondo, D. L., Leyva-González, M. A., Alatorre-Cobos, F., & Herrera-Estrella, L. (2013). Biotechnology of nutrient uptake and assimilation in plants. *The International Journal of Developmental Biology*, 57(6–8), 595–610. <https://doi.org/10.1387/ijdb.130268lh>
- Love, D. C., Fry, J. P., Genello, L., Hill, E. S., Frederick, J. A., Li, X., & Semmens, K. (2014). An International Survey of Aquaponics Practitioners. *PLOS ONE*, 9(7), e102662. <https://doi.org/10.1371/journal.pone.0102662>
- Love, D. C., Fry, J. P., Li, X., Hill, E. S., Genello, L., Semmens, K., & Thompson, R. E. (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>
- Maucieri, C., Nicoletto, C., Junge, R., Schmautz, Z., Sambo, P., & Borin, M. (2018). Hydroponic systems and water management in aquaponics: A review. *Italian Journal of Agronomy*, 13(1/1012). <https://doi.org/10.4081/ija.2018.1012>
- Mchunu, N., Lagerwall, G., & Senzanje, A. (2018). Aquaponics in South Africa: Results of a national survey. *Aquaculture Reports*, 12, 12–19. <https://doi.org/10.1016/j.aqrep.2018.08.001>
- Monsees, H., Keitel, J., Paul, M., Kloas, W., & Wuertz, S. (2017). Potential of aquacultural sludge treatment for aquaponics: Evaluation of nutrient mobilization under aerobic and anaerobic conditions. *Aquaculture Environment Interactions*, 9, 9–18. JSTOR. <https://doi.org/10.2307/26391964>
- Neori, A., Krom, M. D., & Rijn, J. V. (2007). Biogeochemical processes in intensive zero-effluent marine fish culture with recirculating aerobic and anaerobic biofilters. *Journal of Experimental Marine Biology and Ecology*, 349(2), 235–247. <https://doi.org/10.1016/j.jembe.2007.05.023>
- Neto, R., & Ostrensky, A. (2015). Nutrient load estimation in the waste of Nile tilapia *Oreochromis niloticus* (L.) reared in cages in tropical climate conditions. *Aquaculture Research*, 46(6), 1309–1322. <https://doi.org/10.1111/are.12280>
- Nicoletto, C., Maucieri, C., Mathis, A., Schmautz, Z., Komives, T., Sambo, P., & Junge, R. (2018). Extension of Aquaponic Water Use for NFT Baby-Leaf Production: Mizuna and Rocket Salad. *Agronomy*, 8(5), Article 5. <https://doi.org/10.3390/agronomy8050075>
- Petrea, Ștefan-M., Bandi, A.-C., Cristea, D., & Neculiță, M. (2019). Cost-benefit analysis into integrated aquaponics systems. *Custos e Agronegocio*, 15(3), 31.
- Pinstrup-Andersen, P. (2018). Is it time to take vertical indoor farming seriously? *Global Food Security*, 17, 233–235. <https://doi.org/10.1016/j.gfs.2017.09.002>
- Proksch, G., Ianchenko, A., & Kotzen, B. (2019). Aquaponics in the Built Environment. In S. Goddek, A. Joyce, B. Kotzen, & G. M. Burnell (Eds.), *Aquaponics Food Production Systems: Combined Aquaculture and Hydroponic Production Technologies for the Future* (pp. 523–558). Springer International Publishing. https://doi.org/10.1007/978-3-030-15943-6_21
- Ragnarsdottir, K. V., Sverdrup, H. U., & Koca, D. (2011). Challenging the planetary boundaries I: Basic principles of an integrated model for phosphorous supply dynamics and global population size. *Applied Geochemistry*, 26, S303–S306. <https://doi.org/10.1016/j.apgeochem.2011.03.088>
- Rakocy, J. E., Masser, M. P., & Losordo, T. M. (2006). Recirculating Aquaculture Tank Production Systems: Aquaponics—Integrating Fish and Plant Culture. 16.

- Reyes-Lúa, A., Straus, J., Skjervold, V. T., Durakovic, G., & Nordtvedt, T. S. (2021). A Novel Concept for Sustainable Food Production Utilizing Low Temperature Industrial Surplus Heat. *Sustainability (Basel, Switzerland)*, *13*(17), 9786. <https://doi.org/10.3390/su13179786>
- Ru, D., Liu, J., Hu, Z., Zou, Y., Jiang, L., Cheng, X., & Lv, Z. (2017). Improvement of aquaponic performance through micro- and macro-nutrient addition. *Environmental Science and Pollution Research International*, *24*(19), 16328–16335. <https://doi.org/10.1007/s11356-017-9273-1>
- Schneider, O., Sereti, V., Eding, E. H., & Verreth, J. A. J. (2005). Analysis of nutrient flows in integrated intensive aquaculture systems. *Aquacultural Engineering*, *32*(3–4), 379–401.
- Seawright, D. E., Stickney, R. R., & Walker, R. B. (1998). Nutrient dynamics in integrated aquaculture–hydroponics systems. *Aquaculture*, *160*(3), 215–237. [https://doi.org/10.1016/S0044-8486\(97\)00168-3](https://doi.org/10.1016/S0044-8486(97)00168-3)
- Short, G., Yue, C., Abbey, M., Anderson, N., Phelps, N., Venturelli, P., & Vickers, Z. (2018). Consumer preferences for aquaponic produce: Implications from an experimental auction. *Agribusiness*, *34*(4), 742–755. <https://doi.org/10.1002/agr.21562>
- Short, G., Yue, C., Anderson, N., Russell, C., & Phelps, N. (2017). Consumer Perceptions of Aquaponic Systems. *HortTechnology*, *27*(3), 358–366. <https://doi.org/10.21273/HORTTECH03606-16>
- Shu, L., Schneider, P., Jegatheesan, V., & Johnson, J. (2006). An economic evaluation of phosphorus recovery as struvite from digester supernatant. *Bioresource Technology*, *97*(17), 2211–2216. <https://doi.org/10.1016/j.biortech.2005.11.005>
- Sikawa, D., & Yakupitiyage, A. (2010). The hydroponic production of lettuce (*Lactuca sativa* L) by using hybrid catfish (*Clarias macrocephalus* × *C. gariepinus*) pond water: Potentials and constraints. *Agricultural Water Management*, *97*, 1317–1325. <https://doi.org/10.1016/j.agwat.2010.03.013>
- Sonneveld, C., & Voogt, W. (2009). Nutrient management in substrate systems. In *Plant nutrition of greenhouse crops* (pp. 277–312). Springer. https://doi.org/10.1007/978-90-481-2532-6_13
- Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., Vries, W. de, Wit, C. A. de, Folke, C., Gerten, D., Heinke, J., Mace, G. M., Persson, L. M., Ramanathan, V., Reyers, B., & Sörlin, S. (2015). Planetary boundaries: Guiding human development on a changing planet. *Science*, *347*(6223). <https://doi.org/10.1126/science.1259855>
- Suhl, J., Dannehl, D., Kloas, W., Baganz, D., Jobs, S., Scheibe, G., & Schmidt, U. (2016). Advanced aquaponics: Evaluation of intensive tomato production in aquaponics vs. conventional hydroponics. *Agricultural Water Management*, *178*, 335–344. <https://doi.org/10.1016/j.agwat.2016.10.013>
- Sverdrup, H. U., & Ragnarsdottir, K. V. (2011). Challenging the planetary boundaries II: Assessing the sustainable global population and phosphate supply, using a systems dynamics assessment model. *Applied Geochemistry*, *26*, S307–S310. <https://doi.org/10.1016/j.apgeochem.2011.03.089>
- Tamin, M., Harun, A., Estim, A., Saufie, S., & Obong, S. (2015). Consumer Acceptance towards Aquaponic Products. *IOSR Journal of Business and Management*, *17*.
- Tyson, R. V., Treadwell, D. D., & Simonne, E. H. (2011). Opportunities and Challenges to Sustainability in Aquaponic Systems. *HortTechnology*, *21*(1), 6–13.
- Villarroel, M., Alvaríño, J. M. R., & Duran, J. M. (2011). Aquaponics: Integrating fish feeding rates and ion waste production for strawberry hydroponics. *Spanish Journal of Agricultural Research*, *9*(2), 537–545. <https://doi.org/10.5424/sjar/20110902-181-10>
- Weikard, H.-P. (2016). Phosphorus recycling and food security in the long run: A conceptual modelling approach. *Food Security*, *8*(2), 405–414. <https://doi.org/10.1007/s12571-016-0551-4>
- Wu, F., Ghamkhar, R., Ashton, W., & Hicks, A. L. (2019). Sustainable Seafood and Vegetable Production: Aquaponics as a Potential Opportunity in Urban Areas. *Integrated Environmental Assessment and Management*, *15*(6), 832–843. <https://doi.org/10.1002/ieam.4187>
- Wu, Y., & Song, K. (2021). Source, Treatment, and Disposal of Aquaculture Solid Waste: A Review. *Journal of Environmental Engineering*, *147*(3), 03120012. [https://doi.org/10.1061/\(ASCE\)EE.1943-7870.0001850](https://doi.org/10.1061/(ASCE)EE.1943-7870.0001850)
- Yacout, D. M. M., Soliman, N. F., & Yacout, M. M. (2016). Comparative life cycle assessment (LCA) of Tilapia in two production systems: Semi-intensive and intensive. *The International Journal of Life Cycle Assessment*, *21*(6), 806–819. <https://doi.org/10.1007/s11367-016-1061-5>

Yogev, U., Barnes, A., & Gross, A. (2016). Nutrients and Energy Balance Analysis for a Conceptual Model of a Three Loops off Grid, Aquaponics. *Water*, 8(12), 589. <https://doi.org/10.3390/w812058>

Chapter 4- Industrial Symbiosis with Controlled Environment Agriculture: An Exploratory Multiple Case Study Analysis

Abstract

Opportunities to valorize resource streams at all levels of the food system, a key element of critical infrastructure, are garnering heightened interest. The resources consumed and generated by agriculture and food production processes are integral among these and compel multi-sectoral innovation to actualize circularity potential. Born of a kindred vision of resource efficient production, controlled-environment agriculture systems lend themselves well to biocircular outcomes, providing favorable opportunities for both internal resource cycling and industrial symbiosis with external partners. While industrial symbiosis and its scalar variations are a key infrastructural element of implementing circular economy and associated regenerative aims, its use is little researched in the context of controlled-environment agriculture systems, particularly for aquaponic systems- and its component hydroponic and recirculating aquaculture systems. Several examples of industrial symbiosis with controlled-environment agriculture partners are found in Northern Europe, where there is an established history of industrial symbiosis in practice and recent developments are notable. As more regions seek to bolster applications of industrial symbiosis with food production industries, there is a critical need to learn from existing examples and advance understanding of this emergent industrial symbiosis typology. Accordingly, this investigation assesses a selection of these existing examples through an exploratory multiple case study synthesis to help advance understanding and document their motivations and contexts, material exchanges, and emergent organizational and institutional dynamics to set the stage for the expansion of research to support the contribution of this promising nascent industrial symbiosis type to increasing advancement of circular economy in critical food, water, and energy infrastructure toward optimized environmental sustainability and resilience of operations within planetary boundaries.

1. Introduction

Current food production practices contribute significantly to the exceedance of planetary boundaries, particularly impacting nutrient cycling and biodiversity (Steffen et al. 2015; Helenius et al. 2020). Meanwhile, the demand for ecological intensification of food production is growing, shaping an imperative for more food to be produced while also fulfilling further ecosystem services via optimized agricultural practices (Schulte et al., 2014; Tiftonell, 2014; Koppelmäki et al. 2019). The specialization of farms in the Global North into distinct crop or livestock agriculture has intensified spatial separation and fertilizer use, preventing important opportunities for plant nutrient recycling (Buckwell and Nadeu, 2016; Schulte et al., 2019; Parviainen and Helenius, 2020; Koppelmäki et al., 2021) and for application of local manure sources for crop agriculture in regions without nearby livestock (Koppelmäki et al. 2019; Helenius et al. 2020). This has shaped a salient “failure to recycle the nutrients used in

agriculture production” (Helenius et al. 2020), and while there has been an appearance of increased agricultural productivity and efficiency, there has concurrently been drastic decline in the efficient use of nutrients vital for plant growth (Buckwell and Nadeu, 2016; Sherwood, 2020; Helenius et al. 2020). Current agricultural systems retain a high dependence on external energy sources, particularly on fossil fuels (Sherwood, 2020), and unsurprisingly there is increasing demand to sustainably produce food and energy renewably in a coordinated manner (Koppelmäki et al. 2019). Critics of the contemporary predominant food system contend that a shift to “diversified, post-fossil, and circular food systems” (Helenius et al. 2020) is needed (Monteleone, 2015). Thus, the concepts of circular economy (CE) and local exchange of resources must be harnessed toward better operation within planetary boundaries and the introduction of more regenerative models of food production.

One such adaptive model, proposed by Koppelmäki et al. 2016, is that of Agroecological Symbiosis (AES), which applies the concepts of industrial symbiosis (IS) (Chertow, 2000) to localized food systems through an ecological intensification approach of enhanced nutrient recycling and bioenergy efforts within food production and processing (Koppelmäki et al. 2019; Helenius et al. 2020). There are other expected benefits of AES, Helenius et al. 2020 “argue for agroecological symbiosis (AES) as a generic arrangement for re-configuring the primary production of food in agriculture, the processing of food, and development of a food community to work toward system-level sustainability” (Helenius et al. 2020). Initial efforts to investigate the feasibility of AES has been pursued, including an assessment case of Palopuro AES in Finland where three farms, a bakery, and a biogas plant could improve nutrient and energy cycling using system-derived feedstocks (Koppelmäki et al. 2019). Other variants of AES exist though have not been significantly analyzed as such yet. There is a need to study the feasibility of AES and similar IS models with various food production types and differing organizational and spatial scales (Koppelmäki et al. 2019).

A potential typology meriting further exploration is IS with Controlled-Environment Agriculture (CEA), growing approaches which control environmental parameters to grow food year-round indoors (Proksch et al. 2019). In particular, commercial aquaponics operated as a CEA system has a variety of potential integrations with other resource-producing and consuming symbiotic partners, including other food industries (Chance et al. 2018; Horn and Proksch 2020; Horn et al. 2024 *forthcoming*). Aquaponics is the co-production of fish and plants wherein nutrient-rich water from land-based fish production is used to grow produce hydroponically without soil (Rakocy 2012), typically then creating cleansed water for reintroduction to aquaculture use, and accordingly applies CE concepts of reduction, reuse, and recycling internally (Horn and Proksch 2022). As efforts to implement innovative sustainability technologies like aquaponics expands along with the prevalence of discourse around CE and related concepts, it is unsurprising that CE strategies themselves become potential solutions to implementation challenges, like energy demand for CEA operation, that arise along the way (*Chapter 3*). Opportunities for synergetic resource sharing and reuse are increasingly considered when addressing environmental optimization needs, and accordingly, discussion of benefits of business co-location and IS

resource exchanges are arising with greater frequency among aquaponics practitioners and researchers (*Chapter 3*). The nutrient-stream from fish production in aquaponics and its spatially decoupled variants presents a potential IS opportunity of water, nutrient, and biomass resources (*Chapter 3*), moreover, greenhouse and indoor production methods in CEA can benefit from input energy and heat sources that may be generated by industrial symbiosis partners (Horn and Proksch 2020), both commercial and public (e.g. district heating integration).

Additionally, phosphorus (P) recovery opportunities in aquaponics and in IS with aquaculture production on land, i.e. recirculating aquaculture systems (RAS) present an innovative solution to help address the global phosphorus challenge and expected shortages in many regions. RAS are not the typical mode of production currently, rather, standard fish farms use open-cage approaches in which nutrient rich effluent water is exchanged continuously with the surrounding water body (Wang et al. 2012), resulting in nutrient losses, including of particulate organic and dissolved organic P, which can in some cases then go on to contribute to eutrophic water-body conditions in some regions (Hamilton et al. 2016). Hamilton et al. 2016 consider multisectoral P recovery opportunities in the context of Norwegian aquaculture (Hamilton et al. 2016). They note that land-based RAS systems present an opportunity for secondary P recovery (Tal et al. 2009), expressing that these systems result in less P losses and “allow for easier removal and collection of excreted P, feces, and excess feed” (Hamilton et al. 2016), but also face barriers of cost, energy needs, land requirements, and water demand. These barriers may potentially be reduced through IS models, suggesting that such approaches could be of particular interest in the Nordic region. Notably several built and planned examples of IS with RAS and variations of aquaponics are being advanced within Northern Europe and can serve as important initial examples.

