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TETRAS

# Recirculating Aquaculture Systems (RAS) in the Baltic Sea Region

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# Extended summary

The report outlines the possible role of Recirculating Aquaculture Systems (RAS) in transforming aquaculture into a more sustainable and controlled industry, particularly relevant for the Baltic Sea Region (BSR). RAS are land-based systems that allow the continuous reusage of water by filtering and treating waste from production. The central concept of RAS is the recirculation of water, as mechanical, biological, and chemical water treatment systems remove solids, ammonia, $CO_2$, and other by-products, enabling water to be reused up to nearly 100%. The system offers favourable conditions for farmed species, reduces the need for constant water input, limits the discharge of nutrients into surrounding ecosystems, and maintains a high level of biosecurity.

RAS facilities are classified according to their degree of recirculation, with low-reusage systems reusing 50-75% of water, medium-reusage systems achieving 75-90%, and high-reusage or 'fully recirculated' systems reaching above 90%. Some state-of-the-art facilities aim for 'zero discharge' status, though this is both technically complex and financially expensive, requiring highly advanced treatment solutions such as membrane filtration and nutrient recovery.

One of the principal strengths of RAS is the adaptability and environmental efficiency. Unlike traditional flow-through systems, which consume vast amounts of water, RAS minimises water usage, making it especially viable in regions with limited water availability or strict discharge regulations. In a typical flow-through system, 30,000 litres of water may be needed per kilogram of produced fish. In contrast, a high-intensity RAS can achieve the same production with as little as 50 litres of water per kilogram of produced fish, due to the advanced denitrification, oxygenation, and nutrient removal systems.

The technological complexity required for high-recirculation systems comes at a cost. Up-front investment expenses for RAS infrastructure can be considerable, especially when aiming for minimal discharge and a high degree of water-reusage. This report indicates the balance that must be struck between the desired degree of recirculation, investment capacity, and operational risk. For instance, the more complex the treatment chain, the greater the potential for mechanical failure or human error, which could compromise water quality and threaten fish health. To mitigate this, modern RAS facilities implement back-up systems, fail-safe procedures, and continuous monitoring technologies that ensure consistent operation and an immediate response to fluctuations in water parameters.

Risk management is a recurring theme in the innovation of RAS technology. In RAS, risks stem not only from technical failures but also from biological threats, in particularly disease outbreaks, which can spread rapidly within closed-loop systems. However, the biosecurity advantages of RAS are also indicated: the closed nature of these systems offers significant control over pathogen entry and spread. This reduces the need for medications and allows for more precise control of the rearing environment. Many systems use disinfection technologies such as beneficial biofilter bacteria or UV (ultra-violet) or ozone to eliminate microbial threats without harming fish.

Energy use, while higher in RAS compared to open-net or flow-through systems, can be offset by integrating renewable energy sources such as solar panels or by using heat recovery systems. Furthermore, this report notes that side stream productions such as sludge, fish waste, and residual heat can be valorised, for example, by using sludge for biogas or for district heating.

The report presents a detailed case study from Denmark: Skagen Salmon's 4,000-ton Atlantic salmon production facility. This facility employs a fully integrated RAS, with a recirculation rate above 99%. The water volume in the production tanks reaches 38,000 cubic meters, and the treatment system handles over 672 million cubic meters of water annually. The facility uses advanced nitrification and denitrification processes, mechanical filtration, UV disinfection, and oxygenation. Its sludge is used in biogas production and excess heat is used for heating in local homes. Skagen Salmon thereby demonstrates a successful example of industrial symbiosis where aquaculture supports and is supported by surrounding industries. This Danish example is presented in the report to underscore the environmental and operational efficiency that can be achieved in well-designed RAS facilities. The discharged water from this site contains low levels of nitrogen and phosphorus, with the final treated effluent meeting or exceeding the regulatory standards typically applied to municipal wastewater treatment plants. Nevertheless, the cost of achieving this high level of purification is significant. Advanced technologies, including denitrification using external carbon sources, are necessary to remove nitrate from saltwater, which presents challenges compared to freshwater systems.

The status for RAS across the Baltic Sea Region varies. The report provides production data from countries such as Denmark, Sweden, Germany, Finland, Estonia, Latvia, Lithuania, and Poland. Denmark leads in RAS production, primarily producing rainbow trout and Atlantic salmon, with over 21,000 tons produced in 2023. Sweden’s production is more limited, with catfish being the most significant RAS species. In Germany, warmwater shrimp are emerging alongside traditional aquaculture species. Some countries lack official data, and the report notes that statistics are incomplete in several cases, requiring reliance on estimates or case-based knowledge.

In summary, the initial sections of the report indicate that RAS has become an increasingly viable and environmentally responsible method for aquaculture in the Baltic Sea Region. It offers advantages in biosecurity, resource efficiency, and environmental protection, though it requires significant up-front capital investment, expert management, and careful system design to succeed. The development of high-recirculation RAS, as exemplified by projects in Denmark, sets a benchmark for the integration of aquaculture within broader sustainability and circular economy frameworks.

## Warmwater Shrimp Production and the Role of RAS in Europe

The second major thematic area of the report shifts attention from finfish, such as salmon and trout, to the emerging sector of warmwater shrimp aquaculture in Europe, particularly within land-based RAS. While shrimp is a major global seafood commodity, Europe has historically imported most of its shrimp from tropical countries. However, in recent years, there has been a growing interest in local, sustainable, high-quality shrimp production, prompting significant investment in European RAS-based shrimp farming projects.

Europe is the third-largest shrimp importer in the world, and the per capita consumption is high, estimated at 2.2 kilograms annually. This growing demand has inspired a wave of innovation aimed at reducing dependency on import, increasing local supply, and addressing concerns about the impact, environmental and otherwise, of conventional shrimp farming on tropical countries.

Warmwater shrimp farming in Europe is focused on *Litopenaeus vannamei* (Pacific white shrimp), which, due to its fast growth, tolerance to a range of environmental conditions, and relative disease resistance, is the most widely farmed shrimp species globally. Other species, such as *Penaeus monodon* (giant tiger prawn) and *Macrobrachium rosenbergii* (freshwater prawn), are also cultivated to a lesser extent. However, the overwhelming focus in European systems has been on *L. vannamei*, largely due to well-established production practices and the species’ compatibility with controlled environments like RAS.

RAS-based shrimp farming has significant advantages. Because the systems are closed and firmly regulated, many of the environmental drawbacks of traditional open-pond shrimp farming are eliminated, such as mangrove destruction, pollution, and disease spread. Instead, RAS allows shrimp to be farmed inland, close to urban markets, and with minimal environmental impact. Moreover, these systems are scalable and modular, meaning they can be adjusted in size depending on market demand and available capital.

An important technological development within this space is the integration of Biofloc Technology (BFT) into shrimp RAS. Biofloc systems rely on the cultivation of microbial communities (aggregates of bacteria, algae, yeast, and organic particles) which serve both as a water purification mechanism and as an additional feed source. Uneaten feed and shrimp waste are metabolised by heterotrophic bacteria into protein-rich flocs, consumable by shrimps. This creates a semi-closed loop where waste is reused rather than discharged, making BFT an advantageous model for sustainable shrimp production.

The use of BFT is particularly relevant for species like *L. vannamei*, which can efficiently digest bioflocs and thrive in nutrient-rich, slightly turbid water. The report explains that BFT has gained traction because it allows for:

- Enhanced feed conversion efficiency, since bioflocs act as supplementary feed.
- Improved water quality, through natural nitrogen cycling via microbial metabolism.
- Lowered operating costs, because the need for commercial feed and water replacement is reduced.
- Increased disease resistance, as the microbial community can outcompete pathogens.

However, BFT is not without challenges. The systems are biologically complex and require careful management of microbial dynamics, oxygen levels, and solids accumulation. Operators must understand the interplay of carbon-to-nitrogen ratios, microbial respiration, and biofloc volume, and constant aeration must be maintained to prevent anoxic zones. The report indicates that while BFT reduces investment costs (as fewer filtration units are needed), it raises operational demands and limits visibility in tanks, making shrimp monitoring and harvesting more difficult. Turbidity in BFT also prevents easy application of modern image analysis systems, which are increasingly used in clear-water RAS for feeding control and health monitoring.

A side-by-side comparison of clear-water RAS and BFT reveals a trade-off: clear-water systems offer better monitoring in cleaner water, while BFT systems are more cost-efficient and better aligned with circular economy principles. **Error! Reference source not found.** summarises this comparison, noting that RAS tends t o have a higher capital expenditure (CAPEX) but easier management and better shrimp quality, while BFT is cheaper to build and more efficient but operationally demanding.

The increase of shrimp RAS in Europe has led to the emergence of multiple commercial operations. Among the notable operations listed are Crusta Nova (Germany), Alpengarnelen (Austria), White Panther (Austria), Aquapurna (Germany), Swiss Shrimp (Switzerland), and BIOTECNA (Italy). These companies differ in system designs, as some use clear-water systems, while others use BFT or hybrid setups. All of them, however, represent the growing confidence in land-based shrimp production on the continent. Production capacities range from 10 to 30 tons per year in most cases, though several facilities are preparing to scale up significantly.

Despite these promising developments, shrimp post-larvae (PL) supply remains a bottleneck for the industry. PLs were previously typically imported from the United States, as European import regulations only permit specific pathogen-free (SPF) animals. To eliminate this vulnerability, several hatchery projects are underway within Europe. White Panther in Austria already produces around 500,000 PLs per week, supplying about half of Europe's current production needs. Other companies, such as Aquapurna in Germany and Vismar Aqua in Ukraine, are developing in-house hatcheries to reduce dependence on non-European suppliers and ensure more robust control over genetics, biosecurity, and delivery schedules. The report notes that the expansion of hatchery infrastructure will be a key factor in enabling future expansion in European shrimp aquaculture.

From a sustainability perspective, the RAS model for shrimp aligns well with European environmental policies and consumer expectations. Shrimp produced in RAS can be marketed as antibiotic-free, locally grown, fresh, and environmentally responsible. This appeals to a growing demographic of eco-conscious consumers and positions European shrimp as a premium product. However, scaling the sector requires solving not only technical issues but also questions of labour, expertise, energy costs, and investment readiness.

In conclusion, the report portrays the warmwater shrimp industry in Europe as one with considerable potential, made possible by technological innovation and shifting consumer values. The combination of RAS and BFT provides a powerful framework for sustainable, local seafood production, though success will depend on the expansion of hatchery networks, improved operator training, and continued support for research and development.

## Performance Indicators and Benchmarking in RAS Aquaculture

The report establishes Key Performance Indicators (KPIs) for aquaculture systems, with emphasis on RAS in both shrimp and salmon production. The goal is to provide robust, standardised metrics that can guide stakeholders, including farmers, investors, policymakers, and researchers, in assessing the viability, sustainability, and efficiency of aquaculture projects.

To create a holistic framework, the report introduces four primary categories of KPIs:

1. Economic Performance Indicators (Ec-PIs)
2. Social Performance Indicators (So-PIs)
3. Production Performance Indicators (Pr-PIs)
4. Environmental Performance Indicators (En-PIs)

These are designed to be adaptable to different species and systems, but the report focuses on two major production lines: warmwater shrimp (e.g., *L. vannamei*) and Atlantic salmon.

***Economic Performance Indicators (Ec-PIs)***

The economic KPIs address key financial dimensions of RAS, particularly capital expenditure (CAPEX), operating expenses (OPEX), cost of goods sold (COGS), and profitability metrics such as net revenue and break-even points. For example, in a modelled 1000 metric ton/year (MTY) clear-water RAS facility for shrimp, economic indicators include:

- Technology CAPEX: water tanks, filtration systems, biofilters, oxygenation units, and monitoring systems.
- Civil CAPEX: Buildings and facility construction.
- COGS: Feed costs, energy use, labour, maintenance, and PL acquisition.

The report indicates that CAPEX is significantly influenced by recirculation complexity. For shrimp, CAPEX can be reduced in Biofloc Technology (BFT) systems because these systems do not require advanced mechanical and biological filtration. However, BFT systems may incur higher OPEX due to their need for continual monitoring of microbial loads.

In comparing RAS with open-net pen (ONP) systems for salmon, RAS has more costly initial investments but offers longer-term economic stability, especially in regions with harsh weather or limited access to clean open water. The financial modelling shows that as scale increases, unit costs drop significantly, making mid- to large-scale RAS facilities more economically feasible than smaller ones.

***Social Performance Indicators (So-PIs)***

Social KPIs are less commonly addressed in aquaculture, but the report makes a concerted effort to include them. They include measures of:

- Safe job creation
- Employee satisfaction
- Local community engagement
- Health and safety standards
- Training and skills development

RAS facilities often offer stable, year-round employment opportunities, in contrast to seasonal or offshore open-pen operations. Moreover, land-based aquaculture can be integrated into local economies, allowing educational institutions and municipalities to participate in knowledge-sharing, workforce development, and public engagement.

A comparison is provided between So-PIs in the Baltic Sea Region and in Norway, alongside an indication of global best practices. While Norway leads in worker training programmes and safety regulations, emerging European shrimp operations are developing strong community connections and offering employment that requires high levels of technical expertise.

Challenges in implementing So-PIs include a lack of consistent reporting standards, and limited incentives for smaller operations to invest in human resources tracking. The report calls for greater collaboration between industry, academia, and local governments to standardise and incentivise social performance monitoring.

***Production Performance Indicators (Pr-PIs)***

Production KPIs include key metrics such as:

- Feed Conversion Ratio (FCR)
- Survival Rate
- Growth Rate
- Harvest Yield
- System Downtime or Failure Rate

FCR is a key efficiency indicator, as it measures how much feed is required to produce 1 kg of biomass. In well-optimised RAS, both salmon and shrimp can achieve FCRs close to 1.2–1.5, depending on feed quality and environmental stability. The report indicates that shrimp FCRs in BFT systems can be even lower because microbial biomass supplements other feed, offering both cost and sustainability advantages.

For salmon, fully recirculated systems show consistent growth patterns and survival rates when biosecurity is well-managed. However, these systems require highly trained operators to avoid performance fluctuations due to mechanical or biological imbalances.

The report includes long-term data from Danish RAS facilities (2019–2023), showing that RAS can outperform open-pen systems in nitrogen and phosphorus discharge per unit of fish produced, without compromising growth efficiency. In fact, despite the higher degrees of recirculation and lower amounts of discharge, FCRs in RAS remain competitive with and outperform those in open cages, particularly in later years as technology has improved.

***Environmental Performance Indicators (En-PIs)***

The environmental KPIs measure nutrient emissions, energy consumption, water usage, and waste management efficiency. In RAS, the following are critical:

- Nitrogen and Phosphorus discharge per ton of fish/shrimp

- Water usage per kg of feed
- Sludge management and valorisation
- Energy consumption and integration of renewable energy

The report provides detailed environmental data from Danish RAS facilities. For example, Danish Salmon was able to discharge only 15 kg N and 1.3 kg P per ton of salmon produced, demonstrating a high level of environmental efficiency, especially compared to historical figures of 30+ kg N/ton in early systems.

Further insights are drawn from Life Cycle Assessments (LCAs) that compare RAS and open-net pen (ONP) salmon systems. RAS perform better in nutrient discharge, but worse in energy consumption, unless offset by renewable sources. However, the use of sludge for biogas production and heat recovery contributes positively to the circular economy and mitigates environmental impact.

The report also compares clear-water and BFT shrimp systems. BFT reduces water usage to nearly zero and captures waste in microbial flocs. However, it requires more aeration energy and may lack the ability to ‘purge’ shrimp prior to harvest, which can impact meat quality. In contrast, clear-water RAS allow for a cleaner final product and better monitoring of health and growth, albeit with higher water usage and higher CAPEX.

The report indicates the need for a standardisation of KPI tracking and reporting in aquaculture. It calls for greater transparency and comparability across systems, companies, and countries, particularly in the light of increasing interest from ESG-focused investors and sustainability certification schemes.

The report provides a comprehensive and structured approach to evaluating aquaculture performance through KPIs. RAS, especially when combined with innovations like BFT, demonstrate significant potential across environmental, economic, and social metrics. However, successful implementation requires a careful balancing of trade-offs, investment in technology, and capacity building among operators.

***KPI case studies***

After the KPIs have been established, two cases are presented to offer examples of how to work directly with KPIs. The two cases are the state of gender equality in aquaculture in the Baltic Sea Region and the EUs guidelines on how to decarbonise aquaculture.

In the case of gender equality in the Baltic Sea Region, statistical data for countries in the region is used to create an overview of the current state of gender diversity among employees in the period 2005-2025. It is concluded that more consistent and detailed data is needed, but that the existing data shows the sector to be around 75-80% male.

After the quantitative overview is established and analysed, qualitative methods are employed to create a greater understanding of the needs and desires of young women seeking to enter the industry. The aim of this analysis is to gain a greater understanding of what it would take to attract more workers of this demography and how RAS productions can work directly with establishing desirable working environments.

The second case involves a closer look at the issue of decarbonisation in the aquaculture industry. The EU recommendations are presented, and it is discussed how RAS productions can work towards meeting these recommendations.

## RAS vs Open-Net Pen Systems, Life Cycle Assessment, and Regional Innovation

The report includes a comparative evaluation of RAS in comparison with traditional open-pen cage systems for salmon production. This contrast illuminates the trade-offs between environmental sustainability, economic feasibility, biosecurity, and operational complexity, which are key considerations for aquaculture development in the Baltic Sea Region and beyond.

### *Comparing RAS and Open-Net Pen Salmon Production*

The Open-Net Pen model, which is widely used in Norway and other coastal nations, involves floating cages in the sea, where water can flow freely through the system. These installations are less capital-intensive and benefit from low energy costs, as natural water circulation handles filtration, oxygenation, and temperature regulation.

However, ONPs also come with significant environmental problems, including:

- Uncontrolled nutrient discharge into the marine environment
- Risk of disease transmission and escapees
- Dependence on site-specific environmental conditions
- Susceptibility to climate change impacts (e.g., temperature shifts, harmful algal blooms)

In contrast, RAS decouples production from the natural environment, enabling year-round farming independent of location. It allows aquaculture to move inland and closer to urban markets while maintaining strict control over water quality, fish health, and by-product emissions. However, this model incurs higher capital and operational costs, requires highly skilled labour, and demands robust backup systems due to its technological complexity.

The report compares these two systems across all four KPI categories:

### Economic Performance

- CAPEX is considerably higher for RAS. Construction costs, filtration systems, oxygenation units, and building permits all contribute to this. In some cases, RAS CAPEX can be 3–4 times that of open-pen systems.
- OPEX varies. While RAS uses more energy, it often benefits from lower mortality rates, better FCRs, and the ability to sell fish at premium prices due to consistent quality and sustainability credentials.

### Environmental Impact

- Open-Net Pens release nutrients (nitrogen, phosphorus, organic matter) directly into the sea, contributing to eutrophication and the disruption of local ecosystems.
- RAS, by contrast, captures and treats effluents, and the advanced facilities often meet municipal wastewater treatment standards.
- RAS uses more energy but can integrate renewables and valorise side streams (e.g., sludge is turned into biogas; heat recovery).

### Social and Ecological Benefits

- RAS supports local employment, especially in regions without access to the sea.
- It contributes to urban and rural regeneration, offering skilled jobs in food technology, engineering, and logistics.
- Open-pen systems often face social pushback due to concerns about pollution and competition with wild fisheries.

**Fish Welfare and Biosecurity**

- RAS offers a high degree of biosecurity, with closed-loop water systems, disinfection units, and quarantine procedures.
- Open-pen systems expose fish to external pathogens, parasites such as sea lice, and predators.
- Welfare in RAS can be higher, if systems are well managed, due to stable environmental conditions.

The report concludes that RAS is not a universal replacement for open-pen systems but rather a complementary or alternative pathway, especially in regions where environmental regulations are tight, access to coastal sites is limited, or consumer preferences favour local, antibiotic-free products.

***Life Cycle Assessment (LCA): Environmental Impacts of RAS***

To further support system comparison, the report includes a Life Cycle Assessment (LCA) of salmon production in RAS. The LCA examines the full environmental footprint from egg to harvest, considering:

- Energy use
- Water consumption
- Feed production and transport
- Construction materials
- Waste treatment

Key findings include:

- Energy consumption is the main environmental burden of RAS. Filtration, aeration, heating/cooling, and recirculation pumps all contribute to a high consumption of electricity. However, integrating solar panels, heat exchangers, and energy-efficient motors can mitigate this impact.
- Feed production still dominates the carbon footprint, in both RAS and open-pen systems. Thus, improving feed formulations and sourcing sustainable ingredients remains a critical area of necessary development.
- Water use in RAS is drastically lower, especially in high-recirculation systems (above 95% reusage).
- The environmental burden of sludge disposal can be converted into a positive factor when sludge is used for biogas production, in composting, or as fertilizer.

The LCA shows that RAS offers a lower eutrophication risk and reduced marine pollution, making it more suitable in areas like the Baltic Sea where nutrient discharges are tightly regulated. However, to achieve a lower carbon footprint, RAS must rely on renewable energy and circular economy procedures.

In conclusion, this section of the report presents RAS as a robust and increasingly competitive alternative to open-pen aquaculture, particularly in environmentally sensitive regions like the Baltic Sea. Through tools such as LCA and a clear understanding of trade-offs, stakeholders can make informed decisions about how and where to scale RAS in the years to come.

## Aquaculture in the Baltic Sea Region

The report consolidates a comprehensive vision for the development of RAS and warmwater shrimp farming in the Baltic Sea Region. Drawing from technical analysis, case studies, performance data, stakeholder input, and international comparisons, the report articulates both the promise and the complexity of transitioning towards more sustainable land-based aquaculture models.

***Strategic Role of RAS in the Baltic Sea Region***

RAS is presented as a strategic tool for meeting environmental and economic challenges facing the aquaculture sector in Northern Europe. The Baltic Sea is particularly vulnerable to eutrophication and marine pollution, and its surrounding countries have enacted increasingly strict nutrient discharge regulations. In response to these conditions, RAS offers a way to decouple aquaculture from marine nutrient inputs while still expanding seafood production.

By reusing water, capturing nutrients, and enabling full environmental control, RAS supports:

- Environmental stewardship, reducing nitrogen and phosphorus loads in fragile ecosystems.
- Biosecurity and disease control, limiting the spread of pathogens common in open-pen farming.
- Circular economy integration, through resource recycling, energy recovery, and industrial symbiosis.

