Student thesis series INES nr 595

# Sustainability assessment of different crops for aquaponics: an evaluation table for growing crops using wastewater from juvenile Atlantic salmon in RAS

Elísabet Jónsdóttir

2023
Department of
Physical Geography and Ecosystem Science
Lund University
Sölvegatan 12
S-223 62 Lund
Sweden

Elísabet Jónsdóttir (2023).
***Sustainability assessment of different crops for aquaponics: an evaluation table for growing crops using wastewater from juvenile Atlantic salmon in RAS***
Bachelor's degree thesis, 15 credits in *Physical Geography and Ecosystem Science*
Department of Physical Geography and Ecosystem Science, Lund University

Level: Bachelor of Science (BSc)

Course duration: *March* 2023 until *June* 2023

Disclaimer

This document presents work undertaken as part of a study program at Lund University.

# Sustainability assessment on different crops for aquaponics : an evaluation table for growing crops using wastewater from juvenile Atlantic salmon in RAS

---

Elísabet Jónsdóttir

Bachelor thesis, 15 credits, in *Physical Geography and Ecosystem Science*

Martin Berggren
Senior lecturer

Exam committee:
Harry Lankreijer, Senior lecturer
Micael Runnström, Senior lecturer

# Acknowledgments

I would like to thank my supervisor, Martin Berggren, for good support. I would furthermore like to thank Heiðdís Smáradóttir, from Samherji, for advice and sources. Thank you to my mother, sisters, my aunt Rannveig Kristjánsdóttir, and my friends, who not only provided mental support during this process but also read through my drafts and listened patiently to me as I discussed nothing but fish and hydroponics for weeks on end. Nora Behsler, Sarah Dufau, and Vendela Cyrén deserve a particular applause. Lastly, but not least, a special thanks to my father who guided me throughout.

## Abstract

Aquaculture is an expanding industry, supplying closer to 50% of the total fish consumption. Commercialized fish production faces sustainability challenges which are important to address. Aquaponics uses wastewater from aquaculture to grow plants using hydroponics. This is a step towards making the industry more sustainable, but the practice is not straightforward. The plants and the fish thrive at different environmental conditions and not all plants can be grown using aquaponics. The aim of this study was to use literature to find a user-friendly evaluation method and to find suitable crops to grow in a juvenile Atlantic salmon aquaponic system in Iceland. This study used a Multi-Criteria Decision Analysis Method to compare the suitability of different crops for hydro- or aquaponics. The evaluation was based on the three sustainability pillars from the United Nations: economical sustainability, social sustainability and environmental sustainability. An evaluation table was constructed, and three crops were compared for aquaponics in view of these sustainability pillars: basil, lettuce, and soybean. The crops were graded using a score function. The basil received the highest total score and was deemed most suitable for an aquaponic system where juvenile Atlantic salmon is farmed. The basil received a much higher grade in economical sustainability which resulted in it receiving the highest total grade. Lettuce scored the highest in social and environmental sustainability indicating that it is also suitable for aquaponic purposes. Soybean was found to be unsuitable at this point. A sensitivity analysis was performed in the form of “worst case scenario” using the lowest values found in the literature. It revealed that economic sustainability was a controlling factor for the final grading. The evaluation table itself was found to be easy to modify to the user’s needs where both subcategories and weights can be adjusted. It can be applied for other sustainability assessments comparing the suitability of several crops for hydro- or aquaculture and even agriculture. Further studies could include constructing an experiment using juvenile Atlantic salmon in an aquaponic system and comparing several crops in order to get more accurate values on the environmental parameters.


Keywords: Aquaponics, RAS, MCDA, Atlantic salmon Smolt, hydroponics, Sustainability

# Table of Contents

# 1 Introduction

Climate change brings various challenges to the world, one of the most pressing ones being food security (Mbow et al., 2019). The demand for sustainable food production is highlighted further by the combination of climate change and a growing world population (FAO, 2023). Natural resources on both land and water are currently being depleted, with agriculture requiring extensive land use and high amounts of fertilizers that are produced from limited resources (Mbow et al., 2019). Moreover, fish stocks in the oceans and inland waters are either overfished or utilized at their maximum capacity (FAO, 2020). Due to our planet's precarious situation, the United Nations has put forward 17 sustainable development goals (SDG) regarding human health and environmental wellness as guidance for countries to follow (United Nations, 2023). These goals highlight the need for sustainable food production and should be considered not only by governments but also by private companies.

The demand for seafood is high; the annual consumption has doubled in the last 50 years and is expected to increase even further (FAO, 2020). The overfishing and demand for sustainability have in turn led to the aquaculture industry growing steadily in the last decades (FAO, 2020). Aquaculture is the farming of aquatic organisms for enhanced and controlled production, and in 2018 the aquaculture industry contributed to 46% of the total fish production (FAO, 2020). The feed used in aquaculture typically contains wild-caught fish and thus, while aquaculture does not involve fish from the ocean being sold directly to the consumer, it does require the use of valuable natural resources (Salin et al., 2018). Other environmental concerns include high water usage of both sea and freshwater, depending on the chosen farm system and fish species, and nutrient release into natural ecosystems (Salin & Arome Ataguba, 2018). Therefore, all of the SDGs can be applied to aquaculture on some level (FAO, 2017). Considering these goals is an important step towards a future where resources are used in a sustainable way and where the environment is protected.

A particular aquaculture system called Recirculation Aquaculture System (RAS) is receiving increased attention for its potential of making the industry more sustainable. The system has a high rate of reusing water and it allows the producer a facilitated collection of waste and wastewater compared to other systems (Bregnballe, 2015). Additionally, there is increased interest in utilizing the wastewater from the RAS further by combining it with hydroponics, rather than disposing of it. Hydroponics is an agricultural practice of growing crops without soil, providing nutrients only through water (Kledal & Thorarinsdottir, 2018). The combined practice of hydroponics with aquaculture is called aquaponics and is presented as a way towards a more circular economy with a reduced environmental footprint (Kledal & Thorarinsdottir, 2018). The plants utilize nutrients from the wastewater and act as biofilters for the wastewater and in turn the system requires less chemical filtration before the water is returned to the fish tanks (Kledal & Thorarinsdottir, 2018). Furthermore, the water usage is minimal compared to agriculture and hydroponics (Dalsgaard et al., 2013). This both reduces the need for fertilizers when growing crops and utilizes nutrients from the fish that would otherwise go to waste (Kledal & Thorarinsdottir, 2018).

The wastewater from the fish contains two particularly important nutrients for plants, namely nitrogen (N) and phosphorus (P) (Poli et al., 2005). N and P are some of the most important micronutrients for plants, where either one is commonly a limiting factor in plant growth (Dawson & Hilton, 2011). P is not in unlimited supply in the environment, and both P and N have high energy usage when produced synthetically (Dawson & Hilton, 2011). Utilizing the N and P from the wastewater is therefore an important step towards more sustainable agricultural and aquacultural practices. While it might seem simple in theory, the usage of the wastewater from aquaculture is not a straightforward process. The optimal pH level for fish is higher than the one for most plants (Skar et al., 2022). Though some plants can sustain themselves at higher pH levels it limits which crops can be grown and their yield (Skar et al., 2022). Crops that grow in a suboptimal environment can have lower yield and lower quality fruit compared to the ones grown under more preferable conditions (Chapin et al., 2011, Chapter 8). Moreover, the wastewater is not filled with all the necessary micronutrients and those are provided through fertilizer (Atique et al., 2022).

Several studies have been conducted on the growth of crops using wastewater. Hence, it is possible to identify potential crops and limitations for aquaponics using literature. There are many factors to consider when deciding on a crop and while there are plenty of decision-making methods available few of them are very user-friendly (Talukder & Blay-Palmer, 2017). Moreover, these methods can be time-consuming, complicated and, often, based on qualitative grading from experts (Talukder & Blay-Palmer, 2017). With this in mind, there is a need for a simple method where decision-makers can assess the sustainability of crops and compare them to each other. To recognize and compare crops that are suitable for aquaponics, what the limitations are for each one, and what growth potential they have is therefore of importance.

## 1.1 Aim

This study aims to find a method to easily compare and find suitable crops in a hydro- or aquaponic system for juvenile Atlantic salmon (*Salmo Salar*) in Iceland. The aim of this study is twofold:

I. Construct an evaluation table, based on a Multi-Criteria Decision Analysis, in order to assess suitable crops for hydroponic growth
II. Evaluate selected crops using the table, with the objective of using wastewater from RAS

In order to successfully fulfill this aim, the evaluation table needs to include the following objectives: economical sustainability, social sustainability, and environmental sustainability with a clear connection to the sustainability goals of the United Nations. The evaluation table should include parameters that are important to consider when deciding on a crop for aquaponic purposes. It should be simple to use and allow for an easy visualization as to which crop is most suitable. The crops should be graded through a score function to further facilitate the comparison.

# 2 Background

## 2.1 Atlantic salmon juvenile farming

The Atlantic salmon (*Salmo salar*) is a carnivorous anadromous fish, meaning it travels between fresh- and seawater, and is found in the North Atlantic Ocean (Thorstad et al., 2011). The Atlantic salmon has various migration patterns depending on its location, and morphs can be found that either spend the entire life in freshwater or travel to the ocean for feeding before returning to their river for spawning (Thorstad et al., 2011).

Atlantic salmon is favored in food production for various reasons, one being that the fish contains high amounts of protein and lipids in its meat, making it a highly nutritious food source (Sprague et al., 2016). Since the 1970's the farming of Atlantic salmon has increased and in 2019 the global production was over 2.6 million tons (FAO, 2022). As Atlantic salmon is anadromous, farming typically takes place in both freshwater and seawater phases (Bergheim et al., 2009). The juveniles are reared in freshwater and once they reach proper size are moved into seawater where they grow until reaching commercial size (Bergheim et al., 2009). RAS farms are increasingly more common in juvenile Atlantic salmon production (Bergheim et al., 2009). It has been shown to provide relatively large smolts, which is the final juvenile life stage of the salmon before it is transferred to salt water (Thorstad et al., 2011). In RAS, the juvenile fish is grown up to bigger sizes (140-170 g) than in flow-through systems (50-70 g) (Bergheim et al., 2009; Bregnballe, 2015). The water temperature is kept at around 10-14°C and using light manipulation the growth period of the smolt is controlled, pH level is at 6.8-7.3 (Bergheim et al., 2009; Dalsgaard et al., 2013). After about a year, the juveniles are transferred into seawater where they grow until they reach commercial size (Bergheim et al., 2009; Bregnballe, 2015).

### 2.1.1 Feeding

The Atlantic salmon juveniles have high energy requirements and the feed typically contains around >40% protein and >30% lipids (Weihe et al., 2018). A feed conversion ratio (FCR) is used to measure how efficiently the fish uses the feed: the kilograms of feed to every kilogram of weight gained by the fish (Joyce et al., 2019). Farmers try to keep this ratio under 1 and for Atlantic salmon, it is typically around 0.7-0.8 (Bregnballe, 2015; Dalsgaard et al., 2013). Automatic feeding systems are commonly used, and they help keep the FCR low and minimize any feed that is uneaten (Wang et al., 2022). Inevitably there is always some uneaten feed which, along with fecal matter, needs to be removed from the water as it can damage the gills of the fish (Bregnballe, 2015). In nature, the salmon feeds on moving prey, which varies in size depending on how large the salmon is, juveniles will therefore feed on smaller prey and particles compared to adults (Jørgensen & Jobling, 1992). Farm-grown fish is fed feed that has a similar nutrient composition as their natural prey (Salin et al., 2018). The feed is typically in the form of pellets that vary in size depending on the life stage of the fish (Bregnballe, 2015). Pellets for juvenile fish are smaller and have a higher protein content compared to the ones fed to adult fish (Bregnballe, 2015). The feed contains wild-caught fish which has been pointed out to be unsustainable due to overfishing of the stocks (Tocher, 2015). The use of wild fish is important to get the right proteins and lipids. Fishmeal and fish oil are both commonly found in fish feed due to their nutritional composition and digestibility (Bendiksen et al., 2011).

For salmonid species, the lipid composition of the feed is of particular importance as the salmonids are very fatty and rich in omega-3 fatty acids (Salin et al., 2018). The omega-3 contains vital fatty acids for humans and plays a role in, for example, cardiovascular health and neurological development (Tocher, 2015). These important fatty acids are not easily supplemented nor found in just any fat-sourced food which is why the industry continues to use wild-caught fish in the feed (Tocher, 2015). To minimize the use of wild fish in the feed soybeans, wheat, and other grains are often supplemented as protein sources and sunflower oil or other vegetable oils for the lipids (Bendiksen et al., 2011; Bregnballe, 2015).

As the Atlantic salmon is a carnivorous species it has high protein requirements. The breakdown of protein in the feed is part of the so-called nitrogen cycle (Bregnballe, 2015). The fish ingests protein in the form of feed and excrete waste nitrogen as total ammonia nitrogen (TAN) (Bregnballe, 2015). The TAN is both unionized ammonia ($NH_3$) and ionized ammonium ($NH_4^+$)(Bregnballe, 2015). Typically the fish only takes up about 30% of the N in the feed and excrete the rest through feces, gills and urine (Eck et al., 2019). The ratio between the two forms is dependent on the pH level of the water and temperature, but the fish excrete more ammonia in general (Bregnballe, 2015; Eck et al., 2019). The higher the pH level of the water the higher the amount of ammonia. Fish is sensitive to ammonia as biological membranes are permeable to the unionized form, and in high concentrations it can affect the neurological system of the fish (Poli et al., 2005). It is therefore important to either exchange the water frequently, so it does not reach toxic ammonium levels, or filter it through some form of biological filtering (Bregnballe, 2015).

## 2.2 Aquaculture and RAS

There are several types of aquaculture systems, with the most common ones being flow-through systems, and net cages or pens in water bodies (Lembo & Mente, 2019). The flow-through system can be implemented in various ways, in all of which the common denominator is a continuous flow or flush through the tanks of freshwater (Lembo & Mente, 2019). Both the flow-through system and the net pens and cages are known to bring some environmental concerns such as eutrophication, as the effluent from the fish is highly nutritious (Lembo & Mente, 2019). Eutrophication is the process of when a water body, or parts of it, are enriched by nutrients and minerals to the point that the growth of algae is too much (Chapin et al., 2011). This excessive growth results in lower water quality and a change in the ecosystem of the water (Chapin et al., 2011). Increased input of N and P due to anthropogenic activities is commonly the reason for eutrophication (Chapin et al., 2011). With these concerns in mind, the aquaculture industry is in constant development bringing to light new solutions addressing these problems.

The RAS is a land-based aquaculture system thought to be more sustainable compared to other aquaculture systems (Bregnballe, 2015). The tanks are on land and the water in the system circulates back after filtrations and cleaning (Lembo & Mente, 2019). The RAS decreases the amount of water used and the filtration system coupled with the water recirculation prevents any effluent from entering ecosystems and in turn causing eutrophication (Bregnballe, 2015). The solid waste, or sludge, that is collected through the filtering is nutritious and can be used for agricultural purposes as fertilizer (Bregnballe, 2015). New environmental directives such as the EU Water Framework Directive call for sustainable use of water and typically used aquaculture systems such as the flow-through use high amounts of water (*Water Framework Directive (WFD) 2000/60/EC,* 2000; Martins et al., 2010). Aquaculture has other environmental concerns, such as diseases spreading within the farmed fish and to the natural environment, and habitat destruction (Ahmed & Turchini, 2021). RAS systems offer a solution to that as the recirculation of water minimalizes water usage. In a super-intensive system, the recirculation can be up to 99.6% with only 6% of new water intake per day of the total system volume (Bregnballe, 2015). For comparison, a flow-through system requires 100% renewal of water each time it is exchanged (Bregnballe, 2015).

RAS offers control of the water environment. The pH level, water temperature, and oxygen levels are all important variables that affect the health and growth of the fish (Bregnballe, 2015). These are all easily controlled in the RAS (Bregnballe, 2015). The system is suitable for both indoor and outdoor (van Rijn, 2013). However, it is more commonly used indoors so that climatic variables such as rainfall, water acidification, and extreme weather events are not of concern (Ahmed & Turchini, 2021). The main components of the system are seen in Fig. 1. The water in the tanks is removed through an outlet, where it passes through a mechanical filter (Fig. 1). The mechanical filter removes the solid organic particles from the water or the sludge. Through rotation of the drum the solid particles are moved around to the backwash area, where they are washed out of the filter elements (Bregnballe, 2015). From there the sludge enters a tray from where it flows with water to a tank for external waste treatment (Bregnballe, 2015). Filtering of the sludge is important, as the water enters a biofilter in the next step. This helps to prevent clogging of the biofilter, facilitates nitrification, and stabilizes the biofiltration (Bregnballe, 2015).

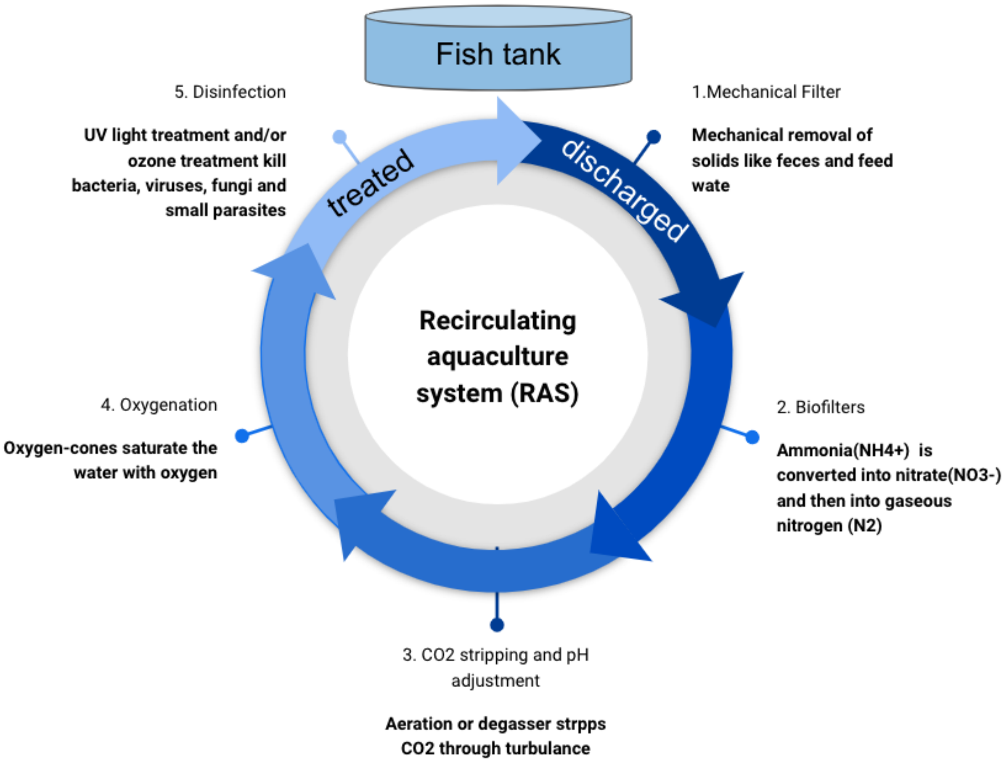


*Fig. 1. Main components of a Recirculation Aquaculture System (RAS). Modified from Bregnballe (2015)*

Finer particles that were not caught in the mechanical filter should be removed through biofiltering (Bregnballe, 2015). The ammonia, from the fish excretion, needs to be transformed to nitrate ($NO_3$) (Bregnballe, 2015). This process is performed by bacteria called *Nitrosomonas* and *Nitrobacter* (Pantanella, 2018). *Nitrosomonas* transforms ammonia to nitrite through oxidation. *Nitrobacter* then makes nitrite into nitrate (Pantanella, 2018). For the biological filter to function properly the water temperature must be above 10°C and the pH level between 7-8. The lower the pH level the less nitrification there is and below 6.8 °C the nitrifying bacteria are unable to function (Al-Hafedh, 2003; Bregnballe, 2015).

The pH level of the water is affected mainly by the $CO_2$ which the fish produces and the acid that results from the nitrification (Bregnballe, 2015). For increasing and stabilizing the pH level again, as well as adding in oxygen, the water is aerated by a degasser (Fig. 1), and a base is added (Bregnballe, 2015). Air is pumped into the water causing turbulation, through which the toxic gas is taken out. It is preferred to keep oxygen levels in the tanks fully saturated. For that purpose, the water is oxygenated through liquid tanks or other methods (Bregnballe, 2015). The final step of the process, before the water returns to the tanks, is to disinfect it. That is typically done through UV light (Bregnballe, 2015). The light is at wavelengths that biological membranes cannot tolerate, consequently killing bacteria and one-cell organisms in the process (Bregnballe, 2015).

## 2.3 Hydroponics and aquaponics

Hydroponics is an agriculture practice that grows crops without soil, using only nutrient-rich water (Kledal & Thorarinsdottir, 2018). There are two main methods for hydroponics, circulating and non-circulating methods (Sardare & Admane, 2013). Each one has different sub-techniques (Sardare & Admane, 2013). Aquaponics use the wastewater from aquaculture to grow crops using hydroponics (Kledal & Thorarinsdottir, 2018). In an aquaponic system the plants are in a closed system, making it a circulating method (Khan et al., 2021; Sardare & Admane, 2013). Fig. 2 displays how the water circulates between the different components of the system. The plants are on growth beds and water from the aquaponic system is directed through, after mechanical and biofiltering (Kledal & Thorarinsdottir, 2018). Several sub-techniques can be used in aquaponics and the selection of the technique is dependent on the crop being grown.

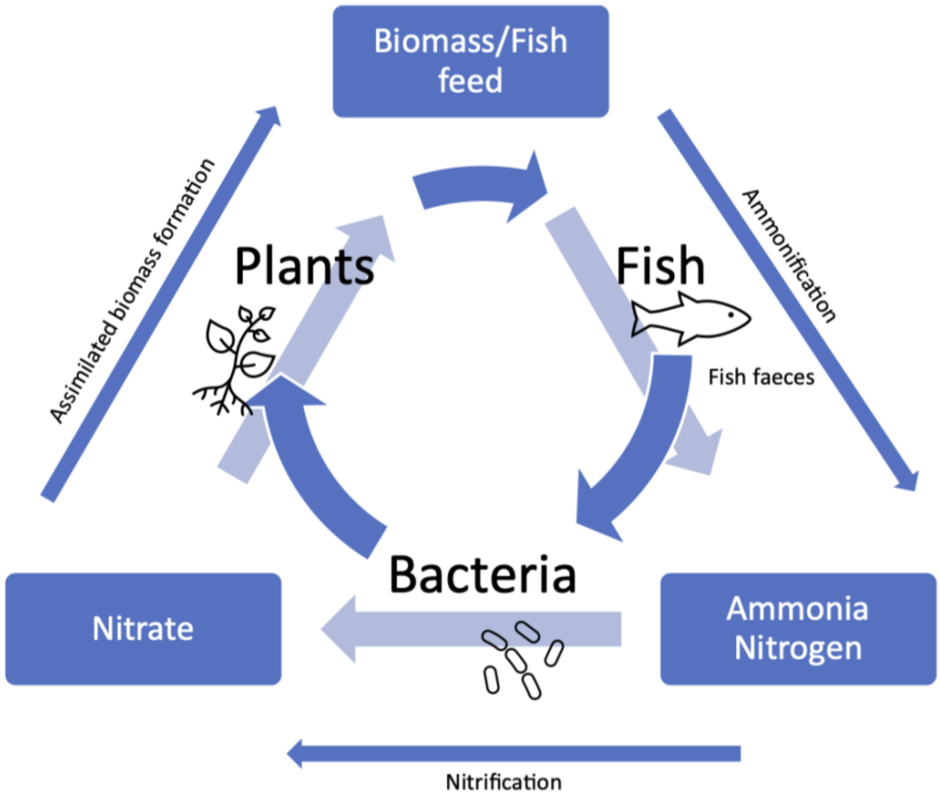


*Fig. 2. The cycling of the water in an aquaponic system. The fish feed is excreted by the fish through feces. The feces contain ammonia nitrogen which is nitrified by bacteria and turned to nitrate. The nitrate is utilized by plants to form plant biomass which is often edible and utilized. Modified from Goddek et al. (2015)*

For the purpose of this paper the Nutrient Film Technique (NFT) and the raft technique will be described. When using NFT long channels contain the nutrient solution, and the plants are grown in the channels (Khan et al., 2021). The flow is constant but the stream is shallow meaning that if it stops the plants can dry up quickly (Khan et al., 2021). NFT is preferred for crops that are fast-growing and short-term such as herbs, lettuce, and other leafy greens (Khan et al., 2021). The floating raft technique is suitable for leafy greens and short-term crops and is common for large scale productions such as commercial purposes (Khan et al., 2021). Rafts with holes drilled through them float on top of the nutrient solution (Khan et al., 2021).

In a hydroponic system, micro- and macronutrients are commonly sourced from mining and industrial practices (Goddek et al., 2015). These are limited resources, and additionally, they have a high carbon footprint due to production and transportation cost (Goddek et al., 2015). Aquaponics has gained more attention as it allows for nutrient recycling and the reuse of water, making it a more sustainable option compared to more common aquaculture and agriculture practices (Goddek et al., 2015). The fish produces $CO_2$ for the plants and the tanks can act as temperature buffers, decreasing the energy consumption in the greenhouse (Kledal & Thorarinsdottir, 2018). Aquaponics reduce the use of these nutrients as the feed from the fish and its excrete contain many of the required nutrients and are hence found in the wastewater (Kledal & Thorarinsdottir, 2018). As the plants take up nutrients from the wastewater they aid in cleaning the water further before it is directed back into the fish tanks (Goddek et al., 2015; Kledal & Thorarinsdottir, 2018). The constant supply of nutrients in hydroponics, especially P and N, has been linked with higher nutritional values in several crops compared to their counterparts grown in field conditions (Paradiso et al., 2012). TAN from the fish can be utilized by the crops after going through biofiltering where it has been turned into nitrate (Eck et al., 2019). Some systems use the crops as the biofilter where nitrifying bacteria are present in the roots (Eck et al., 2019).

The buffer capacity in a hydroponic system is limited compared to the one in soil (Kledal & Thorarinsdottir, 2018; Sardare & Admane, 2013). The availability of nutrients differs based on the pH level, particularly for P (Willumsen, 1980). The pH level in a hydroponic system can fluctuate fast and in a wide range. Thus, it is important to monitor it closely and adjust accordingly (Willumsen, 1980). The type of crop and the composition of the nutrient solution depend on whether the roots release $H^+$ or $HCO_3$ and $OH^-$ (Willumsen, 1980). If cations are taken up more rapidly there will be a release of $H^+$ resulting in a decreased pH. If anions are taken up faster than cations a release of $HCO_3$ and $OH^-$ will lead to an increased pH level (Willumsen, 1980). One of the main challenges in an aquaponic system is the balancing of the optimal pH level for both plants and fish. Fish requires a pH level between 7-9 while most crops thrive on a lower level of 5.5-6.5 (Sardare & Admane, 2013; Skar et al., 2022). Electrical conductance can indicate whether nutrients are needed in a solution. Deciding on an electrical conductance value and trying to maintain that is therefore common in hydroponic experiments (Mackowiak et al., 1999).

## 2.4 Study area

Iceland is a Nordic country that has long been known for its clean nature and renewable energy. The country has a long history of fishing in the ocean (Stjórnarráðið, 2022). However, fish farming at a commercial scale started relatively late in Iceland, with fast expansion in the last couple of years (Hagstofa Íslands, 2022). Investments have increased significantly and were at an all-time high in 2021 (Fig. 3) (Hagstofa Íslands, 2022). Due to the renewable energy and abundance of water, Iceland is a good location to construct a RAS farm as the high energy requirements will be offset. While one company in Iceland has RAS in use already, others have announced intentions to start constructing RAS too (Umhverfisstofnun, 2023). For economical as well as environmental purposes, the companies are increasingly interested in aquaponics (Kledal & Thorarinsdottir, 2018). However, there are limiting factors to consider. Regulation 799/1999 on the handling of sludge prohibits the use of unsensitized sludge in agriculture (*Reglugerð 799/19999 um meðhöndlun seyru*, 1999). Any growing of crops meant for human consumption is therefore not possible without applying for an exception (*Reglugerð 799/19999 um meðhöndlun seyru*, 1999). Another challenge is the geographical location of the country, at latitudes 63-68°N. This results in limited daylight during winter and cold weather. This would require constant heating of the premises for the plants along with light manipulation.

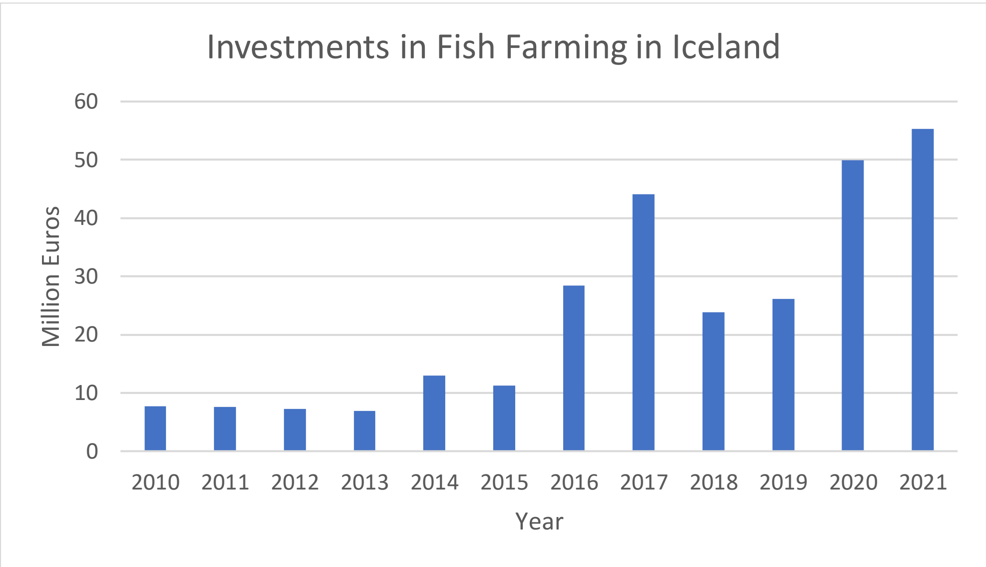


*Fig. 3. Net capital funding for fish farming in Iceland from 2010 to 2021 in million Euros. Source: Hagstofa Íslands. (2022)*

## 2.5 Evaluating sustainable crop choices

The United Nations state that the three pillars of sustainable development are economical, social, and environmental (United Nations, 2023). It is important to consider all three pillars when constructing a business model. If any of the three is not accounted for, the consequences can not only be a loss in profit but also to the environment and the society where resources could be depleted with dire consequences. The Food and Agriculture Organization (FAO) (2017) highlighted four SDGs that are of greatest relevance to aquaculture (Table 1). These goals can all be related back to one or more of the three pillars. Together they make for not only a motivation for this aim but guidance as to what should be considered in the evaluation.

*Table 1. SDG goals of greatest relevance to aquaculture and their relation to aquaculture and aquaponics source: FAO ( 2017) & United Nations (n.d.)*

| | Sustainable Development goals description | Relation to aquaculture and aquaponics |
|---|---|---|
| Goal 2: “Zero hunger” | “End hunger, achieve food security and improved nutrition and promote sustainable agriculture” | RAS allows a more efficient fish production in addition to enhanced biosecurity for the fish. Aquaponics allow a more efficient and sustainable food production and uses nutrients that would otherwise go to waste. |
| Goal 8: “Decent work and economic growth” | “Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all” | Including hydroponics with the RAS will create more jobs. |
| Goal 12: “Responsible consumption and production” | “Ensure sustainable consumption and production patterns” | Reusing the water and the nutrients makes for a more sustainable production of both crop and fish. |
| Goal 14: “Life below water” | “Conserve and sustainably use the oceans, seas, and marine resources for sustainable development” | The RAS has a lower FCR compared to other systems resulting in a more sustainable use of the resources and using the wastewater for hydroponics utilizes the waste even further as excretion from the fish provides nutrients. |

There is a plethora of methods available for assessing sustainability for agriculture and the environment (Talukder & Blay-Palmer, 2017). These methods vary in application, and complications, and only some of them take into account all three pillars of sustainable development (Talukder & Blay-Palmer, 2017). The Multi-Criteria Decision Analysis (MCDA) is a method that is commonly used to help compare qualitative assessments of different options in decision-making for policy or stakeholders for environmental or agricultural purposes (Sadok et al., 2008). Talukder & Blay-Palmer (2017) assessed commonly used methods based on scientific soundness and user-friendliness. There, the MCDA scored the highest for scientific soundness but was deemed less user-friendly compared to the other methods (Talukder & Blay-Palmer, 2017). The MCDA has been widely used for decision-making in the environmental and agriculture industry (Cinelli et al., 2014; Huang et al., 2011).

Within MCDA there are various methods that have different applications and that highlight and consider different options (Sadok et al., 2008). The methods often make use of software to combine, structure, and process the chosen inputs (Huang et al., 2011). However, using an MCDA method can hence be time-consuming as the user has to not only find a suitable method but also know how to apply it (Talukder & Blay-Palmer, 2017). Simplifying this process so that an average user can easily visualize the options they are considering before going into an in-depth analysis could therefore be of use. Sadok et al. (2009) present an MCDA called MASC, a qualitative multi-attribute decision model, that can be used to evaluate sustainable crop choices. This model considers all three pillars of sustainable development and is a good method to build upon and adjust for simplification. The model itself of complex but provides a good frame for simplification. Using the main categories and their subcategories as indications of important parameters a more user-friendly evaluation table can be produced.

# 3 Method

This thesis is done in collaboration with Samherji, an Icelandic seafood company that plans on constructing a RAS farm for salmon in the next years. Therefore, the evaluation does consider Icelandic regulations, Icelandic environment and other constraints. Additional literature was provided by Samherji Fiskeldi in the form of previous master‘s and bachelor’s theses done in cooperation with the company, at Icelandic universities.

## 3.1 Selection of crops and creating the table

For selecting the crops, a literature search was done. One crop was supposed to be found in the feed of the fish, while the other two had to be already in use in aquaponics. If a crop is grown in an aquaponic system and put back into the fish feed this would not only be a crop that can be sold commercially, but it would also contribute significantly to “closing the loop“. The crop would furthermore not be used for human consumption which should facilitate production permits (*Reglugerð 799/19999 um meðhöndlun seyru*, 1999). For all crops it was important that there were several experiments on the hydro or aquaponic growth available. To select the crops already in use in aquaponics, experiments comparing crops were used and the crops with the best growth performance were selected. From there, a second literature search was performed to find which crops had been most researched out of the bunch.

The evaluation table is used as a sustainability assessment to find which crop is the most suitable. The evaluation was mainly based on a method from Sadok et al. (2009). Sadok et al. (2009) divide the attributes into three main categories, that are the same as the pillars of sustainable development: economical sustainability, social sustainability, and environmental sustainability. For subcategories, the model was simplified significantly and combined with Bachinger & Zander (2007) to make it more applicable for aquaponics. Bachinger & Zander (2007) present a model for evaluating suitable crop rotations for organic farming. The model is a software tool and focuses on N usage and leeching, along with weed management (Bachinger & Zander, 2007). Simplifying and combining categories from Bachinger & Zander

(2007) and the method and categories from Sadok et al. (2009) resulted in an evaluation model that was used for the presented results in this paper.

The assigned weights for the grading within each category were based on literature. Sadok et al. (2009) used a qualitative grading system based on eight expert opinions and weighted each subcategory and main category. Bachinger & Zander (2007) used qualitative grading as well but no weights. In this evaluation the main categories were the same as Sadok et al. (2009) and carried the same weights as Sadok et al. (2009) (Table 2). The main categories carry the weights 34% for economical sustainability and 33% for the social and environmental sustainability (Table 2) (Sadok et al., 2009). Sadok et al. (2009) had 18 subcategories and each one had multiple subcategories under that. The subcategories that were chosen and simplified for the table were selected so that no additional coefficients, large formulas or program computations would be needed. The user should be able to find the values through literature and should not have to transform them to another format. Due to the constraints and simplification, all subcategories used in this evaluation were weighted equally. This was deemed most appropriate as Sadok et al. (2009) applied weights that were often equal or close to equal and Bachinger & Zander used expert formulated equations and coefficients and discussed the results qualitatively without applying any weights. Hence, it was considered as the most appropriate option to weigh all categories equally. Table 2 displays the categories and subcategories and their weights in the main and subcategories.

*Table 2. Evaluation categories and subcategories with the chosen weights*

| Evaluation | Weight |
|---|---|
| Economical sustainability | 34% |
| Revenue (€/$m^2$*year) | 50% |
| economic performance (€/kg) | 50% |
| Social sustainability | 33% |
| Nr of plants pr $m^2$ | 50% |
| Physical constraints, yield (g/plant) | 50% |
| Environmental sustainability | 33% |
| $NO^3$-N (mg/L) | 14.3% |
| $PO^4$-P (mg/L) | 14.3% |
| pH level | 14.3% |
| Water Temperature (°C) | 14.3% |
| RH (%) | 14.3% |
| Air Temperature (°C) | 14.3% |
| Crop harvest time (days) | 14.3% |

## 3.2 Categories with motivation and calculations

### 3.2.1 Economical sustainability

In economical sustainability, two categories were chosen: revenue and economic performance. The revenue was based on the estimated gross value per $m^2$ by multiplying the price per kg with the average edible biomass (yield) and the maximum number of plants per $m^2$ (Table 2). The revenue is an important parameter as it gives an indication as to how much the company can expect per $m^2$. The economic performance shows a good comparison of the market value of the plant. The average of the range for each crop was found and equation 1 was used to calculate the grade.

$$y_i = \frac{x_i}{x_{sc\_max}} * w_{sc} \text{ (Equation 1)}$$

$x_i$=literature value
$y_i$= grade per subcategory
$w_{sc}$=weight of subcategory
$x_{sc\_max}$=maximum value between the crops per subcategory

### 3.2.2 Social sustainability

In social sustainability, a normalized grading was used based on the upper limit of each crop's range. This was done as it is assumed that a maximum number of plants will be used for highest revenue. Furthermore, physical constraints like the number of plants per $m^2$ were taken into consideration. Since the size of greenhouses is limited, plants that require smaller space and thrive in higher densities are more optimal to make better use of the premise. This in turn can allow more space for social recreational areas or other use of the area which is a social benefit. Here the plants were given grading based on their upper value, and equation 1 was again used for grading them. The edible biomass, or yield, per plant (g/plant) per year was furthermore taken into consideration as that can be taken as an indicator of manual labor requirements and in turn employees. Generating more jobs is to the benefit of the society. Equation 1 was again used for the yield.

### 3.2.3 Environmental sustainability

In environmental sustainability, the subcategories were graded in two ways. The N and P requirements were compared to the average N and P concentrations in wastewater of a RAS found through literature. The pH and water temperature were furthermore compared to the optimal ranges from wastewater. These parameters were chosen for several reasons, the goal is to reuse the nutrients so the plants should require similar concentrations of N and P as found in the wastewater. The pH level and water temperature both affect the fish as well as the yield and survival of the crop in general and hence must be taken into consideration. A crop that had values that fell completely within the range received a grade of 1, a crop that had values both within and outside the range of the wastewater received a grade of 0.5, and a crop that had values that did not comply with the wastewater at all received a grade of 0.

Crop harvest time equals the number of days it takes from planting the crop until it can be harvested. This gives an indication as to how frequently the crops need to be replanted and how long it will take for the crop to grow. The final variables considered were relative humidity (RH) and air temperature as the crops will be in a greenhouse where the higher temperature requirements result in higher energy consumption and higher RH would require extra water consumption. Here the crops were graded using equation 2, and the lowest value within the range for each crop was used for the calculations.

$y_i = \frac{x_{sc\_min}}{x_i} * w_{sc}$ (Equation 2)

$x_i$=literature value

$y_i$= grade per subcategory

$w_{sc}$=weight of subcategory

$x_{sc\_min}$=minimum value between the crops per subcategory

### 3.2.4 Total score

The total score was calculated using equation 3 and finally adding the weighted score from each main category together. Weights of the main categories were based on Sadok et al (2009). If a crop had a subcategory with no data it received a score of zero in that subcategory.

$z_i = w_{mc} * \sum y_i$ (Equation 3)

$w_{mc}$= weight of main category

$z_i$=weighted grade per main category

## 3.3 Sensitivity analysis

To explore the sensitivity of the evaluation table a "worst case scenario" was created to assess the crops. In economical sustainability the revenue was calculated on the lowest value of plant per $m^2$ as opposed to the highest, which was used in the sustainability assessment. Furthermore, the lowest value in yield was used for the calculation instead of an average of the range. Value for economical performance was kept the same. The scores for subcategories in social sustainability and some in environmental sustainability were based on the limits of the found range for each crop, higher in case of social sustainability and lower for environmental sustainability. For the sensitivity analysis the opposite limit of the ranges was used. For social sustainability a normalized score of the lowest value for each crop was used and vice versa for the subcategories RH, air temperature and crop harvest time, in environmental sustainability. For the subcategories that were graded according to values from the wastewater, pH, N and P values and water temperature, the upper limit of the range for each crop was compared to the range of values found for the wastewater acquired through literature. The upper limit was chosen as the highest value for those subcategories would require increased fertilizer, and a highly unsuitable water temperature and pH conditions for the salmon. Should the upper value fall within the range found for the wastewater the crop would receive a full point, if not it did not get a point.

# 4 Results

## 4.1 Description of chosen crops

The first literature search was carried out to find examples of hydro and aquaponic growth of different crops. N.A. Savidov et al. (2005) tested a variety of crops in an aquaponic system, over 60 different types, and found that basil was one of the most successful crops in the aquaponics. After a second literature search, to see if additional literature on basil was sufficient, basil (*Ocimum basilicum*) was chosen as the first crop. N.A. Savidov et al. (2005) tested several other culinary herbs and vegetables such as tomatoes and mini cucumbers to name a few. The other culinary herbs besides basil were excluded as basil outperformed them, and it was of more interest to compare a different type of plant to basil rather than a second herb. Cucumber was excluded on the basis of limited literature. Yang & Kim (2020) looked at nutrient composition between basil, lettuce and cherry tomatoes, stating that the three crops were the most commonly found in aquaponics. A second literature search resulted in the choice of lettuce (*Lactuca Sativa*) as more extensive literature was found on that specific species in aquaponics compared to tomatoes. For the third and final crop the ingredients of the feed used by Samherji Fiskeldi was studied. Flour, corn meal, rapeseed meal and soy meal were found to be in the feed (Laxá, n.d.). Through a second literature search extensive research by NASA on the hydroponic growth of soybean was found additionally to other literature on the crop (Wheeler et al, 1999). Hence, soybean (*Glycine Max*) was chosen as the third and final crop.

### 4.1.1 The crops and their relation to aquaponics

There is limited literature on hydro or aquaponics growing soybean (*Glycine Max*). During the literature search no examples were found of companies nor commercial production of the plant in a hydroponic environment. Information on the requirements on the crop is therefore solely based on literature for hydroponic growing of soybean, more specifically experiments on the physiological response of the plant to different parameters (Hata & Futamura, 2020). These experiments were mostly done for NASA for researching food production in space (Wheeler et al, 1999). All experiments used the NFT for the hydroponic system (Hata & Futamura, 2020; Mackowiak et al., 1999; Palermo et al., 2012; Paradiso et al., 2012; Wheeler et al., 1999, 2008).

There is more literature to be found for the growth of lettuce (*Lactuca Sativa*) albeit no examples of aquaponics farming Atlantic salmon were found. Several studies found that aquaponics growing lettuce have similar yield compared to hydroponics if supplemented with nutrient solution (Delaide et al., 2016; Monsees et al., 2019; Pantanella et al., 2012). Pantanella et al. (2012) furthermore found no difference in the yield of hydroponics or aquaponics if the N concentrations in the water were above 1.4 mM/L. For technique, floating rafts were commonly used but examples were found of using NFT as well and tilapia was the most commonly used fish species (Abbey et al., 2019; Delaide et al., 2016; Monsees et al., 2019; Pantanella et al., 2012; N.A. Savidov, 2005; N. A. Savidov et al., 2007).

Basil genovese (*Ocimum basilicum*) is commonly used in aquaponics where it grows fast and has high fresh market value (Abbey et al., 2022). No examples were found of Atlantic salmon or other cold water species using aquaponics to grow basil. It was common to add a fertilizer into the wastewater to supply sufficient amount for the plants (Ferrarezi & Bailey, 2019; Saha et al., 2016; N.A. Savidov, 2005). Abbey et al. (2021) reported that nitrate nitrogen had beneficial effect on the yield of the basil while changes in P showed to have little effect. The most commonly used technique was the floating raft and it was paired most often with tilapia but examples were found where crayfish and other species were used as well (Abbey et al., 2022; Ferrarezi & Bailey, 2019; Saha et al., 2016; N. A. Savidov et al., 2007; Yang & Kim, 2020b)

## 4.2 Sustainability assessment

The values for the different parameters, or subcategories, that were found through the literature are presented in Table 3. In economical sustainability the basil had the best revenue and economical performance out of the three crops. The prices for basil and lettuce were based on prices from three of the largest supermarkets in Iceland assuming 25% VAT and 40% profit margin (J. K. Jónsson, personal communication, 4 April 2023). The price of soybean has increased globally by 85.86% in the past three years but prices have been going down in the last year by 12.1% according to Business Insider (2023). The basil has over six times higher economic performance than lettuce and 90 times higher than soybean. It does vary more in revenue while the lowest value for basil is still higher than for both lettuce and soybean. The basil varies by over 600% between the lowest revenue and highest. The lettuce varies by 30% while soybean varies by 26%. Hence, the basil is the most profitable crop out of the three but with much more variability (Table 3).

In social sustainability it is possible to grow up to 50 plants per $m^2$ of soybean compared to a maximum of 30 plants of lettuce per $m^2$ (Table 3)(Monsees et al., 2019; Pantanella et al., 2012; Paradiso et al., 2015; Wheeler et al., 2008). All three crops have similar values in the lowest range, where basil has the lowest of 8 plants per $m^2$ (Ferrarezi & Bailey, 2019). The soybean has the highest variability in the number of plants per $m^2$, ranging from 12-50 plants. For physical constraints or yield the basil shows the largest range, with the highest value of the three as well (Abbey et al., 2022; Ferrarezi & Bailey, 2019; Saha et al., 2016; Yang & Kim, 2020a). The lettuce and soybean have more stability in the range, but soybean has lower values of only 11.3-14.3 grams/plant (Table 3). Thus, the basil has the highest yield while soybean has the highest number of plants per $m^2$ (Table 3).

In regard to environmental sustainability both basil and lettuce show better compatibility compared to soybean. The preferred pH level for soybean is slightly acidic and falls out of the range found for Atlantic salmon in freshwater RAS and no comparable values were found for N and P concentration as they were given for the single element instead of a compound as was the case in sources for lettuce and basil (Table 3) (Hata & Futamura, 2020; Mota et al., 2022; Paradiso et al., 2012, 2017; Wheeler et al., 1999; Ytrestøyl et al., 2020). Wheeler et al. (2009) did however state that the nitrogen source used was $NO_3$-N but the concentration was given only as 7.5 mM of N. The lettuce and basil can not only thrive on a higher pH level but the lettuce also has been grown at lower RH (Abbey et al., 2019; Monsees et al., 2019; Pantanella et al., 2012). No sources reported the RH for basil, but lettuce was found to thrive at RH as low as 40%. The harvest time is furthermore shorter for lettuce and basil, ranging from 21-42 days for lettuce and 21-28 days for basil, compared to 87-144 days for the soybean (Abbey et al., 2019, 2022; Ferrarezi & Bailey, 2019; Palermo et al., 2012; Paradiso et al., 2012; Sfetcu et al., 2008; Wheeler et al., 2008; Yang & Kim, 2020a). Lettuce had the lowest air temperature value out of the three or 16-25°C and soybean had the smallest range from 26-29°C (Abbey et al., 2022; Dougher & Bugbee, 1997; Palermo et al., 2012; Pantanella et al., 2012; Paradiso et al., 2017). Lettuce was found to grow in water temperatures as low as 16°C compared to 18°C for basil and 26°C for soybean (Table 3) (Mackowiak et al., 1999; Saha et al., 2016; Sfetcu et al., 2008). Altogether the basil and the lettuce both have some values that are compatible with the values of wastewater (Table 3) .

*Table 3. Results for the subcategories for lettuce, soybean and basil based on literature. Bolded numbers are the crop with the most optimal value.*

| Evaluation | RAS-wastewater | Lettuce (Lactuca Sativa) | Soybean (Glycene max) | Basil (Ocimum Basilicum) |
|---|---|---|---|---|
| Economical sustainability | | | | |
| Revenue (€/m$^2$*year) | - | 446-581 | 1.08-1.37 | **795-5178** |
| Economic performance (€/kg) | - | 8.4 | 0.6 | **54** |
| Social sustainability | | | | |
| Nr of plants pr m$^2$ | - | 10-30 | **12-50** | 8-24 |
| Physical constraints, yield (g/plant) | - | 136-177 | 11.3-14.3 | **47-306** |
| Environmental sustainability | | | | |
| $NO^3$-N (mg/L) | 26.3–50.3 | 42-197 | No data | **35.4-49.6** |
| $PO^4$-P (mg/L) | 8.2–16.4 | 8.2-27.1 | No data | **8.6-11.5** |
| pH level | 6.8-7.3 | **6.5-7.5** | 5.8-6 | **6.5-8.3** |
| Water Temperature (°C) | 12-14 | **16-28** | 26 | 18-25 |
| RH (%) | - | **40-80** | 65-80 | No data |
| Air Temperature (°C) | - | **16-25** | 26-29 | 21-28 |
| Crop harvest time (days) | - | 21-42 | 87-144 | **21-28** |

### 4.2.1 Score function

Basil had the highest total grade, with a score of 0.79 compared to 0.46 for lettuce (Table 4). The soybean had the lowest score in all categories. The lettuce had the highest grade in environmental sustainability where it scored 0.64, compared to basil scoring 0.61 (Table 4). The basil scored highest in social sustainability with 0.74. In economical sustainability the lettuce received a grade of 0.16, the basil had the highest grade there of 1 and the soybean scored 0.01 (Table 4).

*Table 4. Total grades for each main category, not weighted but normalized, and the total weighted grade. The highest grade possible to receive per category and in total is 1.*

| | Lettuce (Lactuca Sativa) | Soybean (Glycene max) | Basil (Ocimum Basilicum) |
|---|---|---|---|
| Economical sustainability | 0.16 | 0.01 | 1.00 |
| Social sustainability | 0.59 | 0.52 | 0.74 |
| Environmental sustainability | 0.64 | 0.21 | 0.61 |
| **Total weighted grade** | **0.46** | **0.24** | **0.79** |

## 4.3 Sensitivity analysis

In difference to the sustainability assessment that explored the most optimal scenario for commercial growth of the crops, the sensitivity analysis evaluates the “worst case scenario”, or the lowest values found in the literature search. The sensitivity analysis shows that the basil is still the most suitable crop scoring 0.66 while in the sustainability assessment it had a total weighted grade of 0.79 (Fig. 5). Due to the way the crops are graded, i.e. proportionally against each other, it is possible for them to get higher grades in the “worst case scenario” than in the sustainability assessment. For that reason, the lettuce gets a higher total grade in the “ worst case scenario” compared to the sustainability assessment (Fig. 5).

Despite basil receiving the highest total grade the lettuce scored highest in two out of three main categories. The lettuce scored 0.60 in the sensitivity analysis, which is a higher grade than in the sustainability assessment where it scored 0.46 (Fig. 4). The lettuce scored much higher than both basil and soybean in the social sustainability, with a grade of 0.92 where soybean scored second highest with a grade of 0.54 (Fig. 4). This high score is due to its lowest yield being relatively higher than the lowest yield of the other two crops. In environmental sustainability the lettuce had a grade of 0.52 compared to 0.45 for basil. Only in economical sustainability did the basil have a much higher score than the other two crops where it had a full point (Fig. 4).

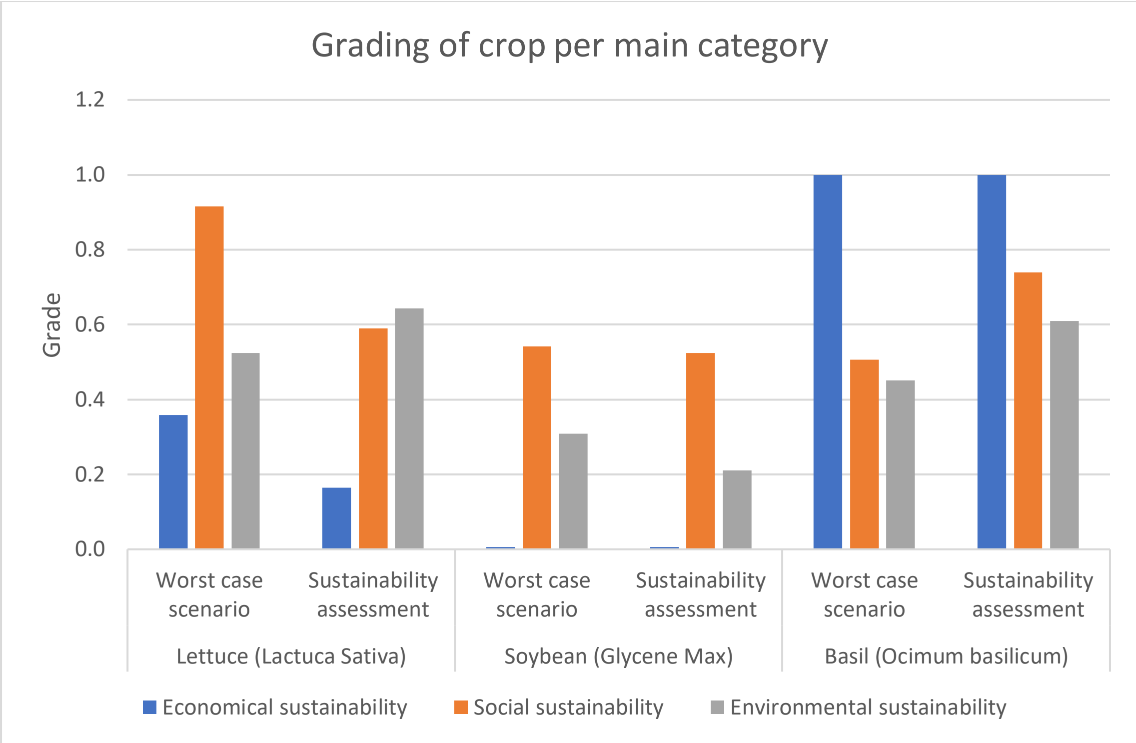


*Fig. 4. Grading of each crop in each category in the sustainability assessment compared to the "Worst case scenario"*

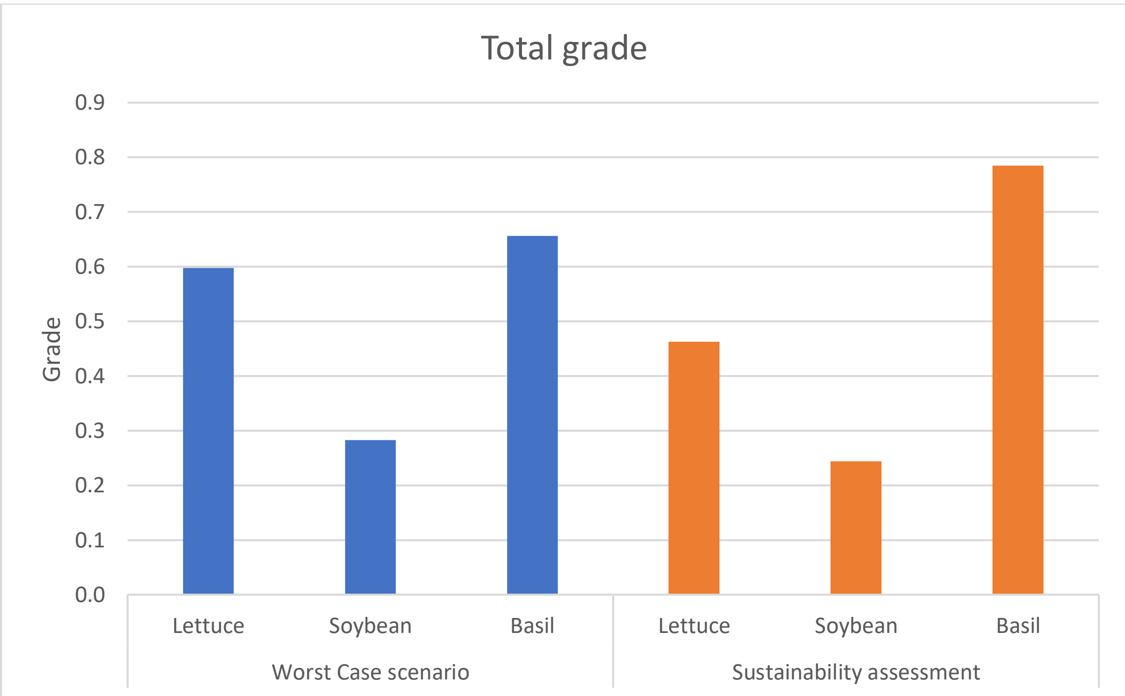


*Fig. 5. Total grade of each crop in the sustainability assessment and in the "Worst case scenario"*

From Fig. 6 it is further visible how much higher revenue there is to be had from basil. Even when there is a 50% decrease in the yield of basil the revenue is higher compared to a 50% increase in yield of both lettuce and soybean.

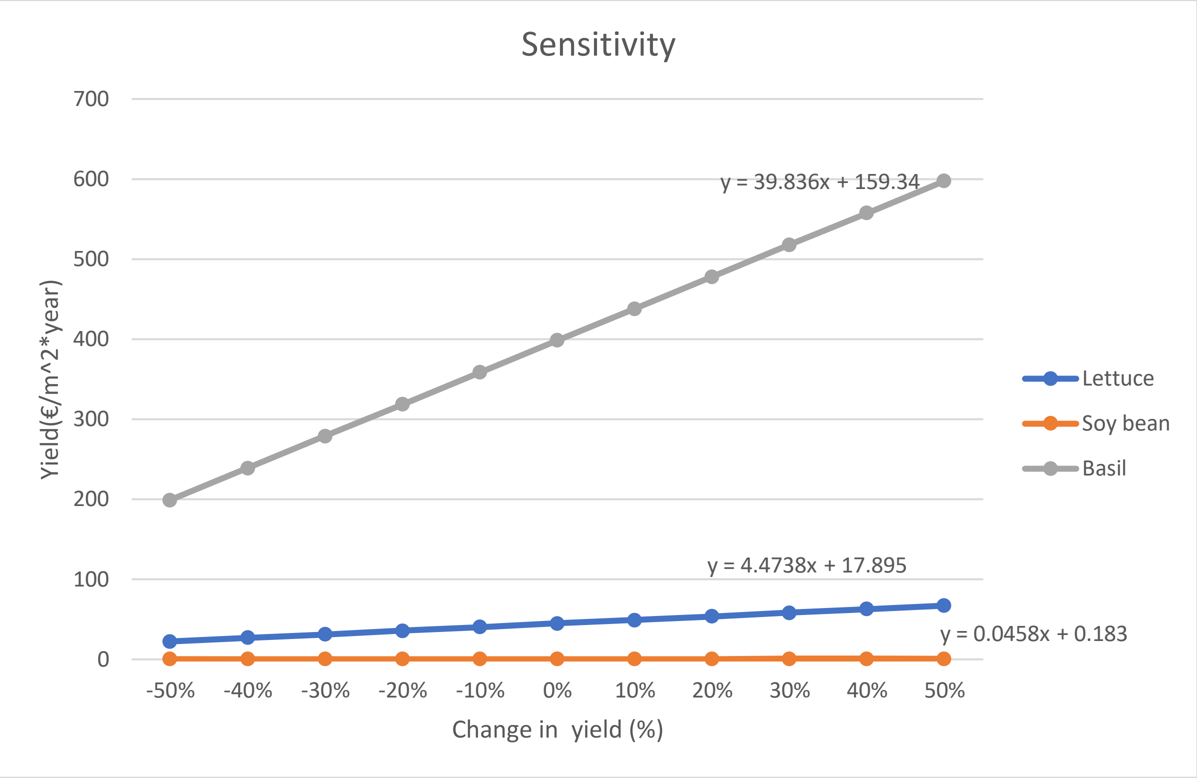


*Fig. 6. Change in yield plotted against the revenue per year*

# 5 Discussion

## 5.1 The evaluation table

The evaluation table allows for an easy comparison of the different requirements and values of each crop, and it is simple to adjust the weights and subcategories if needed. Using the main categories based on the pillars from United Nations highlights the different forms of sustainability and gives a better overview as to what should be considered when growing plants. The current categories are focused on an aquaponic system but can just as well be applied to a hydroponic one. Using the main categories as guidelines, subcategories can be exchanged or added, taking for example water temperature out if evaluating for a soil system. The weights can be adjusted if a particular pillar of sustainability or a parameter is considered to be of higher importance. This makes for a sustainability assessment that is straightforward and can be used directly by decision-makers.

A more complex sensitivity analysis, exploring the different weights and their effect within each main category, would be good to explore in future studies. Sadok et al (2009) did not have equal weights within the subcategories, although they did not differ a lot, and should the evaluation table be expanded, the weights used by Sadok et al (2009) could be used as guidelines. Using the weights as opposed to simply evaluating each parameter subjectively and discussing can help argue for the choice of crop based on a more quantitative assessment as opposed to comparing results as Bachinger & Zander (2007). Albeit the weights and grading are subjective to a certain extent they do prevent a more intuitive selection which can be the case when solely comparing without adding a total grading.

## 5.2 Choice of crop

Basil was the most suitable crop out of the three compared in this study. As it scored much higher than the other two in economical sustainability it is safe to assume that its high market value is a controlling factor for that score (Fig. 6). However, it varied quite a lot in yield between sources. It could be challenging to grow something for commercial purposes where the uncertainty of the edible and in turn profitable biomass varies that much (Table 3). The sensitivity analysis did, however, reveal that even a 50% increase in the yield of lettuce or soybean would still not turn in revenue close to the one of basil, even if there was a 50% decrease in the basil yield (Fig. 6). This, in turn, makes the basil seem, out of the three, particularly suitable in view of SDG 8, which states the importance of sustained and sustainable economic growth and productive employment (United Nations, n.d.).

In all studies found where the basil was said to grow well, it was grown using wastewater supplemented with fertilizer. No crop was identified that was able to thrive using only wastewater. Yang & Kim (2020a) found that in an aquaponic system where no additional nutrients were added, the marketable yield of basil and lettuce was reduced by 56% and 67% compared to ones grown in hydroponics. While it has been suggested in literature to supply these additional nutrients in the fish feed it does not appear to be in production yet (J. K.

Jónsson, personal communication, 4 April 2023). Studies have however found that there is a significant decrease in the use of fertilizer when using aquaponics, where Monsees et al. (2019) found 63% less usage for growing lettuce compared to when using hydroponics. Considering SDG number 12, to provide sustainable consumption and production (United Nations, 2023), using aquaponics to even decrease the usage of fertilizer is a step in the right direction.

From the evaluation table it was clear that the soybean was not a suitable crop for aquaponics. It is a cheap protein source, which is partly the reason it is used in commercial fish feed in the first place. Soybean is a raw produce, used to produce other products and sold through wholesale. Consequently, the price of soybean fluctuates daily based on various market factors. On the other hand, both basil and lettuce can be sold directly to the consumer without going through any additional processing. Thus, the price of soybean will never be as high as the one for fresh produce sold directly to supermarkets. Even if the economical sustainability is omitted the crop did not receive a high grading in environmental sustainability either (table 4). Nevertheless, the idea of utilizing the wastewater for producing feed that will go back to the fish is something that should be further explored.

There are studies on the nutrient composition and growth of cereal crops that are commonly used in the feed (Snow et al., 2008). These studies report good growth albeit the crops are lacking in protein requirement (Snow et al., 2008). Neither soybean nor cereal crops are part of the natural diet of the fish and considering other suitable protein sources that are found in aquatic environments would not only make for a more sustainable production but also make for a feed that is closer to their natural diet (Salin et al., 2018). Additionally, it would connect directly to SDG 14 of conserving ocean resources and to use them sustainably (FAO, 2017). Decreasing or even eliminating the need for wild-caught fish in the feed is something that the aquaculture industry is striving towards.

While studies showed that lettuce and basil could grow at higher pH there is another option that allows for better environmental conditions for both the fish and the plants. Decoupled aquaponics is an example of aquaponics that would allow for more control over the water parameters. Decoupled aquaponics involves two separate systems that can work together (Kledal & Thorarinsdottir, 2018). Instead of the crops acting as a biofilter and being fully integrated in the system the wastewater from the fish is only led into the hydroponic unit as needed and otherwise directed back into the fish tanks as in a traditional RAS (Goddek et al., 2019). This would allow for different levels of pH and water temperature and in turn better environmental conditions for the crops (Goddek et al., 2019).

## 5.3 Uncertainties

The grading of the crops does include uncertainties. The sensitivity analysis revealed that while the basil continued to be the most suitable crop out of the three the difference was much smaller compared to the grading from the sustainability assessment. The grading in most categories was based on normalization and hence proportional differences. This excludes the need for a qualitative assessment and allows for a less subjective grading. The weights used were always equal which facilitates including more categories without having to evaluate what weight they should carry compared to the others and the importance of them. However, it can be argued that some categories should carry more weight than others and that only considering the lower or higher value of a range is not the most accurate selection. Using expert opinions to adjust the weights of subcategories could change the final score of the plants and in turn which crop is deemed most sustainable. Performing a sensitivity analysis on the weights of each subcategory could be useful to further adjust the weights.

## 5.4 Limitations

The evaluation table presented in this study was simplified to make it more user-friendly. Subcategories were limited and particularly in social sustainability other subcategories might have been more suitable but were too extensive and time-consuming for the scope of this study. Sadok et al. (2009) included in social sustainability subcategories such as complexity of implementation and number of specific operations which give a better view of the social sustainability of the operation. To quantify and grade these parameters would however require not only another literature review but also a qualitative assessment of how to grade them. For economic sustainability, the economic performance was calculated from store prices or found through market indexes and for a more extensive analysis, the price of the production, wholesale value, and seed price should be taken into consideration. In environmental sustainability, a subcategory evaluating the susceptibility of pests and diseases would be good to include. These subcategories mentioned could be incorporated but would require an additional qualitative grading system.

## 5.5 Outlook and future studies

The scope of this study was to compare three crops. If this study were to be replicated comparing more plants and their requirements would allow for a better comparison. Furthermore, there were no examples found in the literature of aquaponics using juvenile salmon or other cold water species. Since juvenile salmon has higher protein requirements than tilapia as well as colder water temperatures, an experiment of an aquaponic system using juvenile Atlantic salmon would better indicate what to expect in a commercial setting. Higher nitrogen concentrations in the water would, for example, be expected, due to higher protein content in the feed (Sun et al., 2016). The N:P ratio in the water and the requirements of the plants would also be helpful to include in the evaluation table and consider.

The evaluation table could be used to decide upon which crops are most suitable for the experiment, using only the highest-graded ones. This would allow for more accurate values of pH, temperature, and the nutrient composition of the water. Moreover, it would allow for monitoring the nutrient uptake of the plants. An experiment of this extent is time and resource consuming. However, an aquaponic system offers a sustainable solution for an industry that is only expanding, particularly in the Nordic countries where Atlantic salmon is most commonly farmed (Dalsgaard et al., 2013). Thus, researching how to optimize the system and provide the best growing conditions for both fish and plants should be a topic of interest.

# 6 Conclusion

The first part of the aim of this study was to construct a user-friendly evaluation table to compare sustainability parameters for growing crops hydroponically. This aim was concluded. The table can be used and managed by decision-makers and does not require any external program nor is it very time-consuming. The evaluation table that was constructed was based on an MCDA method from Sadok et al. (2009) and where the three sustainability pillars from the United Nations are used as guidance: economical, social, and environmental. The sustainability pillars act as the main categories, facilitating further the comparison and categorization of the sustainability parameters. It is easily manageable to include as many crops as preferred and to add in more subcategories, or exclude some, if needed.

The other part of the aim was to use literature to find and identify the most suitable crop for juvenile Atlantic salmon aquaponics, out of three selected, using the evaluation table. The three crops chosen for evaluation were basil, lettuce, and soybean. Basil had the best total grade. It received the highest grading in the sustainability assessment and the sensitivity analysis. The sensitivity analysis indicated that the large difference in revenue between basil and the other two crops was the main reason for the high grade. However, the fact remains that it scores much higher in economical sustainability in both the sustainability assessment and sensitivity analysis indicating that it is the best choice out of the three. The soybean was the least preferable crop and does not seem suitable for aquaponic purposes at this stage.

# 7 References


Abbey, M., Anderson, N. O., Yue, C., Schermann, M., Phelps, N., Venturelli, P., & Vickers, Z. (2019). Lettuce (Lactuca sativa) Production in Northern Latitudinal Aquaponic Growing Conditions. *HortScience*, *54*(10), 1757–1761. https://doi.org/10.21273/HORTSCI14088-19

Abbey, M., Anderson, N. O., Yue, C., Schermann, M., Phelps, N., Venturelli, P., & Vickers, Z. (2022). Basil, Ocimum basilicum, yield in northern latitudinal aquaponic growing conditions. *Journal of the World Aquaculture Society*, *53*(1), 77–94. https://doi.org/10.1111/jwas.12819

Ahmed, N., & Turchini, G. M. (2021). Recirculating aquaculture systems (RAS): Environmental solution and climate change adaptation. *Journal of Cleaner Production*, *297*, 126604. https://doi.org/10.1016/j.jclepro.2021.126604

Al-Hafedh, Y. (2003). Performance of plastic biofilter media with different configuration in a water recirculation system for the culture of Nile tilapia (Oreochromis niloticus). *Aquacultural Engineering*, *29*(3–4), 139–154. https://doi.org/10.1016/S0144-8609(03)00065-7

Atique, F., Lindholm-Lehto, P., & Pirhonen, J. (2022). Is Aquaponics Beneficial in Terms of Fish and Plant Growth and Water Quality in Comparison to Separate Recirculating Aquaculture and Hydroponic Systems? *Water*, *14*(9), 1447. https://doi.org/10.3390/w14091447

Bachinger, J., & Zander, P. (2007). ROTOR, a tool for generating and evaluating crop rotations for organic farming systems. *European Journal of Agronomy*, *26*(2), 130–143. https://doi.org/10.1016/j.eja.2006.09.002

Bendiksen, E. Å., Johnsen, C. A., Olsen, H. J., & Jobling, M. (2011). Sustainable aquafeeds: Progress towards reduced reliance upon marine ingredients in diets for farmed Atlantic salmon (Salmo salar L.). *Aquaculture*, *314*(1–4), 132–139. https://doi.org/10.1016/j.aquaculture.2011.01.040

Bergheim, A., Drengstig, A., Ulgenes, Y., & Fivelstad, S. (2009). Production of Atlantic salmon smolts in Europe—Current characteristics and future trends. *Aquacultural Engineering*, *41*(2), 46–52. https://doi.org/10.1016/j.aquaeng.2009.04.004

Bregnballe, J. (2015). A Guide to Recirculation Aquaculture. An introduction to the new environmentally friendly and highly productive closed fish farming systems. the Food and Agriculture Organization of the United Nations (FAO) and EUROFISH International Organisation.

Business Insider. (2023, April 20). *Soybeans*. https://markets.businessinsider.com/commodities/soybeans-price/euro

Chapin, F. S., Matson, P. A., & Vitousek, P. M. (2011). *Principles of Terrestrial Ecosystem Ecology*. Springer New York. https://doi.org/10.1007/978-1-4419-9504-9

Cinelli, M., Coles, S. R., & Kirwan, K. (2014). Analysis of the potentials of multi criteria decision analysis methods to conduct sustainability assessment. *Ecological Indicators*, *46*, 138–148. https://doi.org/10.1016/j.ecolind.2014.06.011

Dalsgaard, J., Lund, I., Thorarinsdottir, R., Drengstig, A., Arvonen, K., & Pedersen, P. B. (2013). Farming different species in RAS in Nordic countries: Current status and future perspectives. *Aquacultural Engineering*, *53*, 2–13. https://doi.org/10.1016/j.aquaeng.2012.11.008

Dawson, C. J., & Hilton, J. (2011). Fertiliser availability in a resource-limited world: Production and recycling of nitrogen and phosphorus. *Food Policy*, *36*, S14–S22. https://doi.org/10.1016/j.foodpol.2010.11.012

Delaide, B., Goddek, S., Gott, J., Soyeurt, H., & Jijakli, M. (2016). Lettuce (Lactuca sativa L. var. Sucrine) Growth Performance in Complemented Aquaponic Solution Outperforms Hydroponics. *Water*, *8*(10), 467. https://doi.org/10.3390/w8100467

Water Framework Directive (WFD) 2000/60/EC, (23 October 2000). https://environment.ec.europa.eu/topics/water/water-framework-directive_en

Dougher, T. A. O., & Bugbee, B. (1997). Effect of lamp type and temperature on development, carbon partitioning and yield of soybean. *Advances in Space Research*, *20*(10), 1895–1899. https://doi.org/10.1016/S0273-1177(97)00857-0

Eck, M., Körner, O., & Jijakli, M. H. (2019). Nutrient Cycling in Aquaponics Systems. In S. Goddek, A. Joyce, B. Kotzen, & G. M. Burnell (Eds.), *Aquaponics Food Production Systems* (pp. 231–246). Springer International Publishing. https://doi.org/10.1007/978-3-030-15943-6_9

FAO. (2017). *The 2030 Agenda and the Sustainable Development Goals: The challenge for aquaculture development and management* (FAO Fisheries and Aquaculture Circular No. 1141; FAO Fisheries and Aquaculture Circular No. 1141). FAO.

FAO. (2020). *The State of World Fisheries and Aquaculture 2020*. FAO. https://doi.org/10.4060/ca9229en

FAO. (2022). GLOBEFISH highlights 1st issue 2022, with Jan–Sep 2021 statistics: International markets for fisheries and aquaculture products. FAO. https://doi.org/10.4060/cc0222en

FAO. (2023). *Food and agriculture organization of the United Nations*. Retrieved April 7$^{th}$, 2023, from https://www.fao.org/fishery/en/aquaculture

Ferrarezi, R. S., & Bailey, D. S. (2019). Basil Performance Evaluation in Aquaponics. *HortTechnology*, *29*(1), 85–93. https://doi.org/10.21273/HORTTECH03797-17

Goddek, S., Delaide, B., Mankasingh, U., Ragnarsdottir, K., Jijakli, H., & Thorarinsdottir, R. (2015). Challenges of Sustainable and Commercial Aquaponics. *Sustainability*, *7*(4), 4199–4224. https://doi.org/10.3390/su7044199

Goddek, S., Joyce, A., Wuertz, S., Körner, O., Bläser, I., Reuter, M., & Keesman, K. J. (2019). Decoupled Aquaponics Systems. In S. Goddek, A. Joyce, B. Kotzen, & G. M. Burnell (Eds.), *Aquaponics Food Production Systems* (pp. 201–229). Springer International Publishing. https://doi.org/10.1007/978-3-030-15943-6_8

Hagstofa Íslands. (2022). *Fiskeldi á Íslandi*. https://hagstofa.is/utgafur/frettasafn/sjavarutvegur/fiskeldi-a-islandi/

Hata, N., & Futamura, H. (2020). Production of Soybean Plants for Hydroponic Cultivation from Seedling Cuttings in a Medium Containing *Rhizobium* Inoculum Depending on Various Concentrations of Nutrient Solution and Different Nitrogen Sources. *Journal of Horticultural Research*, *28*(2), 71–82. https://doi.org/10.2478/johr-2020-0015

Huang, I. B., Keisler, J., & Linkov, I. (2011). Multi-criteria decision analysis in environmental sciences: Ten years of applications and trends. *Science of The Total Environment*, *409*(19), 3578–3594. https://doi.org/10.1016/j.scitotenv.2011.06.022

Jónsson, J. K. (2023, April 4). *Personal communication, Director of Fishfarming at Samherji Fiskeldi.* [Personal communication].

Jørgensen, E. H., & Jobling, M. (1992). Feeding behaviour and effect of feeding regime on growth of Atlantic salmon, Salmo salar. *Aquaculture*, *101*(1–2), 135–146. https://doi.org/10.1016/0044-8486(92)90238-G

Joyce, A., Goddek, S., Kotzen, B., & Wuertz, S. (2019). Aquaponics: Closing the Cycle on Limited Water, Land and Nutrient Resources. In S. Goddek, A. Joyce, B. Kotzen, & G. M. Burnell (Eds.), *Aquaponics Food Production Systems* (pp. 19–34). Springer International Publishing. https://doi.org/10.1007/978-3-030-15943-6_2

Khan, S., Purohit, A., & Vadsaria, N. (2021). Hydroponics: Current and future state of the art in farming. *Journal of Plant Nutrition*, *44*(10), 1515–1538. https://doi.org/10.1080/01904167.2020.1860217

Kledal, P. R., & Thorarinsdottir, R. (2018). Aquaponics: A Commercial Niche for Sustainable Modern Aquaculture. In F. I. Hai, C. Visvanathan, & R. Boopathy (Eds.), *Sustainable Aquaculture* (pp. 173–190). Springer International Publishing. https://doi.org/10.1007/978-3-319-73257-2_6

Laxá. (n.d.). Vörur. *Eco seiðafóður*. Retrieved May 5$^{th}$, 2023, from https://www.laxa.is/is/vorur/vorur

Lembo, G., & Mente, E. (Eds.). (2019). *Organic Aquaculture: Impacts and Future Developments*. Springer International Publishing. https://doi.org/10.1007/978-3-030-05603-2

Mackowiak, C. L., Stutte, G. W., Wheeler, R. M., Ruffe, L. M., & Yorio, N. C. (1999). Tomato and soybean production on a shared recirculating hydroponic system. *Acta Horticulturae*, *481*, 259–266. https://doi.org/10.17660/ActaHortic.1999.481.27

Martins, C. I. M., Eding, E. H., Verdegem, M. C. J., Heinsbroek, L. T. N., Schneider, O., Blancheton, J. P., d'Orbcastel, E. R., & Verreth, J. A. J. (2010). New developments in recirculating aquaculture systems in Europe: A perspective on environmental sustainability. *Aquacultural Engineering*, *43*(3), 83–93. https://doi.org/10.1016/j.aquaeng.2010.09.002

Mbow, C., Rosenzweig, C., Barioni, L. G., Benton, T. G., Herrero, M., Krishnapillai, M., Liwenga, E., Pradhan, P., Rivera-Ferre, M. G., Sapkota, T., Tubiello, F. N., & Xu, Y. (2019). *Food Security. In: Climate Change and Land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D.C. Roberts, P. Zhai, R. Slade, S. Connors, R. van*

*Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)]*.

Monsees, H., Suhl, J., Paul, M., Kloas, W., Dannehl, D., & Würtz, S. (2019). Lettuce (Lactuca sativa, variety Salanova) production in decoupled aquaponic systems: Same yield and similar quality as in conventional hydroponic systems but drastically reduced greenhouse gas emissions by saving inorganic fertilizer. *PLOS ONE*, *14*(6), e0218368. https://doi.org/10.1371/journal.pone.0218368

Mota, V. C., Striberny, A., Verstege, G. C., Difford, G. F., & Lazado, C. C. (2022). Evaluation of a Recirculating Aquaculture System Research Facility Designed to Address Current Knowledge Needs in Atlantic Salmon Production. *Frontiers in Animal Science*, *3*, 876504. https://doi.org/10.3389/fanim.2022.876504

Palermo, M., Paradiso, R., De Pascale, S., & Fogliano, V. (2012). Hydroponic Cultivation Improves the Nutritional Quality of Soybean and Its Products. *Journal of Agricultural and Food Chemistry*, *60*(1), 250–255. https://doi.org/10.1021/jf203275m

Pantanella, E. (2018). Aquaponics Production, Practices and Opportunities. In F. I. Hai, C. Visvanathan, & R. Boopathy (Eds.), *Sustainable Aquaculture* (pp. 191–248). Springer International Publishing. https://doi.org/10.1007/978-3-319-73257-2_7

Pantanella, E., Cardarelli, M., Colla, G., Rea, E., & Marcucci, A. (2012). Aquaponics vs. hydroponics: production and quality of lettuce crop. *Acta Horticulturae*, *927*, 887–893. https://doi.org/10.17660/ActaHortic.2012.927.109

Paradiso, R., Arena, C., De Micco, V., Giordano, M., Aronne, G., & De Pascale, S. (2017). Changes in Leaf Anatomical Traits Enhanced Photosynthetic Activity of Soybean Grown in Hydroponics with Plant Growth-Promoting Microorganisms. *Frontiers in Plant Science*, *8*, 674. https://doi.org/10.3389/fpls.2017.00674

Paradiso, R., Buonomo, R., De Micco, V., Aronne, G., Palermo, M., Barbieri, G., & De Pascale, S. (2012). Soybean cultivar selection for Bioregenerative Life Support Systems (BLSSs) – Hydroponic cultivation. *Advances in Space Research*, *50*(11), 1501–1511. https://doi.org/10.1016/j.asr.2012.07.025

Paradiso, R., Buonomo, R., Dixon, M. A., Barbieri, G., & De Pascale, S. (2015). Effect of bacterial root symbiosis and urea as source of nitrogen on performance of soybean plants grown hydroponically for Bioregenerative Life Support Systems (BLSSs). *Frontiers in Plant Science*, *6*. https://doi.org/10.3389/fpls.2015.00888

Poli, B. M., Parisi, G., Scappini, F., & Zampacavallo, G. (2005). Fish welfare and quality as affected by pre-slaughter and slaughter management. *Aquaculture International*, *13*(1–2), 29–49. https://doi.org/10.1007/s10499-004-9035-1

Reglugerð 799/19999 um meðhöndlun seyru, (2 December 1999). https://island.is/reglugerdir/nr/0799-1999

Sadok, W., Angevin, F., Bergez, J.-É., Bockstaller, C., Colomb, B., Guichard, L., Reau, R., & Doré, T. (2008). Ex ante assessment of the sustainability of alternative cropping systems: Implications for using multi-criteria decision-aid methods. A review. *Agronomy for Sustainable Development*, *28*(1), 163–174. https://doi.org/10.1051/agro:2007043

Sadok, W., Angevin, F., Bergez, J.-E., Bockstaller, C., Colomb, B., Guichard, L., Reau, R., Messéan, A., & Doré, T. (2009). MASC, a qualitative multi-attribute decision model for ex ante assessment of the sustainability of cropping systems. *Agronomy for Sustainable Development*, *29*(3), 447–461. https://doi.org/10.1051/agro/2009006

Saha, S., Monroe, A., & Day, M. R. (2016). Growth, yield, plant quality and nutrition of basil (Ocimum basilicum L.) under soilless agricultural systems. *Annals of Agricultural Sciences*, *61*(2), 181–186. https://doi.org/10.1016/j.aoas.2016.10.001

Salin, K. R., & Arome Ataguba, G. (2018). Aquaculture and the Environment: Towards Sustainability. In F. I. Hai, C. Visvanathan, & R. Boopathy (Eds.), *Sustainable Aquaculture* (pp. 1–62). Springer International Publishing. https://doi.org/10.1007/978-3-319-73257-2_1

Salin, K. R., Arun, V. V., Mohanakumaran Nair, C., & Tidwell, J. H. (2018). Sustainable Aquafeed. In F. I. Hai, C. Visvanathan, & R. Boopathy (Eds.), *Sustainable Aquaculture* (pp. 123–151). Springer International Publishing. https://doi.org/10.1007/978-3-319-73257-2_4

Sardare, M. D., & Admane, S. V. (2013). A review on plant without soil—Hydroponics. *International Journal of Research in Engineering and Technology*, *02*(03), 299–304. https://doi.org/10.15623/ijret.2013.0203013

Savidov, N.A. (2005). *Evaluation and development of aquaponics production and product market capabilities in Alberta. Phase II.* (Final Report-Project #2004-67905621). Greenhouse Crops Program Crop Diversification Centre South Brooks AB.

Savidov, N. A., Hutchings, E., & Rakocy, J. E. (2007). Fish and plant production in a recirculating aquaponic system: A new approach to sustainable aquaculture in Canada. *Acta Horticulturae*, *742*, 209–221. https://doi.org/10.17660/ActaHortic.2007.742.28

Sfetcu, L., Cristea, V., & Oprea, L. (2008). Nutrients dynamic in an aquaponic recirculating system for sturgeon and lettuce (Lactuca sativa) production. *Lucrări Științifice - Zootehnie Și Biotehnologii, Universitatea de Științe Agricole Și Medicină Veterinară a Banatului Timișoara*, *41*(2), 137–143.

Skar, S. L. G., Birkeland, M. B., Nordal, O. A., & Thorarinsdottir, R. I. (2022). Commercial aquaponic system developed for Atlantic salmon ( *Salmo salar* ) production in RAS together with vegetable production – a $CO_2$ zero concept. *Acta Horticulturae*, *1356*, 247–254. https://doi.org/10.17660/ActaHortic.2022.1356.29

Snow, A. M., Ghaly, A. E., & Snow, A. (2008). A Comparative Assessment of Hydroponically Grown Cereal Crops for the Purification of Aquaculture Wastewater and the Production of Fish Feed. *American Journal of Agricultural and Biological Sciences*, *3*(1), 364–378. https://doi.org/10.3844/ajabssp.2008.364.378

Sprague, M., Dick, J. R., & Tocher, D. R. (2016). Impact of sustainable feeds on omega-3 long-chain fatty acid levels in farmed Atlantic salmon, 2006–2015. *Scientific Reports*, *6*(1), 21892. https://doi.org/10.1038/srep21892

Stjórnarráðið. (2022, December 8). *Sjávarútvegur*. Retrieved May 7th, 2023, from https://www.stjornarradid.is/verkefni/atvinnuvegir/sjavarutvegur-og-fiskeldi/sjavarutvegur/

Sun, G., Liu, Y., Qiu, D., Yi, M., Li, X., & Li, Y. (2016). Effects of feeding rate and frequency on growth performance, digestion and nutrients balances of Atlantic salmon ( *Salmo salar* ) in recirculating aquaculture systems (RAS). *Aquaculture Research*, *47*(1), 176–188. https://doi.org/10.1111/are.12480

Talukder, B., & Blay-Palmer, A. (2017). Comparison of Methods to Assess Agricultural Sustainability. In E. Lichtfouse (Ed.), *Sustainable Agriculture Reviews* (Vol. 25, pp. 149–168). Springer International Publishing. https://doi.org/10.1007/978-3-319-58679-3_5

Thorstad, Eva. B., Whoriskey, F., Rikardsen, A. H., & Aarestrup, K. (2011). Aquatic Nomads: The life and migration of the Atlantic Salmon. In Ø. Aas (Ed.), *Atlantic salmon ecology*. Blackwell Pub.

Tocher, D. R. (2015). Omega-3 long-chain polyunsaturated fatty acids and aquaculture in perspective. *Aquaculture*, *449*, 94–107. https://doi.org/10.1016/j.aquaculture.2015.01.010

United Nations. (2023). *Sustainable Development*. Retrieved May 20$^{th}$, 2023 from https://sdgs.un.org/goals

van Rijn, J. (2013). Waste treatment in recirculating aquaculture systems. *Aquacultural Engineering*, *53*, 49–56. https://doi.org/10.1016/j.aquaeng.2012.11.010

Wang, Y., Yu, X., Liu, J., An, D., & Wei, Y. (2022). Dynamic feeding method for aquaculture fish using multi-task neural network. *Aquaculture*, *551*, 737913. https://doi.org/10.1016/j.aquaculture.2022.737913

Weihe, R., Dessen, J.-E., Arge, R., Thomassen, M. S., Hatlen, B., & Rørvik, K.-A. (2018). Improving production efficiency of farmed Atlantic salmon ( *Salmo salar* L.) by isoenergetic diets with increased dietary protein-to-lipid ratio. *Aquaculture Research*, *49*(4), 1441–1453. https://doi.org/10.1111/are.13598

Wheeler, R. M., Mackowiak, C. L., Stutte, G. W., Yorio, N. C., Ruffe, L. M., Sager, J. C., Prince, R. P., & Knott, W. M. (2008). Crop productivities and radiation use efficiencies for bioregenerative life support. *Advances in Space Research*, *41*(5), 706–713. https://doi.org/10.1016/j.asr.2007.06.059

Wheeler, R. M., Sager, J. C., Berry, W. L., Mackowiak, C. L., Stutte, G. W., Yorio, N. C., & Ruffe, L. M. (1999). Nutrient, acid and water budgets of hydroponically grown crops. *Acta Horticulturae*, *481*, 655–662. https://doi.org/10.17660/ActaHortic.1999.481.78

Willumsen, J. (1980). The flowing nutrient solution. *Acta Horticulturae*, *98*, 191–200. https://doi.org/10.17660/actahortic.1980.98

Yang, T., & Kim, H.-J. (2020a). Characterizing Nutrient Composition and Concentration in Tomato-, Basil-, and Lettuce-Based Aquaponic and Hydroponic Systems. *Water*, *12*(5), 1259. https://doi.org/10.3390/w12051259

Yang, T., & Kim, H.-J. (2020b). Comparisons of nitrogen and phosphorus mass balance for tomato-, basil-, and lettuce-based aquaponic and hydroponic systems. *Journal of Cleaner Production*, *274*, 122619. https://doi.org/10.1016/j.jclepro.2020.122619

Ytrestøyl, T., Takle, H., Kolarevic, J., Calabrese, S., Timmerhaus, G., Rosseland, B. O., Teien, H. C., Nilsen, T. O., Handeland, S. O., Stefansson, S. O., Ebbesson, L. O. E., & Terjesen, B. F. (2020). Performance and welfare of Atlantic salmon, *SALMO SALAR* L. post-smolts in recirculating aquaculture systems: Importance of salinity and water velocity. *Journal of the World Aquaculture Society*, *51*(2), 373–392. https://doi.org/10.1111/jwas.12682