While literature has discussed some potential symbioses with aquaponics (Million et al., 2018; Horn and Proksch, 2020), and industrial symbiosis networks (ISNs)- where multiple actors exchange resources in a coordinated manner- with CEA constituents are being developed, few have examined existing examples (Chance et al. 2018), and scholarly documentation of their formation, material design and operation, and organizational and institutional dynamics is limited. Such considerations are pertinent as it has been observed that barriers to AES are not predominantly technical in nature, but rather organizational. Hamam et al. 2022 conducted a literature review evaluating scientific efforts and interest in IS in the agri-food sector, highlighting analytical approaches conducted thus far, and found that studies considered potential tools and methods but overlooked topics of collaboration and information exchange between stakeholders, expressing the need for study of these factors, as they pose “one of the main barriers to the introduction of symbiotic systems” and if better resolved could help “promote the introduction of new techniques and tools for the development of circular production systems” (Hamam et al. 2022). Similarly, “literature identification and discussion of barriers to industrial symbiosis [in general] has noted these include typical business development challenges and other issues rooted in the operational, behavioral, and financial

difficulties of working across organizations” (Horn and Proksch 2022). IS literature has accordingly stressed the need to consider organizational perspectives and develop responsive future research agendas (Andrews 2001; Ehrenfeld, 2000, 2004; Hoffman 2003; Korhonen et al. 2004; Walls and Paquin 2015), as well as to more closely consider intra-organizational level dynamics and the role of context (Yap and Devlin 2017; Faria et al. 2021).

This work accordingly seeks to help respond to this imperative for the AES variant typology of IS partnerships with CEA through the analysis of existing applied examples. Describing and characterizing resource sharing processes and partnerships between aquaponics, and its subsystems hydroponics and aquaculture, with other entities as a distinctive form of IS with CEA (CEA-IS) may serve further studies of their shared benefits and challenges, strengthening pathways to accelerate their adoption and success. This work therefore uses case study methods to elucidate the motivations for these ISNs and analyzes their implementation through material, organizational, and institutional lenses, setting up a platform for further study of key factors in these categories which may influence their success. Accordingly, through exploratory cross-case study analysis of a selection of existing and planned industrial symbiosis networks practicing CEA-IS in Northern Europe, this work seeks to advance and document understanding of their formation, physical, organizational, and institutional dynamics, elucidating vital contextual factors and emergent drivers and barriers to set the stage for the expansion of research to support the contribution of this promising nascent IS type to more regenerative food systems and bioresource self-sufficiency within planetary boundaries. Introducing CEA-IS to the lexicon of IS and CE approaches is vital at this pivotal time for the expansion of circular economy. Entwining food, water, and energy systems, this novel form of IS represents a growing overlap between IS and critical infrastructures as a means of increasing sustainability and resilience globally through local integration efforts.

2. Research Design & Methods

2.1 Case Study Methodology

To characterize and advance scientific understanding of CEA-IS, an exploratory multiple case study analysis is conducted. The holistic perspective (Easton 2010; Verschuren 2003; Farquhar et al. 2020) of case study research supports the examination of a small number of strategically selected cases in their real-world settings (Piekkari et al. 2009), allowing for firsthand learning about organizations (Daft, 1983) and the grounding of investigations in an operational management context (Varadarajan, 2003). As case study methods are particularly appropriate to explore phenomena in their contexts to build nuanced understanding from multiple perspectives (Flyvbjerg 2006; Woodside and Wilson 2003; Farquhar et al. 2020), they are apt for the in-context analysis of emerging CEA-IS enterprises. Given the youth and scant scholarly analysis of this IS typology, an exploratory case study model is selected as a well-suited means to advance a platform for further research and development of CEA-IS analysis within a real-world informed research context. Exploratory studies seek “to develop pertinent hypotheses and propositions for further inquiry” (Yin 2018). Accordingly, rather than requiring propositions

specifically, exploratory case studies necessitate overarching directions to guide them (Burga et al. 2020; Yin 2018). This work seeks to support the contribution of CEA-IS to regenerative food systems and the sustainability and resilience of food, water, and energy systems critical infrastructure by shedding light on emergent drivers, barriers, and contextual factors to set the stage for the expansion of research on influential factors and responsive pathways to optimize implementation success. Case study methods are advantageous to address “how” and “why” questions, as these, when well formed, pertain to the assessment of “operational processes over time, rather than mere frequencies or incidence” in essence querying a selection of contemporaneous events which are not controlled by the researcher themselves (Yin 2018). The questions addressed through this case study are accordingly driven by “how” and “why” considerations, asking:

- How and why is CEA-IS pursued in these cases?
- How are these cases formed and organized through a) material, b) organizational, and c) institutional lenses?
- How and why do emergent trends in the dynamics of the categories above influence the viability and success of CEA-IS?

2.2 Data collection

Case study CEA-IS operations were selected through their alignment with three primary criteria:

1. They are a planned or currently operating business using hydroponic, aquaponic, or RAS growing approaches in a CEA setting.
2. They exchange, or plan to exchange, operational resources such as heat, water, wastewater, nutrients, organic waste streams (sludge, food waste, etc.) with industrial-scale symbiosis partner(s)
3. They are located in Northern Europe.

Interviews with stakeholders from each were conducted during case study visits in person, and via zoom when needed, in March 2023. An interviewee with knowledge of physical systems, planning, and operations represented each CEA-IS case system. Interviews were semi-structured and formatted as an introductory tour of the CEA-IS operation. For consistency, all were asked to give a tour, literal or descriptive, of their organization. Topics addressed were as follows 1) how and why their organization was formed; 2) what key physical characteristics and IS linkages were pursued (note some technical content discussed is excluded from this study as it is considered out of the scope of this work, and in some cases proprietary to the companies); 3) experiences with forming and navigating IS partnerships; and 4) experiences with regulation and government interactions. Further data collection on the case studies was also conducted from publicly available web sources, including material from news outlets as well as documentation and press releases from the CEA-IS organizations themselves, to form a comprehensive assessment of existing documentation on the case systems. Materials were

assessed regardless of initial publication language to ensure comprehensiveness, and sources in Dutch, English, French, Norwegian, and Swedish were accordingly included.

2.3 Data analysis

Interview notes, site visit images, and publicly available sources were analyzed to support the consideration of the case studies' formation, systems integration, and other dynamics influential to their success, this also supported the creation of diagrams to document ISN material flow and interpretation of emergent organizational and institutional dynamics. Interviews were documented with real time notetaking and incorporated into a case study database, formatted as a text document. Document data and accompanying memos were also added to the database and active weblinks saved in a Zotero database. This content was combined to form case study profiles from which information was coded thematically for content on motivations for symbiosis (3.1), material resource exchanges (3.2), and organizational and institutional factors (3.3). Within these three groups, a nested level of coding applied a grounded theory approach to triangulation, in which similar topics and themes from multiple case studies were identified and grouped together to identify trends and factors, discussed below in their respective subsections. Content within 3.3 was also further organized through three organizational theory levels: intra-organizational, the business itself; inter-organizational, information to do with partnerships with other actors; and institutional, interactions with regulatory and governing forces. These levels echo those identified by Walls and Paquin, 2015, for the levels of analysis of IS, with the exclusion of an "individual" level, on which minimal data was collected.

Learning from Farquhar et al.'s insights, this study applies the concept of complementary triangulation as an apt fit for an exploratory cross case synthesis. Complementary triangulation offers an effective mode of explaining different perspectives on the phenomenon being researched (Farquhar et al. 2020). For multiple case study research, triangulation as complementarity helps to address the dynamic that while "any two cases are unlikely to be identical in real life, findings that complement each other, that is, are interdependent and/or overlap may offer the enhanced understanding that case study research is well suited to uncover" (Farquhar et al. 2020). Moreover, as less emphasis is placed on corroboration, the pursuit of complementary data (Erzberger and Prein 1997; Hammersley 2008) becomes a liberating alternative to convergence, which may be constricting (Wolfram Cox and Hassard 2005), and can accordingly offer "arguably greater insight than convergence" (Farquhar et al. 2020). In management theory, complementarity has been applied to help explain the manner in which certain organizational practices and activities enhance one another when adopted in concert (Milgrom and Roberts 1995). Similarly, observations in literature have noted that while complementary findings demonstrate interdependence (Carroll and Rothe 2010), they also "rely on each other for clarity of understanding" (Farquhar et al. 2020)

2.4 Validation

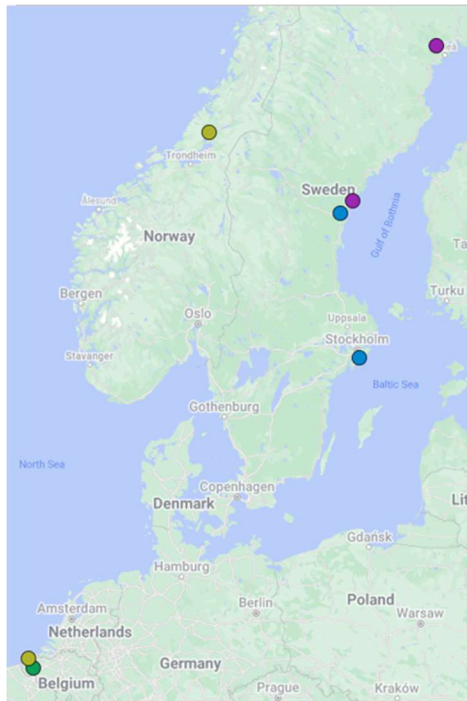
Quality testing is pursued by addressing four tests common in empirical social research and of established relevance in case study research (Taylor et al. 2011; Yin 2018) to help meet the burden of persuasion. These are construct validity, external validity, internal validity, and reliability. Construct validity concerns the identification of “correct operational measures for the concepts being studied” (Yin 2018). To establish construct validity and avoid subjectivity pitfalls, this work aims to meet three tenets described by Taylor et al. 2011: “(1) utilizing multiple sources of evidence, (2) creating a chain of evidence, and (3) reviewing draft case results with key participants/informants” (Taylor et al. 2011; Yin 2018), the third step of which will be continued in future work. External validity concerns the generalizability of findings in a case study (Yin 2018) and is addressed through the definition of inclusion criteria and the application of appropriate theory and replication logic. Internal validity is not required of exploratory studies but typically aims to establish causal relationships between conditions in a case study and can be addressed through tactics including “pattern matching, explanation building, addressing rival explanations, and using logic models” (Yin 2018). Due to the exploratory nature of this study, internal validity is not fully applicable and thus will only be partly addressed through pattern matching and explanation building as controlled for through inclusion of multiple case among which credible causal relationships of thematic content within qualitative results can be preliminarily established with the application of complementary triangulation. Finally, reliability, the confirmation that study operations are repeatable to yield similar results, is addressed by documenting case study procedures followed (Yin 2018).

3. Results

3.1 Motivations for CEA-IS

The following sections discuss trends observed across the exploratory multiple cross-case analysis, including their motivations, physical structure, material exchanges, and organizational and institutional influences. Achieving resource efficiency and resilience through systems integration was a motivation of all the studied cases, consistently described as a process through which other goals can be better fulfilled. All are positioned to achieve additional outcomes relating to commercial food production through the utilization of IS. Two cases tie their production systems to district heating systems while two focus on ISN integration (Table 4.1). Food, energy, and water resources are involved in all the cases, highlighting the influence of the Food-Water-Energy nexus across these three types of critical infrastructure (Allan et. al. 2015; Leck et al. 2015) and the emerging considerations that private-private and private-public forms of IS introduce to efforts to implement sustainability and resilience measures in many regions.

Table 4.1- Overview of Selected Controlled Environment Agriculture- Industrial Symbiosis Case Studies



Name	Founded	CEA type	Symbiosis Type	Status	Location(s)	Latitude
1) Agrotopia	2021	Hydroponics	district	Operating	Roeselare, Belgium	50.94
2) Agtira	2017	Aquaponics	district	Operating	Härnösand, Sweden	60.65
		Hydroponics	industrial	Planning	Boden, Sweden	65.75
3) Big Akwa	2020	Recirculating Aquaculture System	industrial	Planning	Alby, Sweden	59.14
		Recirculating Aquaculture System	industrial	Planning	Sundsvall, Sweden	62.39
4) Columbi Farms	2020	Hydroponics; part of a spatially decoupled aquaponic system	industrial	Planning	Malm, Norway	64.04
		Hydroponics; part of a spatially decoupled aquaponic system	industrial	Planning	Ostend, Belgium	51.23

Agrotopia (Figure 4.1), for instance, seeks to support local agriculture through transdisciplinary research and communication efforts to demonstrate innovative growing technologies and the potential benefits of sustainable systems integration. Agrotopia is an industrial scale rooftop research greenhouse located on the edge of Roeselare, in the agricultural heart of Belgium (1). The space below Agrotopia’s rooftop greenhouse is used by the local vegetable auction, which allows for the sale of produce from multiple producers, offering them consistent sales and easing quality control and certification processes (1). The location is among other warehouses and greenhouses, many associated with regional agriculture. Meant to be accessible to industry, researchers, and the public, the greenhouse acts both as a research center and showcase demonstration of commercial scale growing possibilities (1). To engage with local farmers, tours and regular updates on latest research findings are regularly shared (1). Also considering the benefits of co-location is Agtira, an aquaponic developer and producer based in Härnösand, pursuing a novel “farming as a service” business model, achieved through an expansion of industrial symbiosis approaches. They re-structured and rebranded from being solely a commercial aquaponic production business, *Peckas Naturolingar*, as the company’s management and vision shifted toward more resource-integrated variations of aquaponics. Three primary reasons for this transformation were to transition from R+D to commercial scale, to build closer relationships to supermarkets and be able to sell to them directly, and to further develop the services enabled through CEA (2). As Agtira, the company is now seeking to

develop several more locations where commercial aquaponic or hydroponic production is integrated with local resources, district and industrial, to provide additional services.



Figure 4.1- a) Agrotopia Rooftop Greenhouse and Façade (photographed by author during site visit)

The interviewee from Agtira’s management team described a “farming as a service” business model in which two primary customer types are identified. The first group is in urban settings which Agtira serves by building and operating on underutilized spaces like parking lots (e.g. at grocery stores). In doing so, Agtira aims to cut out intermediaries and act as a service provider so that all the grocery store needs to do is sell the produce. The second group is addressed in industrial settings, with industries connected to resources such as district heating and hydropower. Drivers listed for both types of partnerships, envisioned at multiple potential and planned sites, included removing transport needs via local production, power balancing to support the grid, and using waste heat. Particularly noting the impact of the 2022-2023 fuel shortage on greenhouse production in the Netherlands, Agtira noted an opportunity to focus on better regional resilience of food supply and increase greenhouses in Europe, particularly noting opportunities to harness other resources, including waste heat. Furthermore, grid integration potential can allow Agtira to offer multiple services, in addition to food production, the greenhouse can be used to help balance the grid by turning power on and off as needed and operating at times of lower demand (2). This service may also help secure a better price on power and thus achieve further mutual benefit (for RAS components which need a continual supply, a power station would be used). Collaborations with local Swedish companies that make battery and solar panel technologies are being pursued to develop these approaches (2). Solar power collection ability is best in April through October so combining these methods with underground battery storage is envisioned to bridge the gap. Regional partnerships with state owned power utilities are also in discussion in multiple locations (2).

