The Contribution of Testbeds in Sustainable Innovation

A Case Study of Aquaponics in Sweden

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Abstract

Aquaponics has gained increasing popularity as it offers a more sustainable solution to farm fish and leafy greens sustainably and closer to urban centres. While generally seen as a real potential to improve sustainable food production, the commercialisation of aquaponics globally is though still at its beginnings. Aquaponics stands nowadays at a point being currently mostly tested through testbeds, which can be defined as facilities or similar for testing something in development its real-world context. This study assesses the application of a such a testbed facility in the process of creating a sustainable innovative food production system at the start-up Johannas Stadsodlingar AB in the north of Stockholm, Sweden. Through conducting semi-structured interviews and a qualitative content analysis the following four main themes for the application of a testbed in the context aquaponics are found: 1. An insufficient technological readiness level, leading to a need for proof of concept; 2. Learnings and the overcoming of technical challenges a testbed offers; 3. Reducing risk & building up self-confidence in the system; 4. The demonstration purposes and social influence on people a testbed has. In sum, it can be said that testbeds contribute as an efficient tool in the context of sustainable innovation. Testbeds can serve as very important demonstrating and signalling tools to all stakeholders. They make it possible to develop and achieve innovations in a simulated real-world context before scaling them and making them market ready.

Keywords: Innovation, Sustainable Innovation, Testbed, Experimental Innovation, Technological Innovation Systems, Diffusion, Strategic Niche Management, Circular Food Production, Aquaponics, Sweden

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Abbreviations

FAO	Food and Agriculture Organization of the United Nations
MLP	Multi-Level-Perspective
SLU	Swedish University of Agricultural Sciences
SNM	Strategic Niche Management
TIS	Technological Innovation Systems
UN	United Nations

1. Introduction

This chapter shall present the background of the subject formulating the basis of the problem statement. Furthermore, the aim and research questions of the study are stated. Finally, the delimitations and outline are presented to give the reader a clear picture of the study's content.

1.1 Background

Innovation as a word derives from the Latin word *innovare*, meaning “into new”. In the process of innovation new ideas are exploited, which is often described by the Schumpeterian steps of invention, innovation, and diffusion. Innovation as such is currently at an interesting turning point in which the focus of reducing environmental impact is added creating the terminology of sustainable innovation (Seebode *et al.* 2012).

With an increasing population, the need for agricultural production spaces as well as the demand for more resilient and efficient food supply systems is rising. With our world population estimated to reach around ten billion people around 2050, more than two billion additional people will need to be fed, creating a crucial challenge for humanity (UN 2021). Farming as such has led to immense use of land and water, as well as eutrophication and acidification of these two. Furthermore, overfishing of the oceans has led to aquatic populations of certain fish species, such as tuna or mackerel reduced by around 75 percent, while our fish consumption is constantly rising (Cohen *et al.* 2018; FAO 2020). Moreover, this growing need for resources of food due to population growth is accompanied by an increasing appetite fish due to its appeal for a healthier diet (Bogard *et al.* 2019; Willett *et al.* 2019). As such, a diet rich in plant-based foods, balanced with the least impactful animal protein source foods provide both improved health and environmental benefits (Willett *et al.* 2019).

With an increased popularity of a more fish based diet, constantly increasing marine fishing pressure is not only depleting fish stocks, but causing severe evolutionary changes to fish populations and a substantial environmental threat. (Hollins *et al.* 2018; Trochta *et al.* 2018; FAO 2020). As a result, farming all sorts of fish in aquaculture has seen a constant rise in popularity, leading to a continuous expansion of aquacultures all over the world. However, despite their popularity,

aquaculture techniques also increase environmental burdens such as eutrophication by flushing out nutrient-rich wastewater (Forchino *et al.* 2017).

Due to the limitations of our resources on earth, climate change, and changes in consumption behaviour, adaptions are needed. The development of climate change on planet earth has become more and tangible for humankind. An increase of temperatures, more extreme weather events, and a higher degree of fluctuations in water availability due to floods and droughts occur more often than ever and have led to generally rising human uncertainty (IPCC 2021). Our global food systems account as one of the largest contributors to climate change, as they are responsible for over a third of mankind's greenhouse gas emissions (Crippa *et al.* 2021). As such, mankind faces the challenge to mitigate these by now tangible events and act more sustainably, demanding more sustainable solutions and more specifically sustainable innovation in this direction. These adaptions demand more innovative and sustainable farming methods, meeting exactly these rising demands (Cohen et al. 2018).

One suggested innovative sustainable farming method to farm fish and greens simultaneously is aquaponics (König *et al.* 2016, 2018; FAO 2020). Aquaponics has increasingly gained popularity in the past decade offering a more sustainable solution to farm food closer to urban centres (Tyson *et al.* 2011; König *et al.* 2018). The name aquaponics as such is a synergistic combination of the two words hydroponics (growing greens in water) and aquaculture (breeding, raising, and farming fish in a controlled environment). Aquaponics is generally seen as more resource, cost and material effective than farming fish and greens separately (König *et al.* 2016, 2018; Forchino *et al.* 2017, 2018). Thus, the use of normally non-renewable resources for fertilization is significantly reduced, while the efficiency of water usage is much higher than it is having these two systems separately (König *et al.* 2016, 2018).

Within this process of developing more sustainable innovations such as aquaponics, different prerequisites remain. Thus, experimenting and prototyping is often necessary to achieve commercialisation in these developments and transitions (Sengers *et al.* 2019). As such, functionally and potential impact of innovations can be tested to solve some of our societal challenges such as climate change (Arntzen *et al.* 2019). Within this process innovations can be tested on different levels, beginning with simple proofs of concept, to prototypes, pilots to minimal viable products (Leurs & Duggan 2018). These are moreover often tested within or on testbeds, which can be defined as any facility, device, or means for testing something in its development (Leurs & Duggan 2018; Vinnova 2022). Testbeds as such can offer a closed simulation environment to test and legitimize innovations. They offer preceding possibilities before scaling up systems and technologies, helping transformation processes in sustainable innovation. The role they play in innovation is however not greatly discussed in academia. This creates a gap to

assess the position and purpose testbeds play in these processes and advancements of sustainable innovation, which this master thesis intends to study.

1.2 Problem

In the context of sustainable innovation and how it is taking place it is difficult to directly pinpoint to the real drivers and management implications of these developments. In the field of food production and agriculture, diffusion is taking place rather slowly. Moreover, the transformations taking place within food production are rather generalizable in a direction towards more conventional but smart farming in an upcoming agriculture 4.0 (Rose *et al.* 2021). Moreover, new open and closed food production systems are arising, offering the opportunity for different forms and more efficient food production (Tyson *et al.* 2011). To understand the aspects, drivers, and how such food production systems are being innovated more academic research is necessary.

Aquaponics is one of such proposed closed food production systems being however under researched in a management context. Until today most focus within the field of aquaponics is set on technical and biological perspectives (König *et al.* 2018). While generally seen as a real potential to improve sustainable food production, the commercialisation of aquaponics globally is still at its beginnings (Tyson *et al.* 2011; König *et al.* 2016). Aquaponics such as other larger scale food production systems trying to be more efficient require high capital investments, a knowledge foundation, consistency, and reliability of input (FAO 2020). The current developments in aquaponics can thus be taken as an exemplary analytical example to understand how innovation towards more sustainable food production systems is currently happening in practice.

In the development of such systems experimental testing facilities are often built to create the right environment to test whether the innovation and its variety of facets will work in the intended context (Leurs & Duggan 2018; Arntzen *et al.* 2019). As such, this is a clear management decision mitigating risk by preparing the scaling up and diffusion of such innovations. Moreover, this gives the opportunity for legitimisation as a new technology. By creating a deeper understanding of the concrete practical application of such testbeds in the creation of a sustainable aquaponic system, this study intends to contribute to the development of knowledge around the concrete application of such experimental test facilities in the context of creating innovations with diffusional potential. As such, the Swedish start-up Johannas Stadsodlingar AB and their aquaponic testbed facility producing rainbow trout, as well as more than thirty types of vegetables and greens shall serve as an exemplary case. Thus, it shall be assessed whether and how their entire facility serves the purposes of innovating, creating a business case, preparing a competitive upscaling, and achieving market-readiness.

1.3 Aim and Research Question

The following master's thesis aims at assessing the application of a testbed facility in the process of creating a sustainable innovative food production system at the start-up Johannas Stadsodlingar AB. As such, it intends to contribute to the research field of sustainable innovation exploring what role or purpose such testbeds play and how they contribute within the processes of innovation, serving as a proof of concept, while minimizing financial risk and legitimize new technologies or innovations in a broader sense. This shall moreover be applied to the start-up's context, serving as an exemplary case for a business standing at exactly such a point and wanting to create economic and ecological innovation. With the standpoint at which commercial aquaponics stand at today, the company serves as a perfect example for the development of a sustainable food production system of the 21st century. Resulting, the following research question arises:

> *What does the testbed facility of Johannas Stadsodlingar contribute to the innovation process of developing, testing, and scaling up a sustainable aquaponic food production system?*

1.4 Scope and Delimitations of the Study

This study is methodically limited to the qualitative methods of collecting and analysing primary and secondary data within the frame of a single case study. The empirical evidence is based on what is being communicated by informants as well as corporate documents. These sources represent the perspective of the company and can strive to portray the corporate perspective actions in a way that strengthen the reputation and public perception. This thesis is restricted by a period of five months, taking into consideration a snapshot of the current perception and reflection of the interviewees on the testbed facility rather than in different development phases of it.

This study examines the developments within the innovation processes in aquaponics from a business management perspective and does not focus on it specifically in its technicalities. Moreover, in the scope of this thesis a case study is on the aquaponic testbed facility of Johannas Stadsodlingar AB is conducted creating in-depth insights and reflections about the role, necessities, and the innovation processes to develop such a sustainable circular food production system. Due to the few numbers of commercial aquaponics, a single case study is conducted with the aim to receive deeper insights into this single testbed facility being currently used to test and develop circular automated aquaponics production system.

2. Literature Review and Conceptual Framework

The following chapter gives an introduction into the theoretical background and literature already produced by academia regarding aquaponics, testbeds, general innovation theories and where they already have connected to the field of aquaponics. Lastly, the analytical framework of this study is presented.

2.1 Aquaponics

The name aquaponics is a synergistic combination of the two words hydroponics (growing greens in water) and aquaculture (breeding, raising, and farming fish in a controlled environment). As such, aquaponics is a proposed solution for more forward oriented sustainable farming (Tyson *et al.* 2011; Cohen *et al.* 2018; Palma Lampreia Dos Santos 2018; FAO 2020). Aquaponics is generally seen as more resource, cost and material effective than farming fish and greens separately (König *et al.* 2016, 2018; Forchino *et al.* 2017, 2018). Aquaponics has historic roots. Historian have found that ancient cultures, such as the Aztecs or Chinese settlers applied aquaponic techniques in their farming already around the 5th century AD (FAO 2001; Crossley 2004). Aquaponics has received considerable attention in the last decade (Palma Lampreia Dos Santos 2018). It is suitable to produce marketable vegetables and fish much closer to urban areas. Aquaponics has therefore become a popular and renowned form of more urban farming, making it possible to be closer to the consumer (ibid.).

