Evaluating Sustainability of Saline Aquaponics: Current Insights and Future Directions

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Abstract

Global challenges of population growth, climate change, freshwater scarcity and soil salinization have led to increasing interest in the innovation of saline aquaponics. This food production system integrates aquaculture with hydroponics and utilizes saline water. Although evaluating environmental, economic and social sustainability of innovations is essential for identifying sustainable food production systems, there is a lack of focus on sustainability in current saline aquaponics literature. In the present study, considerations to sustainability of saline aquaponics and its evaluation were uncovered by employing a systematic literature review and expert interviews. Saline aquaponics displays a number of sustainability characteristics, such as its ability to reduce nutrient pollution, utilize saline water and realize social enrichment functions, and effectively responds to pressing trends of for example freshwater scarcity and a growing unsustainable aquaculture sector. The innovation presents a promising sustainable food production system, with increased potential if major sustainability challenges are addressed and research adopts a sustainability focus. The importance of adopting a holistic approach to sustainability and the importance of contextualizing sustainability were demonstrated for saline aquaponics. Based on the uncovered considerations, this research gives direction to sustainability evaluation of saline aquaponics in the future and presents a tailored sustainability evaluation framework.

Key words: Saline Aquaponics, Sustainability Dimensions, Sustainability Evaluation, Aquaculture

Table of Contents

1. Evaluating Sustainability of Saline Aquaponics: Current Insights and Future Directions

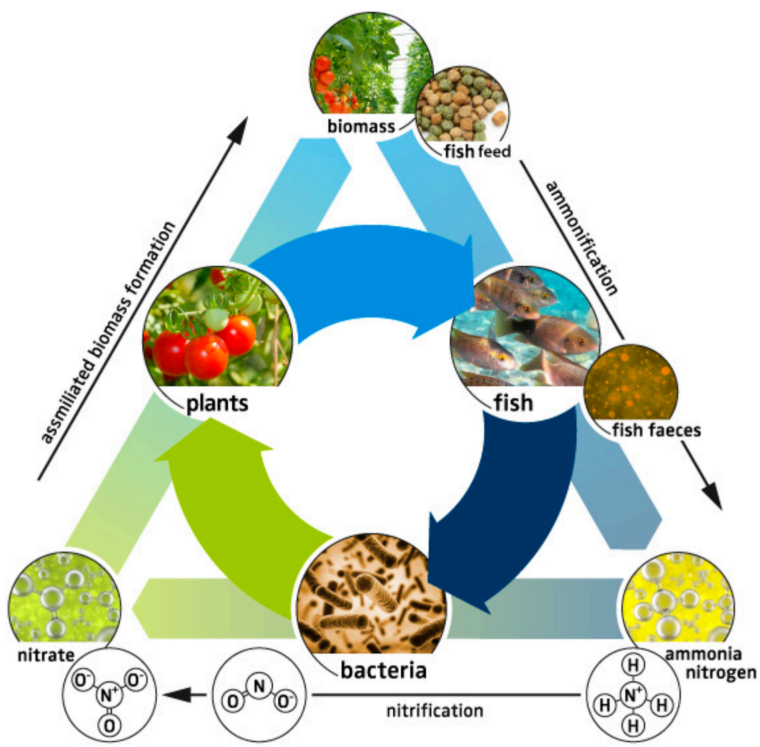
Agriculture is both threatened by climate change and a major contributor to the same problem, making food security a complex global challenge (Spradlin & Saha, 2022). Agriculture has to not only adapt to the effects of climate change and reduce its pressure on natural resources, but also increase production for a growing population in which hunger and poverty is present (Nair et al., 2024).

The Food and Agricultural Organization (FAO) of the United Nations has predicted a 15% increase in consumption of aquatic foods in 2030 (FAO, 2022). Given that aquaculture is the fastest growing sector of world food production, this sector will become even more central in future food security (Yusoff et al., 2024). Aquaculture is characterized by an enormous output of nutrient-rich wastewater in order to maintain water quality for its successful operation (Yusoff et al., 2024). To eradicate the negative impact arising by improperly treated aquaculture discharges, such as eutrophication, recirculating aquaculture systems (RAS) have been integrated with soilless cultivation practices (Yusoff et al., 2024). RAS are intensive fish production systems which use a number of water treatment methods in order to facilitate the reuse of the water, such as a filter to remove solid particles and a biofilter that oxidizes ammonia excreted by the fish (Espinal & Matulić, 2019). However, RAS do not include plant crops. The benefits of combining aquaculture and plant production have been known for a considerable amount of time, but in the last decades the innovation of aquaponics has received increasing attention (Greenfeld et al., 2018).

Aquaponics combines RAS with hydroponics, which is the system that deals with soilless production of vegetables and plants (Shreejana et al., 2022). Within the aquaponics system, two species symbiotically benefit as crops can utilize the nutrient rich wastewater, while simultaneously purifying the water to be again useful for the aquatic animal (see figure 1). The ammonia-rich waste water released by the aquatic animal converts into nitrite and finally nitrate in a biological filtration unit, housing microorganisms, before being supplied to the crops (Shreejana et al., 2022).

Figure 1

Aquaponics Cycle (Goddek et al., 2015)



Besides the benefits of reusing aquaculture wastewater, aquaponics has been praised for other benefits, such as high water use efficiency, high productivity, reduced reliance on synthetic fertilizers and multiple streams of income for aquaponics producers (Nair et al., 2024). Although start-up of commercial farms have increased in the last 15 years, aquaponics has not yet had a large-scale commercial breakthrough, which can be related to profitability among other technical, social and regulatory barriers (Horn et al., 2024) .

The prominent global challenges of freshwater scarcity and soil salinization, has led to increasing interest towards brackish and salt water as alternative water sources and the use of saltwater or salt-tolerant aquatic animals, named euryhaline species, and crops, named halophytes (Gunning et al., 2016). On that account, attention has been drawn to an emerging innovation of saline aquaponics (SA) (Gunning et al., 2016). Freshwater scarcity and salinization are major issues that impact agriculture and will form increasing challenges in the future (Muñoz-Euán et al., 2024). Only 2.5% of water present on earth is freshwater (Mishra et al., 2023). At the same time, it is essential for human consumption and activities, with agriculture representing the greatest demand of this resource (Muñoz-Euán et al., 2024). The pressure on our freshwater resources are increasing due to a growing population in combination with key drivers of climate change and increasing water withdrawal (Huang et al., 2021). On top of this, soil salinization is a major problem as it limits water uptake by plants (Spradlin & Saha, 2022) and contributes majorly to loss of agricultural productivity (Machado & Serralheiro, 2017). Salinized soils are expanding and intensifying, due to climate change and excessive use of groundwater (Machado & Serralheiro, 2017).

SA has been identified as a potential solution for freshwater scarcity, soil salinization and its relation to declining production in semi-arid, arid and coastal regions (Spradlin & Saha, 2022; Verma et al., 2023). Within SA, we can distinguish between marine aquaponics, and haloponics or brackish aquaponics, which utilize saline water lower in salinity (Kotzen et al., 2019). It effectively offers an alternative for the utilization of poor inland saline groundwater and the treating of saline effluent or waste-water, contributing to the sustainability of the system and making the system resilient in the face of climate change by reducing the pressure on limited freshwater resources (Spradlin & Saha, 2022). The previously mentioned benefits of freshwater aquaponics generally apply to SA, however SA also faces challenges to its sustainability, such as high start-up and production costs, complexity in management, lack of knowledge and reliance on energy-demanding aerators and water pumps (Spradlin & Saha, 2022).

Sustainability assessment represents a crucial step guiding sustainable development and the selection of more sustainable innovations before they are widely adopted (Perrin et al., 2023). In this context, it is crucial to evaluate sustainability of agricultural production systems from a holistic definition on sustainability, including the environmental, economic and social dimension (Czyżewski & Kryszak, 2022). However, there is a lack of studies evaluating the sustainability of aquaponics (König et al., 2016).

The aim of this project is to contribute to closing this gap for SA by answering the following questions: what is the potential of SA in presenting a sustainable food production system in light of the three pillars of sustainability? And how can we evaluate the sustainability of SA? This paper will not provide an in-depth sustainability assessment, but will illustrate considerations to sustainability of SA and its evaluation. The main objectives of this research paper are: 1) to provide a comprehensive overview on the current state of knowledge on the sustainability of SA, by uncovering important considerations, 2) to give direction on how to evaluate sustainability of SA, and 3) to identify major knowledge gaps in order to guide future research on this topic. This research does not have a geographical or temporal focus, but is limited by the lack of relevant literature and geographical representation.

2. Methodology

Systematic literature review

In order to gain an overview of the existing knowledge in the sustainability of SA, a systematic literature review was conducted. The systematic review is in line with the PRISMA 2020 Guideline for Reporting Systematic Reviews, following a transparent and standardized procedure (Page et al., 2021). Literature for the systematic literature review was identified in the Scopus database in March 2025. The article selection process went in the following steps (see Figure 2):

1. The first search aimed to identify all literature on SA. Within existing literature on SA, different terms are being used that represent different systems within SA (e.g. marine aquaponics and haloponics) or are synonyms (e.g. marine aquaponics and maraponics). In order to include all articles about SA,the initial search term included all search items that refer to the encompassing term of SA. There was no language-filter applied, nor were articles excluded based on date of publication. This resulted in 32 found documents (18.03.2025).

TITLE-ABS-KEY ("saline aquaponics" OR "marine aquaponic*" OR "maraponics" OR "haloponics" OR "brackish aquaponics" OR "brackaponics" OR "saltwater aquaponic*" OR "seawater aquaponics" OR “halophyte aquaponics” OR “brackish water aquaponics”)

2. Subsequently, a selection filter was applied that filtered out any documents that are not articles. Review articles, book chapters, conference papers and short survey documents are not applicable to the chosen methodology to focus on more in-depth analysis. There

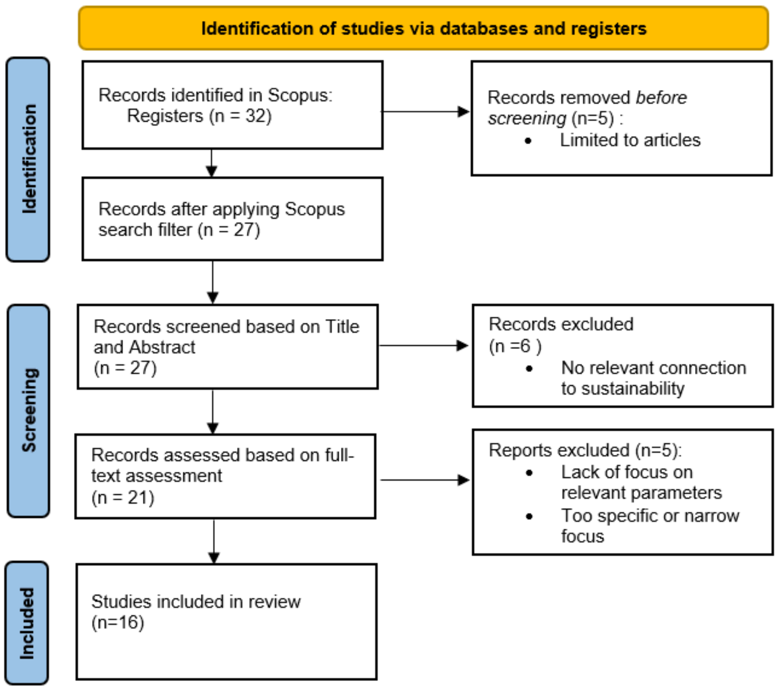
was no selection filter applied that would limit the scope to a certain geographical location, as multiple continents were presented in the identified documents that potentially offer a different perspective. This resulted in 27 remaining documents (18.03.2025).

3. Lastly, the remaining 27 documents were screened in order to exclude articles that are not relevant to the research question. Due to a severe lack of research on the sustainability of SA, articles were also included when indirectly able to give valuable insight on what we know on the sustainability of SA. Firstly, articles were evaluated based on article title and abstract. Secondly, the remaining articles were evaluated based on a full-text screening. Based on this eligibility criteria, a total of 21 articles out of 27 were selected for full-text screening. After full-text revision, another 5 were eliminated from the final selection of articles for systematic literature review, as they did not focus on relevant parameters or were too specific for the scope of the study, such as focussing on the technology of biofloc, specific fish diets or vegetative cuttings. In the end, the systematic literature review included a total of 16 relevant articles.

A data extraction form was designed and refined based on included articles in order to extract data from eligible studies. A bibliometric analysis was carried out to give general information on the literature, such as publications trend and global distribution of publications. Subsequently, a content analysis was carried out, analyzing the articles in light of relevant information to the research question.

Figure 2:

PRISMA Workflow Systematic Review (Page et al., 2021)



Expert interviews

Semi-structured in-depth interviews were carried out with experts in order to complement the results of the systematic literature review. The expert interviews contributed to answering the research question by validating findings of the systematic review, identifying gaps in the literature and giving insight from lived experience. The semi-structured approach allowed the experts to share their specific knowledge and bring up topics to the research question that they deemed relevant. Relevant participants were recruited by the use of an online search engine through exploring professional profiles, publications and organizational websites, and subsequently invited by email. A total of four interviews were carried out in March and April of 2025 and interviews lasted 45-60 minutes. Two participants with academic expertise and two participants with practical expertise were included, to allow for a variety of perspectives. The interviews were conducted in both Dutch and English, with one interview being conducted in English, and both online and in-person, with one interview being carried out in-person. All interviews gained their knowledge on SA mostly within the context of the Netherlands, posing limits to geographical representation. Interview questions (See Appendix 1) were formulated based on the systematic literature review, SA review articles and a theoretical framework. The interviews were transcribed with use of the transcribe software Otter.io and subsequently coded, looking for recurring themes and patterns in the responses. Significant themes within sustainability dimensions were identified that helped guide the research question.

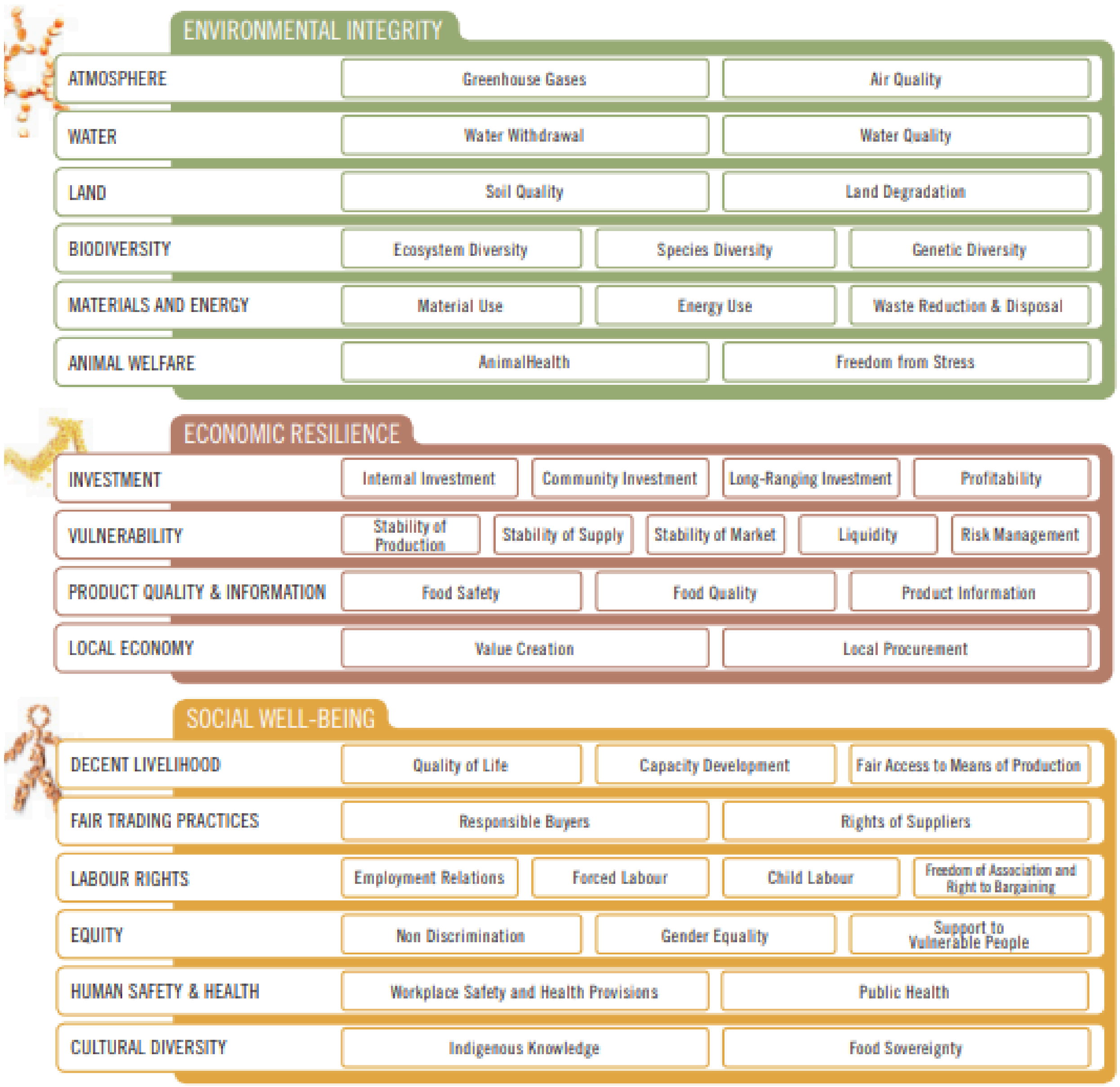
To uphold ethical standards, minimal risk and safety was ensured by adherence to considerations of an ethical checklist provided by the ethics committee of Campus Fryslân. Participants received a comprehensive information sheet and informed consent form, available in Dutch and English, outlining the study's purpose, procedures and potential risks and benefits, which participants were asked to sign voluntarily. Participation was voluntary and participants were informed that withdrawal from the study is possible at any point in time. Participants were kept anonymous, if preference indicated on the informed consent form. Data was handled in accordance with the General Data Protection Regulation (GDPR). All research data, including audio recordings and interview transcripts, were securely stored and not accessible to any other than the researcher. The ethical consideration checklist, information sheet and informed consent form are included in this paper (See appendix 2, 3 and 4). In order to acknowledge how my positionality has influenced the interpretation of my findings, a positionality statement is included in the appendices (see appendix 7).

Theoretical Framework

This research made use of a theoretical framework, the Sustainability Assessment of Food and Agricultural systems (SAFA) framework (see figure 3), proposed by the FAO. The framework, which includes themes and sub-themes for the three sustainability dimensions and is suitable globally, fits the scope of this evaluation. The SAFA framework considers the three initial dimensions of sustainable development, the environmental, economic and social dimension, and adds an additional dimension of governance (Scialabba & FAO, 2014). This research will focus on the three main pillars only. This framework was used in various ways throughout the research: 1) in the formulation of interview questions, 2) in the identification of relevant considerations to the sustainability of SA and 3) as the basis of the development of a new framework tailored to evaluate sustainability of SA.

Figure 3

SAFA Framework (FAO, 2014)



3. Results

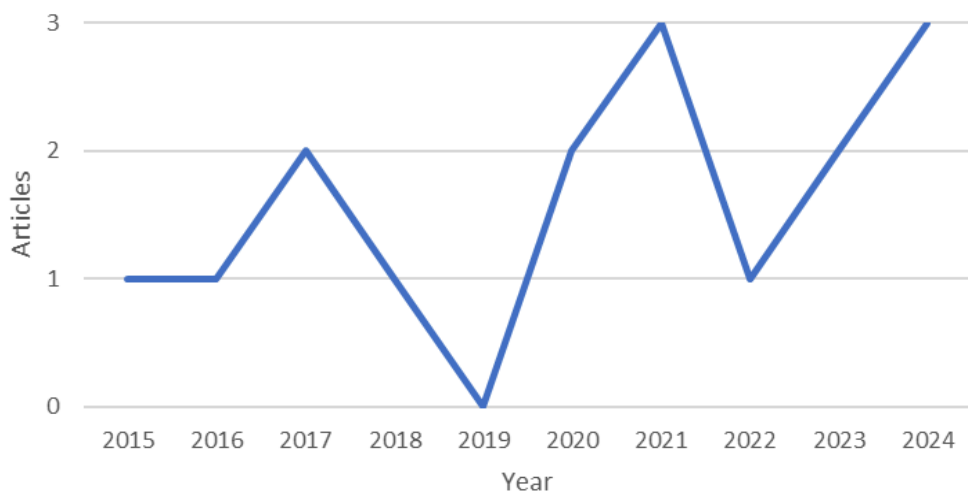
A search in Scopus database was performed on 20.02.2025 which resulted in only two found review documents. There has not yet been a comprehensive review established offering an overview on what we currently know on sustainability of SA, adding on all three dimensions. In line with the research question, this result section will present what we currently know about the sustainability, in all three dimensions, of SA and shed light on important sustainability considerations in the context of SA. The first part of this result section will provide information on the included articles and the SA systems that they studied and subsequently outline the current knowledge on each sustainability dimension. The second part of the results will present the findings of the expert interviews.

Bibliometric Analysis

The systematic literature review included 16 articles. The first article on SA was published in 2015 (Buhman et al., 2015). There seems to be an upward trend in the last five years, although there is presence of large fluctuations and a low number of articles in general (see figure 4).

Figure 4

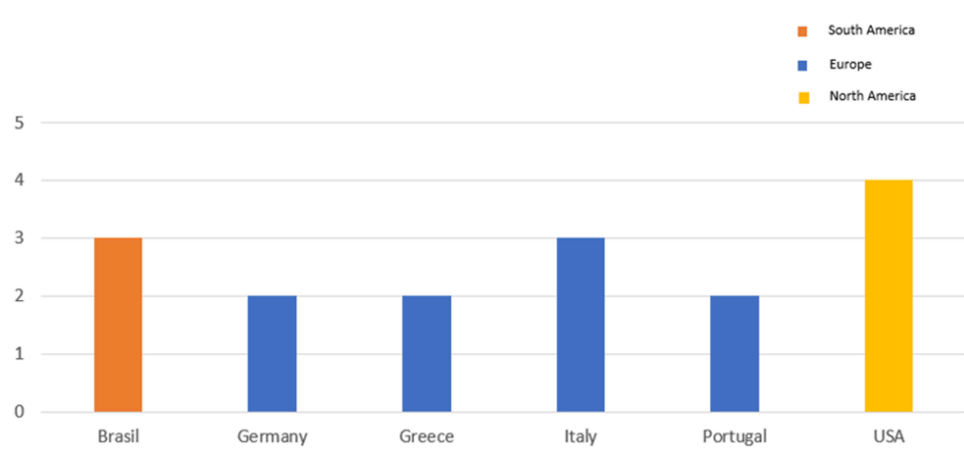
Number of Publications per Year



Even though no language filter was applied, all articles were published in English. The majority of studies were conducted in Europe, followed by North America and South America (see figure 5). However, the publications within the last mentioned continents, only included one country in which studies were conducted.