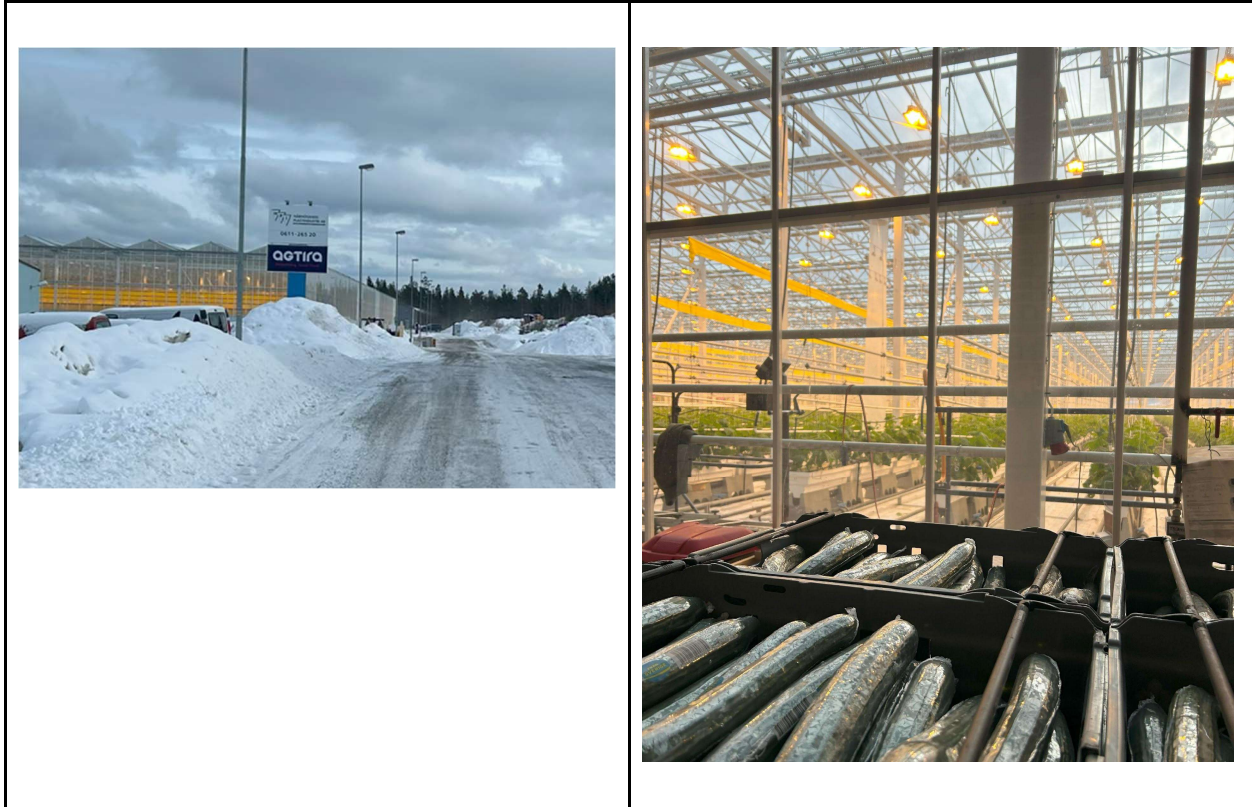


Figure 4.2- a) Agtira’s greenhouse, exterior view, b) Cucumber yield and greenhouse space at Agtira’s headquarters (photographed by author during site visit)

Both Big Akwa and Columbi Farms seek to exchange resource flows with existing or planned private businesses as part of ISNs. Big Akwa, based in Sundsvall, Sweden, seeks to make use of symbiosis opportunities to simultaneously meet more of the market demand for fish via RAS without running into stringent environmental regulations associated with other forms of aquaculture. The company was conducting their investment stage as well as one pre-study and one pre-project at the time of the interview in March 2023. Centrally, Big Akwa aims to build a large-scale rainbow trout farm in mid-Sweden. They intend to address multiple process industry streams, including refining and reusing fish farm waste streams. The standard use for this waste stream is biogas, but Big Akwa will alternatively produce more high value products. Trends of fish consumption are shifting and within recent years people are eating more farmed fish than wild fish (3). Sweden has a low fish production consumption ratio, at 1:32kg, creating a notable opportunity and market for more local production (3). One of the reasons for this low ratio is tough environmental permits in Sweden, but Big Akwa sees the potential of industrial symbiosis to manage fish farming despite stringent effluent requirements, while helping to fulfill the energy and heating footprint of RAS. Approaching similar opportunities from a different angle is Columbi Farms, based in the Trøndelag, Norway, they seek to make productive use of effluent from aquaculture while growing a marketable crop using hydroponic techniques, and thus are setting up a decoupled form of aquaponics between two distinct actors (4). Columbi Farms has

carefully considered their interactions with the United Nations’ Sustainable Development Goals as well as their potential market. They plan to build first in Norway, in the Trøndelag region, and then in the future, on the Belgium coast (Ostend). Columbi Farms will be an indoor hydroponic operation utilizing the output water and nutrients from neighboring RAS salmon production and expects to be Norway’s largest vertical farm.

3.2 Resource Exchanges in CEA-IS

The CEA systems and industrial symbiosis linkages are distinct across the studied cases, though many similarities and trends emerge, use of waste heat and district heat installation was a strategy employed by all the cases, while symbiotic exchange of biomass and nutrient-water was also common, as would be expected with aquaponics systems and their related subsystems (Table 4.2). Currently operating, the Agrotopia (Figure 4.3) warehouse and greenhouse were designed and built concurrently, allowing for structural design and resource integration pre-planning. Water collected from the top of the greenhouse is stored in five large cisterns, which also serve a structural role, holding up the double height greenhouse area (1). Environmental control systems also play a role in facilitating their integration in an urban setting, particularly shading (cloth and film systems) to control light intensity during the day and to prevent light pollution at night while also adding additional insulation. The greenhouse is integrated with district heating.

Table 4.2- Symbiotic Linkages in CEA-IS

Symbiotic Linkages	Used by
Heat (including Combined Heat and Power)	Agrotopia; Agtira; Big Akwa; Columbi Farms
Biomass	Agrotopia; Big Akwa; Columbi Farms
Nutrient-rich water	Agtira, Big Akwa, Columbi Farms
Oxygen &/or Carbon Dioxide	Big Akwa; Columbi Farms

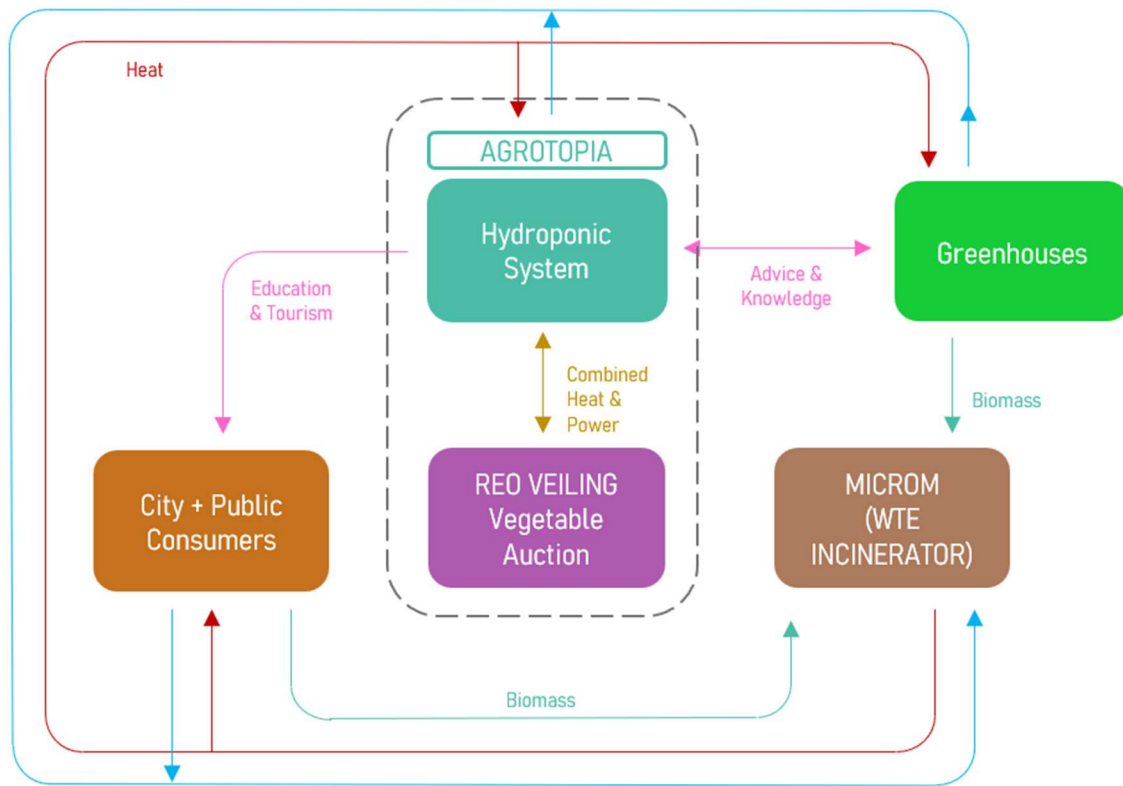


Figure 4.3a- Agrotopia Resource Exchanges

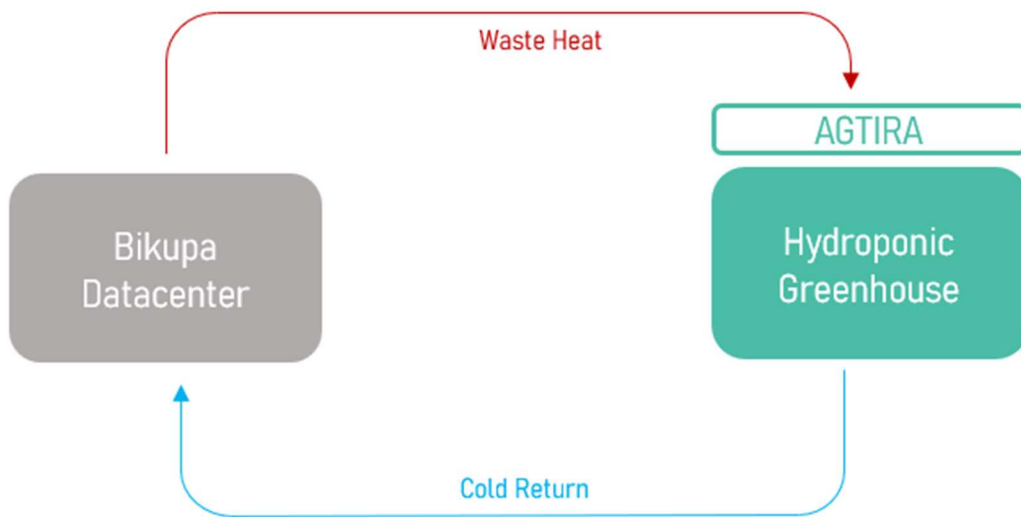


Figure 4.3b- Agtira Resource Exchanges, Boden

The Agtira headquarters includes a 10,000m² and a 12,000m² greenhouse space where cucumbers are grown. The main resource loops on site are water and nutrients in the aquaponic system, and utilization of waste heat from district heating. Several other sites are being developed or planned, including in Östersund where a 10-yr agreement with a grocery chain location has been reached to build a hydroponic facility in their parking lot that will integrate hyper-local food production while also making use of waste heat from district heating. Several similar installations have been built since the time of the interviews. Due to the urban location, curtains to prevent light pollution will be used, this is desired by the community though not currently required in existing codes as urban greenhouses are a new development in the area. Another project where Agtira will make use of existing concrete as foundation for a greenhouse is in development, with a letter of intent advanced in Boden, Sweden. This is the location of an old helicopter base and hangars, where numerous concrete landing pads can be repurposed. An innovative ISN is in development on site, close to a large river which produces three times the power that is needed for the nearest town, making it a desirable location for industries who are increasingly coming to the area. The Boden industrial center project is making a concerted effort to work on how to use energy more than once. The site has polluted ground, making it well suited for above-ground projects that don't require digging. The landing pad is 1m deep concrete, which can be drilled into to put in poles for the greenhouse structure. There is capacity for 2 hectares on each landing pad. A data center for artificial intelligence (AI) operations is operating in the old hangers, and an IS partnership will be pursued to use waste heat from their servers (Figure 4.3b). The concept is to utilize this waste heat and a solar heat panel system to heat water such that waste heat can supply what is needed for Agtira's greenhouse production.

Another Swedish company, Big Akwa, is working toward IS with RAS, and has two different projects in development, one with a paper pulp mill in Sundsvall and another with a hydrogen plant in Alby (Figure 4.5). In Sundsvall, nutrients from RAS will help feed wastewater treatment needs for the paper pulp mill, while heat from the mill will support water heating needs for RAS. These partnerships help support RAS production of Rainbow Trout, which require 45 F water year-round (3). The paper mill in Sundsvall is one of the largest industrial sites in Sweden (Interviewee). Pulp mills separate, clean, and bleach cellulose fibers, "and usually have huge wastewater treatment plants" (3). Big Akwa has agreements to conduct a pre-study there, including testing soil stability. The project at Alby, an hour to the west of Sundsvall, is a symbiosis with a hydrogen plant. Hydrogen plants electrochemically divide H₂ and O, producing O₂ as a waste product. Heat and oxygen can be utilized for RAS production, which can in turn contribute fish biomass byproducts to produce value-added products (VAP), (e.g. fish oil) within the ISN. There is significant green energy in the area including hydrogen plants and wind farms. The larger industrial site in development would be receiving a 750 MW flow. Big Akwa aims to produce 3,000 tons of fish initially in their first phase, and 6,000 tons in the second phase. For successful symbiosis, the RAS systems do not have to be immediately next to their IS partners and can be up to 2 km away and thus is a flexible solution for ISN integration as large scale industry usually has considerable distances between businesses (3). Columbi Farms (Figure 4.6)

is also part of a larger ISN in which RAS production is a symbiosis partner with whom Columbi Farms will fulfill the hydroponic half of a fully spatially decoupled form of aquaponics. The nutrient cycle is obtained via land-based fingerling production, which provides nutrient rich water for Columbi Farms which then returns clean water. An innovative and larger array of partners and resource exchanges are also a part of this ISN effort. For instance, extra biogas materials will be contributed to neighboring biogas production, which in turn may return CO₂ and energy.