In a typical aquaponic system three main live components interact, which are plants, usually fish or other aquatic animals and bacteria. Aquaponics consists of two major parts. The aquaculture part is the "engine" of such a system in which aquatic animals, mostly fish, are raised. The hydroponic part is used for growing plants, mostly leafy greens (Somerville *et al.* 2014). The effluents from raising animals like fish accumulate in the water, which can become toxic to the fish in high concentrations but contain nutrients needed for plant growth (ibid.). Though consisting mainly of these two parts, such aquaponics systems are typically grouped into various components responsible for the removal of solid waste, adding bases to neutralize acids, or to maintain water oxygenation (ibid.). These typical

components include a rearing tank for raising and feeding the fish and a settling basin for collecting uneaten food and detached biofilms. A biofilter usually is placed where the bacteria for nitrification can grow and convert ammonia into nitrates, making it subsequently usable as a nutrient by the plants (Somerville *et al.* 2014). The hydroponic system is the section of the system where plants are grown swimming in rafts by absorbing these excess nutrients from the water. Finally, the sump is the lowest point in such a system where the water flows to, where it is often filtered and pumped back to the rearing tanks (ibid.). The use of normally non-renewable resources for fertilization is significantly reduced in such systems, while the efficiency of water usage is much higher than it is in these two systems separately (König *et al.* 2016, 2018). Aquaponics can hereby, when maintained in a steady state, work as rather simple functioning ecosystems (Forchino et al. 2017).

A wide range of species of fish and vegetables are suitable to be farmed in aquaponics (König *et al.* 2018; FAO 2020). The worldwide most common fish species are freshwater fish such as Nile tilapia and similar sorts of perch, rainbow trout, common carp, Barramundi and African catfish, this though is dependent on the maturity and density of the fish (Somerville *et al.* 2014). All these can be combined with leafy greens, such as lettuce, basil, spinach or other forms of herbs and vegetables (Forchino et al. 2017). The bacteria form a highly important part of aquaponics through nitrification, the aerobic conversion of ammonia into nitrates. Ammonia is gradually released into the water through the gills and excrements of fish through their metabolism (ibid.). This process is one of the most crucial functions in aquaponics as it permits the resulting nitrate compounds to be absorbed by the plants for growth and nourishment (Somerville *et al.* 2014).

Aquaponics offers having two sources of profit, with farmers being able to continue to earn money if the markets for either plants or fish go through a low cycle (Blidariu & Grozea 2011). With a growing number of environmentally conscious consumers, aquaponic systems offer products that are pesticide free, whilst also leaving a minimal environmental footprint (Tyson *et al.* 2011). Aquaponics have a low water usage, an efficient nutrient cycle and need very little land to operate on, giving them a lot of opportunities for economic efficiency (Blidariu & Grozea 2011). As soil is barely needed and only a small circulating amount of water is necessary, aquaponic operations can be set up in areas of poor water and soil quality. These systems can be kept free of pests, weeds, and diseases, allowing for a consistent and quick production of high quality crops (FAO 2001; Blidariu & Grozea 2011; Somerville *et al.* 2014). Aquaponics is hereby a process innovation and should not be mistaken as a product innovation. Its products compete on the market with conventional or organic produce from conventional freshwater and saltwater products, organic aquaculture or wild catch, as well as horticulture (König *et al.* 2018).

Until today, research on aquaponic farms and their economic viability is rather limited and mostly takes place at a development stage, with systems being tested and established for further market-ready upscaling (Forchino *et al.* 2018; König *et al.* 2018). A wide array of analysis, footprint and sustainability research as well as technological innovation system analyses and life cycle assessments have been conducted on aquaponics (Tyson *et al.* 2011; Kloas *et al.* 2015; König *et al.* 2016, 2018; Forchino *et al.* 2018). With the available research, economic viability of aquaponic businesses is usually determined in individual cases. As there are numerous variables including the system design such as weather, local costs of land and energy the profitability of aquaponic businesses diverts (Blidariu & Grozea 2011; Tyson *et al.* 2011). In a study including 257 aquaponic businesses, the median investment cost of these aquaponic businesses remain between $5,000 and $9,999 and only 10 percent of the businesses reported more than $50,000 in annual revenue (Love *et al.* 2015).

2.2 Testbeds

An essential part of innovation and transitions are experimental approaches where prototypes are tested in an early stage before commercialization (Sengers *et al.* 2019). While making innovation safer at the same time as maximising real-world positive impact, such experimentation offers a way of finding out how new technologies or innovations in general can be functional to solve some of society's biggest challenges like climate change, inequality or an ageing society (Arntzen *et al.* 2019).

Within such experimentation innovations are tested on a variety of levels, from proof of concepts, prototypes, pilot projects, to a minimal viable product (Leurs & Duggan 2018). One form of environment of such experimentation are testbeds. As such, they offer a physical or virtual environment, which allows companies, academia or other forms of organizations to test and introduce new products, processes, services or general solutions in specific areas in that environment (Arntzen *et al.* 2019; Vinnova 2022). While not having a settled definition in academia and a terminology being sometimes ambiguous, testbeds come into play at the testing or implementation phase involving the simulation of a real-world environment. Such testbeds can be seen as facilities, devices, or generally means for testing something in its development, though usually referring to them having some contact or influence from their real-world context (Leurs & Duggan 2018; Arntzen *et al.* 2019; Vinnova 2022). Testbeds can vary from directly applied hands-on prototype development such as in manufacturing industries, aircraft engines and to the refinement of intellectual property in such fields as computer software development, where it is shielded from the hazards when testing live (Arntzen *et al.* 2019). The concept of real-world imitating testbeds can also overlap with other

definitions such as demonstrators, sandboxes or proving grounds (Arntzen *et al.* 2019). As such, they can be seen as different to living labs or laboratories. Generally, a commonality with a demonstrator can be seen, describing products already being very close to a market and thus needing more demonstration than testing (ibid.). An illustration of these definitions can be seen in figure 1.

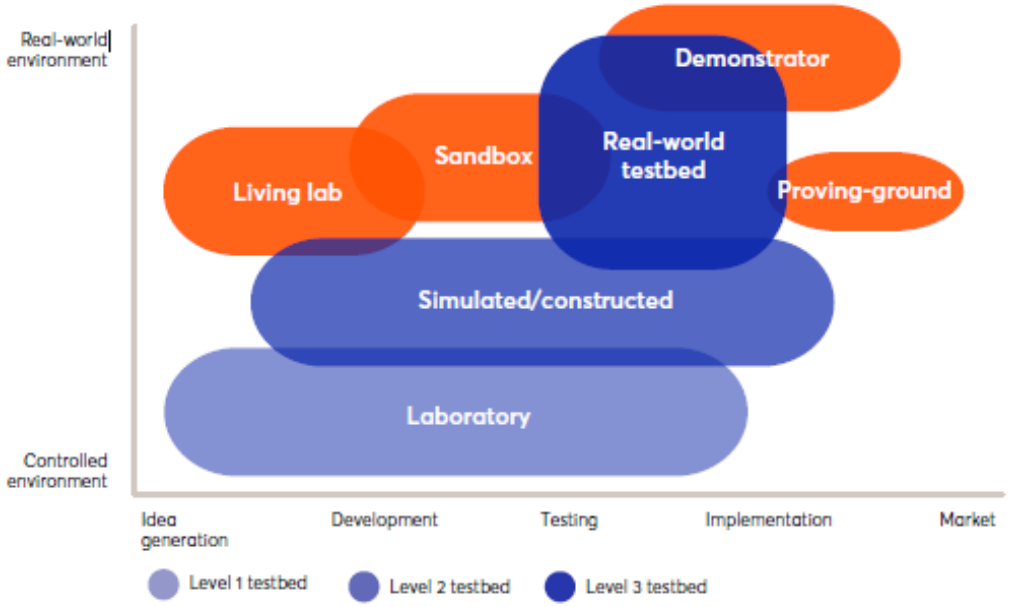

Figure 1. Real-world testbeds placed among other test and demonstration terminologies. (Arntzen et al. 2019)

Testbeds as such are intended to offer a closed simulation environment to test and legitimize innovations. Such testbeds do not only stimulate innovation and precede the scaling up and diffusion of innovations, but are also argued to be used to organize and legitimize new technologies (Bulkeley *et al.* 2019). Such testbeds have until today nearly exclusively been assessed within the fields of urban development, mobility, or the energy sector (Geels 2014; Arntzen *et al.* 2019; Bulkeley *et al.* 2019)

A testbed can therefore be described as a platform for conducting rigorous, transparent, and replicable testing of scientific theories, tools, and new technologies (Arntzen *et al.* 2019). While used broadly across many different disciplines, the term generally describes an experimental approach making use of platforms and environments to develop innovations or new products. Based on these approaches it can be stated that testbeds have until today mostly served a purpose of "testing innovation for verification and proof-of-concept" (Arntzen *et al.* 2019 p. 25). Thus, a testbed, whether it is situated in a laboratory or in the real-world, should test innovative technologies, products, services, or processes. Additionally, testbeds can be seen in the perspective of attaining a wide-ranging number of objectives such as

attracting investments, achieving competitive advantages, or creating more efficient and better public services as seen in figure 2 (Arntzen *et al.* 2019).

Figure 2. Use cases for real-world innovation testbeds. (Arntzen et al. 2019)

2.3 Defining Innovation

Innovation as such is defined in many ways. To be innovative can mean to succeed in exploiting new ideas, while others understand it as improving value to customers although reducing production costs (Francis & Bessant 2005; Berkhout 2014). The Schumpeterian definition of innovation originally bases on a threefold model based on the steps of invention, innovation, and diffusion (Dosi & Nelson 2010). The invention is defined as the development of a novelty, while innovation involves its actual introduction. Diffusion is the stage at which it is adopted by buyers and competitors (Hall 2004; Kahn 2018).

The general process of innovation can also be described as recognising opportunities for profitable change, and furtherly pursuing them to be adopted in practice (Baumol 2002). Innovation is therefore described as something firms need to take part in. They would otherwise not advance, flourish, or even economically survive. Furthermore, past economic growth can directly and indirectly be attributed to innovation that has historically taken place (Francis & Bessant 2005).

2.3.1 Sustainable Innovation

An important modern aspect of innovation is sustainable innovation. Innovations are a process focusing on developing economic or technological development, sustainable innovation though adds the focus of reducing the environmental impact caused by human activity (Seebode *et al.* 2012). It can therefore be seen as new creations occuring within the three dimensions of social, environmental, and economic sustainability. As such, the term sustainable innovation is more disruptive, based on more collaborative approaches and rationale. In the context of sustainability an additional factor of urgency must be taken into consideration. Until today it can be said that innovation had been mainly opportunistically driven, sustainable innovation nevertheless results from a clear need of solving climatic problems (Berkhout 2014).

2.3.2 Diffusion of Innovation

Everett Rogers first established the theory of diffusion of innovation in 1962. Five elements as such influence the spread of a new idea: an innovation, the adopters, the communication channels, the timespan, as well as the social systematic context. As the process is reliant on social capital an innovation needs to be widely adopted for it to self-sustain or reach a critical mass (Rogers 2003; Hall 2004). The tipping point of an innovation reaching diffusion thus lies at the chasm where it achieves to be not only used by early adopters but the so-called early majority, making it a mass product (Moore & McKenna 2014). Diffusion manifests very diversly and is subject to different types of adopters and the innovation-decision process. Thus, another category and factor is the innovativeness of adopters, defining a degree to which individuals are willing to adopt to an innovation (Rogers 2003).

The theory is however also criticised for a lack of cohesion, leaving it stagnant and challenging to apply to new innovations and problems with consistency (Katz *et al.* 1963). Nevertheless, new technologies just as aquaponics, can be well explained through diffusion, showing up how well they are establishing themselves (König *et al.* 2018).