The report suggests that RAS should be understood not simply as a production method, but as a platform for sustainable aquaculture innovation, capable of supporting integrated food, energy, and waste management solutions.

# 1 Recirculating Aquaculture Systems (RAS) in the Baltic Sea Region

## 1.1 What is a Recirculating Aquaculture System?

In a RAS, fish are produced in systems where the production water is purified and reused continuously. A recirculating aquaculture system is an almost entirely closed circuit. The waste products – solid waste, ammonium and $CO_2$ – are removed and converted into harmless by-products by the system components. The purified water is subsequently saturated with oxygen and returned to the fish tanks.

RAS are classified according to their water recycling ratios, estimated as the percentage of the production tanks' water flow treated and returned for reuse per cycle. While traditional flow-through systems with no water treatment have a recycling ratio of 0%, the most advanced RAS technologies have a recycling ratio of 95-99%. Conventionally, fully recirculating systems are defined as systems with a recycling ratio above 90%, while systems with a lower recycling ratio are characterised as 'partial replacement' systems or simply 're-use' systems as opposed to 'recirculation' systems (EUMOFA 2020). The terms 'zero water usage' or 'zero-discharge' are sometimes used in connection with fish farming, and although it is possible to avoid all discharge of sludge and water from fish farms, the wastewater treatment to remove the very last residues is costly (Bregnballe 2022) (see also 1.2).

By recirculating the production water, the water and energy requirements are limited to an absolute minimum. It is not possible to design a fully closed recirculating system. Waste products from the fish must be removed and evaporated water must be replaced.

To ensure good water purification, recirculating systems consist of several components with specific functions. Three different systems can remove the ammonia, phosphorus, and organic matter. The water cleaning system includes mechanical filtering and two biological systems to remove nutrients from the water. Consequently, the discarded production water will have a low concentration of nutrients and organic matter. The systems can in principle be designed so the systems discharge a specific concentration of nutrients and organic waste, but the economic cost and energy consumption increase when purifying the water to very low concentrations of nutrients.

If the systems are operated safely, the level of biosecurity is high in RAS. Microorganisms such as parasites, bacteria, and viruses can be prevented from entering the systems, ensuring a high level of biosecurity. Consequently, the production can be conducted without any or with a low level of medical treatments.
Producing fish comes with a considerable energy footprint. The pumping and cooling of salt water requires energy. The production can be based on renewable energy sources with solar panels on the production facility producing a part of the energy needed.

The feed used for the fish is developed specifically for RAS production. The feed producers develop the feed to make it healthy and environmentally safe. The ingredients in the feed include fishmeal and oil from sustainably fished fish stocks, soy, and various by-products. The feed-producers have realised that the consumers want fish with a low environmental impact, and as a result, soy that causes deforestation in South America has been excluded from the production.

The quality of the produced salmon is high. The fish grow in clean and fresh water, and the fish are constantly swimming in the tanks with moving water. These conditions, combined with the high-quality feed, produce fish with an attractive texture in the salmon filet.

Sludge and heat, in addition to dead fish and by-products from slaughtering, represent valuable side streams (Fig. 1). These assets can be used in the production of biogas and for heating of residential areas or industries.

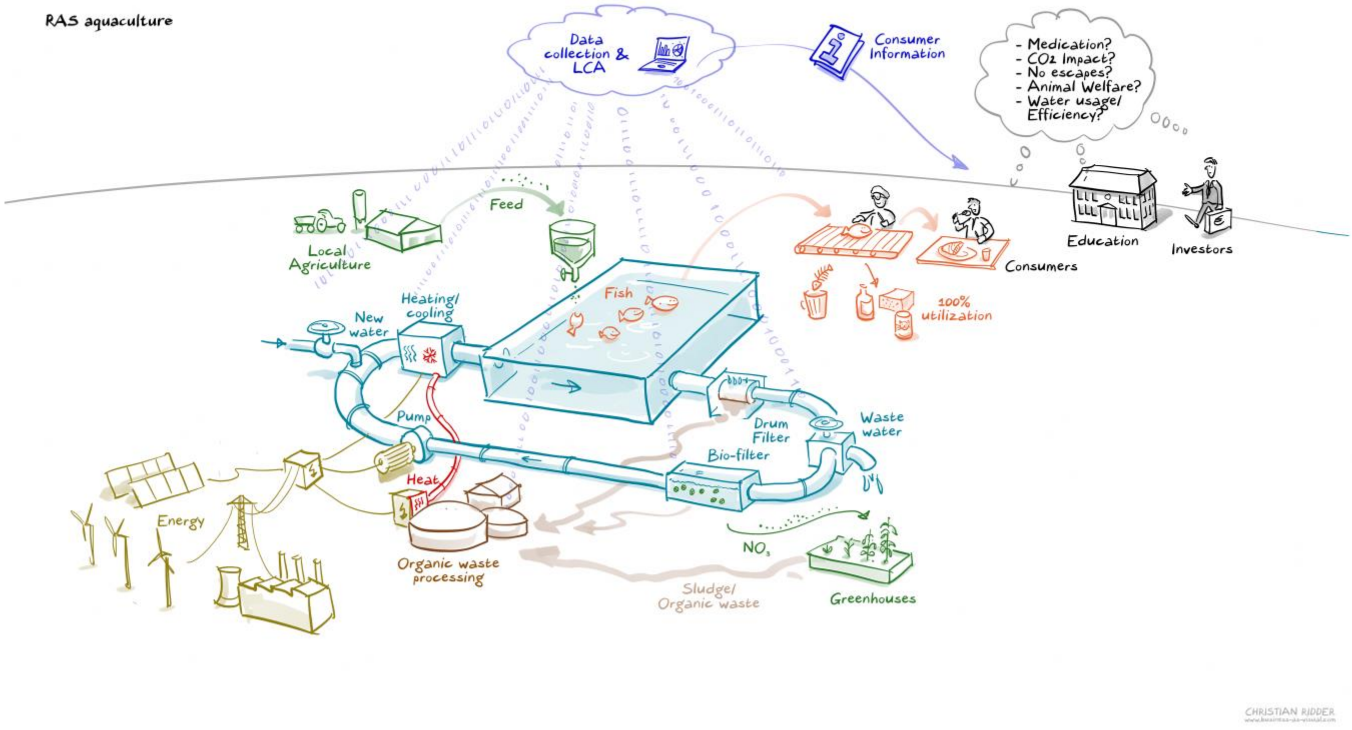


*Figure 1* *Land-based fish farming has the potential for being part of symbiotic set-ups, providing and using resources like water, energy or nutrients to and from other industries (Ref. Christian Ridder).*

## 1.2 Classification of RAS according to rate of recirculation

A RAS can be defined as a system where a part of the water is treated and reused in the fish production, in contrast to flow-through systems with no reusage of water. RAS can be classified according to their degree of water reusage, which ranges from minimal recirculation to highly advanced zero-discharge systems. This classification reflects the technological sophistication, environmental sustainability, and operational complexity of the systems. The degree of water reusage is a fundamental factor influencing the efficiency and sustainability of RAS, shaping how water is treated, conserved, and discharged.

In systems with a low water reusage, water is frequently added to dilute waste products, especially ammonia, and to maintain water quality, resulting in lower reliance on advanced treatment technologies. These systems often involve basic mechanical and biological filtration processes, but their operational simplicity comes with the downside of a high level of water consumption and significant amounts of effluent discharge. In contrast, high-reusage systems achieve more efficient water conservation through sophisticated water treatment technologies that remove solid waste, control ammonia levels, and mitigate pathogen risks. These systems rely on advanced filtration, biofiltration, and disinfection processes to maintain water quality while minimising water exchange. At the extreme end of the spectrum are zero-discharge systems, which represent the pinnacle of environmental sustainability in aquaculture, achieving complete water reusage through the integration of innovative technologies.

Low-reusage RAS typically reuse 50% to 75% of the water pumped out of the production tanks, relying on moderate water exchange to maintain water quality. These systems are generally simple and less costly to implement, making them accessible to smaller-scale operators or those with limited technical expertise. The design of low-reusage systems prioritises ease of operation and maintenance over water conservation. Mechanical filters and basic biofilters handle the removal of solid waste and the conversion of ammonia to nitrate, but other waste products, including nitrate and dissolved organic compounds, accumulate more rapidly. This necessitates higher rates of water replacement, potentially leading to greater environmental impacts in regions with limited water availability or strict discharge regulations.

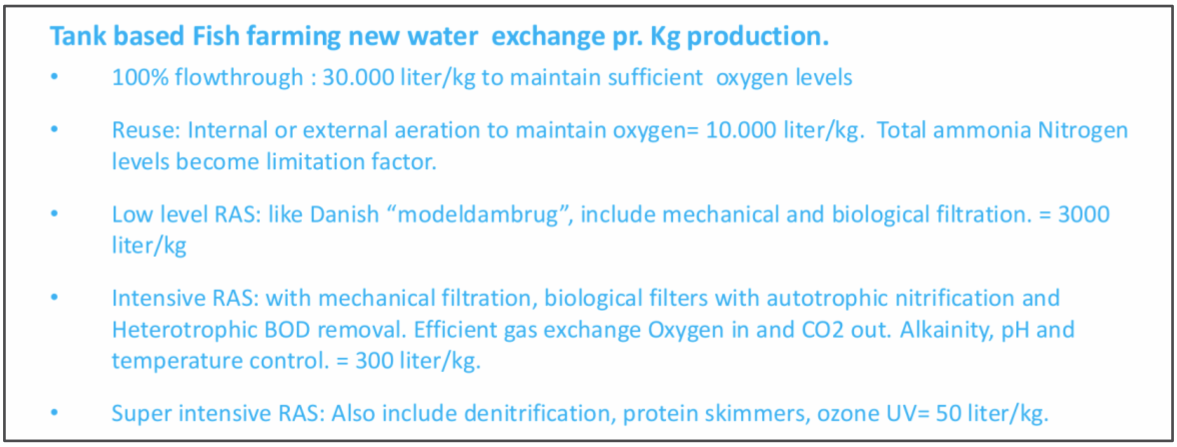
Medium-reusage RAS reuse between 75% and 90% of the water pumped out of the production tanks, striking a balance between water conservation and technological complexity. These systems incorporate more advanced treatment processes to maintain water quality with reduced water exchange. For example, mechanical filtration systems are designed to remove finer particulates, while biofiltration systems are optimised to handle larger amounts of ammonia. Degassing towers or other carbon dioxide removal systems are also typically integrated to prevent the accumulation of $CO_2$, which can compromise fish health and biofilter efficiency. These systems require a moderate capital investment and operational costs but offer significant reductions in water usage and effluent discharge compared to low-reusage systems. Medium-reusage RAS are particularly well-suited for regions with moderate water availability or for species that require stable water quality but are less sensitive to slight fluctuations in environmental parameters.

Fully recirculating or high-reusage RAS are designed to maximise water conservation, achieving water reusage rates of 90% or more of the water pumped out of the production tanks. These systems represent a significant development in terms of technological sophistication and environmental sustainability. To maintain water quality with minimal water exchange, high-reusage systems rely on a variety of advanced water treatment components, including efficient mechanical and biological filters, degassing units, oxygenation systems, and disinfection technologies such as ultraviolet (UV) sterilisation or ozone treatment. In addition to these core components, many high-reusage systems incorporate denitrification reactors to remove nitrate and advanced filtration technologies to control dissolved organic matter. These measures ensure that water quality remains stable even under intensive recirculation conditions, supporting optimal fish health and growth. However, the complexity of high-reusage systems increases the risk of technical failure and skilled operators are required for effective management. The high initial investment and operational costs associated with these systems can also be a barrier for smaller-scale producers, although the long-term savings in water usage and environmental compliance may justify the expense.

At the forefront of RAS development are zero-discharge systems, which achieve complete water reusage without any effluent discharge. These systems exemplify the highest level of environmental sustainability, often integrating aquaculture with other agricultural or industrial processes to create closed-loop systems. Zero-discharge RAS rely on a combination of highly advanced water treatment technologies, including membrane filtration, advanced oxidation processes, and nutrient recovery systems. They are designed to capture and reuse all waste products, converting them into usable by-products such as fertilizers or energy. The inclusion of denitrification reactors ensures that nitrate levels remain controlled, while other technologies recover phosphorus and other valuable nutrients. These systems are highly complex and require significant expertise and investment to implement and operate, making them less common in commercial aquaculture. However, they are increasingly being explored in research and development contexts as models for sustainable food production.

## 1.3 Classification of RAS: water/production rate

RAS can also be classified according to the amount of water that needs to be exchanged in relation to production (new water/kg production). In salmon aquaculture, the exchange of water for a flow-through system (not RAS) is 30.000 L of water per kg production. For a RAS with a low exchange, the rate is 3000 L of water per kg production. For an intensive RAS with mechanical and biological filtering and efficient gas exchange, and control of other water quality parameters, the exchange of water is 300 L water per kg production. For a super-intensive RAS, with denitrification and protein skimmer, ozone and UV, the water exchange is 50 L of water per kg of production (see Fig. 2: slide from presentation by Bækgaard 2024).



**Tank based Fish farming new water exchange pr. Kg production.**

- 100% flowthrough : 30.000 liter/kg to maintain sufficient oxygen levels
- Reuse: Internal or external aeration to maintain oxygen= 10.000 liter/kg. Total ammonia Nitrogen levels become limitation factor.
- Low level RAS: like Danish “modeldambrug”, include mechanical and biological filtration. = 3000 liter/kg
- Intensive RAS: with mechanical filtration, biological filters with autotrophic nitrification and Heterotrophic BOD removal. Efficient gas exchange Oxygen in and CO2 out. Alkainity, pH and temperature control. = 300 liter/kg.
- Super intensive RAS: Also include denitrification, protein skimmers, ozone UV= 50 liter/kg.

***Figure 2*** *Slide from presentation on RAS given by Arne Bækgaard 27th November 2024*

## 1.4 The right balance between water treatment, cost of investment, and risk

Designing RAS involves striking a complicated balance between water treatment efficiency, minimising nutrient discharge, cost of investment, and risk management. These components are interdependent and critical for sustainable aquaculture production.

Water treatment is the cornerstone of a successful RAS. It involves removing solids, managing biofiltration, degassing, oxygenation, and disinfection to maintain optimal water quality for aquaculture species. The effectiveness of water treatment directly impacts fish health, growth rates, and production efficiency. Efficient water treatment systems reduce water usage and minimise waste, aligning with environmental sustainability goals.

Solid waste removal typically begins with mechanical filtration systems such as drum filters, which capture particulate matter before it breaks down into ammonia. Ammonia, a toxic compound for aquatic organisms, is biologically converted into nitrate via nitrification in biofilters. However, the accumulation of nitrate necessitates periodic water exchanges or denitrification systems to maintain balance.

Degassing systems remove carbon dioxide, a by-product of fish respiration and biofilter activity, while oxygenation systems ensure adequate dissolved oxygen levels for fish and beneficial bacteria. Advanced disinfection methods, such as ultraviolet (UV) sterilisation and ozone treatment, are often incorporated to control pathogens and maintain biosecurity.

Minimizing nutrient discharge from RAS is critical for reducing the environmental impact, particularly as relates to eutrophication in surrounding ecosystems. Nutrient discharge, primarily nitrogen and phosphorus, results from uneaten feed, fish excreta, and metabolic by-products. Minimising the discharge of these nutrients requires the optimisation of feed management, the enhancement of waste capture, and the incorporation of advanced treatment technologies.

Feed management plays a pivotal role in reducing nutrient loads. High-quality feeds with balanced nutrient profiles and efficient feeding strategies minimise the generation of waste. Precision feeding techniques, such as automated feeders with sensors to detect fish appetite, further reduce uneaten feed and overfeeding.

Innovative waste capture systems, such as micro-screens, improve solid waste removal efficiency. Additionally, integrating biological treatment systems, such as denitrification reactors and algae-based nutrient uptake systems, can significantly lower nitrogen and phosphorus concentrations in effluents.
Effluent treatment technologies, such as constructed wetlands or advanced filtration systems, provide additional opportunities to reduce nutrient discharge. Constructed wetlands mimic natural ecosystems, where plants and microorganisms assimilate nutrients. Similarly, membrane bioreactors and other advanced filtration systems offer precise nutrient removal but come at higher operational costs.

### Cost of Investment

Water treatment systems represent a major portion of the necessary investment when establishing RAS. High-quality mechanical and biological filters, oxygenation systems, and disinfection units come at substantial costs (Fig. 3). However, cutting corners on these components can compromise water quality, leading to increased mortality rates and reduced production efficiency.

Energy efficiency is a critical aspect of cost management in RAS. Energy-intensive components, such as pumps, aerators, and heaters, significantly impact operational costs. Integrating energy-efficient technologies, such as variable frequency drives and heat recovery systems, can lower energy consumption without sacrificing performance.

The scale of the RAS also influences investment costs. Larger systems benefit from economies of scale, spreading fixed costs across higher production volumes. However, smaller systems may opt for modular designs, allowing for incremental expansion as financial resources and production demands grow.

Financial planning and risk analysis are essential for ensuring the long-term viability of RAS investments. This includes evaluating potential revenue streams, such as selling fish or by-products like fish oil and meal, and exploring funding opportunities, such as government subsidies and private investments.

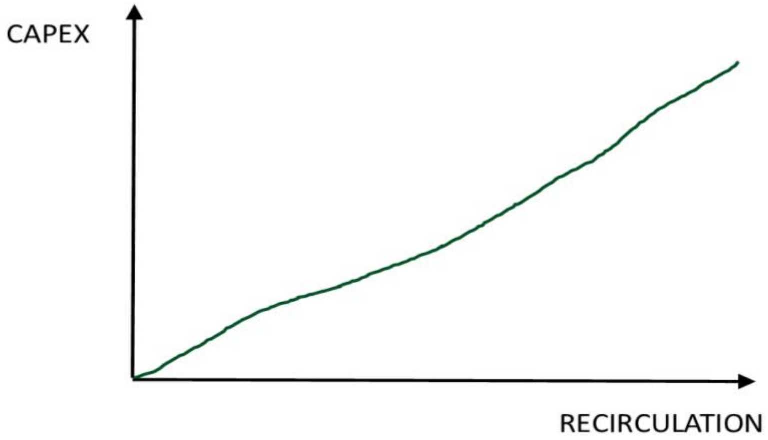


***Figure 3*** *The investment in RAS is correlated to the complexity of the water treatment. As a RAS project is designed in accordance with the local regulations, the regulations impact the investment costs and the pay-back of the investment. Investment in some types of technology will reduce the operation cost (OPEX) and may increase the feasibility of a project.*

## Risk Management in RAS

Risk management is an integral part of RAS design (Fig. 4), addressing challenges such as system failures, disease outbreaks, and market fluctuations. A comprehensive risk management strategy involves technical, biological, and economic considerations to safeguard the operation's sustainability.

System failures, such as power outages or equipment malfunctions, can have devastating consequences for fish health. Redundancy measures, such as backup generators and fail-safe systems, mitigate these risks. Regular maintenance schedules and real-time monitoring systems also help identify and address issues before they escalate.

Disease outbreaks pose significant biological risks in RAS. The high stock densities and recirculated water create an environment conducive to pathogen proliferation. Implementing strict biosecurity protocols, such as quarantine procedures, routine health monitoring, and vaccination programmes, reduces the risk of disease introduction and spread.

Market fluctuations, including changes in fish prices or feed costs, present economic risks. Diversifying production species and markets helps to mitigate these risks. Additionally, value-added products, such as filleted or processed fish, provide alternative revenue streams.

Environmental risks, such as water shortages or extreme weather events, must also be considered. Designing RAS with resilience to local climatic conditions, such as incorporating water-saving technologies or insulating facilities, enhances operational stability.

Balancing risk management with cost considerations involves prioritising high-impact risks and investing in preventive measures. While certain risks, such as disease outbreaks, require upfront investment in biosecurity, others, like market fluctuations, may be addressed through adaptive management practices.

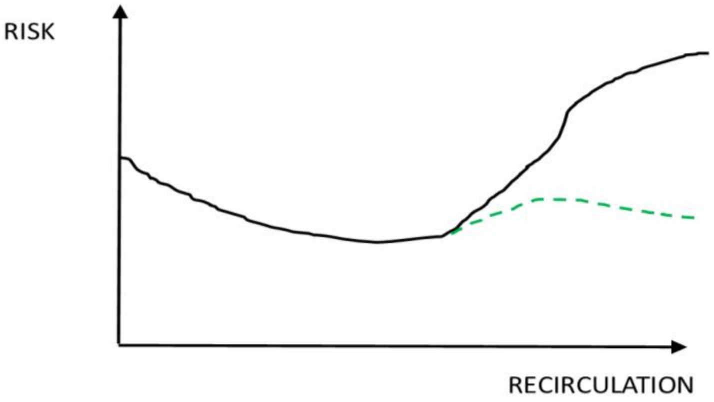


***Figure 3*** *In a low recirculation RAS, or even a flow-through system, the fish producer is very dependent on good water quality, and changes in water quality or the exposure of harmful organisms may result in loss of production. As the water treatment systems are established and the recirculation increases, the fish is produced in a constant and optimal environment with a high degree of biosecurity. As the water treatment becomes increasingly complex, the risk of a mechanical or human failure is to be expected (bold line). To mitigate risks of failure, advanced RAS are equipped with backup systems and monitoring systems that ensure a low risk for production loss (dashed line).*

## 1.5 Integrating Design Elements

The interplay between water treatment, nutrient discharge reduction, cost of investment, and risk management underscores the complexity of RAS design. Achieving a balanced system requires a holistic approach that takes into consideration the interdependencies between these factors.

The degree of recirculation in a RAS is one of the most significant design parameters, influencing both the functionality and the investment cost of the system. As the recirculation rate increases, it becomes necessary to integrate complex water treatment technologies, the energy consumption requirements increase, and the structural scale of the system expands. High recirculation systems (those operating at 95% or more water reusage) demand sophisticated infrastructure and advanced technology, which translates into higher upfront investment costs. On the other hand, systems with lower recirculation rates require less technological sophistication but may incur higher operational costs due to greater water consumption and wastewater treatment needs.

The degree of recirculation in a RAS significantly influences the system's complexity and, consequently, the associated production risks. As the recirculation rate increases, the system's design, operation, and management become more intricate due to the need for advanced water treatment technologies, precision monitoring, and strict operational protocols. This increased complexity introduces additional challenges and risks, both technical and biological, that must be carefully managed to ensure the success of the aquaculture operation. The relationship between recirculation, complexity, and production risk is multifaceted and interdependent, shaped by the demands of maintaining optimal water quality, managing biosecurity, and minimising the impact of system failures.