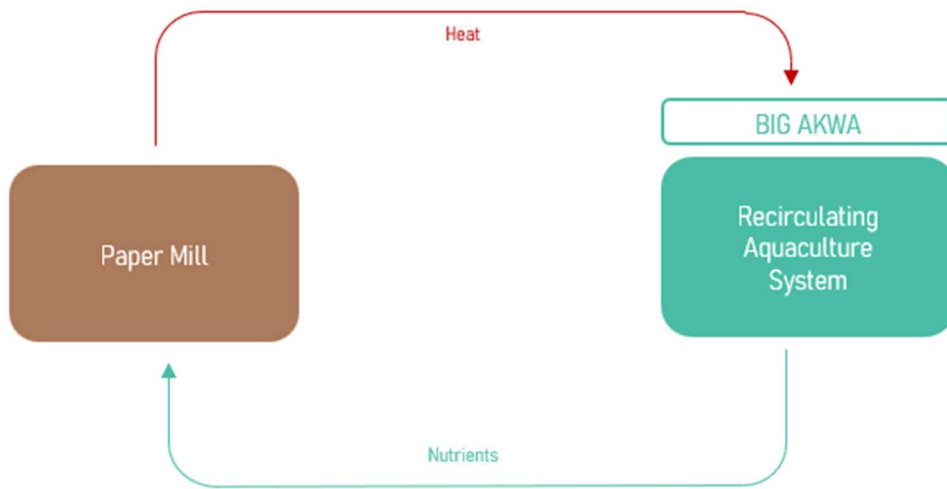


Figure 4.4a- Big Akwa Resource Exchanges, Sundsvall

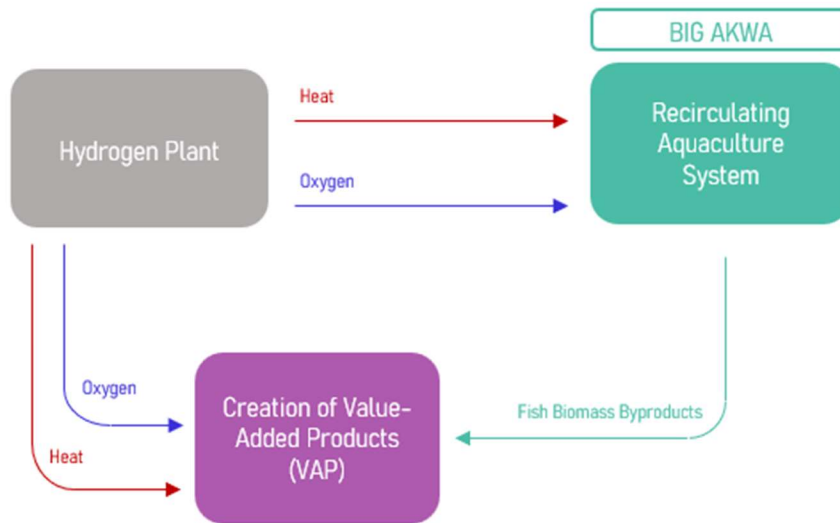


Figure 4.4b- Big Akwa IS Network, Alby

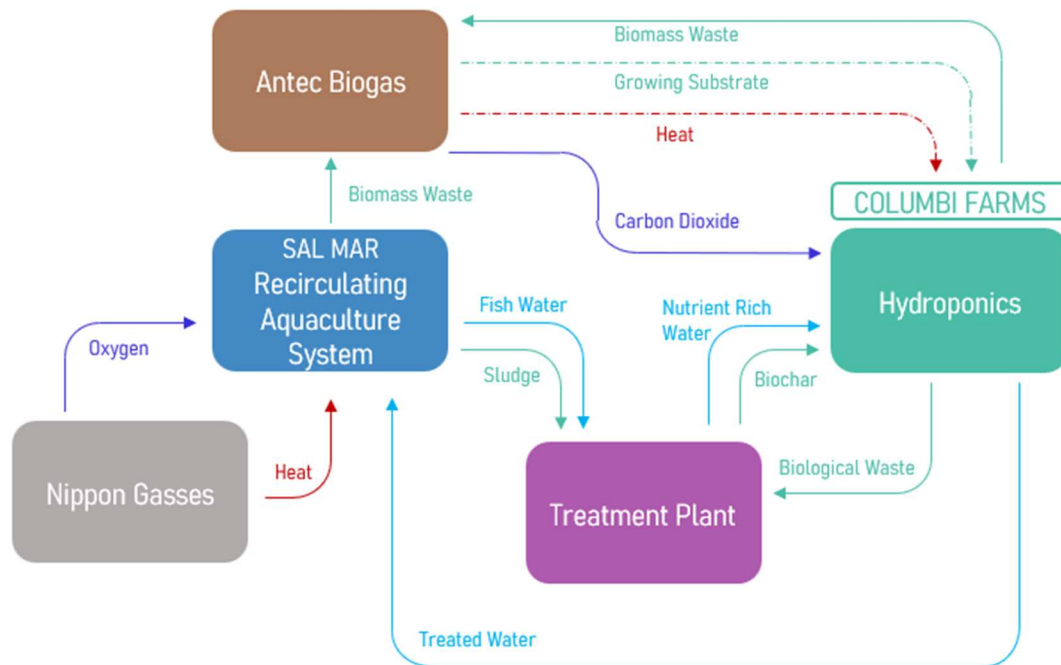


Figure 4.5- Columbi Farms Resource Exchanges

3.3 Intra- and Inter- Organizational and Institutional Context and Trends in Emerging CEA-IS

Intra-organizational (internal), inter-organizational (between firms, at a network level), and institutional (regulatory and governmental interactions) factors all contribute to CEA-IS implementation. A variety of collaborations and partnerships were formed to create the IS cases in this study. Members involved included private actors, public entities, and research groups. For example, the Agrotopia greenhouse opened in September 2021 and is co-owned by research group Inagro, and the local vegetable auction, which uses the space below the greenhouse. Columbi farms also is supported by a combination of private and public partners, though it will ultimately be a commercial ISN. Columbi Farms was established in 2020, entirely under the parent company Columbi Salmon, which was established by Refnes Laks. Refnes Laks is a family run aquaculture business partially owned (~45%) by a larger aquaculture company SalMar. The project is an “IPN” industrial innovation project, supported also by the Norwegian Research Council (NRC). Partners include Terravera (ESG responsibilities), NRC, Innovasjon Norge, NIBIO (doing growing systems research), SINTEF, Nippon Gases, and Antec (biogas), a combination of public and private actors. Biogas is already being produced in the industrial area near Trondheim where they will first establish a farm. The top-down planning approach of Columbi and the larger ISN it is within are notable given a lack of expressed challenges or

barriers with the interviewee, similar initiatives are noted in Boden and Alby, Sweden where some of the cases are planning ISN integration of CEA-IS.

Private partnerships between commercial entities are at the core of both case study examples in Sweden, though local research likely plays a role in supporting the expansion of these ISNs. In their “farming-as-service” model, Agtira has made several agreements with grocery chain locations in Sweden (multiple companies) and implemented operations at their sites accordingly. For instance, Agtira has a 10-year agreement with ICA-Maxi in their Östersund location. For their planned ISN participation in Boden, Agtira has an LOI with Hive Blockchain’s Swedish company Bikupa Datacenter and food group Greenfood to plan their partnership and build a 10,000 m² facility.

When it came to opportunities for partnerships, a few organizational trends are notable, including the growing presence of groups in Sweden, like the renewable energy company in Alby, RES, that are interested in industrial symbiosis (2). Option agreements have been signed and land is being purchased for Big Akwa’s facility there. The cooperation group in this location was started because many companies are developing facilities in this area over the next several years. A few emergent organizational factors were noted that influenced the ease and success of coordination with project partners. It was observed that many larger companies were more difficult to work with than smaller companies, and thus partner company size could be a potential challenge (2). Likewise, it was noted that a top-down planning approach to industrial symbiosis is needed, otherwise it is difficult to coordinate with all members (2). Another positive determinant for successful IS partnerships is mutual benefit (2, 3). “The trick is to find the driver,” expressed the interviewee from Big Akwa (3). This is further highlighted in a statement from the renewable energy company that Big Akwa is partnering with, RES:

"We are happy about the collaboration with Big Akwa. It is a very good example of what a circular industrial park can look like. The vision is that the companies that establish themselves should be able to contribute to and strengthen each other, and that is exactly what is happening here." -Sigrid Nord, project manager RES

An astute observation was shared from the interviewee from Big Akwa relating to the influence of potential ISN member company size, which is that money, both investment and potential savings, holds different weight for different size companies, explaining that 7 million/year USD is significant for a small company, but is not much to a large one (3). An observed moderator to this driver, however, is that there has recently been a threshold crossed such that many companies feel that they must make a sustainability effort, encouraging projects such as ISN formation (3). Unsurprisingly then, convincing large companies to be part of IS has both drivers and barriers. A driver is that they are becoming more interested because of sustainability goals and IS allows them to become more sustainable without changing as much, specifically without having to rebuild processes (3). Avoiding having to rebuild their own processes can yield both economic and sustainability benefits (3). A related caveat, and potential barrier, is that it is

difficult to change existing industrial processes (3). It is important, including for IS, to have redundancy and risk management plans if any ISN member must stop their processes (2, 3).

Regulatory barriers are a common occurrence for commercial aquaponic companies, particularly for the RAS component (Horn et al. 2023). This trend was echoed in the context of CEA-IS across the case studies. When asked about experiences with regulation, the interviewee from Agtira expressed that aquaculture on land (RAS) is not well understood by regulators in terms of environmental impact. Notably, in their region, there are “42 regulations for fish aquaculture, but you only need permission to have cows when you have more than 600!” (2). They have found that regulators do not seem to understand the concept of a closed loop, and for instance ask questions about fish feed (type, amount) but not nutrients, or ask for illogical modifications, such as the example of a very small RAS fish farm in the Östersund region which planners asked owners to surround with a concrete wall. The interviewee further noted encountering intensive regulation in Germany and Sweden. It was expressed that as CEA-IS must work within regulation, to do so the “if’s” in laws are important, and it is necessary to push back on government in some cases explaining and clarifying misunderstood concepts (2). A key moderating factor observed was that having a long track record helps in conversations with the government, and for Agtira it was previously more difficult when the company was younger. This trend is also echoed by existing studies of aquaponics (Horn et al. 2023). Interviewees from all case studies also emphasized the internal experience and knowledge diversity of their start-up and management teams, indicating their importance to forming a successful venture. The importance of persistence and communication were expressed by the interviewee, who explained that Agtira had to really push to achieve their goals despite regulatory challenges, such as in one case when they were “4 million in on investment and asked to move” the proposed location (2). Ill-fitting zoning was also expressed as a potential barrier, a recurring theme for commercial aquaponics development (Horn et al. 2023). For systems integration itself, notably with public entities, like Agtira’s envisioned integration with district heating, government and regulations were in conflict. The interviewee noted that while the city representatives were excited, the city-owned district heating company did not want to make any exceptions or special deals and wished to maintain status-quo pricing models. A rebate system was being considered as a potential workaround. Likewise, the interviewees noted that even if leaders want a system, they can’t control the greenlight from regulators, particularly that they understand and share the circularity goals of Agtira but don’t change regulatory pathways (no easier path for building permits, etc.).

Building instead in an industrial setting, at the time of the interview the Big Akwa interviewee noted that thus far they had experienced “no hindrances related to regulation” (3). Big Akwa was in a permitting and financing stage and had government approval from the county board (located in Härnösand) and were hoping to start construction in summer 2024. Similar observations were advanced among the other cases. Themes observed across the cases are summarized in Figure 4.6, below.

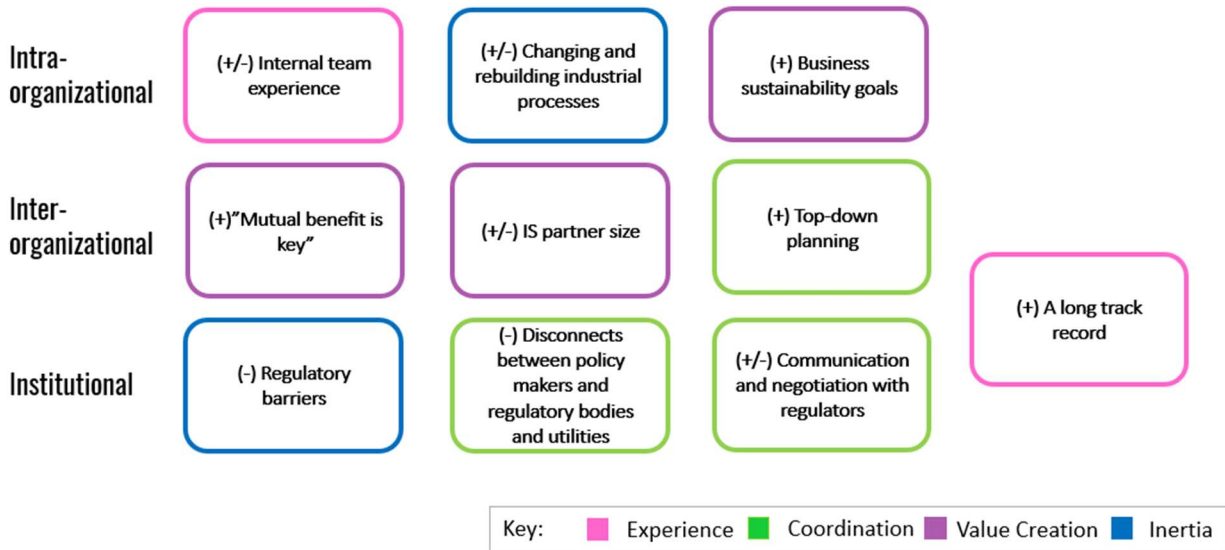


Figure 4.6- Emergent Organizational and Institutional Themes in CEA-IS

These themes reflect the interviewees’ experiences with expertise, both internally and as perceived by potential partners and institutional actors. Value creation, or the shaping of economic, strategic, or other benefit or meaning to the case organizations was also observed at both an intra- and inter-organizational level. Coordination concerns relating to the ability to work together to communicate, plan, and build mutual understanding appeared when multiple actors became involved, at both an inter-organizational and institutional level. Moreover, where difficulty in creating change due to entrenched systems arose, inertia is seen as an influential theme, impacting both policy and industrial processes.

4. Discussion

The first to identify CEA-IS as a specific typology of IS, with its own unique set of drivers, barriers, and contextual factors, this work considers the combination of CEA production techniques, particularly aquaponics and its subcomponents- a circular mode of production in its own right- with larger IS efforts, noting integration with both typical ISN as well as urban IS. Findings reflect the relevance of both CEA and IS research to this deep integration of living systems with industrial scale resource exchanges toward greater resilience and efficiency of critical food, water, and energy infrastructure. The integration of multiple resource streams with CEA offers significant efficiency potential and means of increasing local food production in northerly climates and resilience while also closing loops with energy generation and water treatment/resource-recovery processes, but also brings complexity. It is inherent that uncertainty is a “key dimension” of complexity (Lousberg et al. 2016) and thus unsurprising that successful CEA-IS implementation compels transdisciplinary efforts to diagnose and address challenges and support successful industrial and private-public partnerships for ISN formation. Leveraging existing knowledge and theory from both CEA and IS spheres is accordingly a key

imperative and can support strategies for advancement in concert with learning from existing cases studies. This study supports future research and industry efforts to successfully implement and develop CEA-IS, applying case study methods and complementary triangulation of findings to illuminate emerging themes in motivation and context; symbiotic linkages; and organizational and institutional dynamics. The identification of these dynamics advances the current standard of knowledge to set the stage for future research and development efforts, both documenting and synthesizing material on a previously underexplored, emerging IS type.

Motivations for CEA-IS across the cases included supporting local production- either through direct commercial agriculture or support of agricultural innovation and research, integration with district heat and power systems for increased efficiency, and use of RAS outputs as inputs for other industries. In all cases, symbiotic resource exchange aligned with other organization goals. Material symbiosis linkages among the CEA-IS cases included heat/energy, biomass, nutrient rich water, oxygen, and carbon dioxide. Food is produced by all cases, and symbiotic linkages indicate the Food-Water-Energy Nexus as a relevant lens to these circular economy (CE) informed exchanges among ISNs including CEA constituents, as the critical infrastructure sectors of food, water, and energy are involved in IS toward circular sustainability and local resilience. These sectors reflect trends observed across broader IS research; though appear heightened by the involvement of CEA production which directly implicates all three internally even before synergetic solutions are pursued (Horn et al. 2024, *forthcoming*). Power plants are among the partners occurring most often in IS case studies and are well documented for their ability to act as an anchor, motivating other companies to partner in ISN (Chertow and Miyata 2010; Korhonen 2001a; Neves et al. 2020). This is directly observable in the Alby ISN where Big Akwa is developing their RAS integration. Moreover, the Boden ISN project where Agtira plans to integrate a greenhouse is similarly anchored by hydropower production on the nearby river, which is the primary draw of industries to the area who are then making further efforts for cascading energy use through IS re-use of this hydropower. Integration with electric or heat flows is a strong modifier of CEA sustainability, as resource demands for lighting and heat are among the primary inputs needed to unlock the full resilience and sustainability potential of CEA production, particularly in aquaponics, where water and nutrients are often already relatively well modulated in system design. Through agriculture sectors, both crop and livestock production are observed regularly among broader IS cases (Neves et al. 2020), indoor/ greenhouse and RAS integration are particularly apt for ISN integration due to their capacity for urban and industrial park integration while also potentially benefiting more intensely from the lightening of their operational footprints. Linkages with wastewater treatment, particularly biological treatment processes between multiple constituents were a strong feature of CEA-IS cases in ISN involving RAS systems, which is unsurprising as these systems produce nutrient-rich wastewater, and variations of water and nutrient processing are a core element of aquaponic systems. This aligns with larger IS trends, as “the activities related to waste and water management and recycling ... occupy a prominent place in cases of industrial symbiosis not only to establish the link between industries but also as an active part in the chain of transformation of waste into new products” (Neves et al. 2020). The exchange of water and nutrients using

resource recovery processes in IS can simultaneously circumvent the need for input nutrients and reduce water demand while preventing pollution to natural environments.

Two primary **location contexts** were consistent among the cases. Urban and peri-urban locations tended to align with use of underutilized spaces for greenhouses and were more likely to integrate with district resources like heat, these were generally hydroponics operations. Industrial settings correlate with CEA-IS involving RAS systems and tended to pursue co-location with typical IS exchanges between multiple industries. These cases demonstrated more emphasis on nutrient and water related exchanges, with RAS or aquaponics playing a role as an alternative to industrial wastewater treatment. IS practices can make use of local resources, whether from public or private organizations, demonstrating potential for a range of scales and integrative contexts. While IS is traditionally viewed as occurring in industrial park settings, urban integration brings potential for symbiosis with other resources, such as district heating, as well as the use of potentially underutilized urban spaces which may be already paved, or even polluted, wherein CEA allows for soilless urban food production regardless of local soil conditions. Cities and industries “share some concerns with regard to sustainability, such as high resource consumption, increased greenhouse gas emissions, increased waste and cost of waste treatment” (Neves et al. 2020) as discussed also by (Dong et al. 2016; Simboli et al. 2017; Sun et al., 2017). If IS is extended to include exchanges with urban resources, both can benefit, as is increasingly discussed (Dong et al. 2017; Kim et al. 2018; Ohnishi et al. 2017; Neves et al. 2020), sometimes under the term Urban Symbiosis (Ness and Xing 2017; Van Berkel et al. 2009b, 2009a; Neves et al. 2020), as well as among broader CE discourse (Horn and Proksch 2022). Urban symbiosis has been defined as “the use of by-products (wastes) from cities (or urban areas) as alternative raw materials or energy sources in industrial operations... based on the synergistic opportunity arising from the geographic proximity of urban waste sources and potential industrial users through the transfer of physical resources (‘waste materials’) for environmental and economic benefit” (Van Berkel et al., 2009b). Studies of urban symbiosis (Dong et al., 2013; Ohnishi et al., 2017; Van Berkel et al., 2009a) have sought to identify its impacts, and found that that these include economic and environmental benefits, reducing resource use, CO₂ emissions, and waste generation (Afshari et al. 2018; Dong et al., 2013; Ohnishi et al., 2017; Dong et al., 2016; Ohnishi et al., 2017; Cao et al. 2017; Dong et al. 2014; Van Berkel et al., 2009a; Neves et al. 2020). Moreover, these are observed to be enough to create a net positive effect (Afshari et al., 2018; Fang et al. 2017) so as to be worth it despite potential high costs of symbiosis formation such as “in the exchange of waste heat and energy between industries and communities that requires the construction of necessary infrastructure, and in addition to these costs there is also the uncertainty of supplying these wastes in sufficient quantity and quality to meet the needs of communities” (Neves et al. 2020).