Figure 5

Distribution of Articles Across Countries



Content Analysis

General information

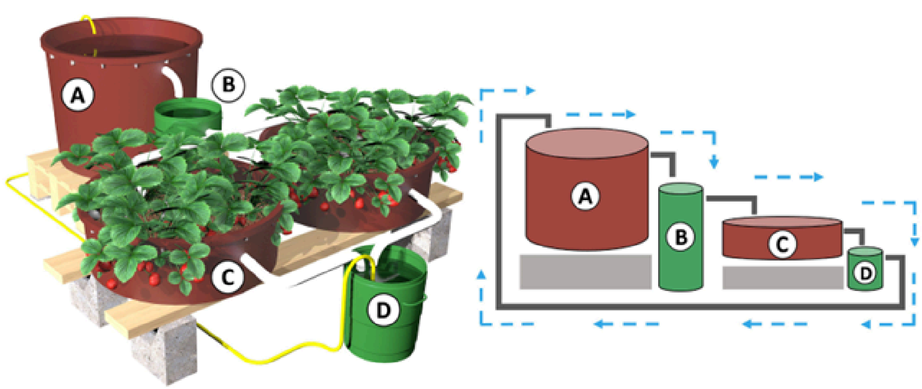
There were only two articles that addressed a sustainability dimension directly, including one Life Cycle Assessment assessing environmental sustainability (Arbour et al., 2024) and one economic evaluation of a SA system (Castilho-Barros et al., 2018). The other articles, besides one article that conducted a multi-criteria analysis to identify most suitable marine aquatic animal species (Rossi et al., 2021), were experimental studies, evaluating the effect of a broad variety of variables on a variety of independent variables within an experimental set-up. A significant number of nine articles (56.25%) measured merely or among other variables, production performance of crop and aquatic animals in the SA system, of which seven articles looked at how the variable of salinity affected production performance. Another considerable part of the included articles (25%) focused merely or among other variables, on evaluating the system's nutrient removal capacity, biofilter performance or other highly similar variables that can be grouped under the capacity of the system to remove nutrients.

Differences among SA Systems

Except for one article (Rossi et al., 2021), all articles conducted research on a specific system that was described. The articles included research on a wide variety of SA systems that most importantly differ in the system being coupled or decoupled, the system's level of technology and the scale of production. A coupled system means that the water cycle is closed (Doncato & Costa, 2021) and the water returns from the plant component of the system back to the fish tanks (Vlahos et al., 2023), which is different from a decoupled system in which this is not the case. Among the 15 articles that conducted research, most articles included a coupled SA system, with five articles that included a decoupled system. In this paper, the system's level of technology refers to technologies adopted to monitor and control growing conditions, by optimizing predominantly temperature with heaters and light intensity with artificial light. From the 15 articles, apart from two articles that conducted research on an outdoor system, all research was conducted in the controlled environment of a greenhouse. However, the level of technology differed, as five of the other 13 systems did not control temperature, while the rest adopted medium or high temperature control. Five of the 15 articles can be classified as high-tech systems, providing at least high control over temperature and light. Monitoring technologies, such as sensors to measure temperature, pH and nutrient levels, were adopted more commonly than control technologies, although the real life implications of this finding might be limited due to the research character of these systems. Considering the system's scale of production, all of the systems were small-scale and experimental-scale (see figure 6), except for the economic evaluation which was conducted on a commercial scale system in Brazil (see appendix 6) (Castilho-Barros et al., 2018).

Figure 6

Example of an aquaponics system showing a small-scale, coupled, low-tech system (Bourdignon et al., 2024)



Besides the system being coupled or decoupled, the system's level of technology and the scale of production, there were other important aspects in which systems differed, such as salinity and studied species. Salinity level ranged between 3 - 32 ppt, with an average of 15 ppt within SA systems. Although marine aquaponics suggests that salinity of used water is comparable to seawater, most included studies used this term to refer to the use of water with a salinity of 10 ppt and higher, which will be adopted in this paper. Other systems are classified under the concept of haloponics. Considering occurence of aquatic animal species within the articles, *Litopenaeus vannamei* (pacific whiteleg shrimp) was the most studied species (39%). Although most of the studies (84.6 %) included euryhaline species, which can tolerate a wide range of salinity levels, other studies included freshwater or marine stenohaline species, which can not tolerate wide fluctuations in salinity (Bordignon et al., 2021). Considering the occurrence of plant species, *Plantago coronopus* (buck's horn plantain) was the most studied species, however this only represents 10% of the studies. Most of the plant species included (68.18%) were halophytes, while relatively salt-tolerant glycophytes, that are in comparison to halophytes sensitive to salt (Vlahos et al., 2023), were also included.

Environmental Dimension

Impact on Water and Biodiversity. While most studies defined SA as an integrated system of RAS and hydroponics, a number studies defined SA in light of the nutrient removal function of the system or biofilter performance (e.g. Buhman et al., 2015), highlighting that this is a fundamental characteristic of the system. Halophyte biofilters show potential to treat marine aquaculture effluent and nutrient rich saline municipal, agricultural or industrial waste water (Buhman et al., 2015). Nitrate-N concentrations normally occurring in marine aquaculture effluents, are said to be suitable for normal growth rate and healthy development of plants, as nitrogen and phosphate are removed and absorbed by the plants (Buhman et al., 2015). It is noted that including a hydroponics subsystem to RAS lessens ecotoxicity and eutrophication caused by discharge of nutrient-rich aquaculture wastewater (Arbour et al., 2024; Doncato & Costa, 2021). In total, 33.3% of the articles mentioned that risk of eutrophication is reduced (e.g. Nozzi et al., 2016). Considering species and ecosystem biodiversity protection, cultivating commercial halophytes as an alternative to harvesting wild populations, is said to enhance conservation of salt marshes and impact on wild populations (Maciel et al., 2020).

Water Use. There is an increasing availability of brackish and salt water that the SA system can utilize and brackish/seawater aquaculture is likely to expand in the face of climate change adaptations (Vlahos et al., 2023). SA is said to use water efficiently (e.g. Nozzi et al., 2016). Two articles specifically mentioned that water was not renewed at any point (Chu & Brown, 2021; Pinheiro et al., 2020). However, freshwater was still used to dilute seawater, as lower salinity levels are favourable for biomass production and biofilter performance (Boxman et al., 2017; Buhman et al., 2015) and 25% of the articles mentioned that freshwater was added to account for evaporation.

Energy. Electricity use is a major environmental concern within the SA system (Arbour et al., 2024). The system is said to have high electricity demands (Chu & Brown, 2021) and to be energy-dependent (Castilho-Barros et al, 2018). The electricity-requiring components that can be adopted within SA are heaters, water pumps, air pumps and lights. However, switching the electricity source of coal or gas to renewable energy is noted as an important strategy, as this would result in a large decrease in environmental impact of more than 90% (Arbour et al., 2024).

Inputs. The inputs mentioned were fish feed and potential additional nutrients. The input of commercial fish feed of fish meal and oil is related to significant sustainability issues (Rossi et al., 2021), which was used in a large majority of the studies included. Strategies were mentioned in order to reduce the environmental impact of fish feed. Rossi et al. (2021) highlight the concept of Self-sufficient Integrated MultiTrophic AquaPonics (SIMTAP), in which another trophic level of detritivores and filter feeders are added that can convert organic sludge into nutritional biomass, which can be again useful to feed other aquatic animals. Furthermore, biofloc technology (BFT) can reduce fish feed use, as microbial flakes formed by bacteria and other microorganisms that mineralize and assimilate ammonia and nitrite, can serve as a supplemental nutrition to the cultured animal (Chu & Brown, 2021; Castilho-Barros et al., 2018). It was noted that RAS aquaculture effluents might not contain or insufficient amount of necessary macro and micronutrients for the optimal plant growth (Buhman et al., 2015). Buhman et al. (2015), highlighted that the lack of sufficient nitrogen, phosphorus and iron can result in reduced plant growth and chlorosis, and suggest the need for additional supplementary nutrients.

Waste. First and foremost, the SA system can be understood in light of how it recycles fish waste into plant nutrients. Considering wate of the system, integrated multi-trophic aquaculture (IMTA), which aquaponics belongs to, is a system generally regarded as waste efficient and responds directly to the criteria of the circular economy (Rossi et al., 2021). Waste that is mentioned is solid fish waste including faeces and uneaten feed, which need to be filtered out and disposed of (Castilho-Barros et al., 2018). Interestingly, the previously mentioned SIMTAP system effectively utilizes this waste.

Fish Well-being. Survival rate of the aquatic animal differed largely across studies and within studies, but four out of six quantified survival rates were above 80%. Depending on the species included, salinity can significantly decrease the survival rate of the aquatic animal, as Pinheiro et al. (2020) showed that the survival rate of pacific whiteleg shrimps went down by

27.7% comparing a salinity of 32 ppt to 8 ppt in the same system, showing that salinity is an important consideration for fish well-being

Economic Dimension

Viability. Economic evaluation and determining viability is highly important for the sustainability and longevity of aquaponics businesses and forms the basis for decision-making on entrepreneurial and public policy level (Castilho-Barros et al., 2018). The multiple streams of income derived from the commercial products of SA production is generally an important instrument to guarantee financial resilience (Castilho-Barros et al., 2018). Castilho-Barros et al. (2018), stated that financial viability was only achieved for the scenario with the highest selling price, which translates into a return on invested capital over six years. The profitability, and therefore attractiveness of starting SA businesses, is placed in doubt due to the perspective of future markets on inputs and sales prices, that the viability of the business is highly dependent on. Achieving marketable yield weight, uncertainty of market, variations in shrimp price and risk of production loss form important financial risks and challenges to economic viability (Castilho-Barros et al., 2018). Interestingly, SA is a way to reduce the economic burden of treating effluent, and add increased economic viability to current RAS businesses (Marques et al., 2017).

Production. Commercial aquaponics production units can vary greatly from 150 m^2 to 3000 m^2, indicating large differences in production (Catsilho-Barros et al., 2018). Salinity is said to impact productivity of both aquatic animals and plants (Chu & Brown, 2021). Salinity's effect on yield or growth of the euryhaline species in a marine aquaponics system, showed varying significant results. Comparing 10 ppt to 20 ppt condition, pacific whiteleg shimp's final weight increased by 11% when cultured at higher salinity (Chu & Brown, 2021). Another experiment showed significantly higher final weight of *Dicentrarchus labrax* (European seabass) in 8 and 14 ppt condition compared to 20 ppt (Vlahos et al., 2023). Higher species' salinity tolerance can explain this, which was also noted for the species pacific whiteleg shrimp. However, comparing the same species there were still varying results, as another study found no effect of salinity on average final weight of pacific whiteleg shrimps across salinity conditions comparing 8 to 32 ppt (Pinheiro et al., 2020). There might have been other environmental conditions of this system that played a role. The adaptive ability of marine euryhaline species were demonstrated in multiple studies as after gradual adaptation to lower salinities some studies found no significant differences in biomass (e.g Pinheiro et al., 2020). Feed conversion rate and survival rate also showed significant relationship with salinity, however these results were also varying and contradicting. Concerning haloponics, the studied freshwater stenohaline species, *Ameriuris melas* (black bullhead) and *Oncorhynchus mykiss* (rainbow trout), showed varying results to slight saline conditions (3 and 6 ppt), with rainbow trout showing adaptability to the haloponics system (Bordignon et al., 2024).

Concerning the crop component, there are multiple factors that influence the cultivation of halophytes, such as salinity. Five out of six articles that studied the effect of salinity on halophyte growth, mentioned significant reduced growth salinity increased after a certain threshold and highest growth was achieved in salinities in the range of 8- 16 ppt. Halophyte species differ in salt tolerance, for example buck's horn plantain yield was 268% higher comparing salinity of 20 and 10 ppt, while *Salsola komarovii* (saltwort) yield increased 62% (Chu & Brown, 2021). Two studies tested the effect of salinity on glycophytes of *Brassica oleracea* (cabbage), *Solanum lycopersicum* (tomato) *and Beta vulgaris* (beet) species in a haloponic system. It was noted that after being acclimated, beet yield significantly increased at higher salinity concentration of 6 ppt and cabbage growth was not significantly affected up till a salinity level of 5 ppt, indicating that also some non-halophyte species are salt-tolerant and adapt well to haloponics systems (Bordignon et al., 2024; Pascual et al., 2024). Two articles also noted decreasing nutrient uptake with higher salinity, this is potentially because of chloride concentrations that limit the ability to assimilate nutrients such as nitrate (Nozzi et al., 2016; Pascual et al., 2024). Salinity affects pH, making it more basic (Nozzi et al., 2016), this alkaline condition is said to promote low iron availability potentially affecting growth of some species (Doncato & Costa, 2021). Two studies mentioned salinity affecting the photosynthetic ability by causing change in chlorophyll content (e.g. Vlahos et al., 2021). A careful balance between fish and plant is highly important for overall production (Boxman et al., 2017). The main disadvantage of the cultivation of marine fish is the limited variety of halophyte plants that can grow at high salinity (Nozzi et al., 2016). Multiple studies indicated higher optimal salinity concentration for aquatic animals than for crop components (e.g. Chu & Brown,).

Beside salinity, light conditions and nutrient concentration affected the cultivation of halophytes. Lower light intensities resulted in increased accumulation of micronutrients accompanied by reduced growth rates (Pascual et al., 2024). Micronutrient supplementation showed significant increase in biomass production of 30% for species with high micronutrient requirements (Doncato & Costa, 2021).

Costs. Although Marine aquaponics systems do not include costs of pesticides, herbicides or cost related to cleaning of the crop (Murteira et al., 2022), moderate to high investment and operating costs were noted (Castilho-Barros et al., 2018). There is a significant financial burden when starting up, due to high construction costs, representing 44.23% of total investment, and acquisition of production equipment, such as infrastructure, pump, filtering system, heaters, tanks, control unit and even a possible backup electrical system (Castilho-Barros et al., 2018). Three studies specifically mentioned fish feed as a major operational cost (e.g. Arbour et al., 2024), which was highlighted as a general characteristic of marine aquaculture. However, the previously mentioned BFT and SIMTAP concept were highlighted to be able to reduce these costs (Rossi et al., 2021; Catilho -Barros et al., 2018). Labor was another major cost that was said to reach up till one-third of total production costs, as highly trained management was required (Catilho -Barros et al., 2018). Other operational costs included plant and shrimp acquisition, land rental, electricity, equipment depreciation and interest on investment (Catilho -Barros et al., 2018).

Market and Income. Marine aquaponics is said to potentially provide a solution to the economic drain of freshwater aquaponics (Chu & Brown, 2021). Four articles stress economic benefits related to the cultivation of marine aquatic species or halophytes, such as higher economic value and increased profitability (e.g. Vlahos et al., 2023), especially in regions where the consumption of marine fish is traditional (Nozzi et al., 2016). Some of halophytes species studied had an existing market for human consumption in parts of the world (e.g. *Sacrocornia amibgua* and *Salsola komarovii*), however articles generally stressed the lack of market for edible halophytes studied (e.g. Boxman et al., 2017). Interestingly, Arbour et al. (2024) stressed some edible halophytes being comparable and substitutable to well-known existing crops in the US. Some species are stressed as high-value luxurious crops and functional foods that offer additional health benefits, which additionally prevent competition with large-scale agricultural production (Boxman et al., 2017). Rossi et al. (2021) and Castilho-Barros et al. (2018) stressed market opportunities related to selling directly to consumers or developing a market niche related to sustainable production features or unconventional species. It was also stressed that species or their secondary metabolites have existing or potential markets outside human consumption, such as for animal feed, biogas production, pharmaceutical application and nutraceutical application (Buhman et al., 2015; Maciel et al., 2020; Marques et al., 2018).

Risk Management. Aquaculture is regarded as a high-risk activity with potential losses from for example disease, equipment failure and electrical failure (Castilho-Barros et al., 2018). Occurrence of one culture loss within a commercial and intensive scale system potentially compromises the entire business. Interestingly, including cultivation of halophytes contributes to the resilience of the business, as this production is often not affected (Castilho-Barros et al., 2018).

Social Dimension

Food Safety. The aquaponics system is said to constitute an important tool for biosafety of food production in urban areas (Castilho-Barros et al., 2018). Marine aquaponics production of halophyte provides social benefits, as reducing dependency on wild populations disables risk from uncontrolled environments, such as presence of contaminants (Maciel et al., 2020). There were no articles that reported presence of pathogenic bacteria in produce, posing harm to human health.

Human Health. It was noted that salinity has an effect on nutrient uptake of plants, lowering the nutritional value of the halophyte (e.g. Chu & Brown). Halophytes can contain high concentrations of essential amino acids and antioxidants (Boxman et al., 2017). Two studies mention the potential to regulate the production of secondary metabolites, such as antioxidants, by creating non-optimal conditions in salinity, availability of nutrients or light intensity (Murteira et al., 2022; Pinheiro et al., 2020). However, it should be noted that these conditions also significantly reduced biomass production. Multiple articles studied the effect of cultivation in marine aquaponics systems on poly unsaturated fatty acid content, which are mostly contained in seafood and considered beneficial for human health. Maciel et al. (2020), comparing halophyte aquaponics production to wild populations, found a shift in major lipids abundance, especially glycolipid class carrying n-3 fatty acids, which are related to bioactive properties of being anti-inflammatory and anti-proliferative. However, Nozzi et al. (2016), comparing freshwater aquaponics to SA found no difference in PUFA profile of the reared fish.

Other Important Themes: Location and Choice of species

Other important themes were location and choice of species. SA is deemed more fit in certain locations, such as coastal areas, arid regions, regions with high freshwater scarcity, regions with non-arable soil and urban areas, due to the saline and soilless character of this type of aquaponics (e.g. Nozzi et al., 2016). Rossi et al. (2021) notes opportunity in the development of local-based systems, taking into account needs and features of an area such as local availability of plant and aquatic animal species, availability of type of water and environmental conditions of salinity and temperature. Location was mentioned to influence economic sustainability directly by being highly important for determining presence of readily-established markets for marine fish species and costs, such as rental costs (Castilho-Barros et al., 2018; Vlahos et al., 2023). Beside species availability, suitable considerations when choosing species are adaptability to salinity and temperature, nutrient requirements, availability of knowledge and susceptibility to diseases, but also favourable economic characteristics, considering growth rate and market potential (e.g. Buhman et al., 2015; Rossi et al., 2021).

Interview Analysis

Participants

A total of four interviews were conducted, of which two are academic experts, who both preferred to remain anonymous. Expert one (E1) is specialized in RAS, nutrient balancing and fish feed and expert two (E2) is specialized in aquaculture in general and fish nutrition. The latter expert has additional expertise in the financial aspects for having worked on a business plan for a SA system. The other two interviewees have mostly practical expertise in SA. An interview was conducted with Mathilde Calamandrei (MC), a graduate student of herbal sciences, who during her internship at foundation Mediamatic managed a SA system. This was a small-scale, non-commercial system located in the urban environment of Amsterdam that utilized canal water in a haloponics system with salinity of 1.5- 3 ppt. Lastly, an interview was conducted with Erik Moesker (EM), founder of social enterprise NoordOogst Aquaponics located in the city Groningen, who conducts research and works on several SA projects.

Environmental Dimension

Impact on Water and Atmosphere. All interviewees mentioned that SA reduces nutrient pollution into the environment. The discharge of effluent in the environment, especially by large saline aquaculture businesses causes eutrophication, negatively impacting biodiversity (E1 & EM). However, E1 mentioned that a plant system being able to eliminate the vast amount of nitrogen and phosphate from the large quantities of effluents is a challenge concerning system design. Regarding impact on atmosphere, MC noted a balanced amount of CO_2 emissions. E1 noted potential of the plants taking up the CO_2 released by the fish in a controlled environment, highlighting limited direct CO_2 emissions.

Water Use. EM and E1 pointed out benefits to environmental sustainability by using saline water instead of freshwater that is scarce. Interestingly, EM highlighted how this trend in combination with soil salinization and increased need of protein gives rise to the necessity and resilience of SA. There was disagreement on the necessity of water to leave the system by either discharging, or replacing culture water. The two experts pointed out that discharge or replacing of culture water is necessary, as eventually chloride concentration becomes too high. Both EM and MC did not point this out and highlighted the closed cycle aspect of a coupled system. All interviewees pointed out the necessity to add water to the system to account for evaporation and an increase of salinity as a consequence of this. MC noted that the system that she managed switched from freshwater to canal water due to the large quantities of water leading up to 100,000 L/ year that needed to be added to account for evaporation. However, it should be noted that the elimination of freshwater was facilitated by the fact that the system used water with a low saline concentration, making it replaceable with canal water.

Energy. MC and E2 mentioned the SA system being energy-dependent and energy-intensive. All interviewees highlighted energy use for maintaining water temperature of the fish and pumping of water. MC mentioned that heating is the most energy consuming. E1 mentioned that energy-use is dependent on fish species included in the system, as fish species have varying optimum temperatures. E2 mentioned the possibility to use renewable energy in order to address indirect CO_2 emissions stemming from use of fossil fuel. EM confirmed this by having practically and successfully used renewable energy for SA systems.

Input and Materials. E1 regarded fish feed as an important sustainability consideration. EM highlighted the potential of seaweed or non-usable processable parts of fish, to be converted into fish feed. Concerning other inputs, E2 mentioned the often occurring necessity of adding additional nutrients in order to supply the requirements of the plant, as a result of nutrient balancing being a significant challenge between fish and plant. This was confirmed by the practical experience of MC, who mentioned that supplementary fertilizers, that included micronutrients and phosphate, were added in the form of chemical fertilizers. Both experts pointed out sustainability considerations to the choice of materials used for the infrastructure of the system. Both pointed out the lifespan of the material, which forms an extra challenge in SA as saline water is more aggressive and corrosion occurs faster. E2 additionally pointed out considerations to emissions in the material production, and the potential of the material to be recycled.

Waste and Fish Well-being. E2 and MC pointed out the solid waste, consisting of faeces and non-digestible part of feed, as waste in the system. EM pointed out a project on including the filter feeders oysters or mussels, which can filter out solid waste and improve water quality, while simultaneously offering a commercial product. Concerning fish well-being, there was one interviewee that expressed consideration to fish well-being, due to rearing conditions (MC)

Economic Dimension

Viability. EM, E1 and E2 noted lack or significant challenge to the economic viability of SA. E2 that carried out a financial analysis of a potential SA business, noted unviability of the business due to high infrastructure costs and high-start-up losses, posing additional challenges to the starting phase of a SA business. EM noted that although faced with significant challenges when trying to scale-up the system in order to reach a viable business model, he believed in economic viability as SA offers an alternative to fishing and agriculture on salinized soils will no longer be possible in the future. EM, MC and E2 mentioned high energy-use and energy-dependency as a significant challenge to economic viability, especially considering fluctuating energy prices, which was specifically mentioned by E2. The same three interviewees highlighted that strategies in order to reduce or eliminate energy dependency and energy costs can improve economic viability, importantly adoption of renewable energies. Additionally, EM noted creating value out of waste streams as a strategy to improve viability.

Production. MC, EM and E1 mentioned that increasing salinity limits crop production. EM and E1 mentioned the need to compromise between plant and fish health and growth, as plant health was said to be ensured under lower salinity than fish health. MC mentioned stable and satisfactory production of glycophytes such as mint, watercress and nasturtium in slight saline condition (1.5-3 ppt). Both experts noted the importance of choice of species by for example reaching sufficient nutrient balance. MC highlighted large differences in the amount of yield among species, noting especially mint and nasturtium being highly productive. Both EM and MC noted the ability to achieve high and stable production by controlling the environment to offer more optimal conditions regarding temperature and light. EM regarded the critique of SA not being able to feed a growing population as a valid critique. E1 highlighted that with enough research and experience, a stable and sufficient production can be realised for a SA system. Lack of knowledge is noted for marine aquaculture, as well as integrative systems and SA in general (E1).

Costs and Management. All interviewees noted energy as the highest cost for a SA system. E1 mentioned that choice of species is highly important for costs, mostly as it highly determines energy-costs. EM noted the production of fish feed from the solid waste of the system in order to reduce feed costs. EM, E1 and E2 declared complexity of management of a SA system. E1 noted the lack of experts specializing in both fish and plant components, and therefore their integration.

Market and Income. EM noted to have managed to gain an income from his SA activities. E1 highlighted the market of SA products as a challenge. The two experts noted the possibility of large-scale SA business selling to existing markets or small-scale producers that can find niche markets, such as selling close to customers and restaurants and/or producing niche products. E1 noted that producing largely produced products offers benefits such as existing demand and price, while the niche markets offer benefits related to being able to achieve higher selling prices although accompanied by increased marketing efforts. In the context of the Netherlands, E2 noted the need of picking a niche market due to the presence of competition from large scale, international producers of salt-tolerant fish species. Concerning the market for halophytes, E1 noted that there is a niche market for halophytes, but that it can be sold for a good price. EM stressed the potential of seaweed, referring to macroscopic marine algae species, as a crop to be adopted in SA for its ability to grow in higher salinity conditions compared to halophytes. He noted that there is an existing market for some applications of seaweed, such as for feed, green manure or seaweed extract present in a large variety of existing products. However, both EM and E2 noted the lack of a market for seaweed products for human consumption in the Netherlands and highlighted consumer acceptance of seaweed as a major challenge. Additionally, there is strong competition from large-scale seaweed producing countries, such as Japan. MC noted they did not have to find a new market for the product nor mentioned challenges to consumer acceptability as the system cultivated glycophytes commonly cultivated in greenhouses.

Risk Management and Local Economy. E2 noted high risks involved with SA production. There is potential to lose fish production in the event of energy failure, without the presence of a generator, or presence of disease among fish. E2 and EM mentioned SA being able to offer jobs, which directly addresses loss of jobs and livelihood in the fishery sector caused by changes in regulation and climate change or loss of livelihood for farmers cultivating on salinized soils.

Social Dimension

Food and Workplace Safety. All the interviewees mentioned that food safety of SA products can be guaranteed. E2 pointed out considerations to feed contamination and pathogenic bacteria. EM noted the tendency of seaweed to store heavy metals, which can have aversive effects on health when seaweed is consumed in large quantities. E2 mentioned that safety of employees of an aquaponics system should be considered.

Human Health. EM and E1 noted SA's ability to offer quality production, although dependent on fish feed and system. EM the possibility of this system to be local, adding to the freshness of produce. E2 highlighted the potential of this system to offer health benefits to countries with lack of fish in the diet of its people.

Other Benefits to Society. MC reported the function that SA systems fulfills for community-building, as colleagues and visitors could help and collaborate in the management of the system. She additionally reported a recreational function, as volunteers and employees of Mediamatic enjoyed helping in the greenhouse. E1 and MC reported educational functions, as there is a possibility to learn about aquaponics, plants and fish by demonstrating and helping in the management of an aquaponics system. E2 highlighted how small-scale systems can increase their income by offering educational and recreational functions.

Other Important Themes: Location, Choice of Species and Type of System

All interviewees expressed that SA is more suitable or advantageous in some locations over others. All interviewees highlighted a preference of locations with connection to the sea or other saline water sources, as this is convenient for uptake, as well as discharge of the water. E2 noted that SA systems have most potential in countries where freshwater scarcity is pressing and there is availability of brackish water sources. EM stressed that these SA activities should be carried out on salinized soils. While location can be decided based on the system, this decision-making process was also noted the other way around. MC mentioned that the location of the SA system being close to the canal, led to the decision to move to using canal water.

Location was highlighted to be important for environmental, economic and social sustainability. Considering environmental sustainability, E1 noted that reduced energy requirements are realized when moving SA systems to climates with longer growing seasons and more optimal temperature and light conditions. E1 also noted how the economic success of SA business is dependent on location, due to differing product prices. Lastly, location also highly shapes realization of social sustainability, as E1 and MC highlighted functions of education, recreation and community-building are facilitated by the location of the SA system being in an urban environment.

Choice of species was not only noted to be important for energy-requirements, EM also noted that choice of species can have beneficial effects on freshwater-use, by choosing species with lower rates of evaporation, and on economic gains, by choosing locally valued species. Additionally, E2 noted that fish feed is highly dependent on choice of species with implications for environmental impact stemming from the source and production process of the feed.

All interviewees agreed that sustainability is dependent on the type of system. Different benefits and drawbacks to sustainability were mentioned to the system being coupled or decoupled, the system's level of technology and the scale of production. Both experts and EM mentioned important benefits of decoupled systems. Firstly, both experts noted the ability to realize optimum conditions for both aquatic animals and crops included in the system, as these conditions do not have to be the same. Secondly, both experts mentioned reduced chance of losses in case of presence of disease, as you can more easily and separately treat the disease in both the aquatic animal and plant part of the system. Thirdly, EM noted that management is easier in a decoupled system. However, both EM and E1 highlight a drawback of a decoupled system by noting that coupled systems have a reduced impact on the environment, as there is a large reduction in water consumption and discharge.

Considering the level of technology, E2 and MC noted that inclusion of technologies able to control environmental parameters result in higher and more constant production, while simultaneously presenting drawbacks to energy-requirements and amount of technical investment. Additionally, E2 and EM highlighted that increased level of control makes a SA system more resilient to climate change. Lastly, scale of production was connected to benefits to sustainability, as EM mentioned that scaling-up is essential to realize a viable business model and sufficient production for a growing population. However, E2 noted that educational and recreational functions are only realized in small-scale systems.

4. Discussion

The aim of this paper is to evaluate the environmental, economic and social sustainability of SA and to gain insight into how to evaluate the sustainability of SA. In summary, this paper has outlined current knowledge within existing literature and has shed light on considerations to the sustainability of SA. The interviews were able to confirm important considerations and shed light on considerations not presented in the literature, such as on fish well-being, system material, local economy and a number of additional social sustainability considerations. This discussion section will first add on how the results inform the first research question. Subsequently it will discuss what the results mean for answering our second research question. Lastly, it will outline limitations and relevant directions for future research.

Sustainability Characteristics, Challenges and Developments

There was an overall low number of studies, which is in line with the fact that the concept of SA is relatively new (Gunning et al., 2016). Multiple trends explaining increasing interest in SA were named, such as increasing freshwater scarcity, soil salinization and increasing need of protein (Vlahos et al., 2023; EM). Additionally, it was noted that SA can improve environmental sustainability and economic sustainability of saline aquaculture practices, which will expand in the future (Marques et al., 2017; Vlahos er al., 2023). We can understand SA in light of its ability to respond to these trends, adding to its resilience and long-term sustainability.

Although aquaponics is recognized as highly valuable for sustainable agriculture and is generally said to present noteworthy sustainability benefits (Verma et al., 2023; Nair et al., 2024), there is a large gap in the literature shedding light on the sustainability of SA with currently only two articles directly assessing a sustainability dimension. Indirectly, the literature shed light on sustainability considerations of mostly the environmental and economic dimension.

Sustainability of SA can be viewed in light of key sustainability characteristics, challenges and current developments addressing sustainability drawbacks. Starting with environmental sustainability, a major inherent sustainability characteristic is the capacity of this system to utilize effluent and thereby reduce nutrient pollution (e.g Buhman et al., 2015; Vlahos et al., 2023, E1 and EM). However, there were multiple challenges noted to realizing this benefit. Firstly, balancing the aquatic animal and crop component of the system in such a way that excess of nitrogen and phosphate is eliminated, remains a main challenge to sustainability (E1; Goddek et al., 2015). Secondly, the need to add supplementary nutrients in order to increase plant performance (E2, MC; Buhman et al., 2015) can pose a considerable drawback to sustainability, as the mining or production of nutrients for chemical fertilizers are connected to significant greenhouse gas emissions (Rodgers et al., 2022). Lastly, the disposal of nutrient-rich sludge diminishes the nutrient utilization efficiency and potentially leads to nutrient pollution (Zhanga et al., 2021). However, an existing development that addresses this latter challenge was named, which is the implementation of another trophic level that can filter and convert the organic sludge (EM; Rossi et al., 2021).

The second key inherent sustainability characteristic of SA emerges from the use of saline water and water efficiency, which latter benefits is especially the case in coupled systems (EM, E1). However, there remain some challenges to water use. There was disagreement among interviewees in the necessity of water to be replaced, but the articles and interviewees all agreed there is a need to add freshwater to the system to account for evaporation. Chandramenon et al. (2024) notes that although there are generally large differences between studies in the sense of water exchange and replenishing rates, water exchange is not mandatory in a conventional aquaponics system, but this might be done in case of rapid increase of nitrite and toxic chemicals (Chandramenon et al., 2024).

Although the previously mentioned challenges to nutrient balancing and water efficiency should be considered, the main challenges to environmental sustainability were highlighted to be energy-use and fish feed input (Arbour etal., 2024; Rossi et al., 2021; E1; MC; E2). Ibrahim et al. (2023) highlights how minimizing energy-consumption is critical for aligning aquaponics practices with sustainability goals and reducing its carbon footprint. The use of renewable energy was importantly named as an effective strategy to decrease environmental impact (Arbour et al., 2024; E2). Decreasing the proportion of fishmeal and fish oil is a challenge to sustainability that needs to be addressed, as conventional fish feed production is characterized by high water consumption and responsible for 23% of captured fish (Goddek et al., 2015). There are also existing developments that try to address the dependence on fish feed, such as adoption of SIMTAP and BFT (Chu & Brown, 2021; Rossi et al., 2021; EM), and E2 noted that environmental impact of fish feed is considerably reduced, choosing some species over others.

Considering economic sustainability, there are again inherent characteristics adding to economic sustainability, such as the multiple streams of income, including of hydroponics as a highly productive method and the general higher economic value of marine aquatic species and halophytes (Vlahos et al., 2023; Nozzi et al., 2016; Catilho-Barros et al., 2018). The main challenges that arose from the literature and the interviews were the integrative aspect of production, the market and high start-up and operational costs. Having to compromise due to varying optimal optimal salinity conditions of euryhaline species and halophytes can reduce production of both components, although highly species dependent (e.g. Chu & Brown, EM, E1). Therefore, attention was directed to the benefits of a decoupled system (E1 & E2), as well as the potential integration with seaweed that can tolerate higher salinity (EM). Secondly, there was noted to be a challenge to the market of halophyte species and seaweed for human consumption due to consumer's acceptance, although region dependent (Boxman et al., 2017; EM; E2; E1). Therefore, halophytes and seaweed have currently more potential to be sold in niche markets, selling them directly to customers or restaurants and for uses outside human consumption (Buhman et al., 2015; Boxman et al., 2017; EM; E2). Interestingly, the successful growth of some glycophytes and freshwater stenohaline species in a slight saline system was demonstrated, without compromise to yield (Bordignon et al., 2024; Pascual et al., 2024, MC). This adds to the economic sustainability of haloponics systems, as the challenge of consumer acceptance is eliminated in this context (MC). Lastly, high start-up and labour costs were noted, as well as major expenditure to fish feed and electricity (e.g. Castilho-Barros et al., 2018; E1, EM). Previously mentioned strategies of renewable energy and alternative fish feed can be effective in order to reduce these latter costs (e.g EM; Rossi et al., 2021).

Considering the social dimension, the literature offered little attention to benefits to human health, and especially food safety. Although quality produce was said to be guaranteed (EM; E1), it remains unclear whether SA production offers additional health benefits. Interestingly, the interviews highlighted additional social sustainability considerations of workplace safety, community-building, recreation and education (MC & E1). Gunning et al. (2016) attributes the educational function of (freshwater) aquaponics to the interdisciplinary nature of aquaponics systems involving chemistry, biology, physics and sustainability, which is applicable to SA.

From our results, it is made evident that SA presents a number of sustainability characteristics, making SA a promising sustainable food production system. There are significant challenges posing drawbacks to its sustainability that need to be acknowledged and addressed. Both literature and interviews were able to name developments and strategies that can improve sustainability, showing the potential for improved sustainability in the future. The lack of research on SA and its sustainability, but also the infancy of knowledge on integrative systems and saline aquaculture (E1; Gunning et al., 2016) adds to that SA might not have realized its full sustainability potential.

Sustainability Evaluation

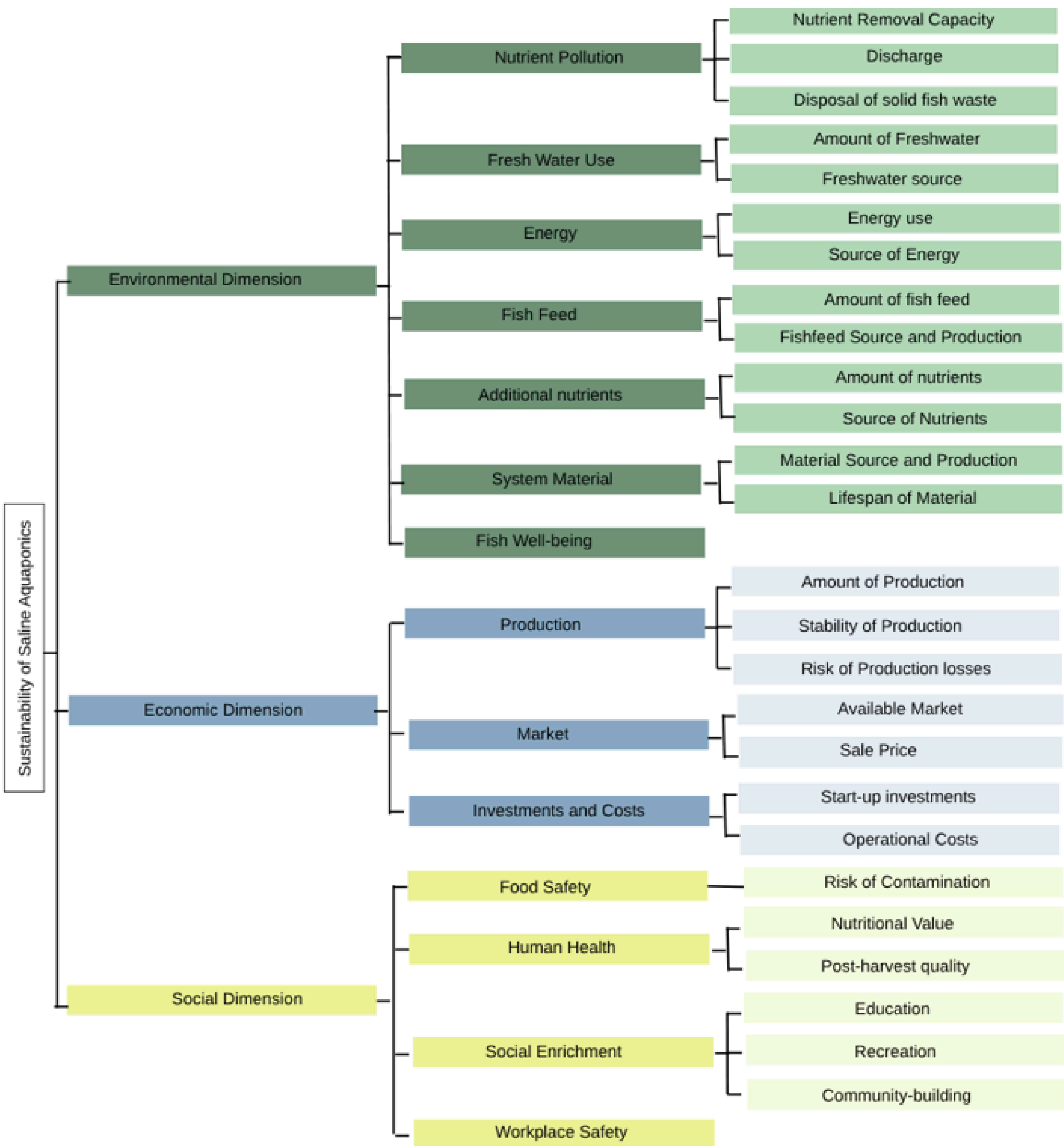
From our results, we can draw valuable information on how to evaluate the sustainability of SA. König et al. (2016) notes how sustainability assessment is complexified by the large number of relevant aspects and presence of interdependencies between aspects. Looking at sustainability holistically, including the environmental, economic and social aspects, was the starting point of this research. This not only because of the importance of balancing these different values (Czyżewski & Kryszak, 2022), but also by the limits of looking at these dimensions separately. The identification of multiple interrelations between dimensions, shows the interconnectedness of these dimensions and therefore the value of looking at sustainability holistically. Multiple synergies and trade-offs between sustainability dimensions were noted and identified, which the most important ones will be noted. Firstly, E2 and MC highlighted that adoption of technology increases production, while also increasing energy consumption, presenting an important trade-off between the environmental and economic dimension. Secondly, synergies between these two dimensions were also named. E2 connected the incorporation of renewable energy both to environmental benefits, by addressing fossil-fuel dependency, and economic benefits, by reducing energy cost. Similarly, replacing or reducing cost of commercial fish feed by adopting BFT, utilizing alternative feed or including filter feeders poses benefits to both dimensions (EM; Rossi et al., 2021). Lastly, E2 highlighted a synergy between economic and social sustainability by noting how small-scale can gain extra income by offering recreational and educational functions, highlighting.

Not only recognizing the value of a holistic approach, but also recognizing the importance of context was shown to be essential for sustainability evaluation of SA. A large variety of SA contextual factors were demonstrated in the articles, considering location, cultivated species and type of system, in terms of coupledness, level of technology, scale of production and salinity. SA was highlighted to be more fit under specific conditions, such as near a water source and regions with high freshwater scarcity (Nozzi et al., 2016; E2; MC). However, due to the high versatility in type of systems and choice of species, it can be successfully implemented in a wide-variety of settings (Gunning et al., 2016). The contextual factors were shown to be highly influential for sustainability considerations. Gott et al., (2019) highlights how sustainability is an outcome from situated practices and cannot be extracted from context and place. This means that these contextual factors should be taken into account in sustainability evaluation. Additionally, it means that increased sustainability outcomes and priority outcomes can be realized when making decisions regarding location, type of system and choice of species.

This paper has used the SAFA framework in order to guide the identification of relevant considerations, however the framework showed limited suitability. The framework's broad application led to minimal relevance of a variety of themes and lacked meaningful specificity relevant for the sustainability of aquaponics. Aquaponics is an atypical and complex food production system, due to its integrated character and wide application potential (König et al., 2016). Schader et al. (2014) highlights that one-size-fits-all sustainability assessment tools are not feasible and come with considerable trade-offs to quality, therefore the approach benefits from being tailored to a specific purpose. Based on the considerations that arose from the results, this paper now presents a tailored framework, based on the SAFA framework, for the sustainability evaluation of SA. This framework is applicable to evaluating the sustainability of individual systems, as well as guiding the evaluation of the innovation of SA as a whole. As this study highlighted the importance of context in sustainability evaluation, it should be noted that this tailored framework should take into account relevant contextual factors. The framework could be expanded including other relevant considerations that were missed in this research and relevant indicators could be selected in order to achieve a measurable assessment tool.

Figure 7

Sustainability Evaluation Framework for SA



Limitations & Research Agenda

This is the first research that shed light on SA from all three sustainability dimensions. There are some limitations to this research, which provide relevant direction for future research. This systematic literature review included a limited number of directly relevant articles posing limits to the conclusions that could be drawn. Future research on SA should have an increased focus on sustainability and take into account the value of offering a holistic perspective. As current research has not yet added on considerations of fish well-being, system material, local economy and social sustainability considerations, these topics should especially be explored, among the other considerations laid out in the framework. Another limitation was the lack of geographical representation in the literature and the interviews. As most research has been conducted in Europe, SA research should be conducted in a higher variety of locations, so contextualized knowledge is gained in a larger range of locations to which SA could provide benefits. Lastly, research should focus on the main challenges that were named in this paper, as addressing these drawbacks will significantly increase sustainability of SA.

5. Conclusion

In conclusion, this paper has evaluated the sustainability of SA and has given direction to its future evaluation. Based on the current state of literature and expert interviews, a broad variety of sustainability considerations were uncovered. SA presents a number of sustainability characteristics, such as reducing nutrient pollution, utilizing saline water and the providing of multiple streams of income. Additionally, it responds to pressing trends of increased need of protein, freshwater scarcity, salinization and a growing unsustainable aquaculture sector. However, there is also presence of a number of sustainability challenges, for example high energy-use, fish feed input and a lack of market, which a number of them can be addressed by adopting existing strategies. SA presents a promising sustainable food production system, with increased potential if sustainability challenges are addressed and research adopts a sustainability focus. This paper has demonstrated the value of adopting a holistic approach by the presence of interconnectedness, and has shown the importance of contextualizing sustainability, especially due to the SA's high versatility in contextual factors. This paper has also offered a new framework, which presents a tailored sustainability evaluation tool useful for evaluating individual systems, as well as the innovation as a whole. While the study was limited by the current lack of focus on sustainability in SA research and lack of global representation, it lays the groundwork for future research exploring the uncovered considerations to sustainability in a larger variety of locations. Ultimately, the findings contribute to the broader understanding of how agriculture can respond to prominent global challenges, such as climate change, freshwater scarcity, soil salinization and a growing population.

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Vlahos, N., Levizou, E., Patsea, E., Tasiou, K., Berillis, P., Antonopoulou, E., Bekiari, V., Martou, N., Morfesis, K., Lazari, D., Chatzimavroudis, C., Krigas, N., Kormas, K., & Mente, E. (2023). Salinity affects the efficiency of a brackish aquaponics system of sea bass (Dicentrarchus labrax) and rock samphire (Crithmum maritimum). *Aquaculture*, *571*, 739493. https://doi.org/10.1016/j.aquaculture.2023.739493

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Appendices

Appendix 1: Interview Guide

Introductie

- Zou u uzelf kunnen introduceren?
- Kunt u uw studieachtergrond en werkervaring kort samenvatten?
- Hoe heeft u uw expertise op het gebied van zilte aquaponics verkregen?
- Waar ligt uw expertise relevant voor zilte aquaponics?

Ecologische duurzaamheid

- Hoe beoordeelt u de ecologische duurzaamheid van zilte aquaponics systemen?
- Hoe beoordeelt u de ecologische duurzaamheid van de inputs van zilte aquaponics? (e.g. water, energy, fish feed of juist gebrek aan bepaalde input)
- Wat zijn de negatieve en positieve effecten van zilte aquaponics op het milieu?
    - Atmosphere/air
    - Water
    - Soil/land
    - Biodiversity
- Zijn zilte aquaponics systemen weerbaar voor klimaatverandering?
- Waar ziet u ruimte voor verbetering of uitdagingen in de ecologische duurzaamheid van zilte aquaponics systemen?
- Wat kunt u zeggen over de factor van geografische locatie binnen de ecologische duurzaamheid van zilte aquaponics?

Economische duurzaamheid

- Denkt u dat zilte aquaponics genoeg en een stabiele productie oplevert?
- Hoe beoordeelt u de economische duurzaamheid/vatbaarheid van commerciële zilte aquaponics systemen?
- Denkt u dat er een markt is/ zal zijn voor de producten van zilte aquaponics systemen?
- Hoe kan zilte aquaponics bijdragen aan de lokale economie?
- Waar ziet u ruimte voor verbetering of uitdagingen in de economische duurzaamheid van zilte aquaponics systemen?
- Wat kunt u zeggen over de factor van geografische locatie binnen de economische duurzaamheid van zilte aquaponics?

Sociale duurzaamheid

- Hoe denkt u dat zilte aquaponics positief of negatief bijdraagt aan het garanderen van leefkwaliteit van de maatschappij?
- Kan er adequate leefkwaliteit worden gegarandeerd voor zilte aquaponics producenten (e.g. eerlijk inkomen, werkomstandigheden)
- Wat kunt u zeggen over de kwaliteit en veiligheid van de productie van zilte aquaponics systemen?
- Op welke andere manieren kan zilte aquaponics bijdragen aan leefkwaliteit van de maatschappij (e.g. educatie)

Appendix 2: Ethical Checklist

1. Participants

- Does the study involve participants who are unable to give informed consent (i.e. people with Learning disabilities)? If yes: Discuss why and what measures you will take to avoid or minimize harm.
    - NO
- Does the research involve potentially vulnerable groups (i.e. children, people with cognitive impairment, or those in dependent relationships)? If yes: Discuss why and what measures you will take to avoid or minimize harm.
    - NO
- Will the study require the cooperation of a gatekeeper for initial access to the groups or individuals to be recruited? (i.e. students at school, members of self-help group, residents of nursing home)? If yes: Who is the gatekeeper? What agreement have you made, and which expectations do you share? Discuss whether and how this cooperation may influence your results.
    - NO
- Will it be necessary for participants to take part in the study without their knowledge and consent at the time (i.e. covert observation of people in non-public places)? If yes: Discuss why and how, and provide a risk analysis if applicable.
    - NO
- Will any dependent relationships exist between anyone involved in the recruitment pool of potential participants? If yes: Explain why and how, and provide a risk analysis
    - NO

2. Research design and data collection

- Will the study involve the discussion of sensitive topics? (i.e. sexual activity, drug use, politics) if yes: Discuss which topics will be discussed or investigated, and what risk is involved? What measures have you taken to minimize any risk, if applicable?
    - NO
- Are drugs, placebos, or other substances (i.e. food substances, vitamins) to be administered to the study participants? If yes: Discuss the procedure and the cost - benefit analysis.
    - NO
- What measures have you taken to minimize any risk, if applicable?
- Will the study involve invasive, intrusive, or potentially harmful procedures of any kind? If yes: Discuss the procedure and the cost-benefit analysis. What measures have you taken to minimize any risk, if applicable?
    - NO
- Could the study induce psychological stress, discomfort, anxiety, cause harm, or have negative consequences beyond the risks encountered in everyday life? If yes: Discuss the procedure and why no alternative method could be used. If necessary, discuss the cost -benefit analysis. What measures have you taken to minimize any risk, if applicable?
    - NO
- Will the study involve prolonged or repetitive testing? If yes: Discuss the procedure and how the interests of the participants are safeguarded.
    - NO

- Is there any form of deception (misinformation about the goal of the study) involved? If yes: Discuss the procedure and provide a rationale for its use.
    - NO
- Will you be using methods that allow visual and/or vocal identification of respondents? If so: Discuss what you will do to guarantee anonymity and confidentiality?
    - I will ask the respondents for consent if the interview can be recorded. If participants consent then I will record the interview in order to recollect the data more easily in the data analysis process. I will guarantee anonymity and confidentiality, as I will be the only person that has access to the audio files and the full transcripts. The files will be stored on the drive of the University of Groningen.
- Will you be collecting information through a third party? If yes: Discuss your choice for this party and the procedure.
    - NO
- Will the research involve respondents on the internet? If yes: Discuss how you plan to anonymize the participants.
    - NO
- How will you guarantee anonymity and confidentiality? Discuss the procedure and estimate the risk of a breach of confidentiality.

    - I will guarantee anonymity and confidentiality by ensuring that interviews are done in a safe space, where participants can answer questions in full privacy. I will with consent of the interviewees, record the interviews to ensure accuracy. I will anonymise any citations of the interviewees in the study paper, by removing names and direct references to their identity. It might be difficult to completely eliminate the possibility of identification by people close to the interviewees, but I will try to the best of my abilities to present their answers in a way that minimizes identification. The risk of a breach of confidentiality is minimal, unless someone finds a way to enter my email, where I will be in contact with the participants.

- What information in the informed consent will participants be given about the research? Please consult the template for information sheets and informed consent sheets for further guidance. Adjust the template to your situation and discuss it with your supervisor. Which procedures are in place in case participants wish to file a complaint?
  - Information sheet and consent form will be provided with this checklist.
- Will financial compensation be offered to participants? Discuss the compensation being offered and the rationale for it.
  - There will be no financial compensation to the participants due to the lack of budget for this research.
- If your research changes, discuss how consent will be renegotiated/
  - In case of changes of the research, we will send our participants an updated informed consent form, which gives them the freedom to keep being part of the research or not.

3. Analysis and interpretation

- What is the expected outcome of your research? Discuss what you would consider a significant result?

    - An expected outcome of the research is gaining insights that confirm or offer new perspectives on saline aquaponics that contribute to the existing literature.
- During the course of research, discuss how unforeseen or adverse events will be managed (i.e., do you have procedures in place to deal with disclosures from vulnerable participants)?
    - The participation pool will be carefully considered as well as the interview questions. Therefore unforeseen situations will be minimal. If vulnerable participants would be identified during the study, I will personally estimate whether the participants are fit to participate and protect them by excluding them from the research if necessary.

4. Dissemination

- Discuss how you plan to share your research findings. Which audience do you intend to target?
    - The findings will be included in my bachelor thesis. Findings will be shared within the University of Groningen. I will share and present my findings during the campus Fryslan conference, open to the general public, fellow students and teachers. My findings will also naturally be shared with the two examiners, which will assess this research. It will also be shared with one researcher and one professor in Padova, who have and will give me additional guidance on this research. I will also share my findings with the participants of this study, as the findings could be interesting to them.

5. Data storage

- Discuss: where your data will be stored and which measures you have taken to make sure it is secure?Which safety precautions have you arranged for in case of data leakage?, whether your data be disposed of. If yes: When? (date) if no: Why not?
  Whether your research involves the sharing of data or confidential information beyond the initial consent given (such as with other parties)? What specific arrangement have you made and with whom?

    - Data will only be stored on personal devices, which are safeguarded with a password and no one else has access. Upon completion of the research, the 23th of June, the recordings and other personal data will be deleted from the device. Data will not be shared with anyone.

Appendix 3: Information Sheet

INFORMATION SHEET:

SALINE AQUAPONICS

Dear,

Thank you for your interest in participating in this research. This letter explains what the research entails and how the research will be conducted. Please take time to read the following information carefully. If any information is not clear kindly ask questions using the contact details of the researchers provided at the end of this letter.

WHAT THIS STUDY IS ABOUT?

This study is part of the thesis research conducted by Sterre Jongsma, a bachelor student of Global Responsibility & Leadership from the Rijksuniversiteit Groningen, faculty Campus Fryslan. This study will explore sustainability of saline aquaponics. The research seeks to gain insights into the potential of this innovative food production system to contribute to the agricultural system in a sustainable way. Apart from identifying the existing information on this topic in a systematic literature review, the second part of the study aims to get the perspective of saline aquaponics companies, academic experts and other experts. In this way the findings of the first study can be confirmed and new findings can be captured. The study will include a total of 3-6 interviews with people that will be identified as experts in the field, by being active in commercial activity surrounding saline aquaponics or being involved in the innovation of saline aquaponics in the field of academia and research. I have identified you as relevant for this research as you can give your unique perspective on the topic of saline aquaponics.

WHAT DOES PARTICIPATION INVOLVE?

When agreeing to participate in this research, you will give up roughly 45-60 minutes of your time. I will ask you a number of questions, you are expected to answer honestly and as completely as possible.. The interview will be organised in person or via online call. The interview will be held in English or Dutch, by preference of the interviewee.

DO YOU HAVE TO PARTICIPATE?

Participation in this research is completely voluntary. You can choose to withdraw from this research at any moment and choose not to answer the question without consequence or providing reason.

ARE THERE ANY RISKS IN PARTICIPATING?

There are no physical, social, economic, legal risks of participating in this research and your anonymity and confidentiality will be ensured, if this is wished for. You are given agency on anonymity, and you can select your preference to be mentioned by name in the research paper at the end of this consent form or at a later point in time. There is also no direct psychological risk when participating in this study, although individuals might experience this for unanticipated reasons. We will not ask you any personal questions.

ARE THERE ANY BENEFITS IN PARTICIPATING?

There are no direct benefits of participating in the research, but your participation will contribute to further knowledge on the research topic and will potentially be valuable to you indirectly or in the long term.

HOW WILL INFORMATION YOU PROVIDE BE RECORDED, STORED AND PROTECTED?

If this is wished for, I will guarantee confidentiality and anonymisation in order to prevent identification of the interviewee. I will do so in the following ways. Your name and any references to your position will be removed from the research paper. During the interview, an audio recording will ensure correct note of the answers provided, useful for data processing after the interview. The transcripts of the recording will not be accessed by anyone else other than the researcher. The data will be stored on a storage platform facilitated by the University of Groningen that is considered safe. When the project is finished, in July of 2025, all the data will be disposed of. The recording and transcription of the recordings will be handled according with the EU's General Data Protection Regulation (GDPR).

WHAT WILL HAPPEN TO THE RESULTS OF THE STUDY?

The research findings will be shared with two examiners assessing the final research report. The findings will be presented at the Campus Fryslan Conference, open to the general public. The findings will also be presented in a final presentation open to fellow students, teachers, relatives and friends to attend. Lastly, the results will be shared with the other participants of the study.

ETHICAL APPROVAL

This research study is in line with relevant ethical guidelines and possible ethical considerations have been taken into account with help of the ethical checklist from the Campus Fryslan Ethics Committee.

INFORMED CONSENT FORM

By signing the informed consent form you are attending to participate and agreeing to the objectives of the study, but are still able to withdraw at any time.

Contact information

Sterre Jongsma

Email address: s.jongsma.4@student.rug.nl

Phone number: +31 612637794

Appendix 4: Informed Consent Form

Title study: Saline aquaponics

Name Participant:

Assessment

- I have read the information sheet and was able to ask any additional question to the researcher.
- I understand I may ask questions about the study at any time.
- I understand I have the right to withdraw from the study at any time without giving a reason.
- I understand that at any time I can refuse to answer any question without any consequences.
- I understand that I will not benefit directly from participating in this research.

Confidentiality and Data Use

- I understand that none of my personal information will be disclosed to anyone outside the study team and my name will not be published, if indicated at the end of this form.
- I understand that the information provided will be used only for this research and publications directly related to this research project. I understand that data (consent forms, recordings, interview transcripts) will be retained on the Y-drive of the University of Groningen server for 5 years, in correspondence with the university GDPR legislation.

Future involvement

☐ I wish to receive a copy of the final research report.

☐ I wish that my anonymity is ensured.

Having read and understood all the above, I agree to participate in the research study:
yes / no

Date:

Signature:

To be filled in by the researcher

- I declare that I have thoroughly informed the research participant about the research study and answered any remaining questions to the best of my knowledge.
- I agree that this person participates in the research study.

Date:

Signature:

Appendix 5: Literature review (n=16)

Arbour, A. J., Chu, Y., Brown, P. B., & Huang, J. (2024). Life cycle assessment on marine aquaponic production of shrimp, red orache, minutina and okahajiki. *Journal of Environmental Management*, *353*, 120208. https://doi.org/10.1016/j.jenvman.2024.120208

Bordignon, F., Birolo, M., Fanizza, C., Trocino, A., Zardinoni, G., Stevanato, P., Nicoletto, C., & Xiccato, G. (2024). Effects of water salinity in an aquaponic system with rainbow trout (Oncorhynchus mykiss), Black bullhead catfish (Ameiurus melas), Swiss chard (Beta vulgaris), and cherry tomato (Solanum lycopersicum). *Aquaculture*, *584*, 740634. https://doi.org/10.1016/j.aquaculture.2024.740634

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Castilho-Barros, L., Almeida, F. H., Henriques, M. B., & Seiffert, W. Q. (2018). Economic evaluation of the commercial production between Brazilian samphire and whiteleg shrimp in an aquaponics system. *Aquaculture International*, *26*(5), 1187-1206. https://doi.org/10.1007/s10499-018-0277-8

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Murteira, M., Turcios, A. E., Calado, R., Lillebø, A. I., & Papenbrock, J. (2022). Relevance of nitrogen availability on the phytochemical properties of chenopodium quinoa cultivated in marine hydroponics as a functional food. *Scientia Horticulturae*, *291*, 110524. https://doi.org/10.1016/j.scienta.2021.110524

Nozzi, V., Parisi, G., Di Crescenzo, D., Giordano, M., & Carnevali, O. (2016). Evaluation of Dicentrarchus labrax meats and the vegetable quality of beta vulgaris Var. cicla farmed in freshwater and saltwater Aquaponic systems. *Water*, *8*(10), 423. https://doi.org/10.3390/w8100423

Pascual, C., Xiang, L., Hernandez, R., & Hall, S. (2024). Optimizing light intensity and salinity for sustainable kale (Brassica oleracea) production and potential application in marine Aquaponics. *Sustainability*, *16*(23), 10516. https://doi.org/10.3390/su162310516

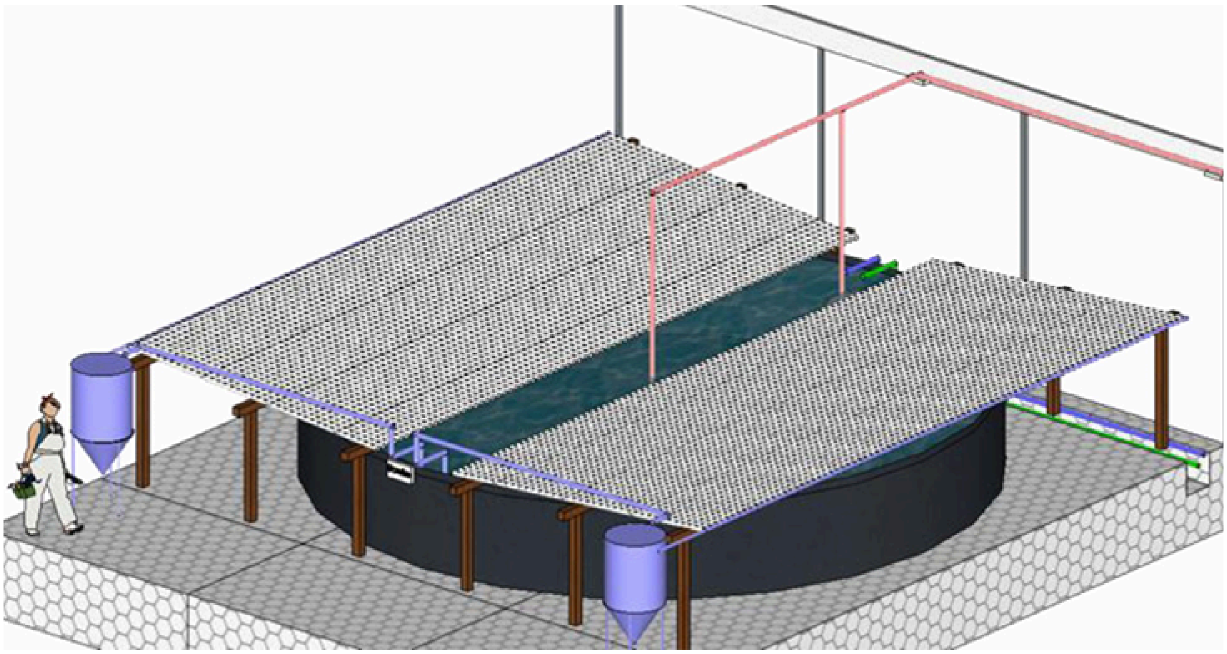
Pinheiro, I., Carneiro, R. F., Vieira, F. D., Gonzaga, L. V., Fett, R., Costa, A. C., Magallón-Barajas, F. J., & Seiffert, W. Q. (2020). Aquaponic production of Sarcocornia ambigua and Pacific white shrimp in biofloc system at different salinities. *Aquaculture*, *519*, 734918. https://doi.org/10.1016/j.aquaculture.2019.734918

Rossi, L., Bibbiani, C., Fierro-Sañudo, J. F., Maibam, C., Incrocci, L., Pardossi, A., & Fronte, B. (2021). Selection of marine fish for integrated multi-trophic aquaponic production in the Mediterranean area using DEXi multi-criteria analysis. *Aquaculture*, *535*, 736402. https://doi.org/10.1016/j.aquaculture.2021.736402

Vlahos, N., Berillis, P., Levizou, E., Patsea, E., Panteli, N., Demertzioglou, M., Morfesis, K., Voudouri, G., Krigas, N., Kormas, K., Antonopoulou, E., & Mente, E. (2023). Investigating salinity effects in brackish Aquaponics systems: Evidencing the Co-cultivation of the halophyte Crithmum maritimum with the Euryhaline Sparus aurata. *Applied Sciences*, *13*(6), 3385. https://doi.org/10.3390/app13063385

Vlahos, N., Levizou, E., Patsea, E., Tasiou, K., Berillis, P., Antonopoulou, E., Bekiari, V., Martou, N., Morfesis, K., Lazari, D., Chatzimavroudis, C., Krigas, N., Kormas, K., & Mente, E. (2023). Salinity affects the efficiency of a brackish aquaponics system of sea bass (Dicentrarchus labrax) and rock samphire (Crithmum maritimum). *Aquaculture*, *571*, 739493. https://doi.org/10.1016/j.aquaculture.2023.739493

Appendix 6: Additional Figure



Example of an aquaponics system showing a large-scale, coupled, high-tech system

(Castilho-Barros et al., 2018)

Appendix 7: Positionality Statement

Positionality

I acknowledge that my positionality has influenced the interpretation of my findings to some degree. My motivation for the topic was sparked during an exchange period in Italy, where I learned and was exposed to SA systems. This experience and context significantly shaped my perception of SA. Similarly, my identity as a student of Global Responsibility & Leadership has influenced this research, by having shaped my perspective on sustainability. Although having informed myself extensively on the topic, I should recognize the limits of my knowledge as a third-year bachelor student with a limited academic background on agriculture and lack of practical experience working with SA systems. Lastly, as this research tries to be globally representable, it is important to reflect on my social and cultural background that I bring with me when conducting interviews and reporting findings. I grew up and lived my whole life in the Netherlands, a high-income country with high food security and an agricultural sector characterized by efficiency and innovation. Although I have tried to be sensitive and inclusive to other backgrounds, this has potentially led to blind spots to considerations that arise from specific contexts, geographical circumstances and cultural values.