## Infrastructure and Technology Costs

A major factor linking the degree of recirculation to investment cost is the infrastructure required for water treatment. Systems with a high degree of recirculation require more advanced and efficient components to maintain water quality despite minimal water replacement. For instance, mechanical filters, biofilters, degassing towers, oxygenation systems, and UV or ozone disinfection units must be sized and designed to handle the continuous treatment demands of the system. Furthermore, backup systems and separation of the production facility into separated strings to contain production problems will increase investment costs.

In high-recirculation systems, biofiltration capacity becomes a critical consideration. Biofilters rely on colonies of nitrifying bacteria to convert toxic ammonia excreted by fish into nitrate. While nitrate is less harmful to fish, it can accumulate over time in systems with a high degree of recirculation, necessitating additional treatment technologies such as denitrification units or water polishing systems. The inclusion of these advanced components significantly increases capital expenditure.

Energy-efficient equipment is another cost driver in high-recirculation RAS. Pumps and aeration systems must operate continuously to circulate water, maintain oxygen levels, and ensure the functioning of biofilters. As recirculation rates increase, the amount of energy required also increases, necessitating the use of variable-frequency pumps and energy recovery systems to keep operational costs manageable. While these energy-efficient technologies reduce long-term expenses, their upfront costs are substantial.

## Water Quality Management and Monitoring

The precision required in maintaining water quality in high-recirculation RAS adds to investment costs. Advanced monitoring systems are essential for continuously tracking parameters such as dissolved oxygen, pH, ammonia, nitrate, temperature, and carbon dioxide levels. Automated monitoring and control systems, equipped with sensors and software, enable real-time adjustments to maintain stable conditions, but these systems come at a high price point.

In lower-recirculation systems, water quality parameters are less tightly controlled due to the frequent exchange of water, reducing the need for advanced monitoring systems. While this simplifies the system design and reduces investment costs, it may lead to higher operational costs associated with water sourcing, wastewater treatment, and environmental compliance.

## Scale and Degree of Recirculation

The scale of the RAS also interacts with the degree of recirculation to influence investment costs. Larger systems typically benefit from economies of scale, where the cost per unit of production decreases as the system size increases. However, for high-recirculation systems, these economies are offset by the increased complexity and redundancy required to ensure water quality at larger scales. Consequently, the optimal size of a RAS may exist in a balance between not being too small due to the cost of the technology and not being too big due to the complexity of the technology. This sweet spot may vary from location to location and differ according to farmed species and available staff.

For small-scale operations, achieving high recirculation rates is often more challenging and cost-intensive because there are no scale benefits. Modular designs and compact treatment units are typically employed in smaller systems, but their per-unit cost is higher compared to those used in larger facilities. Consequently, smaller operations often opt for lower recirculation rates to minimise initial investment costs, even if it means incurring higher water usage costs.

### Trade-offs Between Recirculation and Investment Costs

The relationship between recirculation rate and investment costs is characterised by diminishing returns at higher levels of recirculation. As the degree of recirculation approaches 100%, the incremental cost of achieving further water reusage rises significantly. This is due to the need for increasingly sophisticated treatment technologies and greater system redundancy to address potential risks, such as equipment failures or biofilter overload.

For example, transitioning from a system with an 80% recirculation rate to 90% might involve moderate additional costs for biofilter capacity and oxygenation. However, transitioning from 90% to 95% or higher typically requires investments in denitrification systems, advanced monitoring equipment, and highly efficient degassing and disinfection technologies. These costs can become prohibitive for some operators, particularly in regions with limited access to funding or operators who cannot manage the high operational risks.

### Balancing Recirculation with Investment Viability

Operators must carefully evaluate the optimal degree of recirculation based on economic, environmental, and operational factors. High-recirculation systems are particularly advantageous in regions where water is scarce or where strict environmental regulations restrict wastewater discharge. In such contexts, the higher investment costs can be justified by the long-term savings in water usage and compliance costs.

Conversely, in regions where water is abundant and less expensive, lower recirculation rates may be more economically viable. While these systems incur higher water usage costs, they reduce the need for advanced treatment technologies, allowing for lower initial investment. The decision ultimately depends on the operator’s goals, including production scale, species requirements, and sustainability objectives.

## 1.6 Running at high Recirculation Rates and System Complexity

Fully recirculated RAS (above 90% water reusage) are designed to minimise water consumption and wastewater discharge, making them environmentally sustainable and economically viable in regions where water resources are scarce or heavily regulated. However, achieving the high recirculation rates requires sophisticated water treatment processes, including mechanical filtration, biofiltration, degassing, oxygenation, and disinfection. Each of these components adds layers of complexity to the system, demanding careful design, precise integration, and continuous monitoring.

Mechanical filtration systems, such as drum filters or screen filters, are essential for removing solid waste from the water. In high-recirculation systems, these filters must operate at high efficiency to prevent organic matter from breaking down into harmful compounds such as ammonia. Similarly, biofilters are critical for the biological conversion of ammonia into nitrate through nitrification. In systems with high recirculation rates, biofilters must be carefully sized and maintained to be able to handle the continuous loading of ammonia and avoid biofilm collapse.

Degassing systems, which remove carbon dioxide produced by fish respiration and biofilter activity, are another crucial component. High recirculation rates necessitate efficient degassing to prevent $CO_2$ accumulation, which can lead to acidification and respiratory stress in fish. Additionally, oxygenation systems must maintain adequate levels of dissolved oxygen to support both the fish and the nitrifying bacteria in the biofilters.

Disinfection processes, such as ultraviolet (UV) sterilisation or ozone treatment, play a pivotal role in controlling pathogens in recirculated water. As recirculation rates increase, the risk of pathogen accumulation also increases, and robust disinfection systems are required to maintain biosecurity. However, these systems must be carefully calibrated to avoid harming beneficial microorganisms in the biofilters.

The integration of these advanced technologies in a cohesive system is a complex engineering challenge. Each component must be optimised not only for individual performance but also for its interaction with other components. For example, the efficiency of biofiltration is influenced by the mechanical filtration system's ability to remove particulates, and the effectiveness of disinfection depends on the water clarity achieved by these preceding processes. This interdependence adds layers of complexity to the system design and operation, increasing the likelihood of technical challenges or failures.

### Increased Risk of System Failures

The complexity of fully recirculated RAS inherently increases the risk of system failures. The continuous operation of pumps, filters, and aeration systems creates a dependency on mechanical and electrical components that are prone to wear and tear. Any failure in these components can disrupt the system's equilibrium, leading to rapid deterioration of water quality and potential fish mortality.

For example, a malfunction in the biofilter can result in the accumulation of ammonia, which is toxic to fish even at low concentrations. Similarly, a failure in the degassing system can cause carbon dioxide levels to rise, impairing fish respiration and biofilter performance. The reliance on disinfection systems also introduces risks, as insufficient disinfection can lead to disease outbreaks, while excessive treatment can harm fish or beneficial bacteria.

The interconnected nature of RAS components amplifies the consequences of individual failures. For example, a power outage affecting the pumps can disrupt water circulation, leading to oxygen depletion and the buildup of harmful metabolites. Redundancy measures, such as backup generators and fail-safe mechanisms, are essential for mitigating these risks but add to the system's complexity, cost, and need for specialised staff. Splitting the production into separated independent compartments may reduce losses at system breakdown.

### Biosecurity Challenges and Disease Risks

High recirculation rates increase the risk of pathogen accumulation and disease outbreaks. In systems where water is reused extensively, pathogens introduced through fish stock, feed, or other sources can proliferate rapidly, given the reduced water exchange with the external environment. Maintaining biosecurity in such systems requires strict protocols, including quarantine procedures, regular health monitoring, and the use of pathogen-free water and feed.

The use of disinfection systems, such as UV or ozone, helps control pathogen levels but is not fail-safe. These systems require precise calibration to achieve effective disinfection without compromising water quality or harming fish. Furthermore, the effectiveness of disinfection can be reduced by factors such as high turbidity or the presence of organic matter, necessitating robust pre-filtration systems.

Disease outbreaks in high-recirculation RAS can have devastating consequences due to the rapid spread of pathogens in the closed-loop system. Unlike flow-through systems, where waterborne pathogens are diluted and flushed out, high-recirculation systems retain pathogens unless they are specifically targeted and removed. The economic impact of such outbreaks can be severe, including losses due to fish mortality, treatment costs, and production delays. Splitting the production into separated independent compartments may reduce loss of fish if a pathogen enters the system.

### Operational Expertise and Management Challenges

The complexity of a fully recirculated RAS (>90% recirculation) requires skilled operators with expertise in aquaculture management, engineering, and water chemistry. Operators must monitor and adjust multiple parameters, such as temperature, pH, dissolved oxygen, ammonia, and nitrate levels, to maintain optimal conditions. Advanced monitoring systems with sensors and automated controls can assist in this process but require technical knowledge to operate and maintain.

Training and retaining skilled personnel present a challenge for many aquaculture operations, particularly in regions where access to technical expertise is limited. The steep learning curve associated with managing high-recirculation systems can lead to operational errors, increasing the risk of production losses.

## 1.7 Case: Fully recirculated production of 4,000 t salmon

The Danish company Skagen Salmon have worked on developing projects of 4,000 t Atlantic Salmon at different locations in Denmark (Fig. 5). A setup developed by Skagen Salmon is described in this chapter.

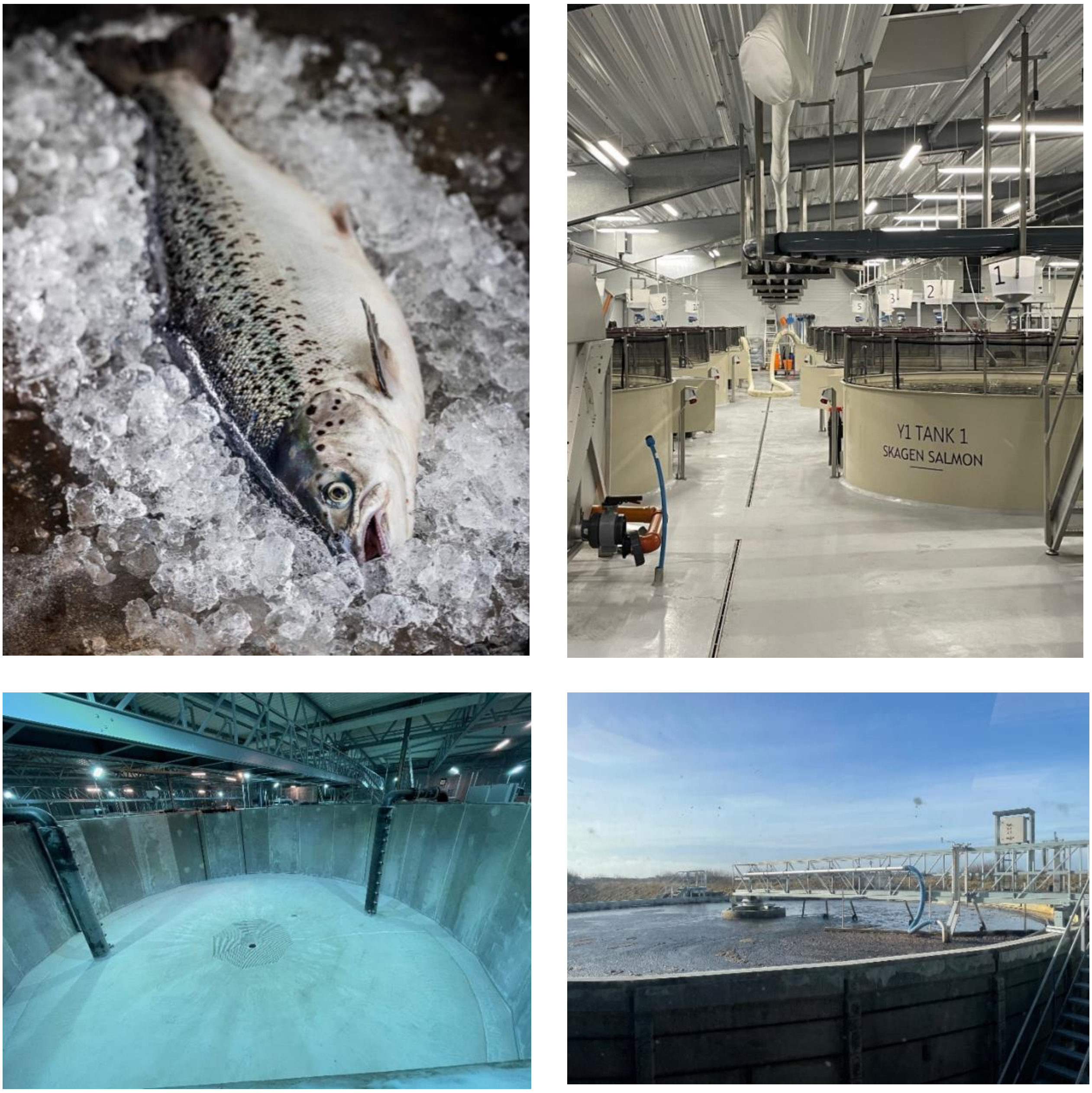


***Figure 4***. *Top-left: Atlantic salmon produced at Skagen Salmon (from Facebook/Skagen Salmon); Top-right: The tanks producing fingerlings; Bottom-left: An empty grow-out tank; bottom-right: The water is treated with denitrification using an external C-source in an outdoor tank. Sludge from the water treatment is used for biogas by the nearby municipal wastewater treatment plant.*

The production of 4,000 t Atlantic Salmon is based on salmon eggs hatched in the plant, and after 21 months of growth, the salmon reach a weight of about 4 kg, ready for the market. The company receives fertilised salmon eggs from an egg producer in Iceland, and after 3 months the fingerlings feed on start-feed until they are 6 months old. After 9-12 months, the fish are ready to smolt, and they are moved to saltwater tanks, where they continue growing from smolt size (100 g, 20 cm) to market size (4 kg, 60 cm) over the remaining period, ageing up to 21 months in total (Fig. 6). The company harvest 80 t of salmon each week, and they are slaughtered in-house.

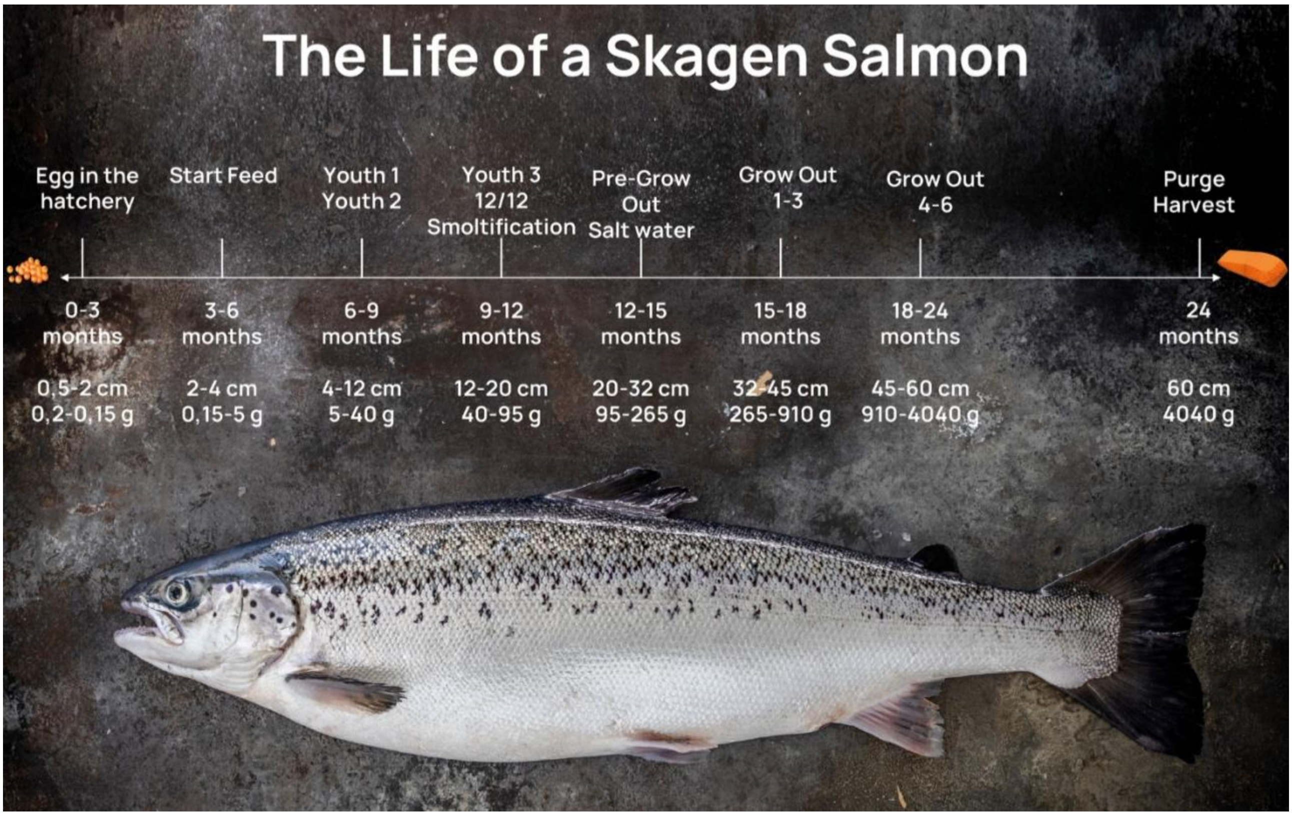


***Figure 5**. The life of a salmon from Skagen Salmon*

The production tanks each hold 30,000 $m^3$ water. As all water is filtered and processed two times per hour, the total filtering/treatment capacity is 525M $m^3$ per year. As the water consumption of saltwater is 1.3M$^3$/y, the recirculation in the RAS is >99%.

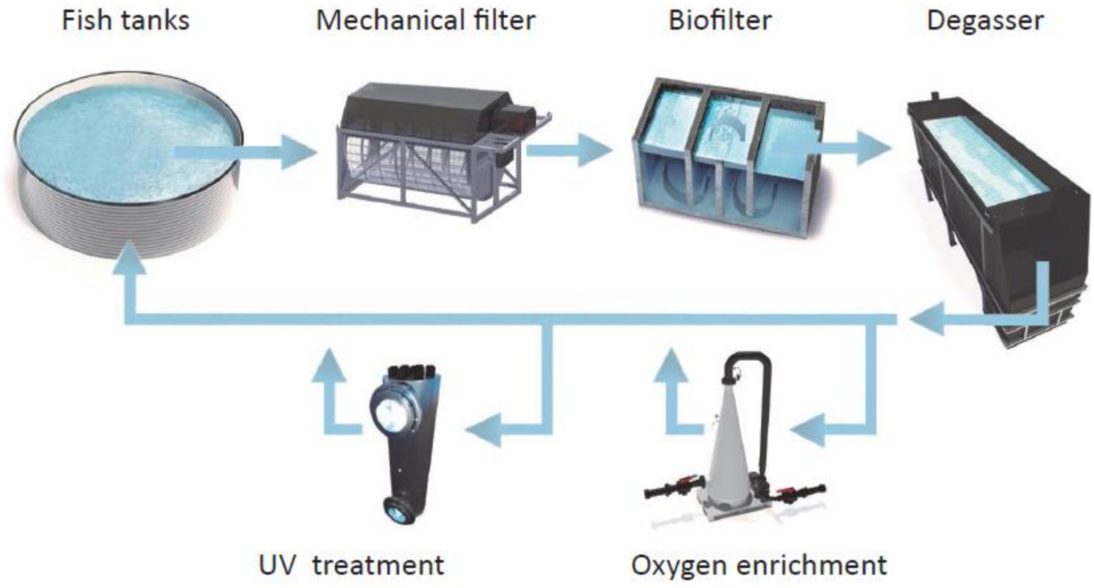


***Figure 6*** *Model of a recirculation system. The basic water treatment system consists of mechanical filtration, biological treatment, and aeration/stripping. Further installations, such as oxygen enrichment or UV disinfection, can be added depending on the requirements (From Bregnballe 2022).*

The production setup is illustrated in figure 7. From the outlet of the fish tanks, the water flows through a mechanical filter and subsequently through a biological filter. The biofilter is a two-compartment system consisting of a filter with a moving bed and subsequently a filter with a fixed bed which polishes the water to reduce the release of particles. Afterwards the water is aerated and stripped of carbon dioxide and returned to the fish tanks. Several other treatments are carried out, such as oxygenation with pure oxygen, ultraviolet light or ozone disinfection of microorganisms, automatic pH regulation to avoid toxicity of ammonium, and heat exchange.

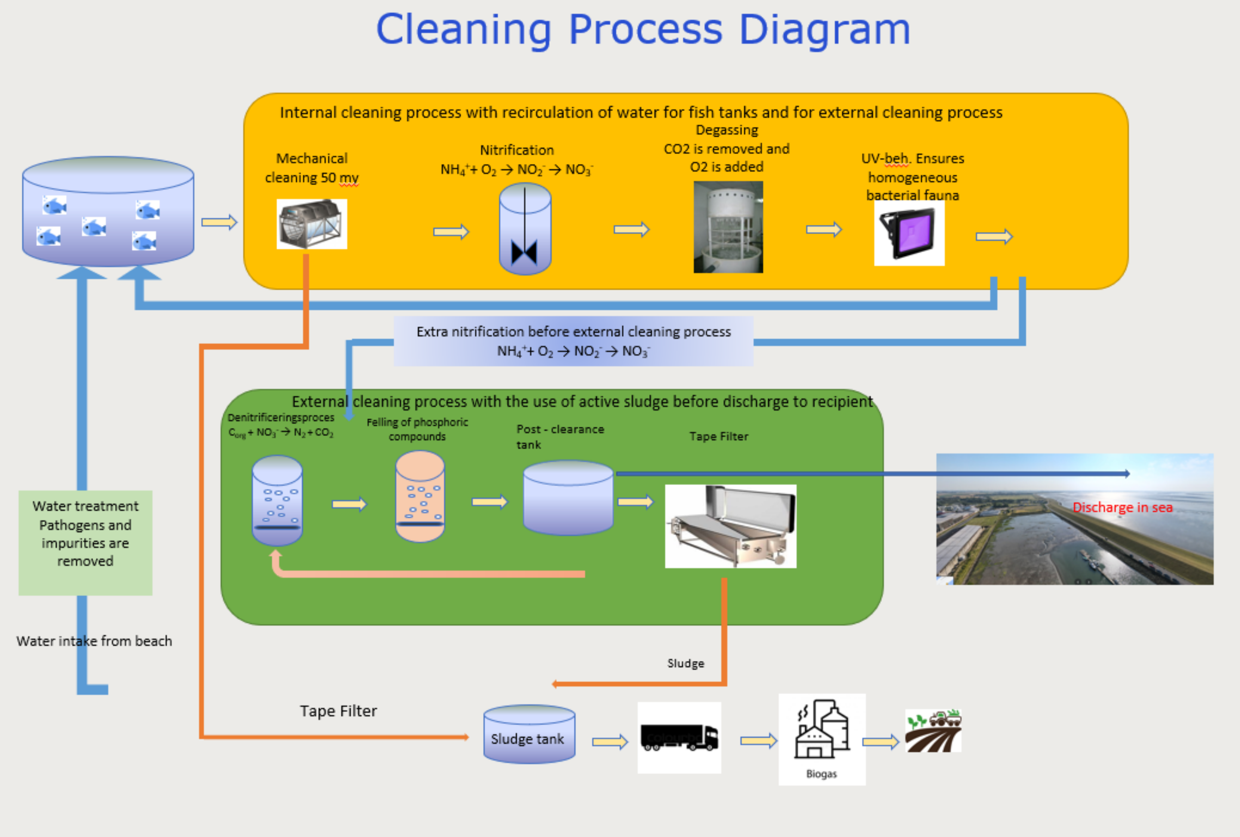


*Figure 7 Cleaning process for the Skagen Salmon Holding fish farm.*

In Fig. 7, the complete water treatment plan is shown from the point where the water enters the system from the sea to when the water returns to the recipient. The treatment of the discharged water includes a mechanical filter, and two biological treatments: a nitrification (aerobic) and a denitrification (anaerobic), a felling process, and a clearance process before the production water leaves the system. The denitrification converts nitrogen in the water to harmless $N_2$, the felling removes the phosphorus, and the clearance removes organic matter from the water. By-products from the water treatment in the form of sludge can be used to produce biogas.

## 1.8 Experience in the cleaning of discharge water

A new cleaning technique, denitrification, has become part of saltwater RAS within the past 5 years. The technique is known from urban sewage treatment plants, but at saltwater RAS fish farms, the challenge is to ensure efficient water treatment in the saltwater environment.

To reduce the nitrogen content to concentrations compliant with the emission requirements, it is necessary to remove nitrate from the wastewater. This is done by biological denitrification without oxygen, where nitrate ($NO_3^-$) is reduced using bacteria and ultimately nitrogen ($N_2$), carbon dioxide, water and bio-sludge are produced:

Organic source + $NO_3^-$ + $H^+$ -> $CO_2$ + $N_2$ + $H_2O$ + bio-sludge

*(**Equation 1** Denitrification process.)*

**Table 1** shows long-term measurements of the concentration of N, P, and COD in the purified discharge water from a Danish RAS producing Atlantic Salmon. The results show that the wastewater treatment complies with the cleaning requirements in place for the sewage treatment plant in Denmark of >5,000 PE (BEK nr 532 af 27/05/2024). For nitrogen, however, an extra effort may be needed. The tested system did not have a final mechanical filtering of the treated water, and as most of the phosphorus is in the form of particles, a mechanical filtration will reduce the phosphorus concentration even further.

***Table 1.*** *Results from a Danish RAS production for the final treated water compared to sewage water treatment targets according to the Danish law for treatment plants >5,000 PE.*

| | Result Danish RAS | Sewage water treatment plant targets |
|---|---|---|
| Total Nitrogen, mg/L | <10 | 8 |
| Total Phosphorus, mg/L | 0.6 | 1.5 |
| COD, mg/L (CSB) | 30 | 75 |

The technology will be further developed, and it is expected that the new denitrification cleaning methodology can be upscaled to 2.6M $m^3$ water/year.

## 1.9 Discharge of nutrients from the realised Danish production as an example

In Denmark, eight saltwater in-land plants (RAS plants) emitted 97 t of nitrogen in 2020 and produced a total of 3277 t of fish (**Table 2**, Miljøstyrelsen, 2021). In 2020, the environmental efficiency of saltwater pond farming was 29.6 kilos of nitrogen emitted per ton of fish produced, and 2.1 kilos of phosphorus per ton of fish produced.

Danish Salmon have a permit to produce 3000 t salmon in RAS and to discharge 45 t N and 3.9 t P. This corresponds to an environmental efficiency of 15 kg N discharged/t fish produced and 1.3 kg P discharged/t fish produced, corresponding to 50-60% of the reported discharge from Danish RAS.

***Table 2***. *Environmental efficiency for Danish saltwater RAS production.*

| Year | Number of RAS | Production (t) | Feed (t) | Nitrogen (t) | Phosphorus (t) | Env. Eff. N (kg N discharged/t fish produced) | Env. Eff. P (kg P discharged/t fish produced) |
|---|---|---|---|---|---|---|---|
| 2020 | 8 | 3277 | 5237 | 97 | 11 | 29.6 | 2.1 |

In 2019, DTU Aqua analysed the efficiency of water treatment at Danish saltwater RAS (DTU, 2019). The water treatment was compared at three RAS: Atlantic Saphire, Danish Salmon, and Sashimi Royal. After treatment of the production water, the Environment Efficiency for N was 1.9, 30.3 and 65.2 kg N/t fish produced, respectively. This corresponds to removal of 45-91% of the N from the production water. The cleaning of the water from Atlantic Saphire is based on technology with which the water is drained to the underground, and the technology is not comparable to the technology used at the other two sites. For the discharge of P, the Environment Efficiency was 1.3, 0.5 and 6.4 kg P/t fish produced, respectively, corresponding to a cleaning of 72-93% of the P.

Based on the Danish reported production of fish and the use of feed, the Feed Conversion Ratio (FCR) can be calculated. Furthermore, based on the use of feed, the emission of N and P can be estimated and related to produced biomass (open cage) or estimated from sampling (RAS). Analysing the data on FCR for 2019-2023 shows no significant difference or a larger value for RAS compared to the open cages systems. From 2020 to 2021 there is a significant improvement which may be caused by the improved RAS technology. For the emissions of N and P, the value for open cage systems were larger than for RAS systems (Fig. 8 and **Table *3***). In 2023 there is a drop in discharge of N and of P from RAS although FCR increase, indicating that the water treatment for discharge water is improved.

***Table* 3.** *Production, use of feed emission of N and P, and the estimated FQR and ratios between emission of N and P and production for open fish farms and saltwater RAS systems in Denmark in 2019-2023. The data is reported data from the fish farmers to national authorities.*

| | Production (T) | Feed (T) | N (T) | P (T) | Year | FQR | N/Production (Kg/T) | P/Production (Kg/T) |
|---|---|---|---|---|---|---|---|---|
| Open Cage | 7364 | 8523 | 304 | 32 | 2019 | 1.16 | 41.3 | 4.3 |
| Open Cage | 7586 | 9013 | 322 | 32 | 2020 | 1.19 | 42.4 | 4.2 |
| Open Cage | 6930 | 8646 | 314 | 30 | 2021 | 1.25 | 45.3 | 4.3 |
| Open Cage | 7874 | 9288 | 324 | 30 | 2022 | 1.18 | 41.1 | 3.8 |
| Open Cage | 6801 | 8553 | 312 | 27 | 2023 | 1.26 | 45.9 | 4.0 |
| RAS | 3539 | 5191 | 86 | 6 | 2019 | 1.47 | 24.3 | 1.7 |
| RAS | 3277 | 5237 | 97 | 11 | 2020 | 1.60 | 29.6 | 3.4 |
| RAS | 3123 | 3567 | 68 | 7 | 2021 | 1.14 | 21.8 | 2.2 |
| RAS | 1697 | 1875 | 52 | 4 | 2022 | 1.10 | 30.6 | 2.4 |
| RAS | 2668 | 3636 | 50 | 5 | 2023 | 1.36 | 18.7 | 1.9 |

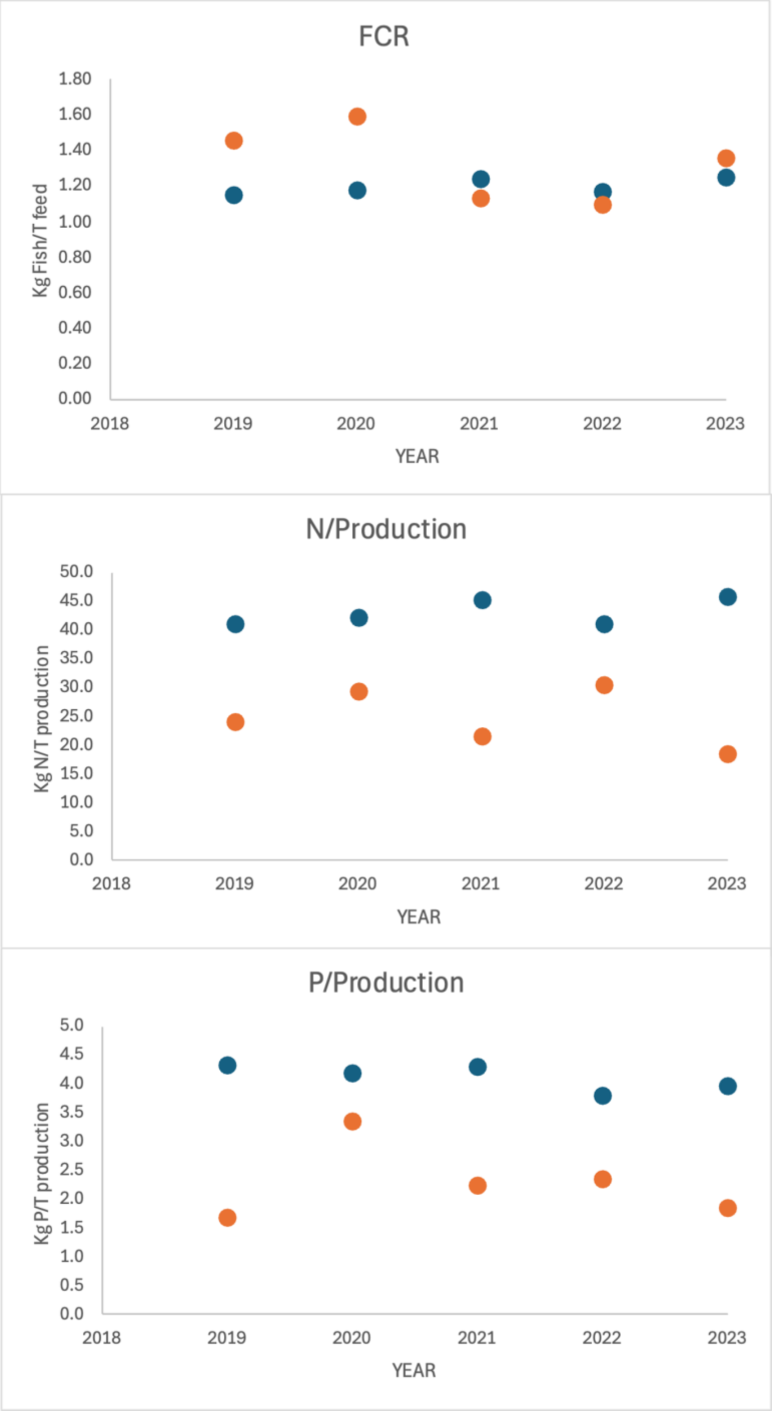


***Figure 8*** *Feed conversion Rate (FCR), emission of N and P per produced ton in open fish farms (blue dot) and saltwater RAS (red dot) in Denmark in 2019-2023. The data is reported data from the fish farmers to national authorities.*

## 1.10 RAS in the Baltic Sea Region

In **Table 4**, an overview is provided of the fish species and total quantities of fish produced in RAS in the EU countries around the Baltic Sea.

There is no comprehensive international overview of the production in RAS facilities, and the figures have therefore been obtained by searching the individual country's registrations where it has been possible to find data. An assessment has been made of whether the data covers RAS production. This assessment is based on knowledge of which fish species can only be farmed in RAS facilities. References to the websites where data is obtained are listed in **Table 4** below. The data is divided according to nation, meaning that for Denmark, Sweden, and Germany, the production figures cover both the Baltic Sea Area and areas outside of it.

***Table 4***. *Fish species and total quantities of fish produced in RAS in EU countries in the Baltic Sea Region 2020-2024.*

| Country | Year | Species | Amount (t) | Note | Reference |
|---|---|---|---|---|---|
| Denmark | 2023 | Rainbow trout, tuna, eel, salmon, pikeperch, sunshine bass | 21,158 | Production of rainbow trout in RAS makes up 88% of the total amount of RAS production | Fiskeristyrelsen https://fiskeristatistik.fiskeristyrelsen.dk/stat/Akvakultur_tab/prod_reg_maengde_23.html |
| Sweden | 2023 | Rainbow trout, eel, catfish | 550 (catfish) | Amount is only based on the production at Gårdsfisk, who produce catfish | Sveriges vattenbruksproduktion \| Svenskt vattenbruk |
| Finland | 2022 | Rainbow trout, whitefish, char | >2,000 | Amount is not statistical verified, but merely a sum from Vielma et al's report | Vielma, J., Kankainen, M. & Setälä, J. 2022. Current status of recirculation aquaculture systems (RAS) and their profitability and competitiveness in the Baltic Sea area. Natural resources and bioeconomy studies 75/2022. Natural Resources Institute Finland. Helsinki. 28 p. |
| Estonia | 2020 | Rainbow trout, sturgeon, eel | 210 | Amount is not statistical verified, but merely a sum from Vielma et al's report | Vielma, J., Kankainen, M. & Setälä, J. 2022. Current status of recirculation aquaculture systems (RAS) and their profitability and competitiveness in the Baltic Sea area. Natural resources and bioeconomy studies 75/2022. Natural Resources Institute Finland. Helsinki. 28 p. |
| Latvia | 2023 | Rainbow trout, carp, Catfish, sturgeon | 125 |  | Latvia - Eurofish |
| Lithuania | 2020 | Rainbow trout, catfish, char, eel, sturgeon | >400 | Amount is not statistical verified, but merely a sum | Vielma, J., Kankainen, M. & Setälä, J. 2022. Status of recirculation aquaculture systems (RAS) and their profitability and competitiveness in |

| | | | | | |
|---|---|---|---|---|---|
| | | | | from Vielma et al's report | the Baltic Sea area. Natural resources and bioeconomy studies 75/2022. Natural Resources Institute Finland. Helsinki. 28 p. |
| Poland | 2024 | Rainbow trout, Arctic char, African catfish, sturgeons, and eel | Rainbow trout, Arctic char – 14,440, African catfish - 450, sturgeons – 380. | | *Serwis Pstrągowy*, SPRŁ<br>Tomasz Kulikowski (Pers. Comm.) |
| Germany | 2023 | Salmon, eel, catfish, warmwater shrimp | 2,107 | The amount is a sum of all fish production in RAS. There are no values for specific species produced in RAS. | Businesses with aquaculture production, quantity produced: Germany, years, aquaculture products, types of installation |

# 2 Production of Warmwater Shrimp

The European production of salmon and trout is well-known, and it is described and discussed in many reports and papers (EU aquaculture 2024, FAO 2024). The production of warmwater shrimp is growing in the EU, and it is a new type of production. Therefore, the production is described in more detail in two chapters in the report to introduce the concept. The first chapter focuses on the technology platforms, and the second chapter focuses on the growing European production of warmwater shrimp.

Europe is the world's third largest importer of shrimp (Fig. 10). However, it has the highest consumption per capita/year with 2.2 kg. To cover this demand, almost all shrimp is imported from traditional producing countries on the tropical belt, with India and Ecuador being the largest producers. In the last decade, important steps have been taken to produce shrimp in Europe, mainly in recirculating aquaculture systems (RAS).

The demand for locally produced fresh shrimp exists, and increasing amounts of capital has become available to allow the development of new operations, which has resulted in an increased size and number of shrimp farming projects in Europe.

***Figure 9** White shrimp (Litopenaus vannamei) (Photo: Pixibay).*

## 2.1 Farming of Warmwater Shrimp: Focus on Species and Larval Rearing

Warmwater shrimp farming, also known as shrimp aquaculture, is a significant sector in the global seafood industry, providing a vital source of protein and economic livelihood for many communities. This aquaculture practice involves rearing various species of warmwater shrimp under controlled conditions, from hatchery to grow-out in ponds or RAS, employing advanced techniques to optimise production. Among the species cultivated, the most prominent include the Pacific white shrimp (*Litopenaeus vannamei*), the giant tiger prawn (*Penaeus monodon*), and the freshwater prawn (*Macrobrachium rosenbergii*).

One of biggest problems remains the supply of PL (postlarvae) for stocking. There are not enough companies or capacity in Europe to provide a high and stable amount of stocking material. In Europe, only SPF-certified animals can be imported, and this reduces the availability of potential suppliers worldwide. Therefore, suppliers without SPF certification, for example many Asian suppliers, are not within the scope of European shrimp farmers.

## 2.2 Species in Shrimp Farming

**1. Pacific White Shrimp (*Litopenaeus vannamei*)** (Fig. 9)**:** This species is one of the most widely cultivated warmwater shrimps due to its rapid growth, high adaptability to various environments, and disease resistance. Native to the Pacific coast of Latin America, Pacific white shrimp farming has expanded globally, particularly in countries like Ecuador, Thailand, China, and Vietnam. Their relatively high tolerance to varying water quality parameters and ease of culture make them a preferred choice for aquaculture production.

**2. Giant Tiger Prawn (*Penaeus monodon*)** (Fig. 10): Known for its large size and distinctive tiger-like stripes, this species is cultivated predominantly in Southeast Asia, India, and Australia. The giant tiger prawn exhibits robust growth rates and is favoured for its meaty texture and flavour. However, susceptibility to certain diseases and a longer grow-out period compared to *L. vannamei* are factors considered in its farming practices.

***Figure 10*** *Giant Tiger Prawn (Penaeus monodon). Photograph by D. De Anda-Fuentes*

**3. Freshwater Prawn (*Macrobrachium rosenbergii*)** (Fig. 11)**:** This species differs from marine shrimps as it thrives in freshwater habitats. Cultivated in Asia, particularly in India, Bangladesh, and Thailand, freshwater prawns are prized for their taste and are well-suited for aquaculture in ponds and rice fields. They require different rearing techniques due to their freshwater preference.

*Figure 11* Freshwater Prawn (Macrobrachium rosenbergii) (FAO).

## 2.3 Larval Rearing in Shrimp Farming

Successful shrimp farming relies heavily on effective larval rearing techniques, as the early life stages are critical for the subsequent growth and survival of the shrimp. The process begins in specialised hatcheries, where broodstock are maintained to produce high-quality larvae. Below are listed key aspects of larval rearing:

**1. Broodstock Management:** Selecting healthy broodstock is crucial. They are maintained in controlled environments with proper nutrition and health monitoring. Broodstock selection based on genetic traits contributes to better larval quality.

**2. Spawning and Larval Rearing:** Once broodstock are induced to spawn, the eggs hatch into nauplii, the earliest larval stage. These larvae undergo molting stages (zoea and mysis) before becoming postlarvae (PL) ready for transfer to grow-out ponds. Larval rearing requires strict environmental control, including water quality parameters (temperature, salinity, pH), adequate nutrition through live feed (algae, Artemia, rotifers), and continuous monitoring to prevent diseases.

**3. Water Quality Management:** Maintaining optimal water quality is essential for larval health. Filtration systems, aeration, and regular water exchange help control ammonia, nitrite, and other waste products that can be detrimental to larval development.

**4. Disease Management:** Shrimp larvae are susceptible to various diseases. Implementing biosecurity measures, such as regular disinfection, quarantine protocols, and monitoring for pathogens, is crucial to prevent disease outbreaks in hatcheries.

## 2.4 Challenges and Innovations in Larval Rearing

Larval rearing in shrimp farming involves some challenges, including potential disease outbreaks, larval mortality, and maintaining consistent quality and quantity of live feed. Addressing these challenges requires ongoing research and innovation in aquaculture technology.

Advancements in larval feeds, such as the development of formulated diets to supplement live feeds, contribute to improved larval nutrition and reduced dependency on live prey. Additionally, the use of probiotics and biofloc technology aids in enhancing water quality and controlling pathogens, promoting a healthier environment for shrimp larvae.

## 2.5 Sustainable Practices and Future Directions

Efforts towards sustainable shrimp farming involve minimising environmental impacts and adopting responsible practices such as producing in RAS. Alternatively, integrated multitrophic aquaculture, where shrimp farming is combined with other species like fish or seaweed, helps optimise resource utilisation and reduces waste.

Future directions in shrimp farming will be the development of more efficient breeding programmes for disease-resistant and fast-growing shrimp strains. Embracing technology, such as genetic selection, biotechnology, and precision aquaculture, will continue to drive advancements in the industry, ensuring its sustainability and meeting the increasing global demand for high-quality shrimp products.

In conclusion, warmwater shrimp farming encompasses diverse species and intricate processes, with larval rearing being a critical aspect for successful aquaculture. Continuous research, technological innovations, and sustainable practices are essential to address challenges and enhance the efficiency and environmental sustainability of shrimp farming, contributing to meeting the growing global demand for shrimp while conserving aquatic ecosystems.

## 2.6 RAS and warmwater shrimps

In recent years, Recirculating Aquaculture Systems (RAS) have emerged as a transformative technology in the aquaculture industry, particularly in Europe, in the production of warmwater shrimp. RAS offers a controlled, closed-loop system that minimises environmental impact, maximises water efficiency, and allows for year-round production, overcoming geographical limitations and ensuring high-quality shrimp output. This innovative approach to shrimp farming has reshaped the aquaculture landscape in Europe.

RAS involve the continuous recycling of water within a closed system, maintaining optimal water quality through filtration, aeration, and biofiltration processes. RAS technology provides precise control over environmental parameters such as temperature, salinity, dissolved oxygen levels, and waste removal, creating ideal conditions for shrimp growth.

The significance of RAS in shrimp production lies in its ability to mitigate environmental concerns associated with traditional aquaculture systems, such as discharge of effluents into natural water bodies, disease transmission, and habitat destruction. RAS facilities can be established inland, allowing shrimp production in regions where traditional shrimp farming may not be feasible due to geographical constraints or unfavourable environmental conditions.