Beyond material aspects of symbiosis, multiple **levels of IS operations** influence implementation success and necessitate analysis accordingly (Andrews 2001; Boons et al. 2011; Walls and Paquin 2015). Walls and Paquin, in 2015, consider there to be four, and looked at “the drivers, outcomes, and influencing factors associated with IS,” reviewing organizational

perspectives in IS literature “through institutional, network/system, organizational, and individual levels of analysis” (Walls and Paquin 2015), factors also considered relevant among other IS studies (Ristola and Mirata 2007, Walls and Paquin 2015, Jiao and Boons 2014, Faria et al. 2021). These were preliminarily considered for CEA-IS in this work, with the exception of the individual level, which may be less essential for this exploratory cross case synthesis, though certainly should be considered further in future work. There is still much unexplored at organizational and institutional levels of analysis, “especially regarding decisions firms make to engage in IS” (Walls and Paquin 2015). Organizational theories include “theories of bureaucracies, organizational structure and functions, excellence in organizational performance, and interorganizational partnerships” (Yin 2018), as well as “social networks, institutional theory, and environmental strategy” among others (Walls and Paquin 2015). As interest in IS has grown, researchers progressively encountered “thwarted IS efforts, even when technically solutions were viable” (Walls and Paquin 2015), driving a focus shift toward the influence of social factors in IS (Walls and Paquin 2015; Faria et al. 2021), including collaboration and relationships, trust, communication, learning, coordination, and more, and increasing application of organizational theory to interpret these phenomena (Walls and Paquin 2015; Hewes and Lyons 2008; Gibbs 2003; Branson 2011; Spekink 2013; Faria et al. 2021). Considering organizational perspectives can help to illuminate the complex dynamics involved in the implementation of IS (Faria et al. 2021), and particularly as interest in IS to reduce environmental impacts has grown “an organizational research approach to IS is needed to understand how environmental and economic value can be created” (Walls and Paquin 2015). Nonetheless, “comparatively little work on IS has been done at an organizational-level perspective” (Walls and Paquin 2015), and little has changed in this regard since their assessment. Notably, beyond intra-organizational considerations, inter-organizational perspectives are also a core consideration for IS, and it has been expressed that the “richest contributions made toward organizational theory in the IS literature are without doubt at the network-level of analysis, as every IS system is a network of relationships and exchanges” (Walls and Paquin 2015). Accordingly, consideration of stakeholder theory plays a central role in analysis of IS, shaping both external pressures and potential collaborations (Walls and Paquin 2015). Stakeholder support is, unsurprisingly, found to be a necessary factor for IS development (Chertow, 2000; Panyathanakun et al. 2013; Tudor et al. 2007; Zhang and Wang 2014; Walls and Paquin 2015), while differences among stakeholder objectives can drive conflicts and shape barriers to implementation (Levänen & Hukkinen 2013). Stakeholders may include ISN co-participants, the public, and government actors/institutions. Accordingly, consideration of institutional perspectives and theory are also essential to the analysis of IS, including by lending insight into how organizations try to influence institutional norms, and how IS can develop organically, and IS studies in turn may contribute to institutional literature by illuminating dynamics of the diffusion and adaptation of practices among actors due to the unique collaborative practices and collective goals inherent to ISN creation (Walls and Paquin 2015). Existing institutional analysis in IS literature has “explored the roles of (a) government policy and (b) governmental agencies in initiating and supporting IS development, though there was some debate over usefulness of government policy versus a free market approach” (Walls and

Paquin 2015), however more research is also needed to unpack the influences of institutional forces like policy and government engagement (Doménech and Davies 2011; Ehrenfeld and Gertler 1997), which can act as both drivers and barriers.

The **factors observed** in this exploratory cross-case synthesis influence CEA-IS at these intra-organizational, inter-organizational (network), and institutional levels, reflecting larger themes of experience, inertia, value creation, and coordination (Figure 4.6). The consideration of **experience** as an influential factor to success was evident at all levels of the analysis. At an intra-organizational level, internal team expertise was seen as an important contributor to success (3,4). Likewise, at an inter-organizational and institutional level, a track record of experience and success as a business was an influential factor to partnership formation and regulatory/governmental support (interviews), findings which echo broader trends for both aquaponics and IS. Perceived novelty of IS can form a barrier to partnerships and institutional support (Paquin and Howard-Grenville 2012), while it has been observed that “it seems likely that IS exchanges involving firms with prior IS experience are more likely to create firm- and policy-level economic and environmental value” (Paquin et al. 2015). Experience closely correlates with the concept of legitimacy, which can mitigate inter-organizational decisions (Paquin and Howard-Grenville 2013) as well as regulatory pressure (Gibbs and Deutz 2007), as the legitimacy of IS among firms or in collaboration with government agencies informs its perceived viability (Walls and Paquin 2015). Moreover, the perception of **value creation** was a core theme among emergent organizational and institutional factors impacting the studied cases. These included increasing motivations for IS enacted at an intra-organizational level, but potentially driven by broader sustainability movements, something which potentially implicates institutional forces. Moreover, at an inter-organizational level, the importance of mutual benefit- and the creation of value to stakeholders therein, was a key factor to CEA-IS implementation. While intra-organizational action has been a considerable focus of literature (Etzion 2007), IS (Chertow 2000) can create additional value that would be unavailable via intra-organizational actions alone (Paquin et al. 2015). Indeed, collective value is an essential consideration for the analysis of dynamics surrounding IS and its outcomes, all of which, “whether economic, environmental, innovation, or learning—ha[ve] to do with how firms create collective value” (Walls and Paquin 2015). In this study, the size of potential resource sharing partners was a notable modulator of such perceived potential benefit and creation of value, particularly as this informs the magnitude of resources and economic implications to a given firm. Accordingly, Paquin et al. 2015 found that both firm size and experience played a role in value creation via IS, noting that “exchanges involving larger volumes of material resources are more likely to create firm- and policy-level value... [and] firms with prior industrial symbiosis experience are more likely to create firm-level value” (Paquin et al. 2015).

Furthermore, intra-organizational IS can become a means of value creation “in response to regulatory constraints” (Paquin et al. 2015), presenting an interacting factor with institutional inertia. Inertia, or lock-in, can result from resource or institutional barriers, preventing actors from adopting new practices (Gregson et al. 2012; Jacobsen 2007; Korhonen 2004a, b; Posch et

al. 2011; Wolf et al. 2007; Walls and Paquin 2015). IS likewise provides a way “to proactively address opportunities created from increasing regulatory restriction” to remain competitive and create value while remaining environmentally responsible, and “in particular, such ‘win-win’ benefits may be reaped through interfirm action as well as internally” (Paquin et al. 2015). CEA-IS may be both driven and restricted by factors shaped through **inertia**, including the difficulties of changing and rebuilding existing industrial processes at an intra-organizational level, and institutional barriers such as regulation which may arise from outdated policies, misunderstanding or lack of regulatory pathways for new technologies and symbiotic approaches, and zoning challenges. The difficulty of modifying industrial processes and technological infrastructure can both block IS by posing logistical challenges, and drive IS for instances in which partnering with other industries circumvents the need for making significant intra-organizational changes in response to new regulations, resource limitations, or other drivers of IS. CEA-IS may hold a similarly complex relationship with resilience, both potentially bolstering the potential resilience of the ISN and local food, water, and energy systems as well as necessitating consideration of process redundancy and risk management to counterbalance the risks of added complexity such that if one organization were to pause production, for instance, others could readjust and continue operations in the interim. Such concerns over creating dependency are regularly observed among broader IS literature (Desrochers 2001; Miller and Mukherji 2010; Walls and Paquin 2015). Resilient systems can absorb disruptions to handle shock, something which can be achieved through IS’ reduction of dependence on external resources (Chopra and Khanna 2012; Walls and Paquin 2015). Appropriate redundancy of ISN design is however necessary to ensure that local resilience via symbiosis does not come at the expense of overall stability of the network.

Coordination was likewise a core theme across emergent organizational and institutional factors affecting CEA-IS implementation. At an inter-organization level, coordination and planning of CEA-IS partnerships were a key factor impacting success, and case studies demonstrated the benefits of top-down planning approaches (interviews). Stakeholders shaping these arrangements could be government actors, or a particular firm that acts as a core “anchor” or intermediary in ISN formation. In an “anchor-tenant” model, anchor firms drive symbiosis by creating consistent, large by-product flows and shaping infrastructure for others (Chertow 2000; Wang et al. 2009; Costa and Ferrão 2010; Walls and Paquin 2015) and play a core role in coordinating the entire ISN (Korhonen 2001b, 2005). Other intermediary types may focus primarily on coordination and communication (Vernay et al. 2013) and include “intermediaries include municipalities, business association, or brokers, as well as NGOs (nongovernmental organizations), steering committees or advisory boards, regional programs, and so on” (Walls and Paquin 2015). Intermediary stakeholders can help create trust through ongoing dialogue and provision of system support (Ashton 2008; Chertow and Ehrenfeld 2012; Baas and Huisingh 2008; Hewes and Lyons 2008; Paquin and Howard-Grenville 2012; Walls and Paquin 2015). Public-private partnerships may also be a promising route for top-down CEA-IS partnership planning for the implementation of new ISNs, as for implementation of other sustainable technologies these have been observed as a means to “utilize various sectors’

resources” to reduce risks and uncertainty while forming shared knowledge and resource bases and increasing resilience to project disruptions (Xue et al. 2021). Such approaches could be especially valuable to overcome the challenges of coordination with and among institutional stakeholders including governmental actors and regulators as described by the CEA-IS cases studied. Previous IS research development (including Alfaro and Miller 2014; Costa and Ferrão 2010; Ashton 2011; Behera et al. 2012; Park et al. 2008) has suggested that the establishment of “positive feedback loops between government, industry, and stakeholders can support IS development,” however more can be done to investigate relationships between IS firms and government actors in ISN formation (Walls and Paquin 2015).

It is generally agreed within IS research that government involvement is an important determinant of favorable institutional conditions (Boons et al. 2011; Boons and Spekkink 2012; von Malmborg 2004, 2007; Liu et al. 2012; Walls and Paquin 2015). In some cases, particularly a study of firms in the United Kingdom, regulatory constraints aimed at environmental impact reduction, though potentially constraining, helped “many firms engaged in IS exchanges to adapt to these regulatory constraints in ways which created economic and environmental value,” a dynamic which may reflect the idea discussed among strategists that such regulation changes can help industry actors to question and innovate business practices, investing to become more competitive (Paquin et al. 2015). There is a need for further studies to illuminate what policy designs drive or prevent IS implementation success (Walls and Paquin 2015), including for particular consideration of CEA-IS drivers and barriers which may build on the initial findings in this cross-case synthesis.

The cases considered in this work were all concentrated in a Northern European context and seem to illustrate that this region is at the leading edge of CEA-IS implementation. Particularly in Sweden, several more CEA-IS projects have been developed in the last year. The emergence of CEA-IS in this region seems to reflect the combined forces of growing interest and implementation of CEA- including RAS implementation- circular economy efforts, and industrial symbiosis in Europe, all of which reflect interconnected sustainability aims, unsurprising given the important role of the European Union in bolstering sustainable development practices (Szopik-Depczyńska et al. 2017; Neves et al. 2020). Neves et al. 2020 reviewed all existing published IS case studies, and observed that Europe ranked second among these with 78 studies (representing 37.5% as compared to 9.1%, or 19 studies in North America), furthermore, “the countries of North and North-West Europe account for the majority of published studies, corresponding to 72% of the total European studies,” (Neves et al. 2020) reflecting circular economy-favorable policy implementation in these regions (Bassi and Dias 2019), a dynamic seemingly reflected in the location of CEA-IS operations as well. The role of policy is notable, and the contrast of North America, where existing regulations, including the US Resource Conservation and Recovery Act which defines many wastes as hazardous, tend not to encourage IS, and existing examples are dispersed (Gibbs and Deutz 2007; Neves et al. 2020). Contrastingly, consideration of circular economy in Europe “dates from the 1970s” (Neves et al. 2020) and has been considerably developed in the time since (Bassi and Dias 2019; Colombo et

al. 2019; Fura et al. 2017; Szopik-Depczyńska et al. 2017), including several notable research funding efforts [expand?]. IS has been advanced as a key approach to resource use efficiency and eco-development on multiple occasions over the last decade in EU communications (European Commission 2018b, 2015; European Commission 2011; OECD 2010). Environmental qualities of other regional critical infrastructure, often a reflection of larger political environments, help shape suitability for CEA-IS and may offer insights for other regions. The use of hydropower, such as in Boden where CEA-IS is in development, can form an anchor for ISNs. Notably Sweden, where several of the cases were located has a strong dependence on hydropower (42% of total energy production), while Norway, where Columbi's CEA-IS effort is underway, "has a strong hydropower industry, with a higher dependence than other countries, that produces energy equal to 93% of the country's energy generation in the form of low-cost and clean electricity" (Xue et al. 2021). As CEA-IS operates at the intersection of critical food, water, and energy infrastructural systems, the way that these are regionally managed may play a key, though currently underexplored, role in their implementation and success, meriting further study. It is vital to consider CEA-IS through an interdisciplinary lens, as current IS or CEA research alone are insufficiently integrated to reflect the complexity of CEA-IS implementation for which agricultural considerations, technological innovation, and IS considerations interact in novel and previously underexplored ways. Technological approaches to agriculture and IS both begin to reframe and localize larger nutrient, water, and energy flows involved in conventional food production, presenting both opportunities for sustainability and new logistical challenges involving both public and private stakeholders. This is highlighted uniquely by a burgeoning trend of CEA-IS, which will hopefully continue to proliferate in coming years as influential factors are increasingly illuminated and barriers ironed-out. Future work may build on this study's initial findings and expand this area of scholarship to further support environmental sustainability and resilience of local food production and green industry.

5. Conclusion

This exploratory cross-case synthesis considered multiple existing and planned CEA-IS operations to clarify their motivations, how they are formed and organized through material, organizational and institutional lenses, and emergent trends in factors in these categories that may influence their implementation success. Setting the stage for further research of CEA-IS operations, findings shed light on emergent practices, such as resource exchanges of nutrients, water, and energy while food is produced through CEA methods in concert with other industries or urban practices, and contextual factors that act as drivers and barriers, reflecting the importance of themes including value creation, coordination, inertia, and experience at intra-organizational, inter-organizational, and institutional levels. Insights support the further development and implementation CEA-IS, and further supportive research, to foster its contribution to regenerative food systems and the sustainability and resilience of critical infrastructures of the Food-Water-Energy nexus- food, water, and energy systems via symbiotic resource exchanges. Future research can leverage this initial study and broaden data collection through survey methods, involving a wider range of stakeholders, cases, or regions, depending

on aims. Further interviews may help expand insights, as in this study interview scope was limited to keep with its exploratory nature, but deeper findings may be possible with expanded interviews and the possibility to further assess influential factors, or even focus on specific factors in depth, building on the emerging factors and themes identified in this exploratory work. Moreover, further study of the multi-faceted dynamics at play in CEA-IS with public infrastructural systems may offer valuable insight for other actors seeking to advance such strategies leveraging the intersection of critical food, water, and energy systems. CEA-IS represents the exciting possibilities of innovation when circularity and symbiotic strategies are pursued by multiple actors in concert. Its implementation and success may be bolstered considerably by multi-modal research considering the influential role of institutional and organizational factors in concert with material and technical considerations, with much yet to be learned for the success of this emergent symbiosis type and its role in addressing vital regenerative aims, translating local circularity into global sustainability.

6. Funding

Valle Scholarship and Scandinavian Exchange Program

7. Acknowledgements

With appreciation to the NTNU Department of Architecture and Planning and C.L. for infrastructural support during the preparation of this study.

Chapter 4 References

- Afshari, H., Jaber, M. Y., & Searcy, C. (2018). Extending industrial symbiosis to residential buildings: A mathematical model and case study. *Journal of Cleaner Production*, 183, 370–379. <https://doi.org/10.1016/j.jclepro.2018.02.148>
- Alfaro, J., & Miller, S. (2014). Applying Industrial Symbiosis to Smallholder Farms. *Journal of Industrial Ecology*, 18(1), 145–154. <https://doi.org/10.1111/jiec.12077>
- Allan, T., Keulertz, M., & Woertz, E. (2015). The water–food–energy nexus: An introduction to nexus concepts and some conceptual and operational problems. *International Journal of Water Resources Development*, 31(3), 301–311. <https://doi.org/10.1080/07900627.2015.1029118>
- Andrews, C. J. (2000). Building a Micro Foundation for Industrial Ecology. *Journal of Industrial Ecology*, 4(3), 35–51. <https://doi.org/10.1162/108819800300106375>
- Ashton, W. (2008). Understanding the Organization of Industrial Ecosystems: A Social Network Approach. *Journal of Industrial Ecology*, 12(1), 34–51. <https://doi.org/10.1111/j.1530-9290.2008.00002.x>
- Ashton, W. S. (2011). Managing Performance Expectations of Industrial Symbiosis. *Business Strategy and the Environment*, 20(5), 297–309. <https://doi.org/10.1002/bse.696>
- Baas, L. W., & Huisingh, D. (2008). The synergistic role of embeddedness and capabilities in industrial symbiosis: Illustration based upon 12 years of experiences in the Rotterdam Harbour and Industry Complex. *Progress in Industrial Ecology*, 5(5–6), 399–421. <https://doi.org/10.1504/PIE.2008.023408>
- Bassi, F., & Dias, J. G. (2019). The use of circular economy practices in SMEs across the EU. *Resources, Conservation and Recycling*, 146, 523–533. <https://doi.org/10.1016/j.resconrec.2019.03.019>
- Behera, S. K., Kim, J.-H., Lee, S.-Y., Suh, S., & Park, H.-S. (2012). Evolution of ‘designed’ industrial symbiosis networks in the Ulsan Eco-industrial Park: ‘Research and development into business’ as the enabling framework. *Journal of Cleaner Production*, 29–30, 103–112. <https://doi.org/10.1016/j.jclepro.2012.02.009>

- Boons, F., Spekkink, W., & Mouzakitis, Y. (2011). The dynamics of industrial symbiosis: A proposal for a conceptual framework based upon a comprehensive literature review. *Journal of Cleaner Production*, 19(9), 905–911. <https://doi.org/10.1016/j.jclepro.2011.01.003>
- Boons, F., & Spekkink, W. (2012). Levels of Institutional Capacity and Actor Expectations about Industrial Symbiosis. *Journal of Industrial Ecology*, 16(1), 61–69. <https://doi.org/10.1111/j.1530-9290.2011.00432.x>
- Branson, R. (2011). Bilateral Industrial Symbiosis. An assessment of its potential in New South Wales to deal sustainably with manufacturing waste.
- Buckwell, A., Nadeu, E., 2016. Nutrient Recovery and Reuse (NRR) in European Agriculture. (RISE, Rural Invest. Support Eur. 92).
- Burga, R., Leblanc, J., & Rezania, D. (2020). Exploring Student Perceptions of Their Readiness for Project Work: Utilizing Social Cognitive Career Theory. *Project Management Journal*, 51(2), 154–164. <https://doi.org/10.1177/8756972819896697>
- Cao, X., Wen, Z., Tian, H., Clercq, D., & Qu, L. (2018). Transforming the Cement Industry into a Key Environmental Infrastructure for Urban Ecosystem: A Case Study of an Industrial City in China. *Journal of Industrial Ecology*, 22(4), 881–893. <https://doi.org/10.1111/jiec.12638>
- Carroll, L. J., & Rothe, J. P. (2010). Levels of reconstruction as complementarity in mixed methods research: A social theory-based conceptual framework for integrating qualitative and quantitative research. *International Journal of Environmental Research and Public Health*, 7(9), 3478–3488. <https://doi.org/10.3390/ijerph7093478>
- Chance, E., Ashton, W., Pereira, J., Mulrow, J., Norberto, J., Derrible, S., & Guilbert, S. (2018). The Plant—An experiment in urban food sustainability. *Environmental Progress & Sustainable Energy*, 37(1), 82–90. <https://doi.org/10.1002/ep.12712>
- Chertow, M. R. (2000). INDUSTRIAL SYMBIOSIS: Literature and Taxonomy. *Annual Review of Energy & the Environment*, 25(1), 313. <https://doi.org/10.1146/annurev.energy.25.1.313>
- Chertow, M., & Miyata, Y. (2011). Assessing collective firm behavior: Comparing industrial symbiosis with possible alternatives for individual companies in Oahu, HI. *Business Strategy and the Environment*, 20(4), 266–280. <https://doi.org/10.1002/bse.694>
- Chertow, M., & Ehrenfeld, J. (2012). Organizing Self-Organizing Systems. *Journal of Industrial Ecology*, 16(1), 13–27. <https://doi.org/10.1111/j.1530-9290.2011.00450.x>
- Chopra, S. S., & Khanna, V. (2012). Toward a network perspective for understanding resilience and sustainability in industrial symbiotic networks. 1–6. <https://doi.org/10.1109/ISSST.2012.6227987>
- Colombo, L. A., Pansera, M., & Owen, R. (2019). The discourse of eco-innovation in the European Union: An analysis of the Eco-Innovation Action Plan and Horizon 2020. *Journal of Cleaner Production*, 214, 653–665. <https://doi.org/10.1016/j.jclepro.2018.12.150>
- Costa, I., & Ferrão, P. (2010). A case study of industrial symbiosis development using a middle-out approach. *Journal of Cleaner Production*, 18(10), 984–992. <https://doi.org/10.1016/j.jclepro.2010.03.007>
- Daft, R. (1983). Learning the Craft of Organizational Research, *The Academy of Management Review*, 8(4), 539-546.
- Desrochers, P. (2001). Cities and industrial symbiosis: Some historical perspectives and policy implications. *Journal of Industrial Ecology*, 5, 29-44. <https://doi.org/10.1162/10881980160084024>
- Doménech, T., & Davies, M. (2011). The role of embeddedness in industrial symbiosis networks: Phases in the evolution of industrial symbiosis networks. *Business Strategy and the Environment*, 20, 281-296.
- Dong, H., OHNISHI, S., FUJITA, T., YONG GENG, FUJII, M., & LIANG DONG. (2014). Achieving carbon emission reduction through industrial & urban symbiosis: A case of Kawasaki. *Energy (Oxford)*, 64, 277–286. <https://doi.org/10.1016/j.energy.2013.11.005>
- Dong, L., Zhang, H., Fujita, T., Ohnishi, S., Li, H., Fujii, M., & Dong, H. (2013). Environmental and economic gains of industrial symbiosis for Chinese iron/steel industry: Kawasaki's experience and practice in Liuzhou and Jinan. *Journal of Cleaner Production*, 59, 226–238. <https://doi.org/10.1016/j.jclepro.2013.06.048>
- Dong, L., Fujita, T., Dai, M., Geng, Y., Ren, J., Fujii, M., Wang, Y., & Ohnishi, S. (2016). Towards preventative eco-industrial development: An industrial and urban symbiosis case in one typical industrial city in China. *Journal of Cleaner Production*, 114, 387–400. <https://doi.org/10.1016/j.jclepro.2015.05.015>

- Dong, L., Liang, H., Zhang, L., Liu, Z., Gao, Z., & Hu, M. (2017). Highlighting regional eco-industrial development: Life cycle benefits of an urban industrial symbiosis and implications in China. *Ecological Modelling*, 361, 164–176. <https://doi.org/10.1016/j.ecolmodel.2017.07.032>
- Easton, G. (2010). Critical realism in case study research. *Industrial Marketing Management*, 39(1), 118–128. <https://doi.org/10.1016/j.indmarman.2008.06.004>
- Ehrenfeld, J., & Gertler, N. (1997). Industrial Ecology in Practice: The Evolution of Interdependence at Kalundborg. *Journal of Industrial Ecology*, 1(1), 67–79. <https://doi.org/10.1162/jiec.1997.1.1.67>
- Ehrenfeld, J. R. (2000). Industrial Ecology: Paradigm Shift or Normal Science? *The American Behavioral Scientist (Beverly Hills)*, 44(2), 229–244. <https://doi.org/10.1177/00027640021956189>
- Ehrenfeld, J. (2004). Industrial ecology: A new field or only a metaphor? *Journal of Cleaner Production*, 12(8), 825–831. <https://doi.org/10.1016/j.jclepro.2004.02.003>
- Erzberger, C., & Prein, G. (1997). Triangulation: Validity and empirically-based hypothesis construction. *Quality & Quantity*, 31(2), 141–154. <https://doi.org/10.1023/A:1004249313062>
- Etzion, D. (2007). Research on Organizations and the Natural Environment, 1992-Present: A Review. *Journal of Management*, 33(4), 637–664. <https://doi.org/10.1177/0149206307302553>
- European Commission, 2011. A Resource-Efficient Europe – Flagship Initiative of the Europe 2020 Strategy. Brussels <http://ec.europa.eu/resource-efficienteurope/> (accessed 01.08.12).
- European Commission, (2015). Closing the loop - An EU action plan for the Circular Economy.
- European Commission. Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 Amending Directive 2008/98/EC on Waste (Text with EEA Relevance), CONSIL, EP, 150 OJ L (2018). <http://data.europa.eu/eli/dir/2018/851/oj/eng>
- Fang, K., Dong, L., Ren, J., Zhang, Q., Han, L., & Fu, H. (2017). Carbon footprints of urban transition: Tracking circular economy promotions in Guiyang, China. *Ecological Modelling*, 365, 30–44. <https://doi.org/10.1016/j.ecolmodel.2017.09.024>
- Faria, E., Caldeira-Pires, A., & Barreto, C. (2021). Social, Economic, and Institutional Configurations of the Industrial Symbiosis Process: A Comparative Analysis of the Literature and a Proposed Theoretical and Analytical Framework. *Sustainability*, 13(13), 7123-. <https://doi.org/10.3390/su13137123>
- Farquhar, J., Michels, N., & Robson, J. (2020). Triangulation in industrial qualitative case study research: Widening the scope. *Industrial Marketing Management*, 87, 160–170. <https://doi.org/10.1016/j.indmarman.2020.02.001>
- Flyvbjerg, B. (2006). Five Misunderstandings About Case-Study Research. *Qualitative Inquiry*, 12(2), 219–245. <https://doi.org/10.1177/1077800405284363>
- Fura, B., Wojnar, J., & Kasprzyk, B. (2017). Ranking and classification of EU countries regarding their levels of implementation of the Europe 2020 strategy. *Journal of Cleaner Production*, 165, 968–979. <https://doi.org/10.1016/j.jclepro.2017.07.088>
- Gibbs, D. (2003). Trust and Networking in Inter-firm Relations: The Case of Eco-industrial Development. *Local Economy*, 18(3), 222–236. <https://doi.org/10.1080/0269094032000114595>
- Gibbs, D., & Deutz, P. (2007). Reflections on implementing industrial ecology through eco-industrial park development. *Journal of Cleaner Production*, 15(17), 1683–1695. <https://doi.org/10.1016/j.jclepro.2007.02.003>
- Gregson, N., Crang, M., Ahamed, F. U., Akter, N., Ferdous, R., Foaisal, S., & Hudson, R. (2012). Territorial Agglomeration and Industrial Symbiosis: Sitakunda-Bhatiary, Bangladesh, as a Secondary Processing Complex. *Economic Geography*, 88(1), 37–58. <https://doi.org/10.1111/j.1944-8287.2011.01138.x>
- Hamam, M., Spina, D., Raimondo, M., Di Vita, G., Zanchini, R., Chinnici, G., Tóth, J., & Mario, D. (2023). Industrial symbiosis and agri-food system: Themes, links, and relationships. *Frontiers in Sustainable Food Systems*. <https://doi.org/10.3389/fsufs.2022.1012436>
- Hamilton, H. A., Brod, E., Hanserud, O. S., Gracey, E. O., Vestrum, M. I., Bøen, A., Steinhoff, F. S., Müller, D. B., & Brattebø, H. (2016). Investigating Cross-Sectoral Synergies through Integrated Aquaculture, Fisheries, and Agriculture Phosphorus Assessments: A Case Study of Norway. *Journal of Industrial Ecology*, 20(4), 867–881. <https://doi.org/10.1111/jiec.12324>
- Hammersley, M. (2008). Troubles with Triangulation, in (Ed) M. Bergman, *Advances in Mixed Methods Research*, London, Sage, pp. 22-36.

- Helenius, J., Hagolani-Albov, S. E., & Koppelmäki, K. (2020). Co-creating Agroecological Symbioses (AES) for Sustainable Food System Networks. *Frontiers in Sustainable Food Systems*, 4. <https://www.frontiersin.org/articles/10.3389/fsufs.2020.588715>
- Hewes, A. K., & Lyons, D. I. (2008). The Humanistic Side of Eco-Industrial Parks: Champions and the Role of Trust. *Regional Studies*, 42(10), 1329–1342. <https://doi.org/10.1080/00343400701654079>
- Hoffman, A. J. (2003). LINKING SOCIAL SYSTEMS ANALYSIS TO THE INDUSTRIAL ECOLOGY FRAMEWORK. *Organization & Environment*, 16(1), 66–86. <https://doi.org/10.1177/1086026602250219>
- Horn, E., & Proksch, G. (2020). Building an Ecosystem: Integrating Rooftop Aquaponics with a Brewery to Advance the Circular Economy.
- Horn, E., & Proksch, G. (2022). Symbiotic and Regenerative Sustainability Frameworks: Moving Towards Circular City Implementation. *Frontiers in Built Environment*, 7. <https://www.frontiersin.org/article/10.3389/fbuil.2021.780478>
- Horn, E., Joyce, A., Chowdhury, R., Caputo, S., Jacobs, B., & Winkler, M. (2023). Translating Environmental Potential to Economic Reality: Assessment of Commercial Aquaponics through Sustainability Transitions Theory. *Circular Economy and Sustainability*. <https://doi.org/10.1007/s43615-023-00291-0>
- Jacobsen, N. B. (2007). Do social factors really matter when companies engage in industrial symbiosis? *Progress in Industrial Ecology*, 4(6), 440–462. <https://doi.org/10.1504/PIE.2007.016353>
- Jiao, W., & Boons, F. (2014). Toward a research agenda for policy intervention and facilitation to enhance industrial symbiosis based on a comprehensive literature review. *Journal of Cleaner Production*, 67, 14–25. <https://doi.org/10.1016/j.jclepro.2013.12.050>
- Kim, H.-W., Dong, L., Choi, A. E. S., Fujii, M., Fujita, T., & Park, H.-S. (2018). Co-benefit potential of industrial and urban symbiosis using waste heat from industrial park in Ulsan, Korea. *Resources, Conservation and Recycling*, 135, 225–234. <https://doi.org/10.1016/j.resconrec.2017.09.027>
- Koppelmäki, K., Helenius, J., & Schulte, R. P. O. (2021). Nested circularity in food systems: A Nordic case study on connecting biomass, nutrient and energy flows from field scale to continent. *Resources, Conservation and Recycling*, 164, 105218. <https://doi.org/10.1016/j.resconrec.2020.105218>
- Koppelmäki, K., Parviainen, T., Virkkunen, E., Winqvist, E., Schulte, R. P. O., & Helenius, J. (2019). Ecological intensification by integrating biogas production into nutrient cycling: Modeling the case of Agroecological Symbiosis. *Agricultural Systems*, 170, 39–48. <https://doi.org/10.1016/j.agsy.2018.12.007>
- Korhonen, J. (2001a). Co-production of heat and power: An anchor tenant of a regional industrial ecosystem. *Journal of Cleaner Production*, 9(6), 509–517. [https://doi.org/10.1016/S0959-6526\(01\)00009-9](https://doi.org/10.1016/S0959-6526(01)00009-9)
- Korhonen, J. (2001b). Some suggestions for regional industrial ecosystems—Extended industrial ecology. *Eco-Management and Auditing*, 8(1), 57–69. <https://doi.org/10.1002/ema.146>
- Korhonen, J. (2004a). Industrial ecology in the strategic sustainable development model: Strategic applications of industrial ecology. *Journal of Cleaner Production*, 12(8), 809–823. <https://doi.org/10.1016/j.jclepro.2004.02.026>
- Korhonen, J. (2004b). Theory of industrial ecology. *Progress in Industrial Ecology*, 1(1–3), 61–88. <https://doi.org/10.1504/PIE.2004.004672>
- Korhonen, J., Huisingh, D., & Chiu, A. S. (2004). Applications of industrial ecology—An overview of the special issue. *Journal of Cleaner Production*, 12(8), 803–807. <https://doi.org/10.1016/j.jclepro.2004.02.002>
- Korhonen, J. (2005). Theory of industrial ecology: The case of the concept of diversity. *Progress in Industrial Ecology*, 2(1), 35–72. <https://doi.org/10.1504/PIE.2005.006782>
- Leck, H., Conway, D., Bradshaw, M., & Rees, J. (2015). Tracing the Water–Energy–Food Nexus: Description, Theory and Practice. *Geography Compass*, 9(8), 445–460. <https://doi.org/10.1111/gec3.12222>
- Levänen, J. O., & Hukkinen, J. I. (2013). A methodology for facilitating the feedback between mental models and institutional change in industrial ecosystem governance: A waste management case-study from northern Finland. *Ecological Economics*, 87, 15–23. <https://doi.org/10.1016/j.ecolecon.2012.12.001>
- Liu, C., Ma, C., & Zhang, K. (2012). Going beyond the sectoral boundary: A key stage in the development of a regional industrial ecosystem. *Journal of Cleaner Production*, 22(1), 42–49. <https://doi.org/10.1016/j.jclepro.2011.09.022>
- Lousberg, L. H. M. J., Wamelink, H. W. F., & De Caluwé, L. I. A. (2016). Managing economic feasibility and social relationships: Interventions to prevent dysfunctional conflict in public–private partnerships. *Engineering Project Organization Journal*, 6(2–4), 166–175. <https://doi.org/10.1080/21573727.2016.1260611>

- Milgrom, P., & Roberts, J. (1995). Complementarities and fit strategy, structure, and organizational change in manufacturing. *Journal of Accounting & Economics*, 19(2), 179–208. [https://doi.org/10.1016/0165-4101\(94\)00382-E](https://doi.org/10.1016/0165-4101(94)00382-E)
- Miller, V. V., & Mukherji, A. (2010). Music: A metaphor for industrial ecology. *Progress in Industrial Ecology*, 7(3), 239–256. <https://doi.org/10.1504/PIE.2010.037778>
- Million, A., Bürgow, G., & Steglich, A. (2018). Roof water-farm. *Universitätsverlag der TU Berlin*. <http://dx.doi.org/10.14279/depositonce-6663>
- Monteleone, M. (2015). Reshaping Agriculture Toward a Transition to a Post-Fossil Bioeconomy. In M. Monteduro, P. Buongiorno, S. Di Benedetto, & A. Isoni (Eds.), *Law and Agroecology: A Transdisciplinary Dialogue* (pp. 359–376). Springer. https://doi.org/10.1007/978-3-662-46617-9_18
- Ness, D. A., & Xing, K. (2017). Toward a Resource-Efficient Built Environment: A Literature Review and Conceptual Model. *Journal of Industrial Ecology*, 21(3), 572–592. <https://doi.org/10.1111/jiec.12586>
- Neves, A., Godina, R., Azevedo, S. G., & Matias, J. C. O. (2020). A comprehensive review of industrial symbiosis. *Journal of Cleaner Production*, 247, 119113. <https://doi.org/10.1016/j.jclepro.2019.119113>
- OECD (2010). *Eco-Innovation in Industry: Enabling Green Growth*. OECD Publishing.
- Ohnishi, S., Dong, H., Geng, Y., Fujii, M., & Fujita, T. (2017). A comprehensive evaluation on industrial & urban symbiosis by combining MFA, carbon footprint and emergy methods—Case of Kawasaki, Japan. *Ecological Indicators*, 73, 513–524. <https://doi.org/10.1016/j.ecolind.2016.10.016>
- Panyathanakun, V., Tantayanon, S., Tingsabhat, C., & Charmondusit, K. (2013). Development of eco-industrial estates in Thailand: Initiatives in the northern region community-based eco-industrial estate. *Journal of Cleaner Production*, 51, 71–79. <https://doi.org/10.1016/j.jclepro.2012.09.033>
- Parviainen, T., & Helenius, J. (2020). Trade Imports Increasingly Contribute to Plant Nutrient Inputs: Case of the Finnish Food System 1996–2014. *Sustainability*, 12(2), Article 2. <https://doi.org/10.3390/su12020702>
- Paquin, R. L., & Howard-Grenville, J. (2012). The Evolution of Facilitated Industrial Symbiosis. *Journal of Industrial Ecology*, 16(1), 83–93. <https://doi.org/10.1111/j.1530-9290.2011.00437.x>
- Paquin, R. L., & Howard-Grenville, J. (2013). Blind Dates and Arranged Marriages: Longitudinal Processes of Network Orchestration. *Organization Studies*, 34(11), 1623–1653. <https://doi.org/10.1177/0170840612470230>
- Paquin, R. L., Busch, T., & Tilleman, S. G. (2015). Creating Economic and Environmental Value through Industrial Symbiosis. *Long Range Planning*, 48(2), 95–107. <https://doi.org/10.1016/j.lrp.2013.11.002>
- Park, H.-S., Rene, E. R., Choi, S.-M., & Chiu, A. S. (2008). Strategies for sustainable development of industrial park in Ulsan, South Korea—From spontaneous evolution to systematic expansion of industrial symbiosis. *Journal of Environmental Management*, 87(1), 1–13. <https://doi.org/10.1016/j.jenvman.2006.12.045>
- Piekkari, R., Welch, C., & Paavilainen, E. (2009). The Case Study as Disciplinary Convention: Evidence From International Business Journals. *Organizational Research Methods*, 12(3), 567–589. <https://doi.org/10.1177/1094428108319905>
- Posch, A., Agarwal, A., & Strachan, P. (2011). Managing Industrial Symbiosis (IS) Networks. *Business Strategy and the Environment*, 20(7), 421–427. <https://doi.org/10.1002/bse.736>
- Proksch, G., Ianchenko, A., & Kotzen, B. (2019). Aquaponics in the Built Environment. In S. Goddek, A. Joyce, B. Kotzen, & G. M. Burnell (Eds.), *Aquaponics Food Production Systems: Combined Aquaculture and Hydroponic Production Technologies for the Future* (pp. 523–558). Springer International Publishing. https://doi.org/10.1007/978-3-030-15943-6_21
- Rakocy, J. E. (2012). Aquaponics—Integrating Fish and Plant Culture. In *Aquaculture Production Systems* (First Edition, pp. 344–386). Wiley-Blackwell. <https://doi.org/10.1002/9781118250105.ch14>
- Ristola, P., & Mirata, M. (2007). Industrial symbiosis for more sustainable, localised industrial systems. *Progress in Industrial Ecology, An International Journal*, 4(3/4), 184. <https://doi.org/10.1504/PIE.2007.015186>
- Schulte, R. P. O., Creamer, R. E., Donnellan, T., Farrelly, N., Fealy, R., O’Donoghue, C., & O’Uallachain, D. (2014). Functional land management: A framework for managing soil-based ecosystem services for the sustainable intensification of agriculture. *Environmental Science & Policy*, 38, 45–58. <https://doi.org/10.1016/j.envsci.2013.10.002>
- Sherwood, J. (2020). The significance of biomass in a circular economy. *Bioresource Technology*, 300, 122755. <https://doi.org/10.1016/j.biortech.2020.122755>

- Simboli, A., Taddeo, R., & Raggi, A. (2019). The multiple dimensions of urban contexts in an industrial ecology perspective: An integrative framework. *The International Journal of Life Cycle Assessment*, 24(7), 1285–1296. <https://doi.org/10.1007/s11367-017-1411-y>
- Spekkink, W. (2013). Institutional capacity building for industrial symbiosis in the Canal Zone of Zeeland in the Netherlands: A process analysis. *Journal of Cleaner Production*, 52, 342–355. <https://doi.org/10.1016/j.jclepro.2013.02.025>
- Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., de Vries, W., de Wit, C. A., Folke, C., Gerten, D., Heinke, J., Mace, G. M., Persson, L. M., Ramanathan, V., Reyers, B., & Sörlin, S. (2015). Planetary boundaries: Guiding human development on a changing planet. *Science*, 347(6223), 1259855. <https://doi.org/10.1126/science.1259855>
- Sun, L., Li, H., Dong, L., Fang, K., Ren, J., Geng, Y., Fujii, M., Zhang, W., Zhang, N., & Liu, Z. (2017). Eco-benefits assessment on urban industrial symbiosis based on material flows analysis and emergy evaluation approach: A case of Liuzhou city, China. *Resources, Conservation and Recycling*, 119, 78–88. <https://doi.org/10.1016/j.resconrec.2016.06.007>
- Szopik-Depczyńska, K., Cheba, K., Bąk, I., Kiba-Janiak, M., Saniuk, S., Dembińska, I., & Ioppolo, G. (2017). The application of relative taxonomy to the study of disproportions in the area of sustainable development of the European Union. *Land Use Policy*, 68, 481–491. <https://doi.org/10.1016/j.landusepol.2017.08.013>
- Tal, Y., Schreier, H. J., Sowers, K. R., Stubblefield, J. D., Place, A. R., & Zohar, Y. (2009). Environmentally sustainable land-based marine aquaculture. *Aquaculture*, 286(1), 28–35. <https://doi.org/10.1016/j.aquaculture.2008.08.043>
- Taylor, J. E., Dossick, C. S., & Garvin, M. (2011). Meeting the Burden of Proof with Case-Study Research. *Journal of Construction Engineering and Management*, 137(4), 303–311. [https://doi.org/10.1061/\(ASCE\)CO.1943-7862.0000283](https://doi.org/10.1061/(ASCE)CO.1943-7862.0000283)
- Tittonell, P. (2014). Ecological intensification of agriculture—Sustainable by nature. *Current Opinion in Environmental Sustainability*, 8, 53–61. <https://doi.org/10.1016/j.cosust.2014.08.006>
- Tudor, T., Adam, E., & Bates, M. (2007). Drivers and limitations for the successful development and functioning of EIPs (eco-industrial parks): A literature review. *Ecological Economics*, 61(2), 199–207. <https://doi.org/10.1016/j.ecolecon.2006.10.010>
- Van Berkel, R., Fujita, T., Hashimoto, S., & Fujii, M. (2009a). Quantitative Assessment of Urban and Industrial Symbiosis in Kawasaki, Japan. *Environmental Science & Technology*, 43(5), 1271–1281. <https://doi.org/10.1021/es803319r>
- Van Berkel, R., Fujita, T., Hashimoto, S., & Geng, Y. (2009b). Industrial and urban symbiosis in Japan: Analysis of the Eco-Town program 1997–2006. *Journal of Environmental Management*, 90(3), 1544–1556. <https://doi.org/10.1016/j.jenvman.2008.11.010>
- Varadarajan, P. R. (2003). Musings on Relevance and Rigor of Scholarly Research in Marketing. *Journal of the Academy of Marketing Science*, 31(4), 368–376. <https://doi.org/10.1177/0092070303258240>
- Vernay, A.-L., Mulder, K. F., Kamp, L. M., & de Bruijn, H. (2013). Exploring the socio-technical dynamics of systems integration – the case of sewage gas for transport in Stockholm, Sweden. *Journal of Cleaner Production*, 44, 190–199. <https://doi.org/10.1016/j.jclepro.2012.11.040>
- Verschuren, P. (2003). Case study as a research strategy: Some ambiguities and opportunities. *International Journal of Social Research Methodology*, 6(2), 121–139. <https://doi.org/10.1080/13645570110106154>
- von Malmborg, F. (2004). Networking for knowledge transfer: Towards an understanding of local authority roles in regional industrial ecosystem management. *Business Strategy and the Environment*, 13(5), 334–346. <https://doi.org/10.1002/bse.419>
- von Malmborg, F. (2007). Stimulating learning and innovation in networks for regional sustainable development: The role of local authorities. *Journal of Cleaner Production*, 15(17), 1730–1741. <https://doi.org/10.1016/j.jclepro.2006.08.014>
- Walls, J. L., & Paquin, R. L. (2015). Organizational Perspectives of Industrial Symbiosis: A Review and Synthesis. *Organization & Environment*, 28(1), 32–53.
- Wang, C., Zhang, G., & Wang, W. (2009). Research on the Industrial Symbiosis Supporting System of Eco-industrial Park. *Chinese Journal of Population Resources and Environment*, 7(3), 61–66. <https://doi.org/10.1080/10042857.2009.10684939>
- Wang, X., Olsen, L., Reitan, K., & Olsen, Y. (2012). Discharge of nutrient wastes from salmon farms: Environmental effects, and potential for integrated multi-trophic aquaculture. *Aquaculture Environment Interactions*, 2(3), 267–283. <https://doi.org/10.3354/aei00044>

- Wolf, A., Eklund, M., & Söderström, M. (2007). Developing integration in a local industrial ecosystem—An explorative approach. *Business Strategy and the Environment*, 16(6), 442–455. <https://doi.org/10.1002/bse.485>
- Wolfram Cox, J., & Hassard, J. (2005). Triangulation in Organizational Research: A Re-Presentation. *Organization*, 12(1), 109–133. <https://doi.org/10.1177/1350508405048579>
- Woodside, A. G., & Wilson, E. J. (2003). Case study research methods for theory building. *The Journal of Business & Industrial Marketing*, 18(6/7), 493–508. <https://doi.org/10.1108/08858620310492374>
- Xue, Y., Lindkvist, C. M., & Temeljotov-Salaj, A. (2021). Barriers and potential solutions to the diffusion of solar photovoltaics from the public-private-people partnership perspective – Case study of Norway. *Renewable and Sustainable Energy Reviews*, 137, 110636. <https://doi.org/10.1016/j.rser.2020.110636>
- Yap, N. T., & Devlin, J. F. (2017). Explaining Industrial Symbiosis Emergence, Development, and Disruption: A Multilevel Analytical Framework. *Journal of Industrial Ecology*, 21(1), 6–15. <https://doi.org/10.1111/jiec.12398>
- Yin, R. K. (with Campbell, D. T.). (2018). *Case study research and applications: Design and methods* (Sixth edition.). SAGE Publications, Inc.
- Zhang, B., & Wang, Z. (2014). Inter-firm collaborations on carbon emission reduction within industrial chains in China: Practices, drivers and effects on firms' performances. *Energy Economics*, 42, 115–131. <https://doi.org/10.1016/j.eneco.2013.12.006>

Chapter 5. Conclusions

Critical infrastructure forms a vital foundation for a functioning society (Forzieri et al., 2018; Stewart et al., 2009; Huddleston et al., 2022), and food and water systems are particularly vital to sustaining human life, entwined closely with both one another and with energy, a sector deeply tied to the climate crisis. The “complexity and unpredictability of contemporary challenges” (Huddleston et al., 2022) necessitates understanding and leveraging the interactions between key systems to develop effective adaptive and mitigative solutions within FWE infrastructures. From this arises a particular niche for engineering and interdisciplinary work: if we are to renovate and refashion our critical infrastructure systems into a sustainable and resilient model that can regenerate and support itself across generations, we must identify paths and act, to design and operate technical and informatic sustainability solutions, with neither rose-tinted glasses nor disillusioned dismissiveness. Our efforts must dig deep, and not only be technically possible, but implemented *well*. It can be observed that models and predictions do not necessarily equate fully to performance or even viability when translated into practice, and this is a gap wherein qualitative work becomes crucial. With this in mind, this work is positioned at the intersection of several disciplines as befitting the integrated nature of many vital sustainability solutions of the modern era. Considering first circular frameworks and implementation strategies for a new realm of resource efficiency, we zoom in on one exemplary strategy, the case of aquaponics, and find notable gaps between theoretical and potential sustainability. We also see that these may be addressed through additional industrial symbiosis measures, the complexity of which must be managed by troubleshooting informational and organizational barriers. Multifaceted, this dissertation is, in its detail, about optimizing the environmental efficiency of aquaponics, a production strategy with both internal and inter-organizational resource symbiosis options, and from another perspective, more broadly directed to support the integration of CE strategies for critical FWE-infrastructure through resource integration.

To realize this, the apt metaphor certainly should not be to reinvent wheels, but rather to close loops, and therefore we must learn and leverage both successful approaches and intersecting goals across sectors. This arises not only in the case of technological innovation, but also in the case of conceptual frameworks. It is vital to identify how they interact and intersect to operationalize them efficiently, and moreover, it is essential to their real-world impact that the implementation strategies they advance and the synergies between these are clarified. Siloed approaches will fail in the face of such wicked problems as global climate change (Lazarus 2009). Addressing identified gaps in the need for holistic review of circular sustainability frameworks and a centralized resource and discussion, as well as the need for more research addressing implementation strategies, *Chapter 2* (Horn and Proksch 2022) sought, through systematic literature review, to: 1. Describe what different regenerative, circular, and symbiotic frameworks exist to conceptualize circularity in the built environment and the relationships, similarities, and differences between them, and; 2. Assess the implementation strategies they recommend in the context of circular city implementation, and the research gaps these

present. Findings identified “considerable overlap between the reviewed frameworks and strong alignments between aspects of all” and “a complex assortment of context specific approaches and implementation strategies across... six thematic areas- *Resource and Material Management, Systems Development and Integration, Bio-based Solutions, Governance and Stakeholder Engagement, Data, Measurement, and Modeling, and Research and Education*” (Horn and Proksch 2022). Moreover, “given the many shared goals, conceptualizations, and strategies espoused under the array of circular sustainability frameworks reviewed above, there is reason to discern value in looking to foundational and parallel concepts as a resource for the strengthening and amplification” of resource circularity (Horn and Proksch 2022). This systematic literature review contributes a supporting resource for future research with circular and sustainable aims, clarifying ideological relationships of circular, symbiotic, and regenerative frameworks and providing a centralized reference of framework definitions and of implementation strategies. Potential limitations include the use of a singular database, that of the University of Washington, rather than multiple, which may have better ensured comprehensiveness of the systematic review. Additionally, a secondary verification process with an additional reader/coder may have been beneficial to provide additional rigor to the review. Future research may benefit from conducting an updated analysis on the implementation strategy aspect of this work, as in the years since its publication there are likely to be new and interesting developments in this regard. Future work could also go a step further in connecting these strategies with existing projects to assess the degree of advancement within different implementation strategies as a metric for the level of adaptation of CE and related measures within given regions.

One of these implementation strategies, aquaponics, makes for a compelling typology for further analysis due to its positionality at the nexus of food, water, and energy critical infrastructure. By producing food while using minimal resources in a controlled environment, it is possible to control growth and resource use parameters more optimally and reduce the degree to which food production is subjected to extreme weather events and climate changes (Horn et al. 2023). It would not be practical nor logical to completely or even majorly replace conventional agriculture with these approaches, but it is likely to be an important means of increasing resilience and re-imagining the relationship between industrial and urban systems and food systems through sustainable resource exchanges in the FWE-nexus. There has been considerable hype about aquaponics, and it might even be fair to say that some of that has faded by now, lost to the oversimplification of an implementation process that should not mimic tech start-ups, but rather something more organic and far-sighted, requiring long-term investment or innovative cost-sharing approaches in the face of short term cost barriers (Horn et al. 2023). Trying to enter, let alone, alter something as vast and entrenched as the traditional food system is no mean feat, and entrants to the industry face considerable barriers (Horn et al. 2023). Moreover, discussions with industry members suggest that theoretical potential, as considered in previous literature, does not immediately equate to implementation or applied performance in real-world context. Particularly, the resources needed for CEA can be met by sustainable resources and technologies, theoretically, but this does not mean that they indeed

are in their current iterations within the commercial aquaponics industry, where there is a need to continue to improve and seek to close such gaps. The alignment between theoretical (as expressed in literature) and applied (as in the commercial field) environmental sustainability of aquaponics has been previously unsubstantiated, and these gaps between literature and practice must be identified to help support more effective real-world implementation. The objective of *Chapter 3* was therefore to assess the alignment- lack thereof- between the hypothetical sustainability of commercial aquaponics and current industry practices in North America, the factors which shape these, and the resulting innovation and research needs to support the sustainability and success of commercial aquaponics. This was achieved through semi-structured interviews with commercial aquaponics practitioners in North America, literature review, engineered process assessment and CEA infrastructure assessment, and qualitative thematic analysis. A novel framework conceptualizing commercial aquaponics through a material flow and process lens is advanced, which may also serve future research and analytical efforts. Findings illuminate gaps between research and practice in North American aquaponics, particularly in energy sources and nutrient recovery processes, and potential means to close these, including through the synergetic relationship of aquaponics to other sustainability-oriented technologies. It is important to acknowledge that this work focused on environmental efficiency and resilience considerations, but social and economic sustainability perspectives are also crucial to form the whole picture. These are addressed in companion analysis of the same cases (Horn et al. 2023) but could still benefit from further and updated investigation. An additional limitation is that the collected datasets were not as comprehensive as might have been possible with further access to the case organizations. It was not feasible to visit sites due to the status of the COVID-19 pandemic at the time of data collection, which would have yielded deeper and more comprehensive insight to the cases, illuminating their system design at another level. Future research could also benefit from expanding this type of assessment to more regions, perhaps even yielding insight through multi-region comparisons. Furthermore, an imperative direction for research building on this study is to consider and address all of the observed gaps between theoretical and applied environmental efficiency of operational practices, some of which are considered in the subsequent analysis presented in *Chapter 4*.

Resource gaps in the operational environmental efficiency of commercial aquaponics, particularly energy in the form of heat and electricity, may be addressed through better access to renewable sources. Here circular frameworks remain relevant, and industrial symbiosis presents a potential solution. Just as aquaponics includes an internal exchange of water and nutrients, it can be integrated with other industrial or district scale systems to make use of waste and shared local resources to close the gaps for its own performance. This is conceptually promising, but potentially difficult to achieve, not least as buy-in is required from multiple stakeholders and participating partners, presenting an array of potential organizational factors influencing implementation success. Nonetheless, a handful of emerging examples exist commercially and merit analysis within academic spheres. While IS strategies are discussed in CEA literature and greenhouses have been documented in previous ISNs, existing literature in

both fields has not yet addressed the increasing implementation of industrial symbiosis with CEA organizations. *Chapter 4* therefore seeks to describe and characterize existing examples of industrial symbiosis with Controlled-Environment-Agriculture operations in Northern Europe and preliminarily assess institutional and organizational factors that influence their implementation. This is conducted through an exploratory multiple case study, employing interview and documentation analysis for four existing controlled-environment agriculture companies planning or participating in industrial symbiosis partnerships. Findings illuminate the motivations, material exchanges and organizational and institutional thematic factors reflecting themes of coordination, experience, inertia, and value creation. *Chapter 4* accordingly contributes vital early insights to a previously under-documented IS typology, documenting and advancing understanding of industrial symbiosis with CEA, including the identification of emergent intra-organizational, inter-organizational, and institutional factors that affect CEA-IS implementation, and creating a conceptual platform for further research of CEA-IS implementation to support their further development (Table 5.1). This initial study can help support future transdisciplinary academic work, which should broaden data collection through survey methods, involving a wider range of stakeholders, cases, and regions as possible. Expanded interviews may also offer the possibility to further assess influential factors building on the themes identified in this exploratory work.

Table 5.1- Overview of Key Contributions

Ch.	Key Contributions
2	<ul style="list-style-type: none"> Clarifies ideological relationships of circular, symbiotic, and regenerative frameworks Centralized reference of framework definitions and of implementation strategies
3	<ul style="list-style-type: none"> Advances new aquaponic systems framework Novel nutrient recovery engineered-process analysis identifies inconsistent technology usage Illuminates previously unexplored gaps between research and practice
4	<ul style="list-style-type: none"> Documents and advances understanding of IS with CEA Identifies emergent intra-organizational, inter-organizational, and institutional factors that affect CEA-IS implementation Creates conceptual platform for further research of CEA-IS implementation

Overall, this work supports the further development and implementation of industrial symbiosis strategies for functioning circular economy within the FWE-nexus, fostering the contribution of aquaponics and its related CEA subsystems to regenerative food systems and the sustainability and resilience of critical FWE-infrastructures. Several themes emerged

throughout the investigations comprising this dissertation, and may pose interesting directions for future development, including the vital interactions of locational context and scalar sustainability; public-private interactions within FWE-infrastructure adaptation; and the importance of leveraging key insights and shared interests between sectors and disciplines toward more effective implementation of resilience and sustainability measures. Expanding “insight and understanding of how different scales and sectors pursuing circular sustainability fit together and can partner to drive change and transformation” (Horn and Proksch 2022) will be a vital direction for continued investigation. Contextual factors, including region, location, and the aims of a given project, among many others, all influence the key question, at what scale should we close a given resource loop? It may be prudent to query multiscale approaches and not assume any one ideal scale of circularity. For instance, context matters greatly for considerations such as whether it is more effective for an aquaponic farm to use waste heat from another business than install their own geothermal heating system. As beneficial as resource integration may be, bias toward increasing systems integration should be avoided, and context and data informed decisions should be pursued to identify appropriate solutions for given projects within FWE-infrastructure. The nuanced role of public and private actors within critical FWE-infrastructure is notable, from the influence of subsidies and regulation within food systems and prevalence of private utilities within water and energy systems.

Similarly, the contribution of industrial symbiosis strategies to FWE infrastructure resilience and sustainability further raises a variety of organizational and institutional considerations, and the need to appropriately balance private and public interests to achieve overall sustainable development goals. It is certainly possible that outsourcing utilities with environmental sustainability intent may have pitfalls in the way it privatizes costs. Noting the often overburdened nature of utility systems, it will be necessary to consider such dynamics through a multilayered perspective. For example, “further study of the multi-faceted dynamics at play in CEA-IS with public infrastructural systems may offer valuable insight for other actors seeking to advance such strategies leveraging the intersection of critical food, water, and energy systems” (Chapter 4). Furthermore, closing gaps in circularity framework implementation, the advancement of commercial aquaponics, and the development of CEA-IS can, in all cases, benefit from “innovation, research, and advocacy to improve technologies, lower costs, and advance successful implementation, wherein there are numerous opportunities to leverage the many overlaps... with other industries and technologies, and much promise to materialize potential environmental sustainability outcomes to their full potential” (Chapter 3). Opportunity exists yet to once again re-engineer the scale and directionality of resource use within critical FWE-infrastructure, this time toward circular, symbiotic, and regenerative modes, and interdisciplinary work is poised at the leading edge of this effort to adapt and mitigate by leveraging understanding and interactions between key systems to help solve the complex environmental challenges of our era.

Chapter 5 References

- Forzieri, G., Bianchi, A., Silva, F. B. e, Marin Herrera, M. A., Leblois, A., Lavalle, C., Aerts, J. C. J. H., & Feyen, L. (2018). Escalating impacts of climate extremes on critical infrastructures in Europe. *Global Environmental Change*, 48, 97–107. <https://doi.org/10.1016/j.gloenvcha.2017.11.007>
- Horn, E., & Proksch, G. (2022). Symbiotic and Regenerative Sustainability Frameworks: Moving Towards Circular City Implementation. *Frontiers in Built Environment*, 7. <https://www.frontiersin.org/article/10.3389/fbuil.2021.780478>
- Horn, E., Joyce, A., Chowdhury, R., Caputo, S., Jacobs, B., & Winkler, M. (2023). Translating Environmental Potential to Economic Reality: Assessment of Commercial Aquaponics through Sustainability Transitions Theory. *Circular Economy and Sustainability*. <https://doi.org/10.1007/s43615-023-00291-0>
- Huddleston, P., Smith, T., White, I., & Elrick-Barr, C. (2022). Adapting critical infrastructure to climate change: A scoping review. *Environmental Science & Policy*, 135, 67–76. <https://doi.org/10.1016/j.envsci.2022.04.015>
- Richard J Lazarus. (2009). Super wicked problems and climate change: Restraining the present to liberate the future. *Cornell Law Review*, 94(5), 1153–1233.
- Stewart, G. T., Kolluru, R., & Smith, M. (2009). Leveraging public-private partnerships to improve community resilience in times of disaster. *International Journal of Physical Distribution & Logistics Management*, 39(5), 343–364. <https://doi.org/10.1108/09600030910973724>

Appendix A- Glossary

- **Aquaponics**- “the combined culture of fish and hydroponic plants in recirculating systems” (Rakocy et al. 2004)
- **Bioeconomy**- “The production of renewable biological resources and the conversion of these resources and waste streams into value added products, such as food, feed, bio-based products and bioenergy” (European Commission, 2012)
- **Circular Bioeconomy**- “The sustainable, resource-efficient valorization of biomass in integrated, multi-output production chains (e.g. biorefineries) while also making use of residues and wastes and optimizing the value of biomass over time via cascading. Such an optimization can focus on economic, environmental or social aspects and ideally considers all three pillars of sustainability” (Stegmann et al., 2020)
- **Circular City (CC)**- A concept for the urban scale “based on closing, slowing and narrowing the resource loops as far as possible after the potential for conservation, efficiency improvements, resource sharing, servitization and virtualization has been exhausted, with remaining needs for fresh material and energy being covered as far as possible based on local production using renewable natural resources” (Paiho et al., 2020)
- **Circular Economy (CE)**- “An economic system that is based on business models which replace the ‘end-of-life’ concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes ... with the aim to accomplish sustainable development” (Kircherr et al., 2017)
- **Controlled-Environment Agriculture (CEA)**- “environmental control in permanent facilities that allow for year-round production regardless of the local climate” this “includes both greenhouses and indoor growing facilities” (Proksch et al. 2019)
- **Critical Infrastructure**- “tangible and/or intangible systems that are vital for supporting human life, and necessary to achieve social, cultural, economic and environmental outcomes” (Huddleston et al., 2022)
- **Food-Water-Energy Nexus**- a concept describing the intersections and interdependencies of food, water, and energy systems (Tien, 2018)

- **Industrial Symbiosis (IS)**- Physical exchanges of materials and resources, including energy, water, and byproducts between businesses (Chertow, 2007)
- **Planetary Boundaries**- “the environmental limits within which humanity can safely operate” (Steffen et al. 2015)
- **Recirculating Aquaculture Systems (RAS)**- “land-based, indoor fish rearing facilities, where fish are stocked in tanks within a controlled environment, and where filtration is applied to purify water through removing metabolic wastes of stock, before being recirculated into the system itself” (Ahmed and Turchini 2021)
- **Sustainable Development**- Global progress which reflects economic, environmental, and societal complexities and accounts for their complexities (UN, 2020)

Glossary References

- Ahmed, N., & Turchini, G. M. (2021). Recirculating aquaculture systems (RAS): Environmental solution and climate change adaptation. *Journal of Cleaner Production*, 297, 126604. <https://doi.org/10.1016/j.jclepro.2021.126604>
- Chertow, M. R. (2007). "Uncovering" Industrial Symbiosis. *J. Ind. Ecol.* 11 (1), 11–30. doi:10.1162/jiec.2007.1110
- European Commission (2012). *Innovating Sustainable Growth: A Bioeconomy for Europe*.
- Huddleston, P., Smith, T., White, I., & Elrick-Barr, C. (2022). Adapting critical infrastructure to climate change: A scoping review. *Environmental Science & Policy*, 135, 67–76. <https://doi.org/10.1016/j.envsci.2022.04.015>
- Kirchherr, J., Reike, D., and Hekkert, M. (2017). Conceptualizing the Circular Economy: An Analysis of 114 Definitions. *Resour. Conservation Recycling* 127, 221–232. doi:10.1016/j.resconrec.2017.09.005
- Paiho, S., Mäki, E., Wessberg, N., Paavola, M., Tuominen, P., Antikainen, M., et al. (2020). Towards Circular Cities- Conceptualizing Core Aspects. *Sustain. Cities Soc.* 59, 102143. doi:10.1016/j.scs.2020.102143
- Proksch, G., Ianchenko, A., & Kotzen, B. (2019). Aquaponics in the Built Environment. In S. Goddek, A. Joyce, B. Kotzen, & G. M. Burnell (Eds.), *Aquaponics Food Production Systems: Combined Aquaculture and Hydroponic Production Technologies for the Future* (pp. 523–558). Springer International Publishing. https://doi.org/10.1007/978-3-030-15943-6_21
- Rakocy, J. E., Shultz, R. C., Bailey, D. S., & Thoman, E. S. (2004). Aquaponic production of tilapia and basil: Comparing a batch and staggered cropping system. *Acta Horticulturae*, 648(648), 63–69. <https://doi.org/10.17660/ActaHortic.2004.648.8>
- Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., de Vries, W., de Wit, C. A., Folke, C., Gerten, D., Heinke, J., Mace, G. M., Persson, L. M., Ramanathan, V., Reyers, B., & Sörlin, S. (2015). Planetary boundaries: Guiding human development on a changing planet. *Science*, 347(6223), 1259855. <https://doi.org/10.1126/science.1259855>
- Stegmann, P., Londo, M., and Junginger, M. (2020). The Circular Bioeconomy: Its Elements and Role in European Bioeconomy Clusters. *Resour. Conservation Recycling: X* 6, 100029. doi:10.1016/j.rcrx.2019.100029
- Tien, I. (2018). Resilient by Design: The Case for Increasing Resilience of Buildings and Their Linked Food-Energy-Water Systems. *Elem. Sci. Anth* 6 (1), 142. doi:10.1525/elementa.142
- UN (2020). “Sustainable Development Goals.” *unfoundation.Org*. Available at: <https://unfoundation.org/what-we-do/issues/sustainable-development-goals/> (Accessed September 20, 2021)