2.3.3 Innovation as a Socio-Technical Process

Conceptualizing innovation as a socio-technical process can be more descriptive to understand sustainable innovation. The term innovation shall in this context not be investigated in a linear perspective, but in a context of social systems through the involvement of people, as well as technology (Berkhout 2014; Geels 2020). Other scholars conceptualise it in that way also as a change of practices, which is a description of innovation adaptions based on verbs instead of nouns (Pantzar & Shove 2010; Hargreaves 2011; Watson 2012). This definition within innovation shifts its focus more towards practices that people have adapted to (ibid.). Thus, it

is critical for sustainable innovations to reach diffusion or changes in human practices to be impactful. Technological advancements brought by innovations are not enough to achieve diffusion and change in practice (Shove & Walker 2010; Mylan *et al.* 2019). As such, scholars argue that innovation is a socio-technical process, meaning that innovation is a process involving not only technological factors, but social factors alike markets, industries, policies, infrastructure, societal discourse, and others (Shove & Walker 2010). Many innovations, especially sustainable innovations face challenges in competing with current regimes (Geels et al. 2008).

As such, not a single improvement but an entire transition from one technological system and all its variety of factors to another are observed (Langendahl *et al.* 2016; Geels 2020). This socio-technical view includes a wide array of actors and factors offering a more holistic view and approach to understand innovations (Berkhout 2014; Geels 2020). This viewpoint can explain where innovations come from and what impact they create in a general as well as in this context of sustainability. The socio-technical process includes many different stakeholders, accounting for the market and its practices, public policy, the already established structures, the technological infrastructure, and the pre-existing knowledge base (Geels 2020). A socio-technical view supports the understanding of the dynamics behind a transition and its bigger picture. Moreover, these different stakeholders are all part of this socio-technical process pushing the transition from a policy side, demanding it from a market side and therefore sparking innovating on an entrepreneurial side, which can especially help in a sustainability context (Berkhout 2014; Geels 2020).

The concept of Technological Innovation Systems (TIS) explains the nature and rate of general technological change (Smits 2002). The main thought behind the approach is that determining factors of technological change are not always to be found in firms or research institutes, but as well in broad societal structures in which firms, as well as research institutes, are embedded (Freeman 1995; Bergek *et al.* 2008). Such TIS can be defined as a network of agents interacting in a specific economic area under an institutional infrastructure involved in the generation, diffusion, as well as the utilization of an innovation (Smits 2002; Bergek *et al.* 2008). The concept can be applied on different levels of analysis. It can be described as a technology within a knowledge field, a product, or as a set of linked products aimed at satisfying a specific, often societal, function (Smits 2002).

The concept of TIS emphasizes that stimulating flows of knowledge is not sufficient to encourage technological change or economic performance (Hekkert *et al.* 2007). Furthermore, the TIS-view approaches structural actors, networks and institutions and analyses what function they play in innovation taking place (Bergek *et al.* 2008). As such, it underlines a need to exploit this knowledge to create business opportunities. It highlights the value of individuals as resources of

innovation, which is occasionally overseen in more macro-oriented sector-oriented innovation system approaches (Hekkert *et al.* 2007). Moreover, the TIS model defines in terms of knowledge flows instead of flows of ordinary goods or services. Thus, TIS can be analysed in terms of system components and dynamics (Carlsson & Stankiewicz 1991).

The Multi-Level-Perspective (MLP) is another prominent framework making such socio-technical transitions understandable (Geels 2020). In the context of sustainability transitions the concept of MLP and its multiple levels can explain how innovations can gain momentum out of a niche to impact a socio-technical regime and then the wider landscape (ibid.). MLP hereby takes multiple societal factors into account when assessing innovations. The MLP describes the regime as a societal structure of institutions, social and organizational structures that shape technological development through their well-established rules and norms (Mylan *et al.* 2019; Geels 2020). Thus, innovations often need to overcome the inertia of such dominant regimes. Innovations are therefore often given protective niches in which they can grow and gain acceleration to breach through towards diffusion and change the regime and later influence the landscape level (Geels 2020). This function of niches is furtherly described through SNM.

2.3.4 Strategic Niche Management and Protective Spaces

Strategic Niche Management (SNM) is an approach focusing specifically on the investigation of small strategic or protective niches to achieve innovation (Schot & Geels 2008). As such, it is an attempt to combine constructivist and technology science into evolutionary economics (Schot & Geels 2008). This can furtherly be applied to the experimental introduction of technologies or innovations using experiments like testbeds or pilot plants (Schot & Geels 2008; Smith & Raven 2012). The approach proposes that innovation pathways can be facilitated by the creation of so-called technological niches i.e., protective spaces. These protected spaces moreover allow a nurturing and experimentation with the co-evolution of technology, regulatory structures, as well as the practice of users (Schot & Geels 2008). Such radical innovations do not serve as simple technological fixes but are socially and technologically interrelated (Schot & Geels 2008).

In these innovation journey actors do not only anticipate but seek to influence the selection process. Thus, they create such spaces in which novelties are experimented and innovated sheltered from mainstream competition. These created spaces can be described as (technological) niches (Schot & Geels 2008). Within this process an innovation or technology situated in a niche is developed away from the mainstream allowing it to develop until it reaches a stage where it can be successfully launched into a market. This then creates market niches, which will eventually lead to a regime shift (Schot & Geels 2008; Smith & Raven 2012). Such innovations and changes can take place in the absence of outside pressure within

existing regimes, however radical innovations are often created in niches where they are protected, which is seen as crucial for bringing about regime shifts (ibid.). Thus, some innovations might arise out of a *fit-and-conform* behaviour, in which diffusion of niche-innovations takes place because they fit within pre-existing environment of selection, or a *stretch-and-transform* behaviour within which an innovation succeeds in regime transformation leading to diffusion (Smith & Raven 2012). These concepts of niches and protective spaces can act as bigger building blocks supporting broader changes for development and are therefore helpful to understand and define how radical sustainable innovations can take place (Schot & Geels 2008; Smith & Raven 2012).

2.4 Conceptual Framework

This study intends to raise the question and build a theory around how testbeds contribute to a modern context of experimentally achieving sustainable innovation. Thus, the frame in which this study sets itself is in-between several innovation theories that approach how innovation can be nurtured until it achieves diffusion. With the aim of assessing the application of a testbed facility in the process of creating a sustainable innovative food production system, the theoretical framework and synthesis is based on the basic ideas of sustainable innovation giving a foundation. These are further built up with the theories of diffusion, socio-technical processes, Strategic Niche Management and Technological Innovation Systems. Thus, this study uses these different innovation theorems to give background and context on how such testbeds hang in-between them and can be described and explained by all of them.

To contribute to the understanding of management implications of testbeds, the study explores the research question through abductively connecting these foundational theories to the case. Additionally, internal as well as external influential factors are added to create four themes out of empirical evidence and theory to create an understanding around how the testbed facility of Johannas Stadsodlingar contributes to the innovation process of developing, testing, and scaling up a sustainable aquaponic food production system. Figure 3 illustrates how the introduced theories, and the empirics are connected within the conceptual framework of this study:

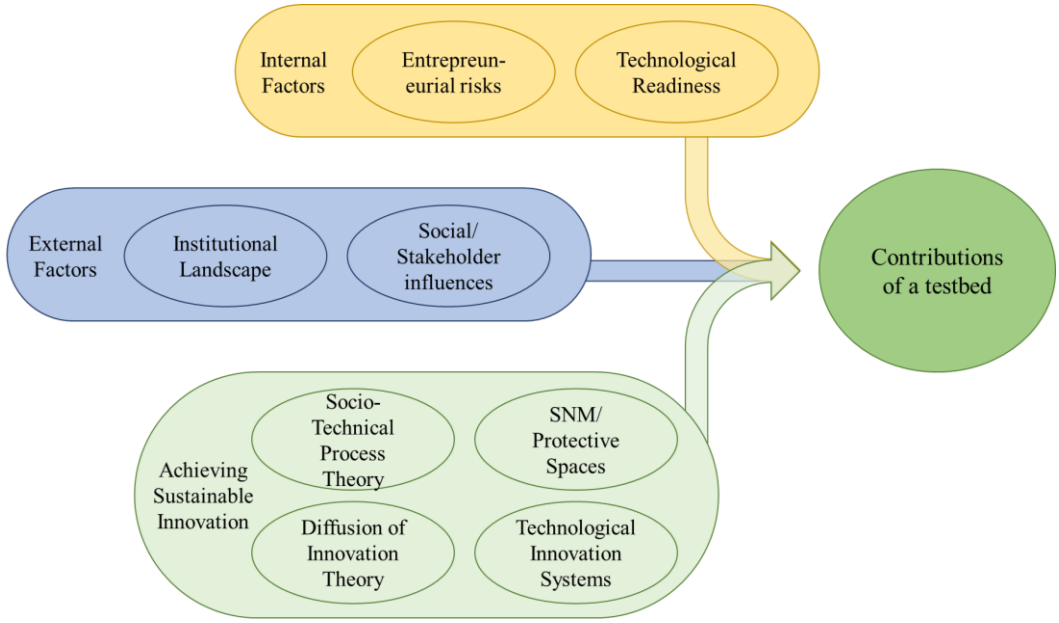

Figure 3. Illustration of the conceptual framework leading to the development of themes

These concepts of innovation from diffusion to the concept of strategic niche management imply that the creation of technological niches and protective spaces enables a small niche the grow out of and nurture diffusion. This shall help to set this study into the right context between this different theories (Rogers 2003; Schot & Geels 2008; Smith & Raven 2012). This study hereby investigates the management activities the testbed adopts and enables for innovation to take place. As a result, this approach shall examine how the testbed contributes to finetune this food production system to become mature, diffuse and fit the socio-technical regime, or even actively change it.

3. Methodology

The following chapter shall present the method and research design applied to conduct this study. Moreover, qualitative, and ethical assurances, as well as how empirical and theoretical data was collected, the delimitations and the chosen method to create an appropriate conceptual framework and to analyse the collected data are described.

3.1 Research Design

A qualitative methodology, or more precisely the application of qualitative methods offers to study a phenomenon within the natural context it occurs in, emphasising on understanding the field of interest through the perspectives of those involved (Carter & Little 2007; Crowe *et al.* 2011; Cresswell 2013; Robson 2016; Bryman *et al.* 2019). Following this approach, the underlying ontology to understand reality in this thesis is based on the approach of constructivism (Mackenzie & Knipe 2006). As such, the reality is understood through interviews to gain new understandings and knowledge through real-life experiencing and social discourse, based on the underlying paradigm of social constructivism (Cresswell 2013; Rashid *et al.* 2019).

Carter and Little (2007) present a framework around qualitative research, in which epistemology, methodology and method are the fundamental interconnected contributors of qualitative research. Thus, this study is epistemologically based on interpretivism. The intention is to grasp the meanings and views of the phenomenon within interviews with the case study cases (Mackenzie & Knipe 2006; Rashid *et al.* 2019). Followingly, the study is able to collect the perspectives of the interview participants, showing perceptions and individual approaches and solutions (Bryman *et al.* 2019; Rashid *et al.* 2019). Hereby, interpretivism can be contradicting the objective view of positivism, as facts are dependent on people's individual values and therefore cannot always be generalized or studied by definite laws (Bryman *et al.* 2019).

Based on this epistemology the study follows a qualitative research approach, exploratorily and abductively developing knowledge and a theory through the research question (Crowe *et al.* 2011; Cresswell 2013; Rashid *et al.* 2019). As such, the study aims at contributing to the literature of innovation theory by exploring the role that testbeds play to achieve and foster sustainable innovation. While

approaches like a cross-sectional study design could be applied, the availability of a single case offering itself to research its testbed, as well as the scholar common-sense of focussing on such a single organization if it is the only available in that field in the entirety of Sweden, argue for the application of a case study design (Flyvbjerg 2006; Zainal 2007; Bryman *et al.* 2019). To apply methods that serve the intention of the study, the research design of a case study with semi-structured and more in-depth interviews with individuals of the organisation are applied. This shall allow the author to inductively deepen the how and why, instead of generating statistically generalizable data around a phenomenon (Eisenhardt 1989; Flyvbjerg 2006; Crowe *et al.* 2011; Cresswell 2013; Bryman *et al.* 2019; Rashid *et al.* 2019).

3.2 Literature Review

To gain precision in the formulation of a relevant research question, to review what has been previously researched and written down a literature review was undertaken (Robson 2016; Bryman *et al.* 2019). Whereas it is discussible whether the systematic or narrative review should be used for qualitative research, a systematic review was conducted to develop a general understanding of the field, identify patterns, and define terminology (Bryman *et al.* 2019). Hereby a clear research and knowledge gap was exposed, while designing a conceptual framework adequate for the study (Robson 2016).

As such, the systematic review concentrated on peer-reviewed journal articles to achieve an as unbiased and trustworthy understanding as possible. No timeframe was specified, more recent research was however prioritised for actuality. Furthermore, the sourcing and scanning of potential literature was undertaken through known databases such as Google Scholar, Primo, ScienceDirect and Web of Science. To gain a deeper understanding around the themes of sustainable innovation, technological innovation systems, the role of testbeds, aquaponics in general and the innovation of aquaponics keywords within the search process were used. Thus, such keywords and different forms of combinations of these were employed: “innovation”, “sustainable/sustainability”, “technological innovation system”, “testbed”, “aquaponics”, “circular business model”. This conducted literature review offered the possibility to identify additional articles and generally relevant literature to the researched field. Additionally, grey literature such as websites, reports and other documents were also reviewed to receive a deeper understanding.

3.3 Unit of Analysis

Within this study the unit of analysis refers to the aquaponics start-up Johannas Stadsodlingar AB and its testbed. Simultaneously, the company and especially within this method its employees serve as unit of observation. As such, Johannas Stadsodlingar and its testbed, which is used to develop the aquaponics production system, serves as an example for the application of testbeds in sustainable innovation.

The choice of a unit of analysis and a unit of observation is necessary to set clear boundaries and describe in what context this empirical case is applicable (Wildemuth 2009; Bryman *et al.* 2019). Such as in this case this can partly be the exact same entity or phenomenon being studied. The interviewees at the organisation serve as units of observation to collect data and information which is analysed in the analysis part of this thesis (Choemprayong & Wildemuth 2009). The aim is to obtain a deeper understanding around the role a testbed plays in such a context. How the data around these units of observation is collected and analysed is described furtherly in the following subchapters.

3.4 Case Study

With the aim of gaining a contextual understanding of the phenomenon, as well as the opportunity to abductively produce a more generally applicable theory, a case study design is applied in this study (Eisenhardt 1989; Stake 2005; Flyvbjerg 2006; Zainal 2007; Brown 2008; Crowe *et al.* 2011; Cresswell 2013; Bryman *et al.* 2019). While there are other possible approaches within qualitative inquiries such as narrative research, phenomenology, grounded theory or ethnography, a case study offers the possibility to study settings in their context (Cresswell 2013; Bryman *et al.* 2019). As such, the case study aims at explaining, exploring, understanding and describing a phenomenon (Stake 2005). Moreover, such a case is not only limited to its own boundaries, but finding a unique case offers the opportunity to learn and derive a theory from that example (Eisenhardt 1989; Flyvbjerg 2006).

Case studies are often criticized for not being generalizable, too practical and biased (Eisenhardt 1989; Flyvbjerg 2006; Zainal 2007; Brown 2008; Crowe *et al.* 2011; Bryman *et al.* 2019). However, case studies offer the opportunity to generalize from a case that a phenomenon can be at all proven to exist (Flyvbjerg 2006). Nevertheless, this does not specifically state that the phenomenon can be considered as significant for a broader context (ibid.). Moreover, case studies can serve to induce or abduct a theory and hereby eventually create a more deeply understandable generally applicable theory (Eisenhardt 1989; Zainal 2007).

Within the broadness of case studies, this thesis aims at conducting specifically a single case study to research the role of the testbed in the bounded context of

Johannas Stadsodlingar. As such, its intention is not too create comparisons, but a more in-depth highlighting of insights that can be of relevance and educational for the broader field of sustainable innovation (Flyvbjerg 2006; Cresswell 2013). Furthermore, a descriptive case study is conducted to find connections between the descriptive theory about the phenomenon and a theory. Thus, clearly specified boundaries of the case study contribute significantly to the studies rigor. Moreover, a descriptive case study offers the potential for digging for abstract interpretations of the phenomenon and thus theory development (Flyvbjerg 2006; Brown 2008; Rashid *et al.* 2019).

3.5 Data Collection

Following the descriptive single case study research design, the data collection is mostly based on conducting interviews. As a primary source of data and information the interviews were held with people working in different roles at Johannas Stadsodlingar as can be seen in table 1 (Eisenhardt 1989; Stake 2005; Brown 2008; Farquhar 2012; Bryman *et al.* 2019). The interviewees were chosen based on their specific knowledge and the roles they hold in relation to their interactions with the testbed (Robson 2016; Bryman *et al.* 2019). Additionally, other forms of secondary data are included to create understanding and achieve triangulation to create validity and reliability (Golafshani 2003). The secondary data served as base of information for conducting the interviews with more sharpened themes and a soft structure to guide the conversation.

Table 1. Semi-structured interviews conducted in the case study

Respondent	Position	Duration	Validation	Date
Thomas Bjelkeman-Pettersson	CEO	50 mins	Recorded in person & transcribed	07.03.2022
Anke Johanna van Lenteren	Head of Horticulture	25 mins	Recorded in person & transcribed	21.03.2022
Tomas Strandberg	Head of Operations	30 mins	Recorded in person & transcribed	21.03.2022
Lisa Henriksson	Head of Bio. R&D	25 mins	Recorded in person & transcribed	21.03.2022
Gabriel von Heijne	Head of Software Dev.	65 mins	Recorded over Skype & transcribed	01.04.2022

3.5.1 Semi-Structured Interviews

This thesis collects its data through interviews with the company Johannas Stadsodlingar AB which follow a semi-structured approach, as methodically recommended by scholars (Eisenhardt 1989; Zainal 2007; Brown 2008; Luo & Wildemuth 2009; Farquhar 2012; Cresswell 2013; Robson 2016; Bryman *et al.* 2019; Rashid *et al.* 2019). Interviews can also be held in more standardized or structured forms with specific questions and a fixed range of answers, as well as in completely unstructured open forms (Bryman *et al.* 2019). Some scholars describe weaknesses within the approach of semi-structured interviews, such as the "interviewer effect" which states that attributes as well as sociodemographic background might influence responses. Thus, leading questions might result in subjective specific answers (Zhang & Wildemuth 2009; Bryman *et al.* 2019). Semi-structured interviews however follow a basic structure and an interview guide to evade such outcome (Luo & Wildemuth 2009; Robson 2016; Bryman *et al.* 2019). Such interviews allow for a higher degree of freedom and more in-depth answers when researchers already have a base of knowledge around a field and aim to enlarge it (Luo & Wildemuth 2009; Robson 2016). As such, interview guides for an introductory and more specific interviews (see *Appendix 1 and II)* are prepared to follow specific themes. Thus, a basic structure is followed to question the descriptive theory, while leaving room for more informative answers and further unplanned supplementary questions to receive more in-depth information (Flyvbjerg 2006; Brown 2008; Bryman *et al.* 2019; Rashid *et al.* 2019).

The interviews are recorded and transcribed with the interviewee's consent. Subsequently, a better conversation and observation is made possible, allowing for better listening and interacting with follow up questions without having to take notes (Farquhar 2012; Bryman *et al.* 2019). Moreover, a repeated and thorough analysis of the transcribed interview is made possible with the aim to achieve an examination as objective as possible. For better face-to-face interactions and an understanding of reactions and contexts the interviews are held physically in person at the facility north of Stockholm or over a video call platform.

3.6 Data Analysis

Following the collection and transcription of data, a qualitative content analysis based on the approaches of Linneberg & Korsgaard (2019) and Ose (2016) is conducted. Hereby, quantification of content in a systematic and replicable manner is achieved (Zhang & Wildemuth 2009; Robson 2016; Bryman *et al.* 2019). Thus, a study of recorded communication of people is conducted, which is done in a standardized methodical analysis form. This is scholarly seen as an appropriate

trustworthy interpretation method when conducting case studies (Zhang & Wildemuth 2009; Elo *et al.* 2014).

Content analysis ensures the researcher to assess the collected materials including searching-out of underlying patterns and themes by moving back and forth between data collection, analysis, and interpretation of the findings (Zhang & Wildemuth 2009; Elo *et al.* 2014; Ose 2016; Bryman *et al.* 2019; Linneberg & Korsgaard 2019). Based on Elo *et al.* (2014) within a trustworthy qualitative content analyses three main stages should be followed: preparation, organisation, and the reporting of the information.

Based on the suggestions of Robson (2016), the stage of preparation includes a review of the existing literature, finding a gap within current research and forming research questions to create findings in the intended direction. Subsequently, sampling, the identification of the unit of analysis, as well as the data collection is conducted (Elo *et al.* 2014; Robson 2016). As such, a flexible design refining the specific tools and hereby the framework of the study is applied. Within the second organisational phase of the study, coding is undertaken, labelling information based on common themes and patterns (Zhang & Wildemuth 2009; Elo *et al.* 2014; Ose 2016; Robson 2016; Linneberg & Korsgaard 2019). More precisely abductive coding is conducted staying close to the data and using terms used by the participants themselves (Linneberg & Korsgaard 2019). As such, induction out of the data, as well as deduction from literature are combined to place the code into the right setting over the different rounds of coding (ibid.). In this phase the method of Ose (2016) is applied, coding the data with the Microsoft programmes Word and Excel. The data is herewith structured and organised, also revising the previously set themes.

Thirdly, in the reporting phase, the gathered data is sorted related to the phenomenon based on the theme categorisation in an abductive approach. As such, the empirics are fed back and compared to previous empirical studies and theories (Zhang & Wildemuth 2009; Elo *et al.* 2014; Robson 2016; Linneberg & Korsgaard 2019). Abduction captures the combination of inductive and deductive elements and through a cycling back and forth between data and theories. Hereby, the author remains open to surprises in the data while at the same time remaining attuned to the existing theory (Linneberg & Korsgaard 2019). The development of a theory out of the descriptive theory can therefore be strengthened with rigorous methodical support (Elo *et al.* 2014; Robson 2016).

3.7 Ethical Considerations

When conducting research ethical issues and questions arise. Especially in the context of social sciences and personal interaction within a qualitative case study, the right approach is necessary to treat respondents ethically, as well as with respect

(Crowe *et al.* 2011; Cresswell 2013; Bryman *et al.* 2019). As such, this study bases its approach on the ethical considerations of protection of a participant from harm, a participant's right to privacy and their informed consent (Cresswell 2013; Bryman *et al.* 2019). Thus, the participants are priorly informed and given as much information as needed for them to make an informed decision to consent partaking in this study (Robson 2016).

Through the consent form the interviewees are informed, which type of data and how this information is later used and analysed. The interviewees will additionally be informed that they have the possibility to refrain from answering questions, restrict their answer to only a limited part or discontinue the interview completely if wished (Cresswell 2013). It is hereby made sure that the participants agreed to be interviewed and recorded followed by a transcript (Bryman *et al.* 2019). The recordings and transcripts are kept with the interviewee's consent to allow for potential later quality and transparency verification. The interviewees are only questioned regarding Johannas Stadsodlingar AB and the testbed with personal topics being left aside. Thus, the ethical issues remain at a low level. Due to the studied testbed being an innovation in current development its technicalities need to be kept confidential. As such, this study discloses all technically specific descriptions and the intellectual property of Johannas Stadsodlingar AB to not harm the business model of the start-up.

3.8 Quality Assurance

In the process of explorative qualitative research, researchers themselves become the instrument (Robson 2016). As such, their prior knowledge and skills become crucial to ensure rigor in the collection of data, analysis, as well as the writing and conclusions drawn in this process (Golafshani 2003; Shenton 2004; Elo *et al.* 2014; Bryman *et al.* 2019). Furthermore, rigorous, authentic, consistent, reliable and trustworthy research can be based on Guba's four criteria credibility, transferability, dependability, and confirmability, which should be upheld to assure research quality (Shenton 2004; Elo *et al.* 2014).

Credibility can be understood as a true picture or adequate representation of the research and the phenomenon or social world it intends to study (Shenton 2004; Zhang & Wildemuth 2009). As in such a case study a single phenomenon is being studied more deeply, there is and will always be a sense of subjectivity (Golafshani 2003). This is always part of such a method, and as such also offers the opportunity to study a case with more depth (Eisenhardt 1989; Flyvbjerg 2006; Bryman *et al.* 2019). As a result, several approaches can be of help to ensure scholar rigor and credibility. Hence, triangulation and pattern matching is applied to receive a variation of perspectives and observations (Golafshani 2003; Bryman *et al.* 2019). This form of cross-checking grants validation and reliability to the study, moreover

the chain of evidence and the theories and models used are documented with interviews being transcribed and validated (Eisenhardt 1989; Golafshani 2003; Drost 2011; Bryman *et al.* 2019).

Transferability is the next criterion of trustworthiness. It strives to safeguard what can be estimated from the findings (Golafshani 2003; Shenton 2004). Especially in such a case of applying aquaponics as an example for the application of a testbed the transferability aims at providing sufficient detail of that field for the reader to clarify whether the prevailing environment is exemplary to another situation, and whether the findings can be justifiably applied to another setting (ibid.). This is furtherly ensured by the clear boundaries and scope of the study to achieve academic rigor.

Dependability and the repeatability or reviewing is the most difficult criterion in the context of qualitative research, however some approaches can be followed in order to achieve it (Shenton 2004; Bryman *et al.* 2019). Golafshani (2003) states that dependability can be seen as irrelevant in qualitative research, as its sheer purpose is to generate interpretational understanding. To ensure a minimisation of bias and errors, the procedures of this thesis are documented, the interviews are recorded, and the latter is fully transcribed. Moreover, the study is audited by several uninvolved parties, as well as a supervisor and an examiner.

Confirmability bases on the expectation that researchers demonstrate that their findings emerge from their data and not just their own predispositions (Golafshani 2003; Shenton 2004). Even though complete objectivity is not possible within such a qualitative method, it is essential to transparently demonstrate where beliefs and opinions arose from and that the research was conducted with good faith (Shenton 2004; Bryman *et al.* 2019). Through multiple sources of primary and secondary data, the understanding of the phenomenon can be validated. Moreover, the beforementioned auditing ensures and strengthens the confirmability of this thesis (ibid.).

Through upholding these criteria, the author intends to ensure rigor and authenticity in this study. As explorative research is conducted the author aims to uphold a consistent, trustworthy, and followable process to make the data collection, thought processes, writing and conclusions drawn comprehensible.

4. Empirical Results

This chapter will present the collected empirical data. In an introduction the chosen case company Johanna's Stadsodlingar shall be presented, followed by the processed data around the role of their testbed collected in the semi-structured interviews.

4.1 Johannas Stadsodlingar

Johannas Stadsodlingar is a foodtech start-up developing circular food production systems based on the principles of aquaponics (described in chapter 2.1). Today vegetable and fish consumed in Sweden are mostly imported. On the one side, fresh vegetables generally travel all the way from the Netherlands, Spain, or Italy, while fish on the other side, mostly comes from the Norwegian fjords. Additionally, overfishing, food waste and eutrophication are becoming more severe ecological problems (Bogard *et al.* 2019; Crippa *et al.* 2021). From a wish to have positive impact in opposition to these developments Thomas Bjelkeman-Pettersson and Anke Johanna van Lenteren founded Johannas Stadsodlingar in 2018 as the initial co-owners of the company. After initially planning to start an aquaponics project in their garage, they found an old barn that was bigger and suited them better, which facilitated to have the same temperature and conditions throughout the year.

With the information of other people building large-scale facilities too early without the appropriate knowledge in the field, Thomas and Johanna took the decision to first build a testbed. They decided to build a first facility of 290m² in a barn in Vallentuna, north of Stockholm, to learn how to run a system containing a mini ecosystem with fish, bacterial cultures, and vegetables. The facility serves as their current testbed to develop their processes and operations for the intended scaling of the production system. This is described in their online building-blog (Bjelkeman-Pettersson & von Heijne 2021).

Today the team of Johannas designs, builds, and operates sustainable circular food production systems. At the core of their systems, they have fish, bacteria cultures, vegetables, and insects collaborating in the natural nutrient processes of aquaponics. The aim is to take a holistic approach to food production applying a

data-driven and automated production style to replicate large-scale, circular, indoor farms (Johannas Stadsodlingar AB 2022).

The basis of the aquaponics nutrient cycle of the company are farmed rainbow trout. They serve as “engine” of the system and supply nutrients to the plants. Building up on that, 30 different leafy greens such as salads, herbs, kale, and more are grown hydroponically repurifying the water system by removing these nutrients. As a result, the farming of these greens makes up between 80 and 90 percent of the volume and income of Johannas (ibid.). These greens can be harvested with their roots, making it possible to store them freshly between one or two weeks longer than conventionally harvested ones.

The production has become a highly sensor-controlled and data-lead process with screens graphically showing the in- and outflows providing an overview of the ongoing processes. Currently, a fish feed with 40% mealworm protein is being tested. The mealworm replaces soy protein and part of the fish meal. The long-term goal is to reduce fish meal content and avoid soy entirely, by substitution with insects and mussel meal. As such, Johannas can provide premium high-quality food from a closed system without any pesticides, insecticides, or antibiotics, reducing emissions and long transports. The current business operation therefore provides locally produced high-quality vegetables and fish to a growing market all year around.

The management team of Johannas has until today grown up to seven people with experience in the fields of aquaculture, horticulture, eco systems, business, law, as well as technology and software. In total more than 12 people are by now involved in Johannas operations. The start-up sells locally to Stockholm-based high-end restaurants, as well as at local food stores and farmers markets. Until today Johannas has taken in 5 million SEK in capital investment to design their first “living food factory” and to create a scalable, replicable solution (Johannas Stadsodlingar AB 2022).

Looking forward Johannas wants to design, build, and operate sustainable circular food production systems. The company will build a second testbed to prove their concept in the fall of 2022. With this second testbed Johannas aims to develop a technologically ready fully automated scalable aquaponics proof of concept for the future. In a long-term outlook these shall work as large-scale automated labour efficient production sites. Johannas intends to design, build, and run these systems by scaling them or building many of these. Thus, these could be licenced to others to build or franchised creating future opportunities for expansion.

4.2 Empirical Evidence

Five interviews between the 07.03.2022 and 01.04.2022 were conducted in the process of collecting information. These are furtherly transcribed and abductively

coded into 25 different original codes (*Appendix 3*). Based on the coding process by Linneberg and Korsgaard (2019) these codes are processed in two cycles and abductively processed creating four separate final themes. These four themes are sorted from most social to most technical and made visually comprehensible by *figure 4* below.

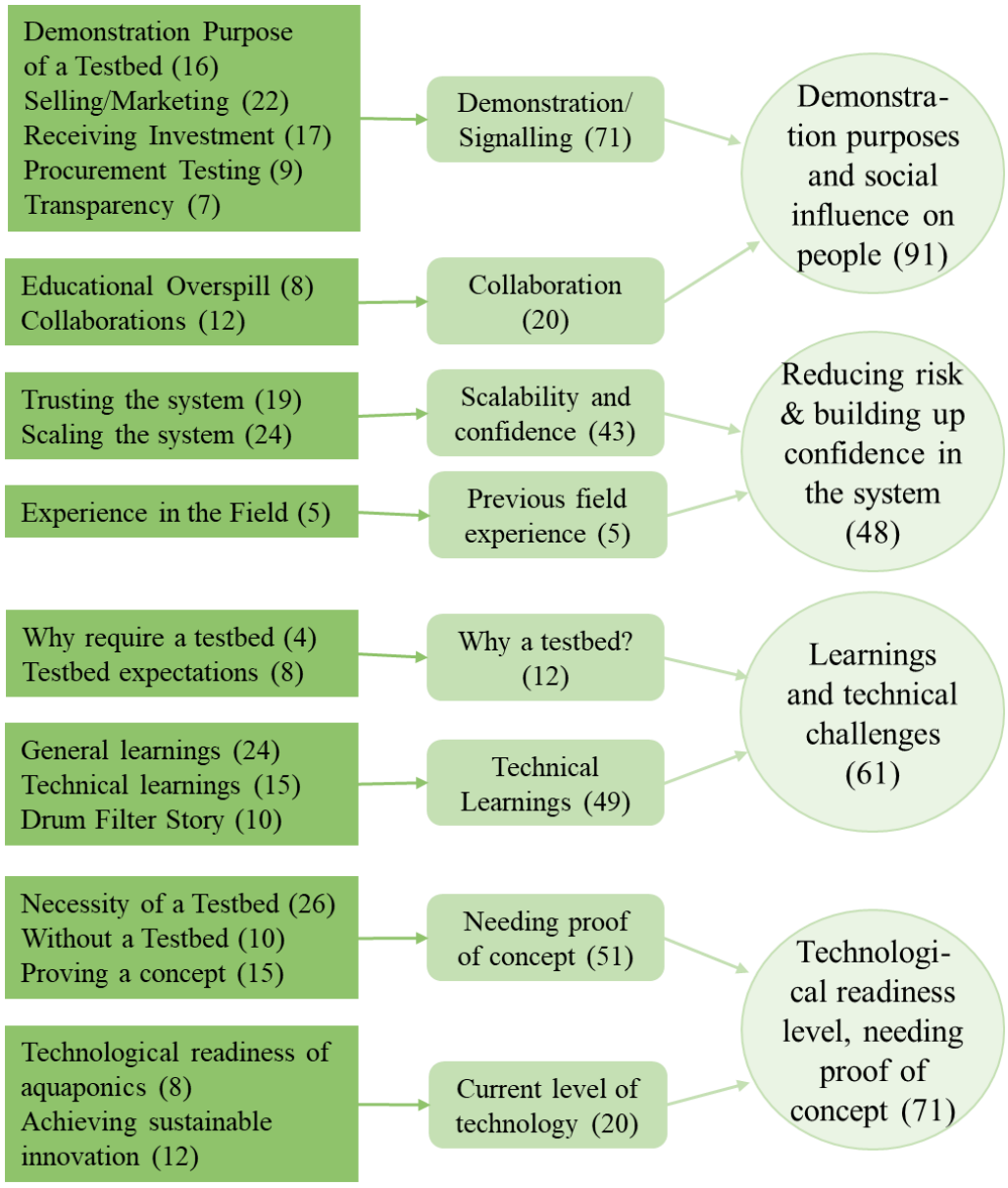

Figure 4. Own visual illustration of the qualitative coding analysis based on the approaches of Linneberg & Korsgaard (2019)

The counted mentions in brackets are transferred and added into the second cycle codes from where they are added to the four final themes on the right. These four

distinguished themes and their empirical data are furtherly presented and described in their following four subchapters.

4.2.1 Demonstration Purposes and Social Influence on People

The interviews clearly indicate the highest importance of testbeds towards the social influence and demonstration purposes they have on all stakeholders around a company. This factor is most often and clearly stated, showing what role this testbed plays in demonstrating how the processes work and that these are all biological processes. It serves in selling the product and giving grocers and chefs the opportunity to try and taste the plants right there where they grow. Today's investors wanted to experience the real running operation to build up trust in the business model. Moreover, the investors only did so because they started believing in the business idea when seeing the testbed working in its real-world context and understanding the potentials it has. On the transparency side, stakeholders could see and comprehend all the processes taking place to understand that the system does not need any pesticides to produce high quality food. Hereby, Johannas Stadsodlingar is signalling that the innovation is achieving its intended purposes through their testbed facility.

Additionally, the testbed has offered potential academic collaborations with different universities of Sweden. This leads to creating academic overspill on all sides, benefitting the company as well as researchers. Statements regarding these topics are found under the categories *Demonstration/Signalling* and *Collaboration.* These statements given are found in *table 2*.

Table 2. Interviewee perception of demonstration purposes and the social influence on people

Category	Perception of interviewees
Demonstration and Signalling through the testbed	"It's also a marketing tool. We can bring people in, (…) you have to bring clients in here or potential clients. So, without you cannot sell this on a PowerPoint slide, there's no way. People have to come in and see it for themselves. And so, it's also been a tool for investors for the next step. Yeah, the pilot facility has been even more useful than we thought it would be" (Anke) "But it is when we get the people out there and show them what we actually do, that's when the light bulb goes on in there. It is very, it's definitely crucial. It's the crucial part of selling this to the world" (Gabriel) "It's probably different depending on who you are, the chefs are most impressed when we put something in their mouths. (…) Uh, but I would guess that if you are an investor, uh, that you're interested in the sort of what surrounds the actual plants in terms of, infrastructure, electronic infrastructure and who we are" (Gabriel)

Demonstration and Signalling through the testbed	"Well, generally most people who come here, whether it's a potential investor, a potential customer or my dad? You know, everyone who comes here, and is like oh, so that's it. (…) And being able to walk around, ask questions, taste the plants you know. How does that look actually? That's important" (Lisa) "Some of the top chefs in the country could come and pick it up, smell it, eat it, and kind of go wow, that's what we want. (…) They were like OK, we want to work with these guys even though they're small. No, they're going to be big one day and we need to start positioning it. Because we're not selling a cheaper product, we're going to sell them a more expensive product because people want what it offers. It's a better product" (Thomas) "I had friends that was chefs. They came in and they tasted, and they said this is really good, this is amazing. You can produce this in the middle of the winter, late fall, or whenever, and it tastes so good, and it lasts so long in the in the fridge? And I think our confidence grew and over the time we have had some of the top chefs in in Stockholm here and they are telling the same story" (Tomas)
Collaboration	"This pilot facility has made us initiate cooperation with, not to brag, essentially every big university in Sweden, we have a PhD student from Gothenburg who is working with aquaponics in general, but specifically fish sludge treatment who visited us a couple weeks ago was very keen on collaborating. We're working together with several researchers from SLU. And we have been asked to be consultants for other research projects and that has much to do with people coming to visit us and say, oh, you know what you're doing here. But also, that we are very open to collaboration, and we can say that this is complex" (Lisa) "We have now two interns from a two-year course in Norrtälje. So, it's an aquaponics engineering course and (…) this has also been quite interesting for us that these people want to come and do their internship here. And which for us is interesting because they're a practical pair of hands. But also, they want to do research. So, you know, we get feedback all the time, which again was not something we had expected. So, this is really amazing" (Anke)

4.2.2 Reducing Risk and Building up Confidence in the System

Additional to the technological learnings a form of self-confidence in the system needed to be built up. Furthermore, a form of system resilience is perceived necessary creating the necessary confidence that this system can be automated and furtherly scaled up. These factors especially regarding scalability were deemed critical in the application of a testbed to create a working market sized circular food production system. Due to the majority not having much experience in the field of aquaponics, the testbed was also deemed critical to gain the necessary knowledge.

These answers regarding system resilience are summed up under the category *Scalability and confidence*. The experience in the specific field is described in the

category *Previous field experience.* Statements given regarding these categories are to be found in *table 3* below.

Table 3. Interviewee perception of needing to build confidence in the system and reduce risk

Category	Perception of interviewees
Scalability and Confidence in the System	"If you start out to build something like this at the scale of times 10 or 50 or 100 as the first project, it feels scary to do that because I think there are enough potholes. Uh, on the road, the likelihood of sort of ditching the product is pretty high" (Gabriel)
	"Right now, I would say, that our level of confidence in the system is much higher than it used to be" (Gabriel)
	"They realise that we actually have some of the best products they can get hold of, period. End of story. Right, and they're like, if you manage to scale this, it's going to be really interesting" (Thomas)
	"If you want to scale that up. You probably want to know how to run it in a small system first and learn. Because I think it's very clear that automation is a crucial part of scaling this up" (Gabriel)
	"And the lesson from that is, since we had the automated monitoring system, we could react before it went south for real because the biggest danger in the system is that the fish dies for lack of oxygen. So yeah, to have several levels of safety is definitely very, very useful" (Gabriel)
Previous experience in the field	"We were just taking evenings and weekends 'cause we both had a job. I'm actually a graphic designer. And I would come and work here whenever I didn't have, you know, something payable to do or billable rather. But the last year and a half it's been more or less full time for me here" (Anke)
	"But I also retrained as a garden designer, just like 15 years ago. And did some courses when we were still living in London with the Royal Horticultural Society, and I sort of come from a horticultural family background" (Anke)
	"No, I have no background at all. But I was part of the company buildings *Smak av Gotland*. So, I knew something about building brands in this industry but nothing from growing vegetables or I knew absolutely nothing about breeding fish, so it's everything is completely new to me" (Tomas)

4.2.3 Learnings and Technical Challenges

While perhaps seeming trivial, a testbed offers more than just basic technical learnings to the case. From the first expectations of the testbed serving the company as a development tool, designing a well-functioning aquaponic system, to overcome unexpected technical hurdles such as the drum filter, which became the bottleneck of the system at some point, these learnings happened thanks to the testbed. As such, the testbed endorsed mastering this complex biological system, which is dependent on a variety of controllable and uncontrollable variables.

The answers why the testbed was originally planned and what the expectations were are summarised under the category *Why a testbed?*. Additionally, the general and specific technical learnings, such as the drum filter story, are compiled under the category *Technical Learnings.* A variety of statements giving examples for these categories are found in *table 4* below.

Table 4. Interviewee perception of needing a testbed for learnings and solving technical challenges

Category	Perception of interviewees
Why a testbed?	"Well, it has to be a testbed at least on some level, a good comparison to the scaled-up system or the real life, I mean, this is real life, it's a real production." (Lisa) "I've had experience doing this stuff before and I was like OK, I'm not doing any of this unless I have a good facility, I can show this for real. Otherwise, I know it's not going to work otherwise" (Thomas) "So, the learning about how the aquaponic system works is very important to know where you want to innovate. And of course, we are innovating on so many different tracks all at the same time. But if you would just look at it abstractly, you may think of totally different things than when you have actually seen it functioning" (Lisa)
Technical Learnings	"But what happens if we add more species into this system? What happens with the microbiome? How can we grow things with fairly low levels of nutrients if compared to hydroponics? Well, what's the reason to that? I don't know, but obviously something is happening in the system, and that's very interesting" (Tomas) "I'm sure Thomas has told you about this drum filter, it's our Achilles heel. We would have never known that. And there are various things that we have learned along the way" (Anke) "The best example because it's so funny, so to speak, it's things that you don't expect and that become really valuable and it's interesting how information about the system can, uh, guide you and how essentially there is very interesting data that we collect that tells us to a very high degree of certainty if the system is running fine or not" (Gabriel)

4.2.4 Technological Readiness Level and Proof of Concept

Within the scope whether necessity is seen regarding a testbed at Johannas Stadsodlingar and the purposes it serves, several patterns of proving a concept are found. These are summed under the category *Needing proof of concept.* Moreover, Swedish technological maturity within aquaponics appears to remain at a level where it requires a testbed for development. These mentions are collected under the category *Current level of technology.* Aquaponics as a commercial business has existed now for quite a while over this globe. In the setting of Sweden however, aquaponics is still in its beginnings. Thus, it is perceived that the technological readiness level is yet too low, requiring an experimental innovation process as in a

testbed. This moreover offers the opportunity to prove the concept in a Swedish environment, considering different climatic and market factors that are completely different to other parts of this world. Exemplary statements for these categories are found in *table 5* below.

Table 5. Interviewee perception of needing a proof of concept

Category	Perception of interviewees
Needing proof of concept	"Yes, I think that building this facility was necessary. There are, it looks kind of obvious, if you have fish, and they swim around, and the water just goes around in a circle and magically the salads appear. But there is actually quite a lot of, I mean, there's gone a lot of thought into just creating this particular system" (Gabriel) "I mean you know it's impossible to design a good complex system on paper. It doesn't work" (Thomas) "I would say it was necessary from several points of view. (…) Every aquaponic system is unique and learning that it can work in California or in the US Virgin Islands. That's a whole different concept from having it work in Stockholm" (Lisa) "I mean there is no aquaponics facility. We could go and learn from locally very easily. (…) We've read a bunch of things. But in the end, if we're going to do this and actually build whole systems, design whole system. We felt we had to build that one ourselves now though. How are we going to learn? It doesn't work, you have to build it. You can't pick up a book and say, OK, we're going to build a really big system based on what I read in this book, that doesn't work" (Thomas)
Current level of technology	"Aquaponics is new in Sweden, but it's not technically a new idea in that sense, so just building an aquaponics facility and producing can absolutely be seen as innovative in the scope of Swedish food production" (Lisa) "Did you look at all the papers written about this, and then? (…) there's very little actual practical knowledge yet I think. Uhm, which is why this is invaluable for us. We need to do practically" (Anke) "If we really want to work with sustainable innovation and not just build PowerPoint slides at universities, but have stuff happening in real life, we have to support people who want to do it practically. And in that sense, I think that whether we're talking about aquaponics or (…) whatever it might be, if nobody does it practically, we still won't have learned anything, and won't change anything (Lisa)

The herewith presented themes and citations will furtherly be analysed based on the theoretical foundations in the following chapter.

5. Analysis

In this chapter, the empirical results are synthesised, discussed, and analysed grounded in the concepts and theoretical foundations laid in chapter 2. Building on these conceptual pillars, the findings are reconnected to these theories from the more specific niche up to the wider view at which aquaponics stands within diffusion to illustrate the abductive process of theory creation to answer the research question.

5.1 The Creation of a Protective Space

The case demonstrates how it is actively pursuing the creation of a small strategic niche in which it gains market traction and slowly grows to push the structures of the market, technology, regulation, as well as the practice of users (Schot & Geels 2008). Thus, the start-up can nurture and experiment with their production and produce in a co-evolution with these other factors:

> "When aquaponics becomes a mature industry that will be totally different. (…) Right now, we try to find restaurants with. I don't know how to say not with an attitude, but that's high-class restaurants that are interested in what we are doing and what we have. But we continuously will have to develop to keep their interest. (Tomas)

With the testbed a socio-technical experimentation with its own protective space and strategic niche has been created, without having any governmental protective policy measures (Schot & Geels 2008; Smith & Raven 2012; Mylan *et al.* 2019; Sengers *et al.* 2019). As the empirics show, the aquaponic system remains a testbed mostly cut off the broad market, while still recreating a small simulated real-world context to achieve the desired developments and learnings. This protective space assists the case in developing its technological solutions and innovations without being pressured by the market, competition, or other bigger financial risks. As such, the time needed to put such a production system into practice is given, which enables the development work to take place within the time frames and testing cycles necessary to do so. The case is hereby actively shaping and influencing its entire surroundings to create and nurture this strategic niche and financially maintains itself through investors:

> "We've read a bunch of things. But in the end, if we're going to do this and actually build whole systems, design whole system we felt we had to build that one ourselves now. How are we going to learn, it doesn't work you have to build it. You can't pick up a book and say, okay we're going to build a really big system based on what I read in this book, that doesn't work. (…) We built the actual aquaponics facility itself just to learn, (…) we designed everything ourselves that was number one. Number two was, there is, you know, there's no way that you know what's going to be a good product in this system. Unless you try it and see how it works with our context, what products do we get to work well or whatever? And if you're going to convince somebody else that these products are good, it can't be done on paper. They have to test them. These are culinary experiences, I mean it's food. (…) To demo that this works and is really good and show customers that it works. And the third, we have to have investors come in. And you know who never invested in a circular food production facility before.

The case in its creation of this protective space is not only anticipating, but actively shaping and influencing customer selection processes. The testbed supports to signal how good the products are and that more sustainable food production is hereby made possible. Furthermore, this slow selective exposure of this new sustainable technology through the testbed can slowly lead to a replacement of other less sustainable production methods (Schot & Geels 2008). Hereby, the testbed pushes a *stretching-and-transforming* because its founders and backers are trying to achieve a regime transformation leading to diffusion in a long-term view (Smith & Raven 2012).

5.2 Changing the Socio-Technical Landscape

In the context of a socio-technical transition process in food systems aquaponics can be a good example of how people as well as technology are involved in the creation of sustainable innovation (Berkhout 2014; Geels 2020). Thus, the embedding of this aquaponic production in its context is slowly taking place over several environments, such as users, the industry, culture, and eventually policies through the testbed (Mylan *et al.* 2019). Moreover, in a multi-level-perspective (MLP) the case's testbed supports the build-up of internal momentum (Schot & Geels 2008). It is hereby nurtured to gain the necessary momentum out of this niche necessary for a change at a landscape level (ibid.). While the case has received financial support from Sweden's innovation hub, the development of the technology takes place within the framework of the testbed without having a governmental regulatory framework (Mylan *et al.* 2019). Thus, it might strengthen the creation of pressure on the socio-technical regime of institutions, social and organizational structures to one day destabilise the regime, which creates a real window of opportunity for aquaponics in this context (Schot & Geels 2008):

> "This pilot facility has made us initiate cooperation with, not to brag, but soon, essentially every big university in Sweden, we have a PhD student from Gothenburg who is working with aquaponics in general, but specifically fish sludge treatment who visited us a couple weeks ago

> and was very keen on collaborating. We're working together with several researchers from SLU. And we have been asked to be consultants for other research projects and that has much to do with people coming to visit us and say that, oh, you know what you're doing here. But also, that we are very open to collaboration, and we can say that this is complex. There are things we need to work on, so it's not just having this facility to show, but also showing that we want to collaborate, which has been of course also very important." (Lisa)

When considering aquaponics through the analytical lens of technological innovation systems (TIS) an explorative and comprehensive picture about the current technological state of aquaponics can be drawn (Smits 2002; Bergek *et al.* 2008). This view helps to understand which roles testbeds play on all sides of such a sustainable innovation. As observed in the empirical research, aquaponics can be seen as an emerging TIS at the border between already present fish and plant production systems still needing proof (König *et al.* 2018). Moreover, aquaponics can be categorized as still in its formation phase in the EU (Bergek *et al.* 2008).

Thus, the markets and consumption behaviour in EU countries currently require entrepreneurs to create and develop their own business models and technical solutions (König *et al.* 2018). Moreover, the current period is characterized by entrepreneurial uncertainty in terms of still modest economic activity, potential markets and a not yet mature level of technology (Bergek *et al.* 2008). The empirical results clearly support this claim, with the case having to build up their business and the testbed for development from scratch. Even though aquaponics shall contribute to a more sustainable food production, the legal and institutional support is currently not present in Sweden. As such, the lack of institutionalised assistance leaves a need of more knowledge and confidence to run and manage these complex food production systems (König *et al.* 2018). Furthermore, entrepreneurs and investors can be observed to be in an environment in which they must uphold the entire risk to develop, build and operate such productions systems. This is additionally shown by the perceived need of the case of a testbed to develop, operate, and later scale up such an aquaponic system:

> "If you start out to build something like this at the scale of times 10 or 50 or 100 as the first project, it feels scary to do that because I think there are enough potholes. Uh, on the road, the likelihood of sort of ditching the product is pretty high." (Gabriel)

5.3 Upscaling and Diffusion of an Innovation

Aquaponics in this Swedish context can generally be seen as still being on the path towards diffusion. While early adopters might have become interested it has by far not yet reached the chasm and hereby the wide masses (Rogers 2003; Moore & McKenna 2014; König *et al.* 2018). The interviewed case supports this emphasising on how important the developments and demonstration purposes of their testbed

are. Thus, a real signalling of confidence and the achieved technological development is necessary:

> "You know some of the top chefs in the country could come, pick it up, smell it, eat it, and kind of go wow, that's what we want. (…) And the distributor could see that happening and were like okay we want to work with these guys even though they're small. Now they're going to be big one day and we need to start positioning it. Because we're not selling a cheaper product, we're going to sell a more expensive product because people want what it offers." (Thomas)

This demonstrates that within the try of creating substitutes for conventional forms of farming in general, as well as aiming at improving current practices within aquaculture and hydroponics a selling narrative remains necessary. More specifically in the context of such new circular food production systems the empirical results show that aquaponics and its prices already are, and will need to be justified by telling a story, showing and proving the quality behind the produce even in the future (Kloas *et al.* 2015; König *et al.* 2018). However, in this process towards a broader market belief and confidence in the products and system are slowly created convincing quality and sustainability-oriented customers. As such, aquaponics may regarding readiness technologically still be standing in a niche requiring such testbeds for development towards more efficiency today. On the sales-side it will for now remain an urban phenomenon that requires innovative marketing and signalling practices to communicate the sustainability and produce quality to argue the price.

Aquaponics today therefore still requires its protected space and strategic niche in the context of Sweden. The case today serves as a suitable facility to educate people and diffuse a variety of learnings and knowledge about the system and the philosophy behind it (Smith & Raven 2012; König *et al.* 2018). Over time it will enable the creation of a working automated system that will confidently be scaled up to an economically feasible production size.

6. Discussion

In this chapter the empirical findings and the analysis relate to the research questions and aim, which are raised in the first chapter. Moreover, this synthesis is set into a broader context giving the holistic scientific contribution this thesis aims to achieve.

This thesis contributes to enrich the context in which the application of testbeds can be put in achieving sustainable innovation aiming to abduct a theory around the application of testbeds. While on the lowest level it might be clear how testbeds help regarding achieving diffusion, market readiness, as well as public knowledge and demand, lifting testbeds up on to a more abstract level in synthesis with innovation scholars shall help to set testbeds in a broader spectrum to achieve sustainable innovation. Hence, this study, besides the mainstream innovation theorems adopts wider approaches on the role testbeds play to enhance the understanding of the potential benefits such testbeds can have in the achieving and accelerating sustainable innovation, especially in this context of food production systems rather than other popular sustainable innovation sectors such as mobility or energy.

This study aims at answering the question how testbeds contribute to the innovation process of developing, testing, and scaling up a sustainable aquaponic food production systems. Thus, four themes are identified through the conceptual framework and the abductive process of combining different perceived business management factors as well as different innovation theories. These four compiled themes are presented in the empirical results (*chapter 4)*. These themes contextualising the usage of an exemplary testbed case are furtherly discussed here and set into context. Thus, the contribution of testbeds in such an environment can be made comprehensible offering a synthesised application of testbeds below:

Demonstration Purposes and Social Influence on People

The case clearly shows how testbeds serve a highly important role in demonstrating and signalling to all stakeholders to create a strategic niche and build up momentum towards a regime change. Within this process towards a broader stakeholder belief, testbeds can contribute to sell, convince, and create trust for people that could not imagine how such a food production system works on paper.

As such, testbeds clearly support the creation of a small strategic sales niche in which high-end restaurants buy the products proving the quality and value the produce has. Moreover, such an accessible testbed offers transparency benefits. Stakeholders can see and comprehend all the processes taking place to understand that the system does not need any pesticides to produce high quality food. Hereby, the testbed facility helps to convince all stakeholders that the innovation is achieving its intended purposes.

Potential investors are convinced by experiencing the running operation gaining trust in the business model and hereby help the entrepreneurs to mitigate their own risk. Similarly, investments only took place once belief in the business idea was built when seeing the testbed working in its real-world context and understanding the potentials it has. This shows how the testbeds endorse a nurturing within this niche helping this circular food production system innovation disrupt the socio-technical landscape and reach diffusion. Over time the testbed will enable the creation of a working automated system that will confidently be scaled up to an economically feasible automatic circular production size system. Hereby, more than the early adopters might be reached, enabling to surpass the chasm and get recognized by the wide masses.

Reducing Risk and Building up Confidence in the System

Testbeds act as a low-risk business opportunity to build up the self-confidence needed in such a food production system with such a variety of biological prerequisites. As the broad societal structures within the socio-technical landscape and technological innovation system of aquaponics demand entrepreneurs to take all risks, entrepreneurs can utilize testbeds to innovate such business ideas with diminished financial risk.

Hereby, a resilient system can be created, giving the confidence that such a facility can be automated and scaled up to an economically feasible production size. Potential bottlenecks and other limiting factors can be discovered earlier making the upscaling of a business idea less financially threatening. Moreover, the nurturing and momentum building of a business innovation is accelerated through the testbed. Thus, big scale production for wider markets can be reached, while having confidence in the production system.

Learnings and Technical Challenges

Testbeds offer more than just basic technical solutions. In systems like aquaponics people are in constant interaction with technology. Thus, while seeming trivial testbeds offer the possibility to design well-functioning food production systems to overcome technical hurdles at a small harmless scale. Especially in the field of such complex biological systems having different prerequisites in every place, a testbed offers to understand such systems at a much lower financial risk and cost.

Technological Readiness Level and Proof of Concept

In a setting like Sweden, where proof of concept due to a currently too low technological readiness level is needed, a testbed can clearly assist in achieving this. It offers the entrepreneurial opportunity to develop such systems in a risk mitigating setup to prove that a concept performs. Especially in a socio-technical landscape like the one aquaponics stands in, such applications can contribute to creating a small strategic niche to grow and nurture out of the small market corner aquaponics currently stands in within the socio-technical landscape of Sweden. As such, the entrepreneurial and technological concept can be demonstrated, and the socio-technical landscape especially on a regulatory and institutional level is actively pushed and transformed.

This generally demands an institutional environment to assist and deliver sustainable outcome in such a direction to support entrepreneurs in understanding the complexity of aquaponic systems and lower the risks and barriers to entry. To become another piece in the puzzle of sustainable food production systems, all actors should be supported and encouraged in the discovery of the best application of aquaponic technology. More institutional support could therefore strengthen knowledge sharing, entrepreneurial innovation, and the creation of legitimation towards potential customers, leaving entrepreneurs with lower risk and a higher willingness to experiment in the example of aquaponics.

7. Conclusions

The aim of this project is to identify the contributions the testbed in the case of Johannas Stadsodlingar AB offers. Factors promoting the application of the testbed in the context of social signalling, proving a concept, and overcoming technical hurdles are identified. In this chapter, the key findings are summarized. This is followed by a conclusion of the learnings illustrating the contribution of the results. Finally, practical implications and future research suggestions are presented.

Using the case of an aquaponic testbed, this study makes an empirical contribution to the literature of experimental innovation, laying a theoretical basis of how such testbeds contribute to developing sustainable production system in an agri-food context. Setting the focus on a food production domain is crucial in terms of sustainability and conceptually interesting due to its structural and systemic specificities compared to other sectors that have already been studied in such a context.

Using these specificities, this study besides the mainstream innovation theorems adopts wider approaches on the way testbeds contribute to enhance the understanding of the potential benefits such testbeds can have in the achieving and accelerating sustainable innovation, especially in this agricultural context. The findings are empirically supported contributions based on four abductively distinguished themes built on perceived business management implications of a testbed of the interviewed case. The four distinguished themes are: 1. The demonstration purposes and social influence on people a testbed has; 2. Reducing risk & building up self-confidence in the system; 3. Learnings and the overcoming of technical challenges a testbed offers; 4. An insufficient technological readiness level, leading to a need for proof of concept.

These four themes help to indicate the importance and contributions of testbeds. This demonstrates how testbeds are beneficial regarding achieving diffusion out of a strategic niche, as well as showing and demonstrating the business case to stakeholders to create trust and demand. It is also clear how testbeds can support the acceleration and nurturing out of such strategic niches through remaining in such a risk-mitigated phase in their beginnings. Moreover, the social influence and demonstration purposes for all stakeholders around a company are especially emphasised. This factor is most often and clearly stated, showing what contribution

testbeds play in signalling that the innovation is achieving its intended purposes. Potential investors want to experience the real running operation to build up trust in the business model, likewise chefs demand to taste the product to build the confidence in a product they would like to cook with in their restaurant. While perhaps seeming trivial, such testbeds offer more than just basic technical learnings aiming at developing a well-functioning aquaponic system. Moreover, a testbed supports the build-up of self-confidence into such a complex technical, as well as biological system, which is dependent on a variety of controllable and uncontrollable variables. This furthermore supports a less uncertain upscaling of such systems as bottlenecks and other problems can be found much earlier.

Aquaponics as a commercial business exists now for quite a while over the globe. In the setting of Sweden however, aquaponics is still in its beginnings. Thus, the technological readiness level is yet too low, requiring an experimental innovation process as in a testbed. This shows how a testbed offers the opportunity to prove the concept in a Swedish environment, considering different climatic and market factors that are completely different to other parts of this world.

This study hereby contributes to justifying why testbed formats are being applied in achieving sustainable innovation making our food production systems more ecological. The case analysis highlights that a convergence of these different factors needing to be tested and demonstrated around an innovative food production system can be achieved by using a testbed to start such a business-related innovation process at a lower risk level and the possibility to transparently demonstrate what the innovation intends to achieve.

7.1 Opportunities for Future Research

The conclusions of this study are based on a single case study with several interviews, representing a single point in time. The reality, however, is in constant change, impacting the testbed, the company, as well as the firm's perception and/or application of the testbed. Thus, a longitudinal approach would be required to attain a clearer understanding of the whole process of shaping, creating, implementing to later reflecting on the usage of a testbed. This study intends to gain in-depth perceptions into the different dimensions of a testbed in the specific context of aquaponics. This thesis can therefore serve as a pilot study, creating a starting point for future research in this direction. A longitudinal study could hereby test what the specific requirements of a testbed are when being built, follow through on how it is then being used to the point of later reflections after potential diffusion and when market readiness has been attained to advance the findings in this field. Moreover, within the field of food production innovations a clear lack of governmental support can be seen. A study investigating how institutional, regulatory, or governmental

support could be set up to encourage such entrepreneurial endeavours could be of great interest.

7.2 Methodological Reflections

This study intends to give an empirical contribution, laying a theoretical basis of how such testbeds contribute to developing sustainable production system in a food production context. As the data is collected from a small sample with unique characteristics and a clear opinion regarding the application and contributions of a testbed the generalizability of the findings might be limited.

Moreover, some data and analysis might have been missed due to the method. As the study intends to dive in and subjectively understand how the testbed might be used and contribute to the purposes of the company, some sides and applications of the testbed may possibly have been missed. This study can therefore not provide a complete picture of how testbeds might contribute to such a context.

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Interviews with Johannas Stadsodlingar AB (face-to-face and over Skype)

Thomas Bjelkeman-Pettersson, CEO, Vallentuna, 07.03.2022

Anke Johanna van Lenteren, Head of Horticulture, Vallentuna, 21.03.2022

Tomas Strandberg, Head of Operations, Vallentuna, 21.03.2022

Lisa Henriksson, Head of Biological R&D, Vallentuna, 21.03.2022

Gabriel von Heijne, Head of Software Development, Uppsala (over Skype), 01.04.2022

Popular science summary

The need for agricultural production spaces as well as the demand for more resilient and efficient food supply systems is rising. Overfishing of the oceans has become a huge global problem, while our fish consumption is constantly rising. Aquaponics has gained increasing popularity as it offers a more sustainable solution to farm fish and leafy greens sustainably and closer to urban centres. While generally seen as a real potential to improve sustainable food production, the commercialisation of aquaponics globally is though still at its beginnings. Aquaponics stands nowadays at a point being currently mostly tested through testbeds, which can be defined as facilities or similar for testing something in development in its real-world context.

This study assesses the application of a such a testbed facility in the process of creating a sustainable innovative food production system at the start-up Johannas Stadsodlingar AB in the north of Stockholm, Sweden. Through conducting semi-structured interviews and qualitative content analysis the following four main themes for the application of a testbed in the context aquaponics are abducted: 1. An insufficient technological readiness level, leading to a need for proof of concept; 2. Learnings and the overcoming of technical challenges a testbed offers; 3. Reducing risk & building up self-confidence in the system; 4. The demonstration purposes and social influence on people a testbed has. In sum, it can be said that testbeds can be seen as an efficient tool in the context of sustainable innovation. They make it possible to develop and achieve innovations in a simulated real-world context before scaling them and making them market ready.

Acknowledgments

In times where a country only a few hours from my hometown is defending itself in a war, this thesis and its contributions feel insignificant. It is not easy to see the purpose of writing and intrinsically motivating oneself when such things are happening in our modern times. However, one must also accept in all this that we can only contribute one step at a time. And so, this thesis shall be my tiny contributing step helping our planet on its path to becoming a bit more sustainable.

I want to express my thankfulness to my supervisor Richard, who understood the situation we students are currently in, writing a thesis in such times. He really helped me along the way. His supervision, encouragement, and enthusiasm supported me to stay motivated and advance.

Furthermore, I want to thank Anke, Gabriel, Lisa, Thomas, and Tomas for sharing their knowledge, experiences and reflections regarding their testbed and developments at Johannas Stadsodlingar AB with me.

Lastly, I would like to thank my girlfriend Julia for the support, as well as my roommate and good friend Leon for our great reflective discussions.

Appendix 1

Questionnaire 1 for semi-structured interview (07.03.2022):

The role of testbeds in the (sustainable) innovation process

Background:
A master thesis within the scope of sustainable innovation theory with special focus on the role of testbeds to achieve, accelerate or generally support the process of (sustainable) innovation. Out of the modernity and personal interest the field aquaponics was chosen as case serving as a general example for innovations applying testbeds.

We will conduct a loosely structured interview, that will likely last around an hour. If you feel that you do not want to answer a specific question, please just say that you have "no comment". An answer can also retrospectively be restricted. Moreover, I would like to ask for your consent to record the conversation for transcription and later analysis to allow for better conversing during the interview.

If wanted, a non-disclosure agreement (NDA) can be set up, that you and any information related to your company mentioned for the purpose of this interview remains confidential throughout this study.

Aim of the study
The aim of this study is to understand what role testbeds play, and how they support businesses in general to develop an offering (technically as well as within the business network).

Research question
How do testbeds support the process of bringing a (sustainable) innovation to market?

General questions

What does your company generally do and what is your role?

Why or how did you decide that building up a pilot facility would be necessary to create such a food production system?

What were the expectations and requirements when building a testbed or pilot facility?

How has the testbed helped to bring the business idea closer to the market?

How has the testbed supported development of technical solutions? Was it needed to proof a concept?

Has the pilot system served demonstration purposes for potential partners, financiers etc and if yes, how?

Has the testbed helped to develop a supply chain or generally system behind it?

What are the challenges you have faced while completing and developing this pilot system?

How could other people benefit or learn from the purposes the testbed served to you?

How do or would “testbed ventures” like Rise (digitalized agriculture testbed) or governmental innovation agencies like Vinnova support your project?

Appendix 2

Questionnaire 2 for all other semi-structured interviews:

The role of testbeds in the (sustainable) innovation process

Background:
A master thesis within the scope of sustainable innovation theory with special focus on the role of testbeds to achieve, accelerate or generally support the process of (sustainable) innovation. Out of the modernity and personal interest the field aquaponics was chosen as case serving as a general example for innovations applying testbeds.

We will conduct a loosely structured interview, that will likely last around an hour. If you feel that you do not want to answer a specific question, please just say that you have “no comment”. An answer can also retrospectively be restricted. Moreover, I would like to ask for your consent to record the conversation for transcription and later analysis to allow for better conversing during the interview.

If wanted, a non-disclosure agreement (NDA) can be set up, that you and any information related to your company mentioned for the purpose of this interview remains confidential throughout this study.

Aim of the study
The aim of this study is to understand what role testbeds play, and how they support businesses in general to develop an offering (technically as well as within the business network).

Research question
How do testbeds support the process of bringing a (sustainable) innovation to market?

General questions

What is your role in the company and how long have you been working here?

Why Aquaponics in an old barn in Husby?

How much have you been working on this in your area of expertise (horticulture, fish farming, operations, software/technology etc.)? How much time (part- or

fulltime) and resources are you investing to get this project and its innovation going?

Do you think that building up a pilot facility was necessary to create or develop such a food production system? Is the aquaponics industry in that regard still underdeveloped?

What were the expectations and requirements when building a testbed or pilot facility in your area of expertise?

How has the testbed supported the development of solutions or innovations in your area of expertise? Was it needed to proof a concept?

Has the pilot system served demonstration purposes for potential partners?

What are the challenges you have faced while developing this pilot system?

How could other people benefit or learn from the purposes the testbed served you? How do you see the role of testbeds generally to achieve sustainable innovation?

Appendix 3

Original Codes of Interview Transcriptions

Recording Agreement	1
Presentation and Background	2
Motivational Background	3
Work/Time Engagement	4
Necessity of a Testbed	5
Expectations of the Testbed	6
Requirements of a Testbed	7
Learnings from a Testbed	8
Proving a concept	9
Demonstration purpose of a Testbed	10
Collaboration Purposes	11
Technological Readiness of Aquaponics	12
Without a Testbed	13
Achieving Sustainable Innovation	14
Experience in the field	15
Selling/Marketing Purpose	16
Educational Overspill	17
Transparency	18
Drum Filter Story	19
Procurement Testing	20
Receiving investment	21
Governmental Support	22
Technical learnings	23
Scaling the system	24
Building trust in the system	25

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