## 2.7 Biofloc Technology (BFT)

Biofloc production of warmwater shrimp or fish can be defined as a variant of a RAS, where the biological water treatment takes place in the production tanks. The biofilter is moved into the production tanks, so to speak. As RAS production expands worldwide, the implementation of biofloc technology (BFT) in RAS has proliferated as well. BFT is defined as the use of aggregates of microbes, especially bacteria, algae, yeast, zooplankton, and protozoa, held together in a matrix with particulate organic matter for the purpose of improving water quality, waste treatment, and disease prevention in intensive aquaculture systems (El-Sayed, 2020). BFT creates an environment where the organic matter (i.e. uneaten feed and fish waste) is converted into high-protein microbial biomass, known as bioflocs. Recycling fish/shrimp farming residues into their own food source creates an internal ecosystem in the rearing system, allowing for an ideal zero-effluent status. The use of BFT in RAS fosters biosecure and resource-efficient land-based aquaculture. Biofloc technology is gaining popularity to manage waste and nutrient retention in culture water. However, this production system requires active management to be successful (BIO-RAS).

Several aquaculture species are well-suited for biofloc technology, including shrimp (such as Pacific white shrimp), tilapia, catfish, and some species of fish like barramundi. These species thrive in biofloc systems because they can efficiently utilise the organic matter generated by the microbial flocs, reducing the need for traditional filtration systems and ensuring better overall water quality.

Advantages

- Enhanced water quality: bioflocs contribute to maintaining good water quality by removing excess nutrients and organic matter.
- Reduced feed costs: bioflocs allow for partial substitution of commercial feed.
- Disease control: bioflocs contain beneficial microorganisms that can outcompete potential pathogens, contributing to disease prevention.
- Water consumption: the recirculation of water considerably reduces the overall water consumption in land-based operations.
- Water quality control: RAS provides precise control of rearing conditions, ensuring optimal conditions for the cultured organisms.
- Fish/shrimp welfare due to the high quality of water and conditions similar to natural environments.
- Modern circular bioeconomy with good growth and feed conversion.
- Lower CAPEX investments into technology, as many standard units in RAS technology are not required as in BFT.

Disadvantages

- Oxygen requirement: the high microbial activity in the system causes an increased need for oxygen, requiring close monitoring and efficient aeration systems.
- Organic matter accumulation: if not managed properly, the accumulation of organic matter can result in deteriorating water quality.
- System complexity: the setup and maintenance of biofloc systems are complex and require specific knowledge or specialised experience to operate them properly. BFT is difficult to control. A robust and detailed understanding of microbial kinetics, mass balance, and process control is necessary.
- Due to turbid water, it is complicated to monitor the status, growth, and feeding rate of shrimp and to apply quickly developing image analysis systems for production monitoring.

- Because of a lack of water disinfection, it is complicated to eliminate pathogenic microorganisms, and therefore there is a higher risk of disease breakout.
- It is not possible to purge shrimps and empty their digestive systems before harvesting.

## 2.8 Comparison between clear-water and BFT systems

Clear-water and a BFT productions are compared in **Table 5**, in accordance with several parameters, including economy and different production parameters.

- Water management
  - Clear-water systems tend to display higher concentrations of ammonia and higher pH levels, while biofloc systems have more elevated nitrite, nitrate, and turbidity levels.
  - Overall, clear-water systems tend to be better for fish farming, and although they have higher operational costs, they are easier to control. Biofloc depends on a biological community of microbes which can be unpredictable.
- Nutrient cycling: BFT systems excel in nutrient cycling as the organic matter is converted into microbial biomass, which serves as a nutrient source.
- Disease management: Biofloc technology enhances disease prevention through the competition between beneficial microorganisms and potential pathogens. clear-water systems also contribute to disease control through disinfection, providing a controlled and clean environment for the cultured organisms.

***Table 5.*** *Shrimp RAS and BFT technology efficiency comparison by different key parameters.*

| Advantages | RAS | BFT |
|---|---|---|
| Lower CAPEX investments | | + |
| Lower OPEX | | + |
| Lower FCR and higher production efficiency | | + |
| Better disease management | + | |
| Easier water quality management | + | |
| More sustainable water and sludge use | | + |
| Easier monitoring of production | + | |
| Better meat quality | + | |
| More available skilled staff | + | |

# 3 Warmwater Shrimp Species in Europe

The adoption of RAS technology in Europe has facilitated the production of various warmwater shrimp species, including the Pacific white shrimp (*Litopenaeus vannamei*) and the giant tiger prawn (*Penaeus monodon*).

Water Treatment and Filtration Systems: Advanced filtration systems, including mechanical, biological, and chemical filtration, ensure the removal of waste particles and maintain optimal water quality. Innovations in biofiltration techniques utilising beneficial bacteria play a vital role in converting toxic ammonia into less harmful compounds.

Automated Monitoring and Control: Integration of sensors and monitoring devices allows real-time tracking and regulation of environmental parameters within RAS facilities. Automated systems control feeding, water quality, and environmental conditions, optimising shrimp growth while minimising human intervention.

Recycling and Resource Efficiency: RAS has a high degree of resource efficiency as water is recycled, and waste products are utilised. Innovations such as the integration of aquaponics or biofloc technology utilise shrimp waste to cultivate plants or beneficial microorganisms, creating symbiotic relationships that enhance overall system efficiency.

Disease Management: Biosecurity measures, including quarantine protocols, UV sterilisation, and constant monitoring, mitigate the risk of diseases within closed RAS environments. Innovations in probiotics and immunostimulants support shrimp health and reduce reliance on antibiotics.

## 3.1 Challenges and Future Prospects

A number of small RAS for shrimp production are established in Europe (**Table 6**, Fig. 12) and despite the numerous advantages, RAS shrimp production in Europe faces challenges related to high initial investment costs, energy consumption, and operational complexities. However, ongoing research and development focus on optimising RAS technology to address these challenges.

Future prospects in RAS shrimp production involve scaling up operations and further refining technologies to make RAS more cost-effective and accessible to a broader range of producers. Collaborative efforts between academia, industry, and government institutions aim to develop more efficient systems, improve shrimp genetics, and optimise feed formulations to enhance growth rates and reduce production costs.

## 3.2 Sustainability and Market Demand

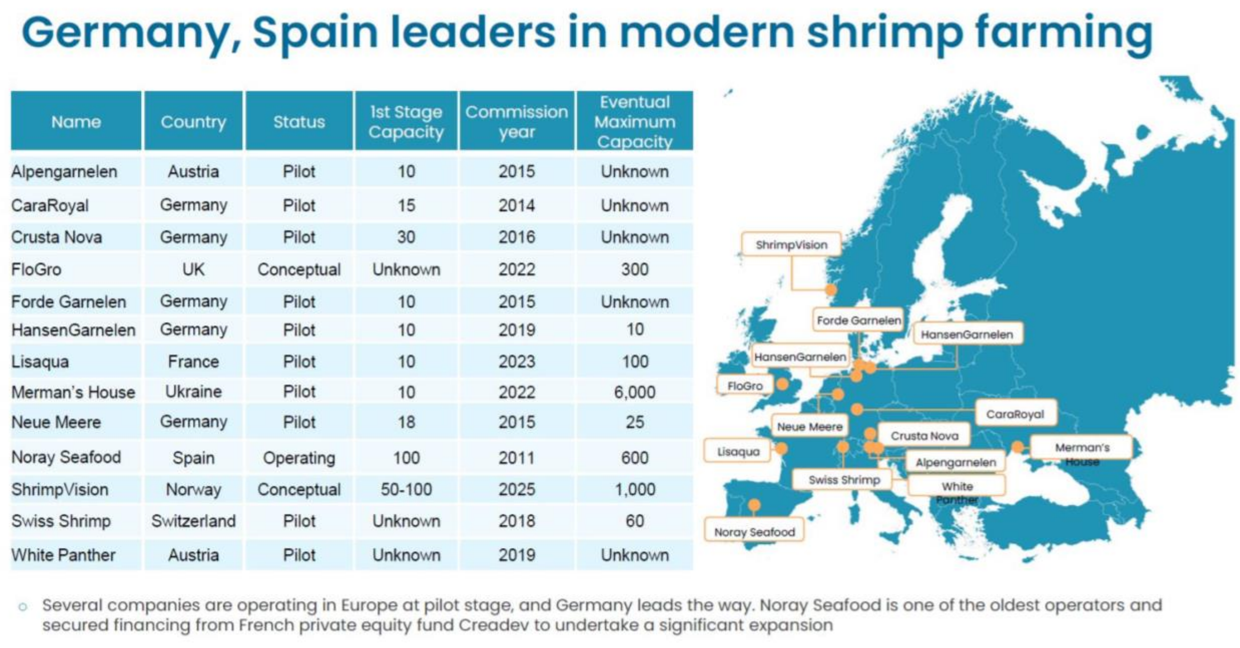
The sustainable nature of RAS shrimp production aligns with consumer preferences for responsibly sourced seafood. European consumers increasingly seek products with lower environmental footprints and higher quality, providing a market niche for RAS-produced shrimp.

The emphasis on sustainability and innovation in RAS shrimp production not only meets market demands but also contributes to the overall development of a more environmentally conscious and economically viable aquaculture industry in Europe.
In conclusion, the adoption of RAS technology has revolutionised warmwater shrimp production in Europe, offering a sustainable and efficient alternative to traditional aquaculture methods. Continuous innovation,

research, and collaboration within the aquaculture sector are essential in further optimising RAS systems, ensuring their economic viability, and meeting the growing demand for high-quality and responsibly produced warmwater shrimps in the European market.

***Table 6.*** *Shrimp RAS companies in Europe and production system used.*

| Company | Country | Capacity (ton/year) | Type of system |
|---|---|---|---|
| **Alpengarnelen** | Austria | 10 | Brown water |
| **Aquapurna** | Germany | | Clear water |
| **Neue Meere** | Germany | 18 | Brown water |
| **Crusta Nova** | Germany | 30 | Clear water |
| **Forde Garnelen** | Germany | 10 | |
| **HansenGarnelen** | Germany | 10 | |
| **Damm Aquakultur** | Germany | | Biofloc |
| **Swiss Shrimp** | Switzerland | Unknown | Clear water |
| **White Panther** | Austria | Unknown | Clear water |
| **CreveTec** | Belgium | Unknown | Biofloc |



Germany, Spain leaders in modern shrimp farming

| Name | Country | Status | 1st Stage Capacity | Commission year | Eventual Maximum Capacity |
|---|---|---|---|---|---|
| Alpengarnelen | Austria | Pilot | 10 | 2015 | Unknown |
| CaraRoyal | Germany | Pilot | 15 | 2014 | Unknown |
| Crusta Nova | Germany | Pilot | 30 | 2016 | Unknown |
| FloGro | UK | Conceptual | Unknown | 2022 | 300 |
| Forde Garnelen | Germany | Pilot | 10 | 2015 | Unknown |
| HansenGarnelen | Germany | Pilot | 10 | 2019 | 10 |
| Lisaqua | France | Pilot | 10 | 2023 | 100 |
| Merman's House | Ukraine | Pilot | 10 | 2022 | 6,000 |
| Neue Meere | Germany | Pilot | 18 | 2015 | 25 |
| Noray Seafood | Spain | Operating | 100 | 2011 | 600 |
| ShrimpVision | Norway | Conceptual | 50-100 | 2025 | 1,000 |
| Swiss Shrimp | Switzerland | Pilot | Unknown | 2018 | 60 |
| White Panther | Austria | Pilot | Unknown | 2019 | Unknown |

- Several companies are operating in Europe at pilot stage, and Germany leads the way. Noray Seafood is one of the oldest operators and secured financing from French private equity fund Creadev to undertake a significant expansion

***Figure 11.*** *Main shrimp RAS producers in Europe (M. Craze, Spheric. 2022).*

## 3.3 Post Larvae (PL) Supply (SUB)

At present, the PLs available to European producers are either imported from outside EU or produced in EU.

### Importation

Currently, the only country allowed to export live crustaceans (including shrimp PLs) to EU is the USA (EUR-lex 2020). At present, the import cost of PLs remains relatively low, relative to the overall capital and labour costs for a European RAS. The logistics of PL delivery by plane have been acceptable, and the system for importation is well-established (Slatter, 2018). Until now, the importation of PLs from the USA has been a convenient option, allowing many small-scale operations to obtain the *seed* to start production. However, importation does not present a long-term solution for PL supply for the European shrimp industry due to a variety of reasons:

- Long transport times can negatively impact growth and survival during the grow-out phase and in the case of customs delays, extended health checks, etc.; a complete loss can and has occurred.
- Limited opportunity for the buyer to inspect the stock before it is received at the farm. Normally, health assessment is a critical part of the larvae selection process as larvae health and vitality directly impact grow-out performance.
- There have been at least two documented cases of larvae arriving from the USA infected with disease. In both cases, this led to the permanent closure of the receiving operation.
- The availability of PLs from the USA is seasonally dependent. Hurricane season in the Gulf of Mexico has a major impact on both PL availability and quality.
- During the COVID-19 pandemic, PL imports were halted, considerably affecting shrimp production in Europe.
- Significant resources are required in transporting PLs by air.
- There is a lack of incentives for USA producers to develop selectively bred lines that meet the specific requirements of EU shrimp production in terms of environmental tolerance, growth rate, and other factors to the culture methods being used in Europe.
- When larger projects (more than >1,000 tons/yr) become operational, the volumes of larvae required will make long-distance air transport an unfeasible option due to both cost and logistical considerations.

### Domestic PL Production

At present there is a very small number of hatcheries in Europe producing PL for sale to third parties, the largest of which is White Panther (Austria), which has been consistently producing since late 2019 and currently provides around 500,000 PLs per week to on-growing operations across Europe. White Panther has the capacity of supplying PLs for about half of Europe’s current production capacity (around 250 tons). If production capacity is to increase, there will have to be an equivalent increase in the number of hatcheries.

Currently, multiple operations are actively pursuing the establishment of in-house hatcheries with the aim of partially fulfilling their demand of PLs, e.g., AquaPurna in Germany. There is also a hatchery project in progress by Vismar Aqua in Ukraine. This project involves the construction of a small-scale hatchery situated next to their RAS shrimp production facility, with the goal of producing 1-1,5 million PLs monthly

Another hatchery project is located in Italy, where BIOTECNA srl Sustainable Aquafarming has a hatchery unit for maintenance and production of shrimp of the species *L. vannamei* and *Macrobrachium japonicus*.

# 4 Knowledge from Past and Current Baltic Sea Region (BSR) Projects and Reports

In recent decades, the Baltic Sea Region has witnessed the implementation of industrial symbiosis (IS) cases and networks, as well as recirculating aquaculture systems (RAS). Below are examples of successful IS and RAS initiatives that focus on treating and recycling industrial waters.

## 4.1 Review of EU projects

**1. SeaFree (Denmark)**
**Partners:** Copenhagen University, Pure Algae, Aarhus University, Drying Mate, Food Diagnostics A/S, Rigi.Care/XOventure, Sigrid Therapeutics, KOST, Kattegatcentret, HanseGarnelen, Innovation Centre Denmark
**Status:** Ongoing (06.2023-06.2027)
**Description:** SeaFree is a Danish innovation project aiming to convert nutrients and $CO_2$ from land-based shrimp and RAS producing fish to valuable seaweed. The project aims to make land-based RAS more sustainable by implementing seaweed production as a form of water treatment, resulting in a side stream of usable and saleable seaweed.
**Website:** www.seafree.org

**2. ALGECO (Norway)**
**Status:** Ongoing (2021-2025)
**Description:** ALGECO uses cost-effective algae technology to promote circular economy development of Norwegian wastewater treatment plants. The project provides a scientific blueprint for a new paradigm of bioeconomy for Norwegian wastewater treatment plants (WWTPs). ALGECO aims to transform municipally treated wastewater from waste into algae-based products by developing and implementing innovative, cost-effective, and viable algae technologies.
**Website:** www.alg.eco

**3. Aqua COMBINE** (Denmark, Sweden, Germany, Belgium, Portugal, Spain, France)
**Status:** Ended (10.2019 – 10.2023)
**Description:** The project aims to demonstrate combined aquaculture and halophyte farming (farming of salt-tolerant plants) using the principles of circular economy, where waste is recovered and utilised within the system to create both internal value and new products, in addition to minimising waste.
**Website:** www.aquacombine.eu

**4. BIORAS SHRIMP** (Italy, Norway, Malta, India)
**Status:** Ongoing (2023 - present)
**Description:** The project aims to develop, improve, and innovate a bio-secure land-based sustainable shrimp culture model to minimise waste, enhance productivity, and recover energy and nutrients for additional biomass production, by applying integrated biosystems principles, in the view of a circular economy process. The project employs a variety of technologies, including RAS, artificial intelligence, real-time sensors, the Internet of Things, effluent treatment, algae culture and aquaponic, and biofloc.
**Website:** www.bioras-shrimp.eu

**5. CIRCALGAE** (Portugal, Spain, Norway, France, Belgium, Germany, Sweden, Ireland, Iceland, Croatia)
**Status:** Ongoing (2022-2026)
**Description:** CIRCALGAE develops circular valorisation of industrial algae waste streams into high-value products to foster future sustainable blue biorefineries in Europe. The project aims to valorise the massively produced but at the same time under-exploited algal biomass into high value-added ingredients for feed, food, and cosmetic applications.
**Website:** www.circalgae.eu

**6. BIS** (Denmark, Sweden, Finland, Norway, Poland, Russia)
**Status:** Completed (01.2019 – 12.2021)
**Description:** The Baltic Industrial Symbiosis – BIS was an Interreg Baltic Sea Region project aimed at fostering symbiotic partnerships by facilitating and supporting partners looking to establish symbiotic relationships. BIS aimed at screening and matchmaking companies eager to find sustainable green business models. The companies received a detailed review of their specific resource streams and advice on what resources they should focus on in relation to resource optimisation.
**Website:** https://interreg-baltic.eu/project/bis/

**7. ULTIMATE** (Italy, Spain, UK, Netherlands, Denmark, Norway, France, Greece, Germany, Israel)
Status: Ongoing
Description: ULTIMATE aims to create economic value and increase sustainability by valorising resources within the water cycle. Wastewater plays a key role both as a reusable resource but also as a carrier for energy and materials to be extracted, treated, stored, and reused within a dynamic socio-economic and business-oriented industrial ecosystem.
**Website**: www.ultimatewater.eu

**8. NextGen Water** (UK, Netherlands, Sweden, Germany, Spain, Czech Republic, Switzerland, Romania, Greece)
Status: Completed (07.2018 – 11.2022)
Description: The project aimed at boosting sustainability and bringing new market dynamics to the water cycle and to the 10 demo cases and beyond. Three key areas of action were:

- Water: itself with reuse at multiple scales supported by nature-based storage, optimal management strategies, advanced treatment technologies, engineered ecosystems, and compact/mobile/scalable systems.
- Energy: combined water-energy management, treatment plants as energy factories, water-enabled heat transfer, storage, and recovery for allied industries and commercial sectors.
- Materials: such as nutrient mining and reuse, manufacturing new products from waste streams, regenerating, and repurposing membranes to reduce water reuse costs, and producing activated carbon from sludge to minimise costs of micro-pollutant removal.

**Website**: www.nextgenwater.eu

## 4.2 Companies

### 1. Pure Algae (Denmark)

**Type of system:** land-based seaweed cultivation

**Description:** Pure Algae is a company focused on the design, build, and operation of land-based seaweed cultivation systems. Pure Algae technology makes it possible to couple these systems to land-based aquaculture systems and transform nutrients and $CO_2$ from process water streams into valuable biomass. It enables RAS facilities to meet the regulations on discharged process water and increase profits by turning process water into a high-value product (seaweed) with numerous potential applications.

**Website:** www.purealgae.dk

### 2. BIG Akwa (Sweden)

**Type of system:** land-based aquaculture in industrial symbiosis

**Description:** BIG Akwa is a food-tech innovation start-up seeking to improve the economic and environmental performance of land-based aquaculture by introducing industrial symbiosis between aquaculture and industry. BIG Akwa aims to couple land-based fish farming with the pulp industry, which generates low-temperature heat typically wasted in production. This heat can be used to keep fish farm water at optimal temperatures ensuring faster fish growth and lower energy usage.

**Website:** www.bigakwa.com

### 3. WA3RM (Sweden)

**Type of system:** Food production systems in industrial symbiosis

**Description:** WA3RM develops regenerative systems based on industrial by-products such as surplus heat, CO2, and sludge. The waste heat is streamed from an anchor industry to an adjacent, purpose-built facility where it can be used as a resource in vegetable production, fish, and shrimp farming, or other innovative applications such as biochar, biofuel, or lye. Any new by-products in the system will be evaluated for a possible loop. This cyclical system is commercially viable for all stakeholders and above all provides a feasible path to a healthier future for our planet.

**Website:** www.wa3rm.com

### 4. Algiecel (Denmark)

**Type of system:** microalgae production system

**Description:** ALGIECEL transforms $CO_2$ emissions and LED light into microalgae biomass and oxygen. The company has developed a plug-and-play photoreactor that can be stacked and packed as it fits into standard shipping containers. The reactor is easily installable and requires little technical know-how from small and mid-size industrial clients.

**Website:** www.algiecel.com

### 5. Swedish Algae Factory (Sweden)

**Type of system:** microalgae production system

**Description:** The company produces diatoms to extract its high-tech silica shells, a material called Algica, for use in different applications. The company uses nutrient-rich water from nearby food industry, enabling the recycling of nutrients. After the nutrient-rich water has passed through the algae production, clean water is transferred back to the food industry. The organic biomass that remains after the extraction of Algica is used to produce energy, fertilizers, and feed.

**Website:** www.swedishalgaefactory.com

### 6. SMÖGENLAX (Sweden)

**Type of system:** Salmon RAS production
**Description:** Recirculating aquaculture system producing salmon with a capacity of 2000 tons annually in the first phase, and 6000 tons in the future. The company is part of the Sötenas Symbiosis Centre. The system uses heat and energy from a water treatment and biogas plant, and the nutrient-rich water from the RAS is used to produce algae, whereas feed and fish residues are used to produce biogas, and the sludge is used as fertilizer.
**Website:** www.smogenlax.se

**7. Matorka** (Iceland)
**Type of system:** Arctic char RAS production
**Description:** Recirculating aquaculture system producing Arctic char. The plant sources all its water from precipitation and snowmelt and uses 100% clean geothermal electricity to power the facilities.
**Website:** www.matorka.is

## 4.3 Industrial Symbiosis Networks

**1. Sötenas Industrial Symbiosis Centre** (Sweden)
**Description:** Industrial and social symbiosis network in Sötenas municipality, Sweden, where synergies between industrial actors involved in renewable energy, food production, land-based aquaculture, algae production, and marine technology take place to improve material and energy efficiency in the region.
**Website:** www.symbioscentrum.se

**2. Kalundborg Symbiosis** (Denmark)
**Description:** Partnership between sixteen public and private companies, who buy and sell waste and/or residuals from each other in a closed cycle of industrial production. A variety of by-products are traded, such as steam, ash, heat, sludge, and others that can be physically transported from one company to another.
**Website:** www.symbiosis.dk/en/

**3. Händelö** (Sweden)
**Description:** The eco-industrial park consists of a waste incineration plant that sends steam to fuel a grain-based ethanol production plant for biofuel production, a biogas plant, and a carbon dioxide factory. The waste energy provides electricity and district heating for Norrköping, and the residual steam is used in the ethanol production plant. Any parts of the raw material that do not become biofuels are used as protein-rich animal feed. The carbon dioxide produced during production is sent to the Norlic carbon dioxide factory, which turns it into carbonic acid and resells it to the food industry. The ethanol plant also sends its residuals to the adjacent biogas production plant, where biogas is produced for the automotive industry and as manure to nearby fields.
**Website:** www.heip.se/en/

**4. Skive Green Lab** (Denmark)
**Description:** Green and circular industrial park where sustainable energy is generated and supplied to local business, who transform it into heat, electrofuels, and other green products.
**Website:** www.greenlab.dk

# 5 New Technology and Innovative Solutions

The regulation of nutrient discharges from RAS is a very significant barrier to innovation. Today, regulations stand in the way of an increased production of fish in land-based aquaculture. The HELCOM (2013) regulation limits the use of the Baltic Sea as a recipient of water for land-based fish farms, even if the water is treated with the best and most efficient technology. The HELCOM Nutrient Reduction Scheme includes Maximum Allowable Inputs (MAI) of nutrients to seven major Baltic Sea sub-basins in order to meet the standards for a good environmental status. The basis for MAI is that the quantitative targets on specific eutrophication indicators (HELCOM, 2013a) must be reached. In the development of the MAI targets, the nutrient reduction targets for each country (CART) were determined based on inputs in a reference period (1997-2003). As it is not optimal to formulate the country commitments in terms of reduction requirements relative to nutrient inputs in a specific reference period, the 2018 Brussels Ministerial Declaration stated that although it would be possible to recall the CART of the 2013 Ministerial Meeting, the updates made to the BSAP national commitments should be formulated in a way that ensures fulfilment of MAI. In the nutrient input reduction scheme included in the 2021 Baltic Sea Action Plan, the CART was replaced by Nutrient Input Ceilings (NIC) which define maximum inputs via water and air possible to achieve good environmental status with respect to eutrophication for Baltic Sea sub-basins for each country (HELCOM 2021).

The authorities in Denmark have been open to discharge of small amounts of nutrients to some water bodies (BEK nr 1349 of 16/06/2021). The amount of nitrogen that can be discharged is determined by the size of the catchment area for the water area. This means that areas with large catchments have a larger nitrogen quota. Since a large catchment also often results in poor water quality, the largest quotas of nitrogen that can be applied correspond to areas with poor water quality. It will be difficult to get a permit for fish production in these areas due to other considerations such as the poor water quality. The scheme will thus not ensure the establishment of new land-based fish farms, but only minor expansions of existing fish production. A RAS will not be economically profitable if there is no possibility of discharge, or if the handling of the water is too costly. The handling of water from the production, including its contents of dissolved nutrients, is then a critical barrier for the land-based aquaculture industry.

## 5.1 Discharge of nutrients in the future

The production of fish and shrimp in RAS is still under development and further research is needed to develop concepts that are sustainable in relation to both economy and environment. A report from DTU (2019) identified technology that may be implemented in saltwater RAS to reduce the discharge of nutrients to the recipient. The report describes a test at a Danish RAS of active sludge as a carbon source in the denitrification process. The denitrification takes place in a tank without media, and to avoid loss of bacteria, the water will after the denitrification be held in a sedimentation tank. The sedimented material, including bacteria, will be returned to the denitrification tank. The system can remove 334 g $NO_3$-N/day. It is expected that a RAS with this type of technology can remove >90% of the N, reducing the environmental efficiency to approx. 5 kg N/t produced fish.

## 5.2 Alternative methods for water handling

The biggest limitation to growth in the RAS sector is a combination of the efficiency and the cost of water handling. The most modern RAS facilities manage to feasibly remove 90-95% of the N and P before discharging the wastewater. In the Baltic Sea region, this is not enough. Because of the poor conditions of the marine environment, it is unthinkable that the industry can grow without finding either better water treatment methods or alternative uses for the wastewater, or a combination hereof, if the solution eliminates the need for discharge.

A wide variety of solutions have already been developed (**Error! Reference source not found.**), from c omplicated membrane distillation to low-tech reedbeds, etc. The biggest challenge is the removal of the final fraction (5-10%) of N and P from the discharge water, which is crucial for enabling production in the Baltic Sea area. Under the present regulatory regimes, it is very difficult as well as expensive to achieve zero discharge, but in a symbiosis setting or through changes to the present legislation, the solutions presented below could play a vital part in growing the RAS industry, not only in the Baltic Sea region.

***Table 7.*** *Overview of different alternative or complementary forms for water treatment.*

| Technology | Functionality, Pros & Cons | Level of Readiness | References |
|---|---|---|---|
| **Membrane filtration / reverse osmosis & membrane distillation** | A single feed stream is directed through a membrane system, where it is segregated into permeate and retentate.<br>Very efficient filtration method. Water can be reused as technical water but can't be reused in saltwater RAS as it removes the salt, as well as N and P. Disposing off the reject may be challenging and is further analysed as part of pilot 1. | Tested in full scale manufacturing environment | Alfa Laval<br>Veolia Water Technologies<br>Bollfilter |
| **Moving Bed Biofilm Reactor** | Based on biofilm principle. Solutions are used for removal of BOD/COD and nitrogen. | Tested full scale in several RAS systems | Kruger |
| **Cultivation of freshwater fish in warmwater RAS (Fish instead of domestic animals)** | Process water is stored in large lagoons and used for watering fields during dry season.<br>No discharge of water into waterbody. Large need for arable land for water distribution (100 ha/400-ton fish). | Annual production above 400 ton per site. 12 contracted producers (2021). | Gårdsfisk<br>Svensk fisknäring |
| **Aquaponics** | The integration of aquaculture and hydroponics. The byproducts (waste) are used to produce a secondary crop.<br>Less costly water filtration system, but issues arising with one crop may affect the other. Sturgeon, micro algae, and lettuce in California reduces the waste streams by up to 80%. | Full scale production | https://tsarnicoulai.com/our-farm |

| Technology | Functionality, Pros & Cons | Level of Readiness | References |
|---|---|---|---|
| **Saline (double closed loop) Aquaponics** | Growing shrimps in one loop and cleaning the nutrient rich water by producing sea asparagus, sea beans, and seaweed in another loop. | Small commercial plants. | Beach City Aquaponics |
| **Decoupled aquaponics** | The byproducts (waste) are used to produce a secondary crop.<br>More complex system, as systems are segregated. If problems with one, the other is not affected. The double recirculation system provides optimised conditions for the fish and plant part independently from each other, to increase the productivity of both. | Facilities have demonstrated an ability to produce 24 tons fish and 12tons tomatoes a year (in Germany) and 30 tons fish and 360 tonsvegetables a year (in China). | INAPRO |
| **Macro algae (land-based)** | Seaweed grown in nutrient-rich effluent water from seafood production uses the excess nutrients for growth. The $CO_2$ from the seafood production is utilised for photosynthesis by the seaweed, increasing the production and nutrient fixation.<br>Production of another high value crop generates additional turnover.<br>Large production required for feasible RAS production. Water may not contain enough nutrients to support the algae. | 60 tons process water produces 300 tons seaweed<br>8 x 1,000 litres in a 40’ container. | Pure Algae<br>Project Seafree<br>University of Copenhagen |
| **Mussels** | Filter feeder. Filters out phytoplankton feeding on the excess nutrients. Several additional ecosystem services. Can remove between 1.6-3.0 t/ha N and 0.1-0.17 t/ha P. Area efficiency 16-77x greater than sugar kelp and eelgrass (N-capture).<br>Can’t remove nutrients from a specific source but only what is carried through the facility. The | Proven technology both as wild catch and cultivated.<br>Very good results in test environment as land-based mussel filter. | Baltic Blue Growth<br>Baltic Muppets<br>NIFIMU<br>NIFIMU |

| Technology | Functionality, Pros & Cons | Level of Readiness | References |
|---|---|---|---|
| | lower the salinity, the slower growth is. | | |
| **Micro algae (land-based)** | Deep sea algae do not need light.<br>Micro algae can remove 50% of the nutrients.<br>Micro algae can be engineered to suit a specific purpose to create a value product. | Full scale plant established.<br>Full scale plant under construction. | Swedish Algae Factory<br>Maripure |
| **IMTA** | Waste-products from single species production systems can be recovered as feed, fertilizer, and energy by other species. | Land-based and open water pilots. Capacity of land-based pilot in Brazil: 7,200 shrimp, 140 tilapia, 4 kg seaweed (sea lettuce) and 200 oysters[1] | Astral Project |
| **Biofloc** | Nutrients and organic matter remain in the system and are recycled by microorganisms.<br>Cost-efficient filtration of process water.<br>It is difficult to keep an eye on the fish/shrimp as water is unclear if not a separated system. | Land-based pilot in Brazil (as above). | Astral Project |
| **Woodchip bioreactors** | Filtration of water through a basin filled with wood chips. Stable year-round removal of nitrate, but initial toxic leaching. Low investment and operating cost but large space requirement. | Tested full scale on freshwater trout farms (1,500 tons/year), but saltwater warrants further studies. | Jedsted Mølle Dambrug<br>DTU Aqua |
| **Reed beds / Constructed Wetlands / Plant lagoons** | Engineered solution based on natural processes for treatment of effluents.<br>Works on saltwater RAS.<br>Takes up a lot of space to reach sufficient capacity.<br>Vertical wetlands can be used as<br>primary treatment processes, whereas horizontal systems are | Full scale plant established. | Aqua+pri |

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[1] Conversation with Prof. Dr. Luis Poersch

| Technology | Functionality, Pros & Cons | Level of Readiness | References |
|---|---|---|---|
| | commonly used for secondary or tertiary treatment. | | |
| **Crushed concrete** | DTU Aqua report not yet released | | FosVind |
| **Zeolite** | Can reduce the N content to bring it below the maximum operational levels (for fish). | Only lab-tested. Pilot and full-scale tests needed to confirm potential. | Zeolit i Akvakultur |
| **Aquaporin filters** | Selective transport of molecules, both faster and more selective than other synthetic filters. Reduced energy consumption compared to other filters. | Proven technology for wastewater treatment plants | Aquaporin |

# 6 Methodology for Assessing KPI

To compare different technology platforms for producing fish in aquaculture, KPIs (Key performance indicators) estimated for the different processes can be compared to a benchmark. The benchmark will typically be another type of aquaculture or other types of primary production of food. The benchmark for a RAS production of salmonids in a full recirculation system can, as an example, be farming of salmonids in pen-cages in the Baltic or the production in RAS with a low circulation.

The KPI's can be organized thematically, addressing economic (Ec-PI), social (So-PI), production (Pr-PI) and environmental (En-PI) factors. The KPIs can include different parameters – see also appendix 1.

This chapter gives a brief introduction to the concept of KPIs in aquaculture, and in the next chapters, KPIs are identified and analysed for warmwater aquaculture (Chapter 7) and salmon production (Chapter 8) in RAS systems. For the environmental KPIs, climate impact is an important indicator that can be estimated by an LCA. Chapter 9 demonstrates the use of LCA for salmon production in RAS.

## 6.1 Economic Performance Indicators (Ec-PIs)

The Economic Performance indicators include indicators that describe the investment cost (**CAPEX**), cost for running the production (**OPEX**), and the financial result of the business.

The indicators for economic results can include:
**Value added** with depreciation (Net Value added (NVA) or without depreciation Gross Value Added (GVA)
**Earnings Before Interest and Tax** (EBIT),
**Net Profit including all costs**.
Furthermore, the relative economic performance indicators can be related to the revenue as the **EBIT margin** (EBIT/total income), and the performance can be assessed in relation to the **assets or the investment** as ROA= (EBIT/total assets) or ROI (EBIT/ invested money).
The performance can be assessed as the **profit per unit of product** and as Net profit/produced biomass.

## 6.2 Social Performance Indicators (So-PIs)

Social Key Performance Indicators (So-PIs) for aquaculture encompass a range of factors that assess the industry's social impact and responsibility (Leroy Seafood). Some possible So-PIs include:

- **Employment and Labour practices:** evaluating the number of jobs created, worker safety, fair wages, and adherence to labour laws within the aquaculture operation.
- **Community engagement:** measuring the level of engagement with local communities, such as supporting local businesses, offering community outreach, and involving community members in decision-making processes.
- **Health and well-being of workers:** monitoring the physical and mental well-being of aquaculture workers, ensuring access to healthcare, safe working conditions, and a healthy work-life balance.
- **Gender Equality:** evaluating the promotion of gender equality within the industry, including opportunities for women in leadership roles and equal pay for equal work.
- **Stakeholder engagement:** assessing the involvement of various stakeholders, such as local communities, non-governmental organisations, and government agencies, in decision-making and planning processes.

- **Transparency and accountability:** ensuring that aquaculture operations are transparent about their practices, environmental impact, and any potential social concerns, and that they are held accountable for any negative consequences.
- **Education and training:** evaluating efforts to provide education and training opportunities for employees, contributing to their personal and professional development.
- **Conflict resolution:** measuring the ability of aquaculture operations to address and resolve conflicts or disputes with local communities or other stakeholders in a fair and responsible manner, e.g. conflicts on water use and land use.

## 6.3 Production Performance Indicators (Pr-PIs)

The production can be assessed according to different KPIs in accordance with how well the feeding of the fish is transformed to production (**FCR – Food Conversion Ratio**). Indicators such as **growth** and **mortality** are internal indicators describing production, whereas indicators such as treatment of **parasites** and **infections** are external indicators describing production (PerformFISH 2018)

## 6.4 Environmental Performance Indicators (En-PIs)

The environmental performance indicators include **discharge of nutrients and organic matter** to the recipient. The nutrients can fuel unwanted growth of microalgae and reduced oxygen concentration. The **emission of greenhouse gasses** (GHG's) from the construction and maintenance of production facilities, from the production of feed, and for operating the production can be separated in different KPIs, but an LCA uses the total emission per produced number of fish to estimate carbon footprint. Impact on biodiversity of the production, including the production of feed is also an important KPI.

## 6.5 Case: Gender in Aquaculture in the Baltic Sea Region (So-PI)

As examples of how to work directly with Social Performance Indicators in RAS in the Baltic Sea Region, an overview of the current state of gender equality is presented here in addition to reflections on how these KPIs may be improved in the future.

The question of gender equality is an overlooked factor in aquaculture. The sector is male-dominated due to the long historical precedence of fishery and production jobs being associated almost exclusively with a male labour force. However, because aquaculture and fishery have long been male dominated does not mean that it must remain so. In particular, the technological and innovative developments made possible by systems such as RAS, where it is no longer necessary to out to sea for several days to secure fish for eating, offer an opportunity to reimagine which workers are well-suited for working in aquaculture.

The fact that RAS can be placed in-land, close to communities, make possible a work-life balance more attractive to female workers who still, across the Baltic Region, carry the greater responsible for family life and childcare. Additionally, instead of requiring mostly physical strength and endurance as is the case for traditional fishery, operating an RAS requires knowledge of complex technological systems and a great attention to detail. This difference may also suggest that the male-dominance in aquaculture can perhaps be reconsidered in the future, should RAS become more prevalent.

In the following, an overview of current initiatives promoting female participation and employment in aquaculture and in fishery and blue economy more generally in the Baltic Region and in the EU is presented. Then, an indicative analysis is presented of the gender distribution among employees in the aquaculture sector across nations in the Baltic Sea Region (Denmark, Sweden, Finland, Estonia, Latvia, Lithuania, Poland, and Germany). The analysis was performed by gathering statistics from each nation's statistical agency from as long a time period as was made available and calculating the percentage of female employees across time to make visible any developments in the gender distributions.

Subsequently, portraits of three different female figures in aquaculture are presented. These portraits are based on interviews, and the portraits include reflections on how these women's reflections and insights in their position in aquaculture as well as hopes for the future indicate directions the sector can take to foster not only sustainable production but also equitable and innovative working environments.

## Statistical developments in gender distribution, country by country

In general, female workers make up a minority in aquaculture in the Baltic Sea Region. However, getting a complete and detailed picture of the state of gender distribution among aquaculture workers is complicated by differences in data collection between nations as well as large gaps in the data. The following analyses are based on public data made available through national statistics offices, and so it may be possible that more detailed data has been collected but is not publicly available. However, it has not been possible within the scope of this project to obtain this data.

Fig. 12 shows the data on the total number of female workers (as percentage of the total number of workers) in aquaculture from the 8 nations (except Germany, where data was not available).

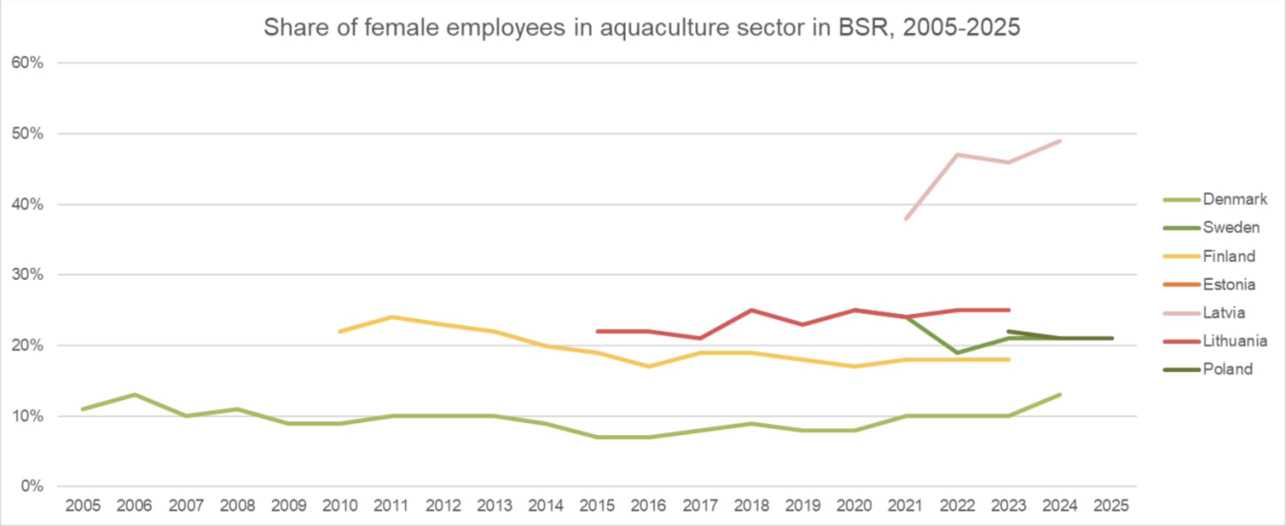

***Figure 12**. Graphed data on the number of female workers (as percentages of the total number of workers) for each nation in the BSR.*

### *Denmark*

Of the countries surrounding the Baltic Sea, Denmark appears to have the most consistent and detailed data on the gender distribution of workers in the aquaculture sector. The Danish Agricultural and Fisheries Agency compiles annual data on aquaculture, covering production, trade, quotas, etc. as well as some social dimensions of the sector, including the gender of workers in the sector. These numbers are furthermore divided into subsectors in aquaculture, including freshwater ponds, RAS with different degrees of recirculation, as well as systems cultivating mussels and seaweed. Statistics are available covering the period 2005-2024. These detailed statistics allows for an analysis of gender distributions in the aquaculture sector that not only shows development across the 20-year period, but in which it is also possible to discern possible differences between the different types of aquaculture systems.

Analysis of the statistical data, however, shows little to no development over the 20-year period in the numbers of men and women in the aquaculture sector in Denmark. Across the sector of the whole, the number of women in the workforce has been stable in the range 8-13%. One significant development, however, is that in the period 2005-2024, the amount of the women workers employed on a part-time or seasonal basis lowered from 70% to 30% of the total female workforce in aquaculture. This indicates that even if the total share of women in the workforce has remained more or less the same, the female aquaculture workers are increasingly employed on more stable and permanent grounds.

If we examine more closely the gender distributions in the different aquaculture system types, a few things become apparent. In mussel farming we find the lowest share of female workers, never going above 4% across the 20-year period. In RAS, the share of female workers is at more or less the same level as the aquaculture average, averaging 11% in the period 2005-2020, however with a slight rise to 14% in 2020.

After 2020, the statistics are further specified into RAS with low, medium, and high degrees of recirculation. Between these system types, there are significant differences. In the period 2021-2024, systems with medium and high degrees of recirculation sit slightly above the aquaculture average with averages of 15% and 13% female workers, respectively, with increases to 18% and 17% women in 2024, indicating a potential further increase in years to come. In systems with low degrees of recirculation, the share of female workers went from 0% to 3% in the period 2021-2024. This indicates an almost entirely male-dominated workforce in RAS with low recirculation in comparison with RAS with higher degrees of recirculation, where female workers make up an increasing number of the total workforce. The reason for this difference is not clear from the statistics themselves but may instead be discovered by examining the working culture and company culture in the relevant systems (Danish Agricultural and Fisheries Agency).

***Sweden***

In Sweden, the national statistics are generally less detailed, and data is not available before 2020. In comparison to Danish aquaculture, the share of female workers in Swedish aquaculture steadily averages around 22%, with no indication in the data that this number is on the rise. Sweden also disaggregates their statistical data somewhat, dividing the data according to whether or not the work is paid and according to the aquaculture system types. From this data, we can see that the gender distribution in aquaculture using tanks, basins, and RAS more or less matches up with the general aquaculture averages, with an average of 18% and a range of 14-22% female workers across the period 2020-2024, with no indication that the number will rise in the future.

One significant development, however, is that the amount of unpaid female workers has decreased from around 30% to 12% of the total amount of female workers in the sector. Not unlike the development in Denmark, this indicates that women are perhaps gaining a more stable and fairly remunerated position in the aquaculture sector (Jordbruksverkets statistikdatabas).

**_Finland_**

In Finland, statistical data is available for the period 2010-2023, showing the distribution of men and women among aquaculture workers, although the data is not specified further according to aquaculture system types. The data shows a slight decrease in the share of female workers of the total aquaculture workforce, going from 22-24% to 18% across the 14-year period. The total number of aquaculture workers has remained steady in the range of 350-400 total workers in the sector, and so the apparent decrease in female workers cannot be immediately explained by the statistics. Despite the decrease of female workers in Finnish aquaculture, the nation is more or less on par with the averages in the rest of the Baltic Sea Region, although it will be important to keep track of whether this trend of decreasing numbers of women continues in the nation (Statistics Finland).

**_Estonia_**

In Estonia, data on gender in the aquaculture sector is scarce and unsystematic. Because Estonia only engages in freshwater aquaculture production, it is not required that they submit data for EU reports. Some data is available via Estonia's national statistics office, showing that over a 32-year period from 1989 to 2021, the total number of employees in the fishing and aquaculture sector diminished from approx. 23,000 to less than 1,000, indicating that this is a disappearing sector in Estonia. However, no data appears available with further detail or disaggregation of the category of 'fishing and aquaculture.' The distribution of gender seems to follow general trends in the Baltic region, with 128 female employees out of a total of 1,130 in 2011 (11.3%) and 131 female employees out of a total of 854 in 2021 (15.3%). However, a more directed, organised, and detailed data collection is needed for further conclusions on the state of gender in the Estonian aquaculture sector (Statistics Estonia).

**_Latvia_**

Like Estonia, the data on gender in aquaculture in Latvia is limited and there are some inconsistencies, making it difficult to discern the full picture of gender distribution in the country's aquaculture sector. In Latvia's national statistics, data is available for the period 2021-2024, and data is available in three categories, which have been combined for the purposes of this report: aquaculture and fisheries production managers, aquaculture workers, and fishery and aquaculture labourers. In these categories, the share of female workers is surprisingly high in the Latvian statistics, rising from 38% to 49% in the period, although within the managerial category, men still make up 60-70%.

These national statistics are however complicated and cast into question by an economic report from 2021 by the Scientific, Technical and Economic Committee for Fisheries (European Commission). In this report, it is indicated that in Latvian aquaculture, 17.1% of the workers were female when the data was gathered in 2017. The report also states that this number is based on the member states' own reporting. Of course, it is not impossible that the share of female workers in Latvian aquaculture increased from 17% to 49% across the 8-year-period of 2017-2024, however, this would be a highly significant outlier from the rest of the Baltic region and would require further and more detailed data to confirm (National Statistical System of Latvia).

**_Lithuania_**

In Lithuania, data on gender in aquaculture is available for the period 2015-2023. The data is not specified according to aquaculture system type, the data on the overall number of workers is disaggregated according to system type, showing that RAS has made up 20-30% of the total amount of aquaculture workers in the period.

Regarding the distribution of gender in the workforce, Lithuania appears to be on par with the rest of the Baltic Sea Region, averaging 21-25% female workers in the sector across the 9-year period. There is some indication that this number is growing, as the highest percentages appear later in the period, but the growth is minimal overall (Lithuanian national fisheries data collection program).

Another significant gendered dimension in Lithuanian fishery and aquaculture is that despite the majority of male workers in the aquaculture sector, women appear to be the majority of workers in the processing of fish in Lithuania, making up 68% of the fish processing workforce in 2020. The causes of this clear gender division between production and processing may be culturally or historically conditioned, and further investigation is needed (Eurofish, 2022).

***Poland***

In Poland, there is only limited data available regarding the distribution of gender in the aquaculture sector. Data is only publicly available for the period 2023-2025, and it is not disaggregated according to aquaculture type. The data shows the distribution of men and women to be stable around 21-22% women across the 3-year period, and it thereby follows the general tendencies for the Baltic Sea Region (Statistics Poland).

***Germany***

In Germany, no national statistics are apparently available regarding the gender distribution in the aquaculture sector. The report STECF-20-12, by the EU commission 'Scientific, Technical and Economic Committee for Fisheries,' which analyses data submitted by each nation, indicates that the German aquaculture sector employed 38% women in 2017, but the data behind this figure is not available, nor is there data available from other years.

## Conclusions on the basis of the statistical analysis

Based on the statistical data gathered and analysed in this section, a few tentative conclusions can be drawn. First of all, it appears that the number of women in aquaculture across the region is stable at around 20-25% for most nations (Sweden, Finland, Lithuania, and Poland) with the exceptions of Denmark, which averages 8-13% women and Latvia which averages around 38-49% women (although this data is dubious as it does not clearly line up with the numbers reported to the EU).

These conclusions, however, must be viewed in the light of the quality of the data available. There are two main factors that have impacted the inquiry above:

1. **Lack of data**

Overall, there appears to be a serious lack of readily available data regarding the gender distribution in the aquaculture sector in the Baltic Sea Region. Many nations in the region, including Poland, Germany and the Baltic nations Estonia, Latvia, and Lithuania have only very general data or data across a limited time-span available in their national statistics. This poses a problem for assessing the current state of gender distribution in the sector, as the conclusions based on this data can only be very tentative and do not offer a full picture of the sector.

2. **Inconsistencies in data collection methods**

Just as there is a lack of data across the region, the data is collected by different parameters in each nation. Whereas Denmark collects gender data that is disaggregated according to different aquaculture systems (albeit the list of the different systems undergoes changes, making it difficult to track changes across time) as well as disaggregated according to a fulltime/parttime divide, other nations disaggregate the data according to other parameters, or do not disaggregate the data at all. These inconsistencies mean that it is difficult if not impossible to compare fairly across national borders, and no full picture of the region can be drawn up.

### Recommendation

In other to view the full picture of the state of gender distribution in the aquaculture, it is necessary that fuller datasets are available, tracking the genders of employees in the sector across time, and collecting data according to parameters that are the same across nations in the region.

For these purposes, we can perhaps look to the data collection in Denmark, where gender data is not only disaggregated according to employment status (fulltime, parttime, and seasonal) but also divided up according to aquaculture system.

With such data for the entire region, it may be possible to see whether there are certain aquaculture systems that are better at attracting female employees, and it may be possible to analyse what are the conditions in an aquaculture workplace that invite a more equitable distribution of genders among employees.

## How to attract female employees to future RAS endeavours – a qualitative approach

In order to change the current employee composition and potentially attract more female workers in the establishment of RAS productions in the Baltic Region in the future, it is important to understand the workers from a qualitative perspective in addition to the quantitative developments. A qualitative approach to these issues, including survey methods and interviews could show a fuller and deeper picture of issues that are important to younger female workers interested in the aquaculture sector.

In the following, the results are presented of a pilot study using qualitative methods to understand female workers' needs and desires in the industry. It is our belief that further studies of this kind in the future will be an important part of ameliorating the social impacts of RAS in combination with collaboration with local communities and educational centres.

Interviews were performed in autumn 2025, aimed at understanding the subjects' current situation as well as their hopes and dreams for a future working in aquaculture. The interviews were carried out both in person and over video and were subsequently transcribed. The texts were then analysed and representative quotations selected for the purposes of this report. Below, preliminary conclusions based on the interview data are presented.

### Interview subject 1: Amalie

Amalie is 18 years old, and she lives in Denmark, where she studies at Hansenberg vocational school at their programme for aquaculture. As part of this educational programme, she is an apprentice at a production site in Nibe, helping to raise salmon from 5 to 40 grams.

**'I went out to see her [the friend's] apprenticeship, she also lived in Nibe, and there was a place that needed an apprentice, so I figured I should try it out.'**

For Amalie, what was most important was that there was a clear path to apprenticeship, and that she trusted her friend's recommendation. Important to note here is also that Amalie visited the apprenticeship before she even started the educational programme, and so it was clear to her from the beginning what the work entailed.

**‘[The best thing about the programme] is that we’re outside all the time. It’s very active work. That’s what I like about it.'**
For Amalie, the everyday experience of the work is important. She does not like sitting still but prefers to be working actively and be in direct contact with the fish she is producing. It is significant that she emphasises the everyday experience of the work rather than any technical aspects.

**‘I’m fine with [working with mainly male colleagues]. I think I can work with everyone. So it doesn’t really matter what gender they are.'**
To Amalie, the gender of her colleagues does not necessarily matter, but she does note that her current co-workers are two men in their 20s, and that she finds it easy to relate to them, because they are close to her in age. This is significant, because it shows the importance of looking at multiple factors at once when considering the employee composition and the workplace culture.

**‘[when asked about her hopes for a future career] I want more responsibility. Where I work now, I’d like to also work when I’m fully trained and maybe be responsible for the hatchery, where the small fish are, and have some more responsibility. I like being able to decide things and not be doing the same thing all the time.'**
Not only does Amalie want to work in aquaculture, she is ambitious and wants to be part of a developing workplace, and she wants to be entrusted with responsibility. She wants to have a varied working life, and she is interested in developing and optimising current systems.

### Interview subject 2: Nele

Nele is 25 years old, and she lives in Kiel, Germany, where she is finishing a master's degree in Biological Oceanography. Throughout her degree, she has specialised in aquaculture, particularly the farming of seaweed and algae.

**‘At the beginning, I was mostly focusing on climate change, but also what we can do about eutrophication and the bigger picture, because that’s what I’ve learned from my bachelor’s. And then, I had a talk with one of my professors, and he told me about this project where they want to reduce eutrophication by farming algae. And I really like field work, and I really like to have like a project that has an impact and […] connecting the overall picture to something you can do directly where you live.’**
Here we see again the power of personal recommendation. Nele entered this field because she was recommended to do so by a professor she trusted. Additionally, Nele explains how she had a conversation with a young female scientist in the project group, and that this connection made her able to envision herself in the project, because she met someone not unlike herself doing the same thing. Important to note is also the emphasis Nele puts on impact and direct action. For her, it is important to see the direct results of her work, both in terms of working directly with the ocean but also in terms of taking action against the effects of climate change.

**‘the type of work, even if it’s just like small parts of it, you’re going out on a ship, you don’t do that in most other jobs, so that’s a fascinating part […] I had sampling days just standing in the ocean, collecting my algae, and being connected to the ocean, not just standing in the laboratory and dissecting algae, you’re really standing there in the rain, then, you’re really there.'**

For Nele, another important part of the work is feeling connected to the water and to be doing the work outside and in the elements. She cannot imagine a full career of only laboratory work or only office work, she is most fascinated by the active and outdoor part of aquaculture work.

**‘I have different visions. I have this wish to have a positive impact on environmental pollution, and I think there are different ways to go there, so at the moment I am looking for jobs more in the administrative side, like in Ministries […] But imagining myself sitting at my desk 8 hours a day, that’s maybe not what I imagined for myself. Then there is the second version, going more into practical work, like bigger algae farm projects, but I’m struggling to find existing projects because it’s all in the research and trying out things. And then there’s the third idea, to do environmental education, because that’s what I’ve been doing most of the time next to my studies, informing people about the ocean, working with kids and also being outside […] so I have interesting topic, interesting work and then nice working conditions but maybe not as impactful. So, I’m struggling with what direction to go, and at the moment, I’m focusing on Germany, so that makes it difficult with the aquaculture part.'**

When Nele imagines her future career, she is finding it difficult to combine her different wishes. She wants to work in a way that is active and in direct touch with the ocean, but she is struggling to find jobs where such work would also involve direct climate impact, which is very important to her. She is not able to find projects with a place for her where she could work with aquaculture production directly that would also have a climate protection dimension. Furthermore, she is aware that she is limited by living in Germany, where aquaculture remains a minor part of the blue economy.

**‘I think I would prefer to have at least one or two colleagues that are female, so that you can rely on others in any situations where you are a bit unsure. […] I think if I would be the only woman in the room, then I think I would be a bit intimidated, speaking up and being seen.'**

Although Nele does not find it problematic to be a part of a team consisting of mostly men, she also emphasises the importance of having colleagues that she feels she can identify with and share her insecurities with.

## Preliminary conclusions

From our interviews with Amalie and Nele, a few things stand out as common desires and concerns for these young women interested in entering a career in aquaculture:

1. **They enter the field through personal recommendation.**
   Both Amalie and Nele decided to enter the field of aquaculture because they were personally recommended to do so, Amalie by her friend who was in the same programme as her, and Nele by a trusted professor. This shows the significance of word-of-mouth but perhaps also the fact that aquaculture is not so present in for example educational guides or among educational councillors. Attempts at improving the general awareness and popularity of aquaculture educational programmes should work deliberately with how awareness of these programmes can be spread via both publicity and word-of-mouth recommendation.

2. **It is necessary to be able to envision a career path in aquaculture, and space must be made for workers’ ambitions.**
   For Amalie, it is easy to envision her career in aquaculture, because she wants to continue working at the place of her apprenticeship, and she is ambitious on both her own and the production site’s behalf. For Nele, however, it is difficult to fully envision the career she desires in aquaculture,

because she is unable to find a working place and job role that accommodates her wants for both impact and a daily working life in close connection with the water. For both Amalie and Nele, their career desires and ambitions could easily be met and come to fruition in a RAS production, where they would be able to work directly with the fish, while still being part of technological development and protection of the climate. The question that remains, however, is how and when such job opportunities would be made available for these women, and how to best spread the word of such opportunities.

3. **The gender composition of the employee group is not important in and of itself, what is important is to have colleagues that you feel are similar to you and whom you can entrust with insecurities.** Neither Amalie nor Nele found it problematic to work in an environment with a vast majority of male colleagues. What was important, however, was having colleagues they trusted and with whom they had a good relationship. For Amalie this was found among male co-workers around her same age, while Nele found a lot of value in having at least one or two young women like herself in the project group whom she could entrust with question and concerns. In this regard, it is important to emphasise the necessity of a nuanced and multidimensional employee composition that is diverse in relation not only to gender but also to age, race, socio-economic background, etc.

As the analysis of these interviews have shown, there are many important insights to be gained from taking a qualitative approach to the So-PIs established in this report. We recommend that such investigations are continued and further developed in the future to maintain and explore the social dimension of RAS and the future of recirculated aquaculture in the Baltic Region.

## 6.6 Case: Decarbonising aquaculture (En-PI)

An important issue in the development and implementation of new aquaculture technologies and processes is the general goal of decarbonising the sector with the aims of minimising the climate impact of aquaculture production.

The EU aims to be carbon neutral by 2050. Being carbon neutral means having a net-zero greenhouse gas emission, where any emissions must be equally balanced by the removal of greenhouse gases from the atmosphere. In order to meet these goals, the EU is implementing climate targets for 2030 and 2040, indicating the necessary milestones for meeting the 2050 goal.

In the case of aquaculture, several projects and reports have specified current problems and possible future solutions within the sector and within the fisheries sector more generally. An overview of the insights of these is given below, followed by a summary of the conclusions that can be drawn from them.

***Table 8**. Overview of select EU and EU-affiliated reports on decarbonising aquaculture and fisheries.*

| Title | Type/organisation | Time | Insights and recommendations | Reference |
|---|---|---|---|---|
| A pathway to decarbonise the EU fisheries sector by 2050. | Report / OCEANA & Alma Maris | February 2023 | • Further data collection is necessary<br>• An important principle of sustainable transitions is 'implementing and improving | Alma-Maris (2023) |

| | | | | |
|---|---|---|---|---|
| | | | the uptake of existing technologies'<br>• Efforts should be aimed at shifting vessels from fossil fuels to renewable energy, such as solar energy | |
| Energy transition in the EU fisheries and aquaculture sector | Briefing / European Parliamentary Research Service | June 2023 | • Aquaculture and fisheries were impacted by skyrocketing fuel prices in 2022<br>• A switch should be made to renewable energy and sustainable feed practices in aquaculture<br>• It is also suggested that a switch is to sustainable aquaculture alternatives (e.g. seaweed farming) could reduce carbon emissions | European Parliamentary Research Service (2023) |
| Decarbonisation of fisheries and aquaculture in the Region Emilia-Romagna | Onsite peer review / Interreg Europe | June 2024 | • More detailed data is necessary, including vessel fleet data and a greater understanding of $CO_2$ emissions in the entire supply chain.<br>• It is necessary to raise awareness of decarbonisation measures along the entire value chain, including with suppliers.<br>• Efforts should be aimed at preventing and recycling fish waste, including in aquaculture systems<br>• Circular projects should be supported | Interreg Europe (2024) |
| Techno-economic analysis for the energy transition of the EU fisheries and aquaculture sector | Report / European Climate, Infrastructure and Environment Executive Agency | June 2024 | • Energy management data and audits are necessary to get the full picture of emissions<br>• Efforts should be aimed at precision fish farming, where the optimisation of feed rations can reduce Feed Conversion Ratio (FCR)<br>• Research and development are needed in novel feed formulations. It is suggested | De Vet et al (2024) |

| | | | | |
|---|---|---|---|---|
| | | | that traditional feed based on, for example, fish meal is replaced with feed based on insects or by-products from other sectors<br>• Vessels should be electrified, and efforts should generally be aimed at transitioning to renewable energy | |

## Conclusions

This review of recent reports and knowledge on the decarbonisation of the aquaculture sectors shows a collection of more or less operationalisable action points and possible transitions to making aquaculture and the implementation of RAS in larger scale as sustainable as possible.

In general, it is agreed that more and higher quality data is necessary to paint a full picture of carbon emissions and possible areas of action in the aquaculture sector and the fishery sector more generally. It is recommended that analyses akin to Life Cycle Assessments are carried out to fully understand emissions along the entire production and value chain, and potential emissions from suppliers should be included in these analyses.

Furthermore, RAS productions are encouraged to continue investing efforts into developing technologies and methods, including sustainable and alternative feed practiced, the development of circular projects and waste reduction, and precision fish farming.

Mentioned repeatedly in these reports is the problem posed by vessel fuel and the encouragement to electrify fishery and maintenance vessels. This is likely due to the fact that 73% of greenhouse gas emissions in the fishery sector in the EU stems from vessels (De Vet et al). Recirculating Aquaculture Systems (RAS) can be framed as a significant resource in meeting this goal, as this production format does require the use of vessels, an aspect that can be emphasised when positioning RAS for future sector growth.

However, RAS does have a relatively higher energy consumption in comparison to, for example, Flow Through Systems (FTS) (De Vet et al). This is exemplified in Table 9, which shows the estimated emissions of CO$_2$ from trout production in the EU in 2019, divided into FTS and RAS. These numbers show that emissions from RAS in 2019 were 6.95 tonnes CO$_2$ per produced ton of trout, whereas FTS only emitted 2.49 tonnes CO$_2$ per tonne of produced trout. The higher rates of emission in RAS productions are caused by the higher requirement of energy to keep the systems running. These can potentially be lowered or mitigated by the installation of photovoltaic (solar) panels.

***Table 9**. Estimated CO2e emissions from trout farming in 2019 in EU (De Vet et al, table 2-25).*

| Production System | EU Production 2019 (tonne) | CO$_2$e emissions (tonne) |
|---|---|---|
| Flow Through Systems (FTS) | 180,366 | 450,013 |
| RAS | 16,471 | 114,506 |
| Total | 196,837 | **564,519** |

# 7 Key Performance Indicators for Warmwater Aquaculture

The production of warmwater shrimp in the Baltic area is an expanding industry, but currently only small productions have been established (se also 3.1). In the future, the structure of the industry may include small productions for local markets (10-20 MTY (metric tons per year)) and large productions supplying a European or global market (+1000 MTY).

This chapter addresses KPIs for a 1000 MTY production. Currently there are no RAS shrimp facilities (either clear-water or biofloc) operating even close to this capacity. There are several companies that are currently developing the required technology for production of this size. However, to date there are no technology providers who could provide necessary technology and know-how for such a large facility in the Baltic area with sufficient degree of operational reliability originating from building, testing, and operating such a facility in a commercial application.

To be able to prepare comprehensive and credible feasibility studies and business plans for a 1000 MTY facility, it is essential to begin by analysing the potential for smaller scale facilities and build from there. In this report, such smaller operations are considered and analysed. This approach has several key reasons, that should be addressed before upscaling:

- Proof of concept
- Risk assessment and mitigation
- Data availability and reliability
- Current technological constraints
- Regulatory compliance
- Environmental impact
- Scalability assessment

Although small productions can sell a relatively larger fraction of the production at a high priced market such as web-shops (100 EUR per kg) or to high-end restaurants, when compared with the prices closer to the global market (7 EUR per kilo without head and shell), it is almost certain that larger scale facilities would be more cost-effective, providing that future market conditions will have the necessary demand with suitable product pricing. Currently, there are several very ambitious projects willing to explore and push the envelope on commercial indoor shrimp cultivation using RAS.

## 7.1 Economic KPI (Ec-PIs) for 1000 MTY RAS shrimp facility.

In feasibility studies, Economic Performance Indicators, Ec-PIs, are crucial for determining whether the proposed shrimp farming project is financially viable and sustainable under current and forecasted market conditions. They help in identifying the potential financial risks and returns and provide guidance for strategic decision-making. In business plan preparation, Ec-PIs are vital in projecting financial performance, attracting investors, and securing funding. They provide a comprehensive financial picture of the project, highlighting profitability, cost structures, and revenue streams.

Economic Performance Indicators are often interdependent and influence each other. For instance, Return on Investment (ROI) is affected by both the Net Present Value (NPV) and the Payback Period. A higher NPV typically indicates a more profitable project, potentially leading to a higher ROI. Similarly, a shorter Payback

Period can enhance the ROI by reducing the time frame for recovering the initial investment. Operating Margin directly impacts the profitability metrics such as ROI and NPV, as it reflects the efficiency of the business in generating profit per unit of sales. Cash Flow Analysis is pivotal for understanding the liquidity position, influencing decisions on CAPEX, and affecting the IRR. In summary, these indicators are interconnected and must be evaluated collectively to get a comprehensive understanding of the financial viability of the shrimp farming project in RAS.

Depending on the required applications, there can be numerous types of KPIs. For the current stage, the following Ec-PIs are considered:

- EBIT and EBITDA
- Net operating income
- Free cash flow (financing and pre-financing)
- Equity FCF
- Project IRR
- Equity IRR
- Project ROI (in years)
- Equity ROI (in years)

To provide illustration of the presumptive economic performance differences due to sensitive Ec-PIs, three scenarios are considered (**Table 10**):

1. Pessimistic
2. Neutral
3. Optimistic

These scenarios include variations in the CAPEX, COGS, and variation in the possible product sale price. All the scenarios consider that:

- Facility will be in full operation by the end of year 3.
- Financing will be at 50% intensity (for Capex) with interest rate of 6-7.5%
- The annual depreciation rate will be 7-8%
- Estimated COGS do not include other services, processing, marketing, administration cost (SG&A)

***Table 10.*** *Three scenarios for the Ec-PIs going from pessimistic to optimistic*

| **Pessimistic** | |
|---|---|
| Total Hard Capex (mil.) | 8,650 |
| Total COGS (yearly) (mil.) | 1,400 |
| ExWorks Sale price/ kg (HOSO fresh) | 25 |
| EBITDA by year 4 (mil.) | 1,100 |
| Project IRR | 10% |
| Project ROI (years) | 10.2 |
| Equity IRR | 11% |
| Equity ROI (years) | 11.1 |

| **Realistic** | |
|---|---|
| Total Hard Capex (mil.) | 8,050 |

| | |
|---|---|
| Total COGS (yearly) (mil.) | 1,370 |
| ExWorks Sale price/ kg (HOSO fresh) | 28 |
| EBITDA by year 4 (mil.) | 1,430 |
| Project IRR | 14% |
| Project ROI (years) | 7.94 |
| Equity IRR | 17% |
| Equity ROI (years) | 8.61 |

| **Optimistic** | |
|---|---|
| Total Hard Capex (mil.) | 7,400 |
| Total COGS (yearly) (mil.) | 1,280.40 |
| ExWorks Sale price/ kg (HOSO fresh) | 30 |
| EBITDA by year 4 (mil.) | 1,720 |
| Project IRR | 18% |
| Project ROI (years) | 6.54 |
| Equity IRR | 24% |
| Equity ROI (years) | 6.4 |

What can be drawn from the balance sheet calculations for different scenario estimations (Table 10), is that this business (and product) has huge sensitivity to sales price, meaning that there is a substantial inherent risk in the business model. This is linked to the available market demand at given sales prices and at given market location. To further identify this risk (and opportunity), more detailed research and analysis is required.

Furthermore, extra research, calculations, and estimations are required to include possible overhead costs and possible marketing expenditures into the business plan. Currently these costs have not been included in COGS calculations due to the different nature of such costs (overhead costs and marketing expenses are not directly linked to the production process).

## 7.2 Breakdown of the Economic Performance for 1000 MTY clear-water RAS production facility.

The following CAPEX, COGS (and dependent Ec-PIs) are estimated for 1000 MTY warmwater shrimp RAS aquaculture systems based on a range of sources, including research on operational data from existing aquaculture companies, internal cost projections for similar existing and upcoming projects, and insights from potential technology developers. These estimates, while reflective of current industry standards and trends, are preliminary and may be adjusted with new data or changes in market and technology landscapes. It's important to recognize them as initial calculations and estimations, subject to the inherent uncertainties of financial forecasting in a dynamic sector.

### Technology CAPEX.

Further breakdown is specified for the technology components and excludes civil works, infrastructures, and any additional service areas or offices. The estimated prices are Ex works from various country origins, excluding delivery, duties, taxes, insurance, etc. These estimates are based on 2021-2022 pricing, reflecting probable total engineering package costs. This is a general estimate, and item specifications or prices may vary from the initial estimate due to detailed design, regulations, local parameters, and fluctuations in the prices of goods and transportation.

Technology Capex breakdown:

1. Engineering know-how (planning, detailed design, supervision, and required training)
2. Tanks & tank equipment (layering, lift system etc.)
3. Water treatment and filtration (sand filters, drum filters etc.)
4. Electricity & control (switch board, electricity panels, control unit, fans & air blowers, circulation pumps, frequency control, emergency generator, etc.)
5. Heating system (including heat pumps and heat exchangers)
6. Instrumentation & analytics (sensors related to monitoring water quality parameters (oxygen, pH, salinity, flow meters, level indicators, humidity meter, cables etc.)
7. Oxygen system (oxygen generator, main diffuser, compressor & dryer, oxygen piping)
8. Harvesting & counting devices (shrimp pump and counter)
9. Process items (feeders, holders, piping, pumps, valves)
10. IT (computers, communication, Aquamanager control software (yearly fee), underwater cameras (yearly fee))
11. Laboratory equipment (portable DO / pH / $CO_2$ meters, scales, buckets, containers, nets, catchers)
12. Processing unit (ice machine, pealing machine, scales, packing & labelling machine)
13. Inlet water purification (water reservoir, UV system, sand filter)
14. General unexpected costs (reserve)

The investment in tanks, filtration systems, and engineering constitute more than 50% of the total cost for the technology (Fig. 13).

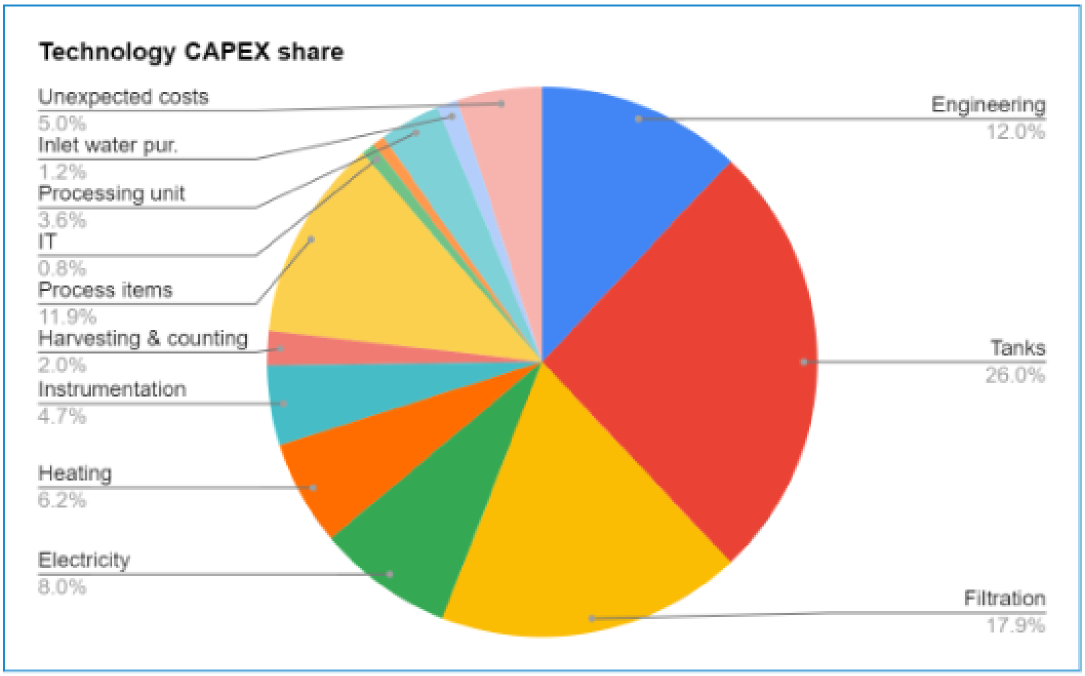

***Figure 13**. The allocation of cost for technology for a system producing 1000 MTY*

## Civil CAPEX

Other construction works include the construction of buildings and the area surrounding the production facility, which constitute 43.1% of the total CAPEX (Fig. 14)

1. Main building
2. Service buildings
3. Earthworks & development
4. Territory

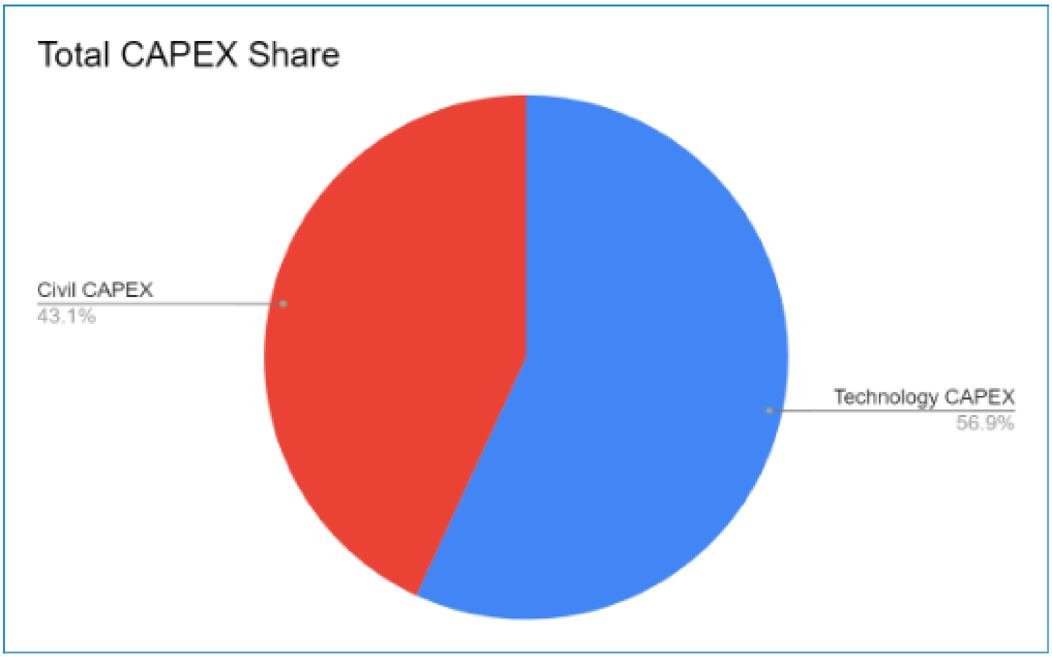

***Figure 14.*** *The allocation of cost of technology and cost of buildings and the surrounding areas.*

## COGS breakdown.

Further breakdown is specified for the net production processes (COGS – Cost of goods sold) (Fig. 15) and **does not include buildings/production equipment, other services, processing, marketing, administration cost (SG&A)**. The estimated prices are Exworks from origin country, excluding delivery, duties, taxes, insurance, etc. These estimates are based on 2021-2022 pricing. This is a general estimate, and item specifications or prices may vary from the initial estimate due to detailed design, regulations, local parameters, and fluctuations in the prices of goods and transportation.

Estimated COGS breakdown:

1. Post Larvae
2. Feed
3. Labor
4. Electricity
5. Heating
6. Insurance for livestock
7. Salt
8. Water / wastewater (annual replacement)
9. Pure Oxygen
10. Repairs

11. Packaging materials
12. Miscellaneous production expenses

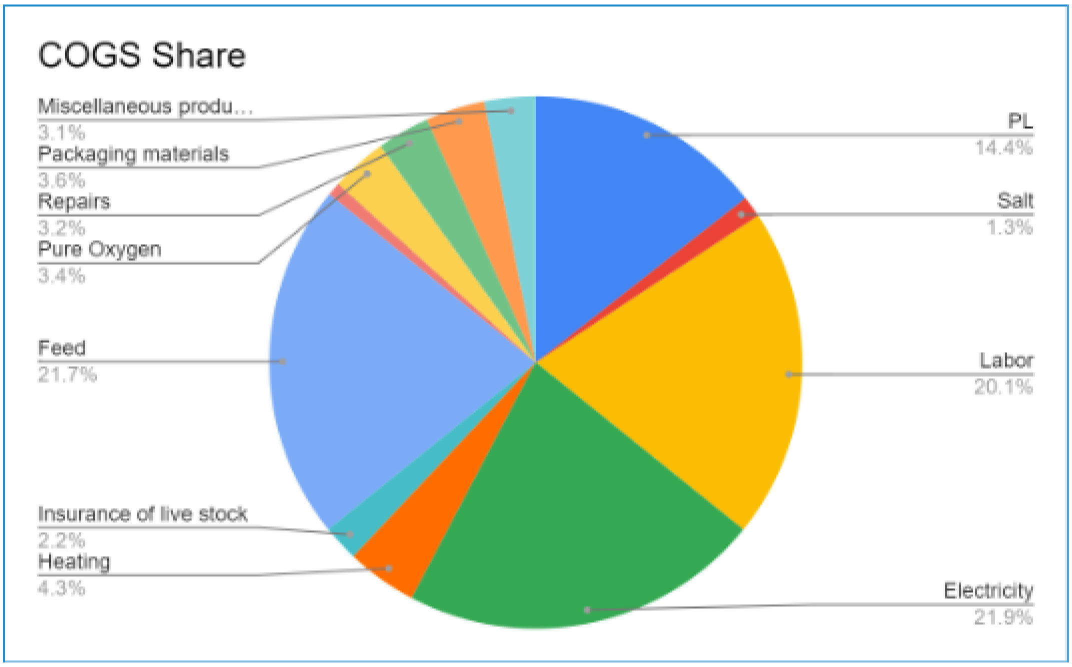

***Figure 15****. COGS – Cost of goods sold for a 1000 MTY warmwater shrimp production*

## 7.3 Social Performance Indicators (So-PIs) in Warmwater Aquaculture

Warmwater aquaculture refers to fish farming and seafood production in higher-temperature waters, which includes species such as tilapia, catfish, and shrimp. While it offers economic and food security benefits, it also introduces social challenges such as labour rights, environmental justice, and community displacement. Production of warmwater shrimp is a new economic activity in the Baltic Region, and it is not possible to analyse So-PI specific for this production form. The analysis therefore addresses RAS aquaculture in the Baltic Region, in general.

Social Performance Indicators (So-PI) are essential tools for assessing and managing the social impacts of organisations, particularly in sectors such as warmwater aquaculture. These indicators help evaluate how activities affect communities, employees, and other stakeholders, ensuring sustainable and socially responsible operations. This chapter delves into the application of So-PI within the warmwater sector, emphasizing the Baltic Sea region and Norway, and it highlights global best practices.

Here are some key aspects of So-PIs:

1. **Health**: Measuring access to healthcare, health outcomes, and the prevalence of diseases.
2. **Education**: Assessing literacy rates, school enrolment, and educational attainment.
3. **Economic Stability**: Evaluating employment rates, income levels, and economic opportunities.
4. **Housing and Living Conditions**: Looking at housing quality, affordability, and living standards.
5. **Social Inclusion**: Measuring the integration and participation of marginalised groups in society.
6. **Safety and Security**: Assessing crime rates, personal safety, and the effectiveness of law enforcement.

7. **Civic Engagement**: Evaluating participation in civic activities, such as voting and community involvement. (EPA 20217)

These indicators aid in evaluating how activities affect communities, employees, and stakeholders, ensuring sustainable and socially responsible operations.
So-PIs are crucial for ensuring that aquaculture contributes positively to local communities rather than causing harm. Some key dimensions of So-PIs include:

- **Stakeholder Engagement:** Ensuring that local communities, workers, and indigenous groups are involved in decision-making processes.
- **Labor Rights Protection:** Monitoring working conditions, fair wages, and workers' rights.
- **Community Development:** Assessing contributions to local infrastructure, education, and health services.
- **Social License to Operate:** Ensuring that businesses earn and maintain the trust of local communities.
- **Transparency & Reporting:** Promoting accountability through public sustainability reports.

## So-PIs in the Baltic Sea Region

The Baltic Sea region has seen an increase in aquaculture activities in response to a growing seafood demand. However, balancing economic growth with social responsibility remains a priority.

Key Social Performance Indicators (So-PIs) in this region include:

- **Community Involvement:** Many aquaculture projects are required to engage with local communities, ensuring that their concerns are addressed.
- **Employment Opportunities**: Hiring local workers and supporting skill development through vocational training programmes.
- **Environmental Education:** Many initiatives educate communities on sustainable practices, fostering greater support and collaboration.
- **Access to Coastal Areas:** Ensuring equal access to marine resources for small-scale fishers and indigenous communities.

One major initiative is the 'Baltic 2030: Bumps on the Road' report by the Council of the Baltic Sea States, which highlights the importance of sustainable development goals (SDGs) in the region. (Nordic Council, 2018).

## So-PIs in Norway

Norway is one of the largest aquaculture producers globally, particularly for species such as salmon. The country has a strong regulatory framework that prioritises both social and environmental sustainability.
Some of Norway's key So-PI initiatives include:

- **Strict Labour Laws:** Norwegian regulations ensure that aquaculture workers receive fair wages, safe working conditions, and union protections.
- **Indigenous Rights Protections:** Policies specifically protect the rights of Sámi communities who depend on fisheries and aquaculture for their livelihoods.
- **Research & Innovation Investments:** Norway invests heavily in R&D for sustainable aquaculture technologies, such as land-based fish farming to reduce environmental impact.
- **Transparency & Certification:** Norwegian companies follow Global Reporting Initiative (GRI) standards, ensuring transparent sustainability reporting.

## Global Best Practices in So-PIs for Warmwater Aquaculture

Several global models demonstrate how best practices in social performance can be successfully integrated into warmwater aquaculture. These include:

**A. Adherence to Global Standards**

Organisations worldwide adhere to GRI Standards, which provide comprehensive sustainability guidelines. These help ensure transparency in reporting social and environmental impacts.
Reference: globalreporting.org

**B. Community-Based Aquaculture in Southeast Asia**

Countries like Thailand and Indonesia have pioneered community-based aquaculture, where local fishers co-manage fish farms with private investors. This improves livelihood security while ensuring sustainable practices.

**C. Fair Trade Certification in Latin America**

Shrimp farms in Ecuador and Mexico have adopted Fair Trade certification, ensuring that farmers receive fair wages and better working conditions while meeting strict environmental and social performance benchmarks.

**D. Benchmarking & Performance Assessment (International Water Association)**

The International Water Association (IWA) has frameworks for assessing and improving the performance of water-dependent industries, including aquaculture.
Reference: iwa-network.org

**E. Sustainability Key Performance Indicators (KPIs)**

Sustainability KPIs help businesses track their progress in labour conditions, social inclusion, and local development.
Reference: purplegriffon.com

## Challenges in Implementing So-PIs for Warmwater Aquaculture

While Social Performance Indicators (So-PI) are crucial for Recirculating Aquaculture Systems (RAS), several key challenges hinder effective implementation:

- Regulatory Gaps: Many nations lack robust policy frameworks to enforce social sustainability metrics in aquaculture operations, making standardisation difficult across regions.
- Economic Pressures: RAS facilities often face financial constraints, leading to compromises in social responsibility initiatives to maintain profitability.
- Data Collection Issues: Unlike environmental parameters, social impacts in RAS operations are inherently qualitative and harder to measure consistently.
- Limited Community Awareness: Local communities around RAS facilities frequently lack understanding of their stakeholder rights and available support mechanisms.

## Recommendations for Strengthening So-PIs in Warmwater Aquaculture

To strengthen Social Performance Indicators (So-PIs) in warmwater aquaculture, several recommendations should be considered. Governments should mandate So-PI reporting in aquaculture industries to ensure standardised reporting. For example, the Southern Regional Aquaculture Center has implemented detailed reporting frameworks to monitor the impacts of various aquaculture practices (Southern Regional Aquaculture Center, 2020).

Standardised reporting aids in tracking progress and identifying areas for improvement. Companies should conduct regular community consultations to enhance stakeholder engagement. In Pakistan, community consultations on fisheries and aquaculture policy have proven effective in aligning industry practices with local needs and expectations (FAO, 2010).

These consultations ensure that the voices of local communities are heard and considered in decision-making processes. Governments and NGOs should provide training programmes for workers to build capacity. For instance, Southern Maine Community College offers short-term training programmes that cover topics such as farmed shellfish, algae species, and aquaculture production systems (Southern Maine Community College, website)

These programmes equip workers with the necessary skills to adopt sustainable practices and improve their overall performance.

Financial rewards should be offered to companies that excel in social performance as incentives for sustainable practices. Economic performance indicators, such as those used by the European Commission, can help identify companies that are making significant contributions to social sustainability (Guillén & Llorente, 2019)

These companies can be rewarded through subsidies or tax incentives to encourage continued excellence. Additionally, countries should exchange best practices and case studies to foster stronger global collaboration. The Global Salmon Initiative exemplifies successful collaboration by sharing experiences and working together to achieve ASC certification across salmon farms (Global Salmon Initiative, 2019).

Such collaborations accelerate improvements in social performance and sustainability in the aquaculture sector. By implementing these recommendations, the aquaculture industry can enhance its social performance, ensure the well-being of workers and communities, and contribute to the long-term sustainability of the sector.

Social Performance Indicators (So-PIs) are essential for balancing economic growth with social responsibility in warmwater aquaculture. The Baltic Sea region and Norway serve as strong examples of localised approaches, while global best practices provide valuable insights into achieving sustainable social performance.

By adopting and adapting these best practices, other regions can enhance their social performance, ensuring the well-being of both local communities and the environment.

## 7.4 Production Performance Indicators for warmwater shrimp (Pr-PIs)

In the context of a large (business-oriented) production facility for warmwater shrimp in a Recirculating Aquaculture System (RAS), Production Performance Indicators (Pr-PIs) are important for several reasons:

- Optimisation of production processes
- Quality control

- Resource management
- Scalability and expansion planning
- Risk management
- Compliance and reporting

Each Pr-PI provides a different lens through which the efficiency and effectiveness of the shrimp production process can be viewed. Together, they give a comprehensive picture of the operation's health, allowing for informed decision-making in both feasibility studies and business planning. Understanding and optimising these indicators are vital for ensuring the economic viability and sustainability of a large-scale shrimp farming operation in a RAS.

Pr-PIs that directly correlate to business KPIs:

- **FCR** – critical in aquaculture. Represents the efficiency of converting feed into shrimp biomass. Currently, an FCR of 1.5 to 1.8 is commonly targeted in clear-water RAS production of shrimp. Biofloc systems usually have lower FCR (closer to 1.2-1.4) due to nutrient recycling and supplemental feed source.
- **Growth rate** – Iin well-managed RAS for Vannamei shrimp, growth rate currently average 1 to 1.5 grams per week, reaching harvestable size of 18-25grams in 3-4 months.
- **Survival rate** – controlled conditions of RAS and reduced disease risk significantly increase survival rate. Due to more (and easier) control in clear-water RAS than in Biofloc, clear-water systems should indicate higher survival rates. But contrary opinions and mixed data also come from biofloc proponents.
- **Stocking density** – shrimp require more surface area rather than water volