The Achievability of Implementing Aquaponics within Swedish Food Production

What are the obstacles relating to commercialisation of aquaponics?

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Abstract

In a report in 2017, the Food and Agriculture Organization of the United Nations (FAO) determined that food production would need to be intensified by 50% between the years 2012 and 2050. In the same report, it was also determined it would not be environmentally sustainable to off-set more land for agriculture, to produce more crops with high nutritional value. In the consecutive report (2018), the obstacles of rural farming was highlighted within the context of migration and urbanisation.

Aquaponics (AP) is often identified as an agri-aquacultural system that can be implemented in non-arable and urban areas to increase food security in a sustainable way.

This work aims to explore the relevance and potential hindrances to implementation of commercial aquaponics in Sweden through a qualitative review of existing literature related to system design, social aspects such as Swedish legislation and policy, economy, as well as sustainability. Several obstacles that could potentially constitute a hindrance were identified. The obstacles are multi-faceted and relate to social aspects in Sweden, including public knowledge of aquaponics as a sustainable food production system, economical viability, legislation leading to high administrative load, competition from similar systems and a lack of education, as well as the advanced biotechnological nature and infancy of the system itself leading to risk of failure. There are still several topics that require research. In Sweden specifically, future research is suggested to focus on combinations of species suitable for the Swedish market, as well as the development of computer modelling of aquaponic systems based on Swedish parameters.

Keywords: Aquaponics, Aquaculture, Recirculating Aquaculture System, Hydroponics, Swedish Policy, Sustainable food production

Sammanfattning

I en rapport från 2017 fastställde Förenta Nationernas Livsmedels- och Jordbruksorganisation att produktionen av livsmedel behövde ökas med 50% mellan åren 2012 och 2050. I samma rapport framgick att det inte vore miljömässigt hållbart att avsätta mer mark för jordbruksproduktion för att kultivera grödor med högt näringsinnehåll. I nästföljande års rapport (2018) så belystes problematiken i lantmässig produktion i kontexten flyttströmmar och urbanisering.

Ofta identifieras akvaponik som ett agri-vattenbrukssystem som kan implementeras på icke odlingsbar mark och i urbana miljöer, som ett sätt att öka självförsörjningsgraden på ett hållbart sätt.

Detta arbete tar som mål att undersöka relevansen för, och de potentiella hinder som kan mötas av, kommersiell akvaponik i Sverige. Detta görs genom att kvalitativt utvärdera litteraturen kopplad till akvaponisk systemdesign, sociala förhållanden så som lagskrivning och regler, ekonomi, samt hållbarhet. Flera hinder som potentiellt kan motverka implementering an akvaponik i den svenska livsmedelsproduktionen kunde identifieras. Hindren är mångfasseterade och kopplar till sociala aspekter, så som konsumenters igenkänning av akvaponiska produkter som hållbara livsmedelsalternativ, ekonomisk lönsamhet, lagskrivning som leder till hög administrativ börda, konkurrens från likartade livsmedelsproduktionssystem, samt brist på utbildning. Andra aspekter så som systemets avancerade natur och de barnfel som kvarstår från att systemet är en relativt ung teknologi utgör även de ett visst mått hinder eftersom dessa aspekter ökar risken att misslyckas. Det kvarstår flera ämnen som kräver vidare internationell forskning. I Sverige, specifikt, föreslås att forskning tar sikt mot marknadsspecifika kombinationer av livsmedel som kan produceras i akvaponiska system, samt datormodellering av odlingar med svenska parametrar i åtanke.

Nyckelord: Akvaponik, Vattenbruk, Recirkulerande vattenbrukssystem, Hydroponik, Svensk politik, Hållbar livsmedelsproduktion

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Abbreviations

AP	Aquaponics
FAO	Food and Agriculture Organization of the United Nations
IAAS	Integrated Agri-Aquaculture Systems
IMTA	Integrated Multi-Trophic Aquaculture
RAS	Recirculating Aquaculture System
SLU	Swedish University of Agricultural Sciences
UVI	University of Virgin Islands

1. Introduction

In order to understand what hinders the traction of commercial aquaponics in Sweden, it is first important to understand what aquaponics are, why it gained popularity in research and development, as well as the political and societal views of food produced in such a system and what circumstances, laws and policies may constitute a hindrance now.

1.1 Outlining the Themes of the Thesis

The research question for this literature review was what are the obstacles hindering the widespread implementation of commercial aquaponics in Sweden, what constitutes these hindrances, and is it currently a realisable option for achieving sustainable food production in Sweden?

To answer this question, this work has taken a thematic approach where the overarching theme is the achievability of implementing AP within Swedish food production, and the underlying themes branch out to discuss the likelihood of this achievability, naturally taking into consideration the barriers too. The two main themes we are exploring are social aspects, as well as biotechnological aspects, that are hindering implentation of commercial AP in Swedish food production. The latter aspects are discussed through the scope of education and knowledge intensity. Within the theme of social aspects, we will look at four minor themes, which are public view, political barriers, education and knowledge, and competing technologies that are causing dubiety to whether AP would be the best course to attain sustainability. Within biotechnological factors, light will be shone on the complexities and infancy of the system and its inherent interdisciplinary nature. This thematic approach will help us dive into the existing research within this field, and specify the different aspects that will allow this work to answer the reasearch question.

For the benefit and understanding of the reader, it will be divided into four main sections including an introduction with background. The second main section will be focused on factors hindering the implementation of AP in Sweden related to social aspects. The third main section will focus on the biological and technological hindrances to commercial AP being brought into Swedish food production. These two main sections, focusing on guiding the reader through the existing reaseach and knowledge available, aim to set the stage for the next part of the literature review that looks towards analysis.

The fourth section of this work will then aim to critically analyse and conclude the importance of the research question and the findings. This section will uncover the gaps and weakness of existing literature and areas in need of enhancement. Throughout this final sections this work hopes to tie together the existing literature with the importance of the research question, as well as make suggestions that could lead to the successful implementation of the system.

1.2 Aquaponic Technology

Commercial aquaponics (AP) due to its infancy come in a vast array of slightly different models, from low to high tech. In this section we attempt to outline the most essential parts of a commercial AP system, further developments of the system design, as well as shine some light on promising technology that could be introduced as part of the system. This review notes that some pro-innovation bias should be considered due to certain models being advocated for by researchers commonly found in the litterature, as well as sustainability aspects of AP being affected by its level of technological advancement. The more technologically advanced the system is, it can be considered initially less economically sustainable, with time potentially more economically suistainable, more environmentally sustainable depending on location, and more or less socially sustainable. Generally speaking, the least advanced backyard models (Malcolm 2006, Bernstein 2011, see Goddek et al. 2019) are not present in the commercial context as the increase of production from technological advancements was the reason it was adopted as an industrial practice (*ibid*).

The basic modern commercial AP system consists of one or several fish rearing tank(s), an aeration or/and pure oxygen unit, a sanitising unit, a degasser unit for lowering the hydrological gas pressure (sometimes combined with aeration unit) and systems for removal of sludge (sedimentation tank, filters, pumps). The basic system also needs a biological filter including the microbiota responsible for metabolic waste conversion to plant available nutrients. This can be attached, i.e where the microbiota is growing on a substrate such as sand or stones, or suspended in fish rearing tank such as in the case of biofloc culture (BFC), where microbes are allowed to accumulate in flocs, freely in the water. Furthermore, plumbing infrastructure, and a hydroponic unit including pumps and plumbing corresponding to the type of hydroponic system in use, as well as computer systems for monitoring and automation including fish feeding automation, are included in basic commerical AP systems (Goddek et al. 2019).

In terms of more technologically advanced systems, water cleaning systems that remove unwanted source water chemistry and microbial load, e.g through reverse osmosis, may be applied (Lennard and Goddek 2019). Furthermore, sludge digesters may be employed in a separate loop to mineralise some of the solid waste fractions for further use in the hydroponics unit, reducing the amount of nutrient additions needed to support optimal plant growth, aswell as reducing biowaste outflows (Lennard 2017, see Lennard and Goddek 2019; Palm et al. 2019; Zhu et al. 2024). Further still, RAS in combination with plant factory technology, where plants are cultivated vertically in isolated housing under artificial LED light, such as the vertical aquaponic system at the Aquaponics Research Lab, University of Greenwich (Khandaker and Kotzen 2018), may be considered a highly technologically advanced technique potentially well suited for commercial production in peri-urban and urban areas, or within institutions for STEM education. This type of AP system puts further emphasis on the technological knowledge of the user, but is highly efficient in terms of land use.

1.2.1 Coupled vs. Decoupled Aquaponics

AP systems can be coupled or decoupled. This differrentiation in technology can also be denoted as single- or multiloop systems (Goddek et al. 2019) or, rarely, permanently coupled and on-demand-coupled (Baganz et al. 2021). In the original system, the effluent water is transported from the RAS unit to the hydroponic unit, where plants take up excess nutrients, and then transported back, creating a single-loop system where water is shared between both units continuously. Contrastingly, design proposals by Goddek et al. (2015), Kloas et al. (2016), Suhl et al. (2016), suggest a combination of a RAS unit with a recirculating hydroponics unit. This allows for adaptation of the water chemistry to more closely resemble that of hydroponics, without the need to make considerations for the fish health. Early trials of the design model, while intuitively beneficial, proved to require large additions of mineral fertilizer to support the hydroponics unit, and sometimes critically high levels of nutrients of the RAS unit due to issues related to a number of things, mostly related to the scaling of the hydroponic unit. When solar radiation was high, the hydroponic unit used more water due to higher evapotranspiration and left less time for water to accumulate nutrients, leading to deficiencies. Respectively, when solar radiation was low, the hydroponic unit required less water and the nutrients accumulated to critical levels in the fish rearing unit. Since then, the addition of a third loop, for mineralisation and mobilisation of solid waste, has been suggested, which has also been seen in coupled aquaponics (Goddek and Joyce et al. 2019), as well as a desalination unit (Goddek and Keesman 2018). Some advocates for the decoupled type of AP system have prevalently suggested that water pH constitutes the most critical compromise between the preferences of the fish, supporting microbiota and plants. This view, however, has been superseded by Nichols and Lennard (2010, see Lennard and Goddek 2019), Eck (2017), Vimal et al. (2017) and others. AP systems have a higher microbial load than standalone hydroponics. It is now believed that the diverse microbial community present in an AP system, similarly to soil microbes, are forming symbiotic and tripartite associations within the rhizosphere of aquaponically grown plants. This is claimed to promote nutrient uptake in pH conditions that contextually to standalone hydroponics would be deemed sub-optimal (Lennard and Goddek 2019). Adjustment of pH may still be useful in decoupled systems, however, as it increases the mineralisation rates in the mineralisation loop (Goddek et al. 2019). Since sanitisation has no way of discerning between harmful and helpful microbiota and due to reasons of nutrient mediation, disinfection of the nutrient solution commonly seen in the litterature related to aquaponics, is being more and more discouraged in favour of an ecological approach (*ibid*).

1.3 Aquaponics: A Debated Definition

Aquaponics is the coupling of two separate food production systems, namely aquaculture and hydroponics (Rakocy and Hargreaves 1993, see Lennard and Goddek 2019). By coupling these technologies they are able to draw benefits from eachother; the hydroponics unit can use effluents stemming from the animals as fertilizer instead of relying solely on finite mineral fertilizers, and the aquaculture can enjoy clean water replacement with less emissions going into the surrounding environment, which are linked to causing eutrophication of surrounding bodies of water. This counteracts two major sustainability issues concerning each respective technology (Lennard and Goddek 2019). Palm et al. (2018) attempted to define AP systems as mini, hobby, domestic and backyard, small/semi-commercial and large scale, depending on their size. These definitions will likely need to be adapted due to differences in definition when considering AP and recirculating aquaculture systems (RAS), which is illustrated by Espinal and Matulic (2019) using different sizes to describe scale. In this review, commercial scale refers to the smallest economically viable installation seen through the scope of companies that generate profit.

Aquaponics as a concept is said to have ties to ancient China some 1500 years ago where fish was reared in rice paddies, as well as South America circa 1000 years ago, where plants were cultivated on raft systems called Chinampas (Komives and Junge 2015). However, these ancient models poorly represent modern AP, as there was little or no interest to rear fish to an extent where the fish itself would contribute largely to the nutrient profile in regards to the cultivation of plants. Modern AP is said (Lennard and Goddek 2019) to have been invented during the late 1970's, into the early 1980's, by Dr. James Rakocy and his colleagues at the University of Virgin Islands (UVI). Although, some of the early contributions to the birth of the technology, according to Espinal and Matulic (2019), should be attributed to Lewis, Naegel, Waten and Busch, as they are said to have made the first attempts of creating systems with integrated fish and vegetable production. It falls under the category Integrated Agri-Aquaculture Systems (IAAS) (Gooley and Gavine 2003), which is a broader approach. Some researchers (e.g Palm et al. 2018) have defined some of these broader IAAS systems as AP, for instance, including pond systems of aquaculture, aswell as topsoil cultivation of plants being fed wastewater from aquacultures, in their definition of AP. This, however, has been determined to cause confusion and should continue to be denoted as IAAS (or possibly trans-aquaponics, see Baganz et al. 2021) for several reasons, including but not limited to, concerns on waste management and sustainability (Lennard and Goddek 2019). We will delve further into these reasons throughout the course of the review. Furthermore, AP can be divided into two subsets of technologies where one represents the one-loop, fully recirculating model, such as the UVI-system developed by Rakocy and his colleagues; or decoupled multi-loop AP developed in the mid 2010's by Kloas et al. (2015), Suhl et al. (2016) and Goddek et al. (2016). The difference between these applications will be introduced in section 1.4.1. In this paper, the definition of AP will be restricted to the combination of tank based aquaculture such as recirculating aquaculture systems (RAS) with attached biofilters or biofloc culture (BFC) systems, and soilless culture systems (hydroponics and substrate culture), regardless of being one-, or multi-loop systems, for reasons discussed below.

1.3.1 Tightening the Definitions

Aquaponics as a technology has its rationale based in sustainable food production practices (Gooley and Gavine 2003, see Lennard and Goddek 2019; Palm et al. 2019). Part of that rationale is the sharing and recycling of resources. The resources can be defined as the net inputs to the systems. The major inputs in an AP system are water, fish feed, and to some extent mineral fertilizer (*ibid*), as well as plants and fish which are also the outputs. Early definitions would exclude something like early decoupled aquaponics due to the fact that less fertilizer to the hydroponics unit are derived from fish waste, but this review has included it due to its frequently alleged potential for industrial scale AP (Goddek and Körner 2019). Within the EU commisioned Horizon project COST FA1305 a first draft definition based on Palm et al. (2018) was attempted to be "*a production system of aquatic organisms and plants where the majority (>50%) of nutrients sustaining the the optimal plant growth derives from waste originating from feeding the aquatic organisms*" (Lennard and Goddek 2019). This definition encompasses the sustainability approach through using primarily aquaculture wastewater as the nutrient supply for the hydroponics unit, while leaving a fair amount of leeway towards economical sustainability. Lennard and Goddek (2019) argued that aquaponics cannot replace conventional methods of food production unless the consumer is offered more than an ideology; the produce from such a system must be able to be sold to a wide range of consumers and therefore must meet the quality requirements of the market and said consumers, or it won't be economically sustainable. Therefore, an approach that lets the hydroponics unit work under optimal nutrient conditions, such as within a multi-loop (or decoupled) system (Goddek 2017) – which boasted the potential of higher control of water chemistry parameters - would be incorporated in the updated definition (Lennard and Goddek 2019). Regardless of which approach one might have towards defining Aquaponics, whether it is the nutrient recycling, sustainability, economical drivers, or indeed, all of the aforementioned, a few deductions can be made. Earthen pond–, as well as raceway– systems, which never reach nutrient levels that can sustain optimal plant growth (Lennard 2017, see Lennard and Goddek 2019), and where metabolic waste can freely leave the system and therefore isn't used for plant cultivation (Fitwi et al. 2012), should be discounted from the definition. Only tank based aquaculture can produce wastewater, which at least approaches the nutrient levels required for sustaining optimal plant growth (Rakocy 2006; Dauda et al. 2019). Furthermore, open-field cultures, where nutrient enriched water from the aquaculture unit is used to irrigate field crops, are subjected to leakage to surrounding bodies of water, soil erosion, nutrient loss due to uptake into untargeted organisms, and other unsustainable agricultural practices (such as high demand for pesticides) and should also be discouraged from the inclusion in the definition (Lennard and Goddek 2019). Tyson (2011) argues that AP systems strive to use and recycle resources as efficiently and sustainable as possible, which can not be done in conventional open-field cultivation. However, should a waste-stream arise from the individual appropriated AP technology, that can not be used by the hydroponic unit to produce crops, then, adding those waste streams to open-field crops to minimize the waste of nutrients is encouraged (*ibid*). As these developments of the definition were included in the ensuing publication of the EU commissioned COST FA1305 project summaries (Goddek et al. 2019), they should be regarded as the most updated definition according to the EU. Further development of the definitions and nomenclature are being attempted (Baganz et al. 2021) in an almost humourous manner (Palm et al. 2023), where titles of publications are being drawn up in correspondence to each other. These are in particular relating to the coupling aspects (covered in section 1.2.1), as well as similar systems falling under the umbrella of IAAS. These new definitions, however, have not yet been widely adopted and are subject for further debate. This review will therefore, for the purpose of simplicity and benefit for the reader, use widely adopted terms which was found to be recurrent in the litterature.

1.4 Aquaponics and Sustainability

Sustainability in terms of agricultural practices can be split into three sub-sections; environmental, economical and social sustainability are relevant points of measurement. As AP is a relatively new technology, many of the claims in favour of the sustainability aspects of AP need to be considered as specific assessments related to only the systems that have been studied, and might not be indicative from one aquaponics application to another (König et al. 2016). Cascante et al. (2022) argues that pro-innovation bias should be evaluated, and the spread of highly technologically advanced ideals can promote social injustice by negatively affecting financially weak farmers. The economical viability of a technique is said by König et al. (2016) to depend largely on the perception of the products by the consumer. In this regard, aquaponics and similar ventures, in the Swedish context, remains largely untested.

In the face of the reports from Cascante et al. (2022) and König et al. (2016), the agricultural sector is bound by planetary boundaries. In this context, Conjin et al. (2018), who studied the current land used to sustain the populations in relation to population growth until 2050, concludes that effectivising the use of finite resources, and increasing the land use efficiency are key bullet points in need of improvements. They warn that if ignored, our planetary environment will be at risk for deforestation occurence in favour of creating more agricultural land, leading to biodiversity loss and climate change. They also conclude that diet adaptation and waste reduction will not be sufficient to prevent such an outcome, while they still remain to be important goals. Aquaponics may be another useful ammendment to this matrix, and may be called sustainable because of the technology's inherent ability to use both nutrient and land resources effectively (Goddek et al. 2019).

1.5 Potential of Aquaponics in Sweden

While popularly envisioned for arid regions (Conjin et al. 2018) due to the effective use of water, the prospect of Aquaponic technology farming has reached Sweden.

Statistics Sweden (2020) reported that seven per cent of the land area in Sweden is used as agricultural land. Despite this, the Swedish Board of Agriculture (2009) estimates that only six and a half per cent is to be considered arable, meaning that more land is being farmed than is to be considered arable. In 2017, the Swedish government released a proposition (Prop 2016/17:104) regarding the Swedish food supply strategy until year 2030. The overarching theme of this proposition, was a vision to increase Swedish primary production through promotion of agriculture and alleviation of administrative load for farmers, increase Swedish exports of food, increase Swedish food sovereignty, and reduce the overall food supply vulnerability. A point of priority was also to ensure that the Swedish environmental sustainability goals were being upheld in this process. Swedish fish farming was, in 2019, estimated to cover four per cent of the total fish sold for human consumtion (Borthwick et al. 2019) and so made up one of the sectors with the largest growth potential. The highest amount of fish produced via fish farming was reached during the 1980's (Gregg and Jurgens 2019), but was, at the end of the decade, linked to eutrophication. This resulted in a negative public view (*ibid*). Aquaponics are closed technological systems that inherently strives to recycle the waste from aquaculture as efficiently as possible, through hydroponic plant production (Lennard and Goddek 2019). While some open systems of rearing fish and cultivating plants together ascribe to being aquaponics, it is by definition (uncovered in section 1.1) more accurate to designate these systems as IAAS's because they do not strive to use nutrients as efficiently as possible in a hydroponics unit. It is plausible that the AP sector will expand in Sweden due to the limited availability of arable land, as well as the possibility to establish AP's in urban areas (Joyce et al. 2019) – reducing the need for transports that are using fossil fuels. A combination of aforementioned characteristics, and with the political will to increase food production in a sustainable way, it may be a promising technology. With the 2022 Russia-Ukraine war driving a decrease in global food security (Hassen and El Bilali 2022) due to the soaring prices of oil, gas and wheat (OECD 2022) – all important key items for food production – the question of increasing Swedish resilience towards global food security challenges become even more present. The current state of food security in regards to fish may be in jeopardy as commodity price inflation continues to be moderately (>5%) high in Norway (World Bank 2024), which supplies as much as 84% of the imported fish (Borthwick et al. 2019). While there currently seems to be a downtrend in Swedish commodity inflation (World Bank 2024), import reliance remains high. It is therefore worth considering the state of our closest trading partners aswell as the overall global situation. Imported fish constitutes two thirds of the fish consumption in Sweden (Borthwick et al. 2019).

2. Social Aspects of Aquaponics

This first section will be covering findings of factors hindering the implementation of the technology through the scope of social dynamics, legislation, market and finance. The first sub section will cover findings in the theme of public view, where we explore the views potentially hindering commercial aquaponics development through the lens of consumer and legislator perspectives. The following section will delve further into obstructions resulting from the policy making process, policy maker knowledge base, financial viability, and administrative load for producers. Other themes in this section will focus on obstructions stemming from education (or lack thereof), and finally we will look at competing technologies.

2.1 Public View

Aquaponics has been closely related to aquaculture, which could amount to a hindrance through the public perception of negative environmental sustainability aspects of traditional cage aquaculture (Gregg and Jurgens 2019). In contrast to this, current fish consumption in Sweden largely originate from aquacultures through the import of Norwegian salmon (Borthwick et al. 2019). Others found that the aquaponics identity suffers from a lacking social recognition (Eichhorn and Meixner 2020; Hao et al. 2020), which could be interpreted as a low consumer interest, making industry actors and investors less likely to endeavor. In addition, high investment costs and high energy consumption compared to some competing technologies, leading to relatively high production costs and end user prices, constitute a hindrance.

This marks a need for further identity construction for AP produce within the Swedish and European consumer pool, to recognise the system as environmentally sustainable, as green consumption was found to be one of the main secondary drivers to consumer interest. Further development of cheaper technology to drive down pricing, as well as further, and perhaps different, government funding, were also recognised as important for the technology to be successfully implemented (Specht et al. 2019; Hao et al. 2020; Eichhorn and Meixner 2020; Horn et al. 2023). In the face of this, due to AP being a relatively young technology, there is a disparity in the definition of what should be considered aquaponics. The EU commissioned COST FA1305 project sought to bridge this disparity through a set of general principles (Lennard and Goddek 2019), yet, the disparity remains due to a lack of certification schemes as well as established industry actors' disagreement. As different systems denoted as AP, with different environmental and socioeconomic sustainability outcomes, continue to sell their products under the AP flag, the risk of confusing legislators on how to appropriately support the industry, as well as potential consumers of what they are actually paying for, remains high (*ibid*). Green consumption being a main secondary driver to consumer patterns further begs the question of the sustainability of AP, which will also rely on a unification of definition. Currently, while attempts are being made to assess this aspect through advanced modelling and tools, demonstrated by Francisco et al. (2024), the disparity in the definition and furthermore, the differing outcomes depending largely on the physical location of implementation, remains a challenging bridge to cross.

2.2 Policy and Legislator Knowledge

Gregg and Jurgens (2019) reported that permitting for larger scale AP farms in Sweden had a handling time of up to six years before granted, three times as long as its neighbouring country Denmark. The administrative load was deemed high for nearly all scales of aquaponic applications.

In recent years, The Swedish Board of Agriculture, together with The Swedish Agency for Marine and Water Management (2021), released a report that included a progress evaluation for the food strategy goals (Government Offices of Sweden 2017) relating to aquaculture, resulting from Prop. 2016/17:104. They summarise that their strategies had a limited effect on goals relating to economy, product development, environmental sustainability, as well as alleviation of administrative load for producers. In light of this, the Swedish Government appointed a special investigation on the 30 June 2022. The primary objective was to alleviate the administrative load and increase the profitability and sustainability of Swedish aquaculture practices. Unfortunately, the employment record for the investigation showed no experts in the field of Aquaponics. The 800 page report (SOU2023:74) that ensued mentions the technology a total of three times, and contains confusing definitions on what AP systems are. In the report, decoupled aquaponic systems are labelled as open flowthrough systems where the effluent water is discharged to external recipient outside the system, despite research design approaches typically being closed systems to the same degree as coupled (Goddek et al. 2016). This can be viewed as an obstruction to promoting the system specific benefits of AP systems, potentially creating biased legislation, favoring one model over the other, as well as its environmental sustainability potential. Furthermore, no claims on site-based benefits are made. AP-systems differ from similar IAAS models in that it has a hydroponic unit, which is often considered unsustainable (Blom et al. 2022). AP systems recover the environmental sustainability lost in energy consumption by not being bound to rural open-field agriculture, the latter often linked to habitat loss and other unsustainable properties. The meaning of this is that environmental benefits are typically linked to its inherent ability to recycle land already in use in urban and peri-urban sites (Körner et al. 2021). The lack of mentioning this in the SOU2023:74 report can lead to hindrance for the legislators in giving out targeted funding which is specific to AP.

In December 2023 the Swedish government made changes to financial grants to AP farms given from the European Maritime, Fisheries and Aquaculture Fund (SFS2023:937), removing AP from possible recipients. In a press message two months later (Government Offices of Sweden 2024), they announced the reinstatement of AP, as well as IAAS farms, as possible recipients with an expanded national grant of 640 million Swedish crowns. By June, further changes were made which meant AP could now also be given financial aid through the European Agricultural Fund for Rural Development (SJVFS2024:11), and all financial aid applications were moved to The Swedish Board of Agriculture, in an attempt to reduce the administrative load on producers caused by dealing with multiple departments that may not naturally intersect, as well as for the promotion and inclusion of more circular food production technologies. Grants of funding to greenhouse producers can be given for construction or renovation of greenhouse(s), irrigation systems, systems for handling of fertilizers and pesticides, systems for composting and, broadly expressed, systems for enabling the employment of circular cropping methods including aquaponics. This is a promising and overall positive change. However, the acquisition of marginal urban and suburban land is still one of the largest investment costs (Joyce et al. 2019) when establishing an aquaponics farm, to fully exploit the benefits of the technology, and no subsidiarys for urban or suburban land acquisition in shrinking cities is included in the government financial aid plan. One of the main environmental sustainability claims ascribed to AP systems is its ability to be implemented in the rim of urban settlements, instead of occupying limited arable land (Joyce et al. 2019). This also serves to reduce environmental and financial costs of transport (Baganz 2020). Furthermore, FAO (2018) reports suggest that the rural labour force is in decline world wide, increasing the difficulty to reach the Swedish goals of increased food production in a rural setting. In rural settlements, population density is typically lower and the intrasectional competition for competent labourers is higher. In the case of AP which, compared to less technologically advanced agri- and horticultural systems, puts extra emphasis on the expertise of the labourers (Baganz 2020), this could mean high costs for the acquisition and retention of staff in a rural setting due to competition. Financial aid for paying the labour force is not granted by the Swedish government. Early predictions on the economic viability of AP have in later years been described as economical myths. It is now known that AP is paired with economical viability challenges due to high investment costs, high labour costs, and high costs of operations related to energy consumption. (Turnsek et al. 2019).

2.2.1 Administrative load

The administrative work load, or simply administrative load, if high, could constitute a hindrance due to resulting in more work compared to other business ventures. Gregg and Jurgens (2019) deemed the administrative load in Sweden to be high. To run an AP farm, the producer needs to go through many administrative tasks to get started and further during operations. The extent of the administrative load is demonstrated in table 1, which was produced using a web tool called Mina Checklistor (Verksamt 2024). The web tool is created for producing check lists for certain specific types or general types of companies. The prompt used was to create a checklist for an aquaculture company, as creating a specific checklist for an aquaponic company was not available. The website that contains this tool is funded and published jointly by three Swedish government agencies, namely the Swedish Companies Registration Office, the Swedish Tax Agency and the Swedish Agency for Economic and Regional Growth. This review adds the last point on the list based on a requirement on hydroponic practicioners (The Swedish Board of Agriculture 2024). Note, that the list may not be exhaustive, may be subjected to change with time and is made solely for the purpose of demonstrating the administrative load encountered by primary producers employing AP technology. An assumption is that the basic administration required for owning a company is already met and will not be included in the table.

Before operations	During operations
Permits granted by the Unit for Environmental Protection at the regional government agency (Länsstyrelsen) are needed for farms using more than 40 tonnes of animal feed annually. The application needs to be accompanied by an environmental consequence assessment which can require hiring of consultants.	Record keeping is required during operations for several things relating to the fish welfare and records must be kept for at least 5 years. The record needs to contain the species, categories and quantities of fish, any internal or external transportation of fish, animal health declarations, mortality rates, bio-security measures. It is also required to note health controls and laboratory test results.
A permit is needed if a sludge digestor is utilised for remineralisation of the solid waste fraction to recycle more nutrients.	A system for record keeping of purchases and deliveries is required to ensure tracability of commodities.

For building an AP farm, permits from the municipality are needed for construction of buildings, recounstruction of buildings which significantly affect their purpose, or changing the cover materials of buildings.	AP farms are accountable for breeches in their responsibility relating to fish welfare and health. Any suspicion of disease or sudden increases in mortality rates must be reported to a licensed veterinarian. The veterinarian in term needs to send samples to an accredited laboratory for evaluation of disease presence. Some disease need to be reported to The Swedish Board of Agriculture.
Production of fish species that are not endemic to Sweden requires a permit from the regional government agency.	Special permits granted by The Swedish Board of Agriculture may be required to bury diseased animals. Some areas allow for burial of diseased animals that have not been processed without applying for permits.
Any primary production company in Sweden needs to register their company at the regional government agency. This is accompanied by controls which assure that the producer adheres to the rules and responsibilities of primary producers mandated by the Swedish National Food Agency.	Any changes to the facility including animal transportation pattern changes must be reported to The Swedish Board of Agriculture.
The Swedish National Food Agency also handles applications and approvals of any parts of a farm which are intended to process or sell the produce. This is accompanied by a fee and recurring controls, which are also accompanied by a fee.	All aquaculture farms including aquaponics are required to hand in an environmental report annually.
Commercial production of fish also needs to be registered with The Swedish Board of Agriculture. A biosecurity plan* is needed. Hiring of external consultants may be needed.	EU and government financial aid applications need to be handed in annually. For AP farms, this may require several applications.

AP farms which intend to hold more than 35 tonnes of fish annually need a preliminary examination performed by the regional government agency’s agricultural unit to control that the facility satifies the demands on animal welfare.	An application for taxation refunds for expenditures relating to energy consumption needs to be handed in annually.
Permits for rearing is needed from the fishery unit of the regional government agency.	
Any facility which is intended to hold animal feed needs to be registered with the regional government agency.	
Food production facilities need to be registered with the local municipality office if they intend on selling produce locally.	
If the AP farm receives payments with cash, debit cards or payments via electronic payment facilitators, it needs a certified cash register system. It also needs to register the cash register with the Swedish Tax Agency.	
AP farms of the decoupled system design variety, which intend to use pesticides in the recirculating hydroponic unit, require a physical person who will handle those pesticides to get a license through the regional government agency.	The chemical pesticide license needs to be renewed every 5 years and requirements include the person to take a course. Extensive record keeping of pesticide use is required and records must be kept for a certain amount of time. The regional government agency performs controls.

Table 1. Visualisation of administrative load from Verksamt (2024)

*The biosecurity plan includes identifying how disease can find its way into the system and adding countermeasures to the operations to counteract such emergence.

2.3 Aquaponics: A Knowledge Dependent Technology

For anyone to start or operate an AP farm, a certain amount of criteria relating to the fitness of the business practitioner or company must be met. To run an aquaculture farm, the water chancellery at the Swedish Board of Agriculture require a designated person, owner or employee within a company, which is principally responsible for the aquaculture. In accordance to the second chapter, 8 § of SJVFS 2019:6, this designated person needs to have to have 1) Sufficient competence to run operations in accordance to animal welfare policies 2) A theoretical education background in aquaculture technology 3) Experience working with aquacultures. The designated person is required through the second chapter 10 § of SJVFS 2019:6 to be able to provide evidence of points 2) and 3) through grades, proof of employment or similar. In practice, this means that any endeavour would require competence in two separate fields, aquaculture engineering (or similar) and horticulture (or similar). Until 2021, no institution in Sweden provided an education targeted at aquaponics, meaning that investors and small scale startups may immediately get overwhelmed by the relatively large demand on expensive competence acquisition. Comparatively, the acquisition of agricultural land for growing crops, while also overseen by the regional government agency, require little to no formal education and can sometimes be superseded for residency purposes (SFS:1979:230). A conventional standalone aquaculture also requires qualified personnel, but compared to aquaponics, a business venture in aquaculture requires no agri- or horticultural expertise. A yearly financial report from an industrial aquaponics farm (Peckas Naturodlingar 2019) identified the reliance on recruiting, developing and retaining qualified staff, within the scope of competing companies offering better compensation for work, as the company’s first point of risks. The company has since then changed name to Agtira. The same evaluation of risks was noted last year (Agtira 2023). This can be also be extrapolated from Bosma et al. (2017) where labour costs constituted nearly half the costs in an aquaponics project. The technologically advanced method of farming that is AP should also be evaluated further as a hindrance for implementation, as lack of knowledge can lead to to poor quality in the decision making process of planning and operating an aquaponics farm (König et al. 2018). With the findings of heterotroph bacteria mediating nutrients to plants contextually to hydroculture, high pH, the world of aquaponics has moved its scope beyond technology and much research is now focused on the microbiology, potentially leading to the necessity of more expertise. Since 2021, a higher vocational education at Campus Roslagen in Norrtälje municipality has been educating students towards the purpose of becoming aquaponics engineers, with slots for 30 students per year. The education and numbers of alumni is still small, and is only offered on two locations in Sweden, namely Väddö (20 slots) and Härnösand (10 slots).

2.4 Competing Technologies

A point in social aspects creating hindrance for the development of commercial aquaponics in Sweden, is market competition from established actors in both soilless culture and aquaculture. Until recently, few examples of AP were able to compete with the overall quality and quantity seen in standalone productions of convetional hydroculture (Kloas et al. 2015; Suhl et al. 2016; Monsees et al. 2017), speaking of the difficulty imposed on the producer. Furthermore, RAS compared to net pen aquaculture has high operating costs in small to medium scale and at large scale the investment cost comparison is still considerable (Espinal and Matulic 2019). Still, the cost of investments and operations in AP farming leading to high prices (Joyce et al. 2019) makes it difficult for AP system farms to compete for lower prices.

Further limitations on industrial emergence are the prospects of competing semi-circular aquacultural and agricultural systems currently employed or under development. One example of such a system employment is the established company Gårdsfisk, which combine RAS technology coupled with separately private-owned conventional soil farms. Like aquaponics, this is a type of IAAS, sometimes referred to as trans-aquaponics (Baganz et al. 2021) but would be excluded in any traditional definition of aquaponics due to emission and relatively low recycling capabilities. The cooperation is contract based, meaning that Gårdsfisk employs farmers and supply them with fish and RAS, but effectively own the fish. The farmer is paid a share in the profits based on the contract, performs the labour during operations and also gets to use the fish rearing effluents for crop cultivation. This system generally boasts a lower investment cost due to approaching already existing agricultures and sharing the costs between two companies. Thereby, investing in a RAS system is typically the only needed expansion of infrastructure, and the fish rearing company Gårdsfisk reduces their labour costs and tax costs for environmental impact.

Another prospecting system to consider, which is still in its pilot stage, is Integrated Multi-Trophic Aquaculture (IMTA). This system, similarly to the previously described IAAS system, is a semi-circular system which employ several trophic levels to reduce but not completely negate eutrophication associated emissions, but are more similar to conventional cage aquacultures in that it does not typically use land based crop cultivation for cleaning the water. As with aquaponics, early Cost-Benefit Analysis models of these systems are yet to prove themselves. A competitive positive for aquaponics in the context of IMTA is that it might be applicable in closed containment aquaculture such as land based RAS (Knowler et al. 2020).

3. Biotechnological Obstacles

There are several factors that pose problems for the implementation of aquaponics at a commercial scale, relating to the biology, technology and the specific system requirements for success, that can be viewed as an obstruction. In this section we will outline what some those factors are, relate them to previously mentioned hindrances through the scope of requirements on qualified operators and risk of failure, and attempt to shine some light on research that might help overcome these obstacles, but also on research that may further exacerbate the knowledge intensity demand, and risk increase production costs.

3.1 Source Water and Production Water Quality Demands

Aquaponic and hydroponic systems have a relatively high demands on the water quality. In recirculating hydroponics, the chemical composition can change over time leading to reduced production and precipitation and accumulation of salts leading to toxicity (Maucieri et al. 2019). As a nutrient rich environment, aerated for organisms to thrive, the proliferation of opportunistic bacteria is of concern for both fish and plants, but also for biofilters, and the source water is a potential vector. While rain water is usually free from microbes, the containers for gathering and storage may be sources (Lennard and Goddek 2019; Joyce and Timmons et al. 2019). When proper biosecurity measures such as sanitisation of source water aren't employed, risks increase for pathogens, including human pathogens such as *Chryseobacterium* spp. (Dinev et al. 2023) which also typically stem from the source water. To exacerbate this further, Antaki and Jay-Russel (2015, see Joyce and Timmons et al. 2019) showed that human pathogens can remain in the gutbiota of fish without acting pathogenic towards the fish. Water containing calcium can affect the buffering capability, and industry standard chemicals used to adjust pH may not be applicable. Sodium and chloride can accumulate in the system as it is not used by plants. Source water needs to be carefully evaluated and sanitised (Lennard and Goddek 2019). For accurate calculations of nutrient additions to support optimal plant growth, respect must be given to the source water, but also to the general water temperature in the system (Maucieri et al. 2019), particularly in smaller scale aquaponics where temperature is typically adapted to accommodate the natural environment of the fish. In larger scale, the water temperature is sometimes adjusted during transport in the infrastructure as means of sanitisation or to fit the optimal environment for the target species. Espinal and Matulic (2019) express that over 40 parameters affect what is to be considered good water quality in RAS and lists five parameters that are critical to continuously monitor, them being dissolved oxygen used by fish for cellular respiration, ammonia levels which when elevated are toxic to fish, biosolids (turbidity) which affect the gills performance negatively, carbon dioxide, and total gas pressure (TGP). High dissolved carbon dioxide interrupts the fish ability to diffuse carbon dioxide into the water, as a byproduct of the fish's cellular respiration. This leads to a pH drop in the blood of the fish which impedes the haemoglobins ability to carry oxygen, leading to hypoxia. Total gas pressure is monitored as high TGP can cause bubble disease in fish, because gas form nitrogen enters the bloodstream. Bubble disease is considered a serious health condition in fish. Furthermore, nitrate and alkalinity are also monitored but are less critical. Nitrate has a low toxicity in fish but high concentrations may cause health problems. Alkalinity is monitored as the nitrification process in the biofiltration is acid-forming and thereby constantly reduces the waters ability to buffer pH. If the pH drops, the nitrification process stops leading to ammonia accumulation (*ibid*).

3.1.1 Fish Feed, Nutrients and Biofilters

The commercial success and sustainability of an AP system seems to, among other things, rely on its ability to cycle nutrients to plant available forms and thereby reduce inputs of conventional hydroculture minerals while still optimising the hydroculture production (Goddek and Joyce et al. 2019). Choice of fish feed will generally affect the composition of plant available nutrients the most (Robaina et al. 2019), but fish species (Knaus and Palm 2017) and variation will affect feed conversion ratio and stocking density preferences, which in turn also affects the nutrient composition. Other important factors are water temperature, microbial composition as an effect of water maturity, as well as the life stage of the fish (*ibid*; Eck et al. 2019). The choice of fish feed in aquaponics needs careful consideration for the plants as well, as traditional fish feeds contain an amount of sodium chloride which can accumulate in the system, as well as deficient amounts of potassium, phosphorus, iron, manganese and sulphur (Robaina et al. 2019). While nutrients are genereally thought to be available under different pH conditions in an aquaponic system (Lennard and Goddek 2019), careful monitoring of pH must be performed as inorganic phosphate which is already deficient, binds to calcium in pH above 7.0 (Joyce and Timmons et al. 2019). In coupled systems, additions for plants can only be made with respect to the fish and some have detrimental effects on the fish growth. It is believed that fish feed will therefore, at a developed stage, constitute a compromise between the two systems (Robaina et al. 2019). Contemporary studies focus on developing performance metrics (Colt and Semmens 2022), feeds targeted specifically at aquaponics (Shaw et al. 2022), and using machine learning for optimising the nutrient supply (Dhal et al. 2022; Liu et al. 2024). In commercial practice, the RAS water is typically allowed to mature together with the biofilter that is inoculated with nitrifying bacteria and fed organic matter. This practice was found to reduce risk of pathogens, but if there is an occurance, sanitisation of the water is necessary. This can disrupt the biofilter, in particular in suspended growth types such as biofloc culture (Espinal and Matulic 2019) that is sometimes employed instead of RAS due to the reduced need for pumping (Dauda et al. 2019). Hence, after disinfecting, the fish waste to nutrient conversion is disrupted which also create favourable conditions for the occurence of new opportunistic pathogens. For this reason, it can be necessary to use probiotics (Joyce and Timmons et al. 2019). Computerisation and monitoring is, for reasons listed in this section, necessary for any commercial application and operators need a working understanding of all aspects of the conversion of nutrients. One way to make nutrient composition more predictable is through the sequential rearing of fish in different tanks as proposed by Rakocy (2012).

3.1.2 Disinfection Practices and Microbial Balance

One consideration for the development of the more ecological practice of not disinfecting the nutrient solution is that this approach, which promotes the proliferation of heterotrophic bacteria and their useful effects, also increases the microbial contribution to dissolved carbon dioxide and total gas pressure (Espinal and Matulic 2019), two particularly energy consumptive and obstreperous parameters related the water quality for fish. In a COST FA1305 survey among aquaponics practitioners in 2018, it was determined that 83% of the participants had observed disease in the hydroponic unit (Stouvenakers et al. 2019). Another concern may be the increase in biofilms which constitute one of the major contributors to biosolids in RAS (*ibid*). The ecological approach is more feasible in small scale productions as the risk of causing potential harvest loss due to water quality fluctuations imposed by the microbial community has more financial consequences in a large scale production (Joyce and Timmons et al. 2019; Palm et al. 2019). One way to make it more cost effective is to place the aquaculture unit within the same building as the plants. Körner et al. 2017 simulated a model to utilise the extra carbon dioxide in photosynthetic processes, reducing energy consumption for such systems. Another benefit of this model was found to be that the RAS system seemed to act as a temperature buffer in the greenhouse and thereby reduce heating costs, while the extra energy consumption for heating the RAS unit was little, and it added to the relative humidity in the greenhouse. As the model and simulation was made at Copenhagen university, it may have implications for Sweden. A futher concern however, when abstaining from sanitisation of the water, is the microbial accumulation and sudden release of hydrogen sulphide as this has been shown to cause catastrophic loss of fish stock for a majority of species, with critical levels in the micromolar range of concentration (Espinal and Matulic 2019; Bergstedt and Skov 2023). Further still, the carbon/nitrate (C/N) ratio increases with the maturity and microbial activity of the water and must be monitored, as a high concentrations of carbon is linked to fluctuations in the microbial community composition, which can lead to biofiltration failure (Eck et al. 2019).

3.2 System Design and Technology

In the largest sense of industrial production currently found in Sweden - i.e in the order of 10,000-15,000 square metres of greenhouse - the question may be raised on choice of system design. As a way to increase the productiveness of the system, an approach where separating the loops, with RAS and biofilter in one loop and hydroculture in a separate recirculating loop was proposed by several researchers during the mid 2010's (see section 1.4.1 and sources therein). Early iterations of this new decoupled design showed promising results in theory but not so much in practice (Goddek and Joyce et al. 2019). Problems included having to add too much conventional hydroponic fertilizer for the technology to be cost effective and sustainable. The scale of the hydroponics loop in relation to the RAS unit, was found to be largely dependent on evapotranspiration. As this is not a constant value, depending on the installations' latitude but also due to daily variations, new modelling was required. The problems included a large deficiency of nutrients for the crops when evapotranspiration was high, and, more rarely, critical levels of nutrient concentrations leading to leaching and waste in the RAS unit, when evapotranspiration was low. Further development suggested adding a mineralisation loop incorporating sludge digestion to increase the nutrient concentrations. However, as this was a possible addition in one-loop aquaponics, there needed to be a rationale to the new design (*ibid*). To tackle this new development, researchers involved looked at additions of a desalination unit (Goddek and Keesman 2018), as well as system sizing (Goddek and Körner 2019). The conclusion of the new computer models was that systems needed to be in the scale of between 11520 square metres (tomato) to 15750 square metres (lettuce) in the northern latitudes to obtain an optimal system stability and performance, and incorporating the new expensive infrastructure. Jansen and Keesman (2022) finally concluded that balancing nutrients for the fish and plants growth becomes very complex in the northern latitudes and thus this model may not be appropriate for greenhouse production in Sweden, but is still prevalent in the literature. Stalport et al. (2022) stressed the need for unification of system modelling tools in a review of existing ones, as they were found to be scattered, unavailable or highly specific to their research scope. This exacerbates the need for knowledgable designers and engineers for building an AP farm.

4. Discussion, Suggestions and Conclusion

This final section of the literature reivew aims to critically analyse and conclude the findings within the themes of this work. It also aims to suggest improvements with the AP systems' particular properties in mind, which have been uncovered in the themes as well as within the introduction.

4.1 Discussion and Suggestions

Regarding the aquaponics recognition in the consumer base, recommendations identified for increasing the social recognition include the development of Swedish NGO's and, through them, the development of certification schemes. It is notable that the NGO Refarm Linné is currently active on the Swedish scene, however their focus is on small-scale aquaponics (Hjelm 2021). While there is still an amount of disagreement in the community of researchers regarding the threshhold for fish feeding waste nutrients supporting plant growth to be 80% (Lennard 2017, see Lennard and Goddek 2019) or 50% (Goddek 2017) needed to be classified as AP, this may have implications for a future emergence of certification schemes with focus on environmental sustainability, which can affect the value of the products.

Legislators can thereby make more informed decisions on level of support in the individual application of the technology, as seen from farm to farm, and develop further support in terms of centralised information campaigns and relative pricing which can all augment the economic viability (Röös et al. 2020). Financial aid for investments in AP farms could be targeted towards the acquisition of urban and peri-urban land recycling, e.g. by granting building permits only if the rooftop is being marketed for rural prices per square metre, with a legal clause that it is used exclusively for commercial AP production, as rooftop AP has been shown to increase the sustainability and overall economic viability of AP technology. This viability stems from utilising waste heat recovery in such implementations (Pineda et al. 2020; Körner et al. 2021). Aforementioned targeted financial aid, paired with certification schemes, may also work as a driver for future producers to consider applications that serve to increase the nutrient recycling and/or environmental sustainability. While AP is typically linked with high investment costs and therefore low economic sustainability (König et al. 2016), the pursuit of socioeconomical sustainability is often linked with trade-offs in environmental sustainability

(Scherer et al. 2018). Start-up and small scale AP farms are particularly vulnerable to the high investment risks (Joyce et al. 2019), not only due to their costs, but also because of their standing in the market. Gregg and Jurgens (2019) describe small to mid scale AP farms in the context of Global Value Chains-theory as often falling into a captive value chain, which requires high levels of coordination between producers, buyers and legislators. Captive value chains are described as value chains where larger companies noted as lead firms exert a considerable amount of power due to the high competition among smaller scale produce suppliers. The lead firms (such as slaughterhouses, technology providers or wholesalers) do not necessarily compete with the producers which can augment the producers operations due to lead firm investments - but the low autonomy of the producers due to the high costs of changing trade partners is paired with a considerable amount of risk in a venture with already high investment costs (Gereffi et al. 2009; Gereffi et al. 2018). In the perspective of Maslow's hierarchy of needs (Maslow 1943), the physiological needs, where access to food is included, are viewed as more important and it could be argued that sacrifices in economic sustainability, in favour of environmental sustainability, may at some point be required. The funding from governments can lead to the advent of cheaper AP technology which in terms can lead to higher profitability. Another targeted funding to promote aquaponics development was found to be the acquisition and maintenance of a competent labour force. The proportion of cost for salaries and social fees for the agricultural sector, compared to the company income, has decreased from 33.5% to 19.5% between years 2010 and 2022, respectively, as showed by a report on the national agricultural accounts. The report, however, stresses that the report is generalistic in its essence and thereby does not serve to determine results of different production orientations (The Swedish Board of Agriculture 2022). Section 2.3 as well as section 3 highlighted the requirements in commercial AP for particularly expensive labour due to its interdisciplinary nature. While the efforts of research connected to machine learning may help reduce the overall cost of operations through reduced labour (Dhal et al. 2022; Liu et al. 2024), it does little for the careful design and maintenance of the system required, and labour dynamics remains one of the largest weaknesses that must be addressed. This is further proven by contemporary industry practitioners (Agtira 2023). The targeted funds suggested can serve to help AP companies compete against other similar productions, not just in the market but in the retention of staff and social sustainability. Efforts of intersectional government cooperation between the Swedish Agency for Marine and Water Management, the Swedish Board of Agriculture and the Environmental Protection Agency were recognised but needs to be further fortified and developed for the benefit of reducing the relatively high administrative work load imposed on AP practitioners.

The IAAS labeled as trans-aquaponics (Baganz et al. 2021) in Sweden has implicated benefits in terms of sustainability and increased food security. The expansion of this practice however, is relying on susceptible established open-field farmers and therefore limited. With increased education, and off-setting urban and peri-urban rooftops, aquaponic farming has the potential of filling in the gaps.

As for comments on system design, the decoupled model which is often found in the litterature seems incompatible with the Swedish variability of solar radiation (dependency explained in section 1.2.1) as shown by Goddek and Keesman (2018) and Jansen and Keesman (2022). Some consideration, however, might be advisable in the case of building plant factories (Khandaker and Kotzen 2018), as the evapotranspiration in such systems is theoretically more uniform which may reduce the need for supporting systems such as desalination and mineralisation systems, and/or the energy consumption in such support systems.

The use of sludge digester loops to increase nutrient recycling and nutrient concentrations has been debated in the context of food safety, with concerns for the spread of coliform bacteria. These specific concerns thus far seem unsubstantiated (Pantanella et al. 2015). However, Zhu et al. (2024) stresses, as research moves on with anaerobic sludge digesters, that research needs to focus on the effect of anaerobic supernatants on the food safety of plants that are produced in such a system, as there may be other microbes than coliforms that can affect the food safety negatively. The implications on increased environmental sustainability by sludge digesters are quite clear, however, by reducing the need for additional fertilizers (Goddek and Joyce et al. 2019). Another use of anaerobic sludge digestion, while not leading to increased nutrient recovery, also promotes sustainability, as these systems can be adapted for the production of green energy through the production of biogas (Obaideen et al. 2022; Bórawski et al. 2024). Hydroponic farming is linked to high use of energy and sometimes evaluated as causing more environmental impacts than traditional open-field farming, by reports such as the one by Blom et al. (2022). While this report fails to appropriately assess a few things, such as the eutrophication potential, it also highlights the difference in using green energy, as do others (e.g Romeo et al. 2018). Furthermore, in the Swedish context, Moberg et al. (2020) reported that extinction rate, phosphor application as well as nitrogen applications constituted the largest environmental impacts in Swedish food production. These are all impacts which can be diminished by the careful design and implementation of aquaponics (Körner et al. 2021), which is seen as a general improvement of independent hydroponics (Chen et al. 2020).

Further research is needed to develop computer modeling of designs and environmental sustainability assessments, specific for the Swedish latitudes and energy sources. This modelling can help future prospectors determine size for commercial success. Furthermore, a framework for fish and vegetable species, which combine beneficially in aquaponics, and are marketable in Sweden needs to be developed, for diversification of production. The current achievability of commercial AP in Sweden was deemed difficult but not impossible. Improvements to the themes highlighted in this review can lead to increased success.

4.2 Conclusion

The hindrances to implementation of commercial aquaponics found, was illustrated in section 2 through the themes. Within these themes it was discovered that AP systems suffer from low public recognition, insufficient legislator knowledge and thereby ability to identify system specific needs for success, relatively high administrative load, competing technologies that may also be considered sustainable, as well as the advanced technological nature of the system, emphasising requirements on competent and qualified labour. The requirements on competence and knowledge was further illustrated throughout section 3. These themes highlight the overall difficulty of implementation and could help current prospecting investors make informed decisions on whether or not to invest and if so, in what type of AP system design and location. It could help legislators expand their assessments for current needs to further develop the industry, as well as help illustrate the need for researchers to develop models adapted for the Swedish market. It could also inspire current practitioners in the Swedish industry to form NGO’s specifically for commercial applications of the technology and, through them, develop certification schemes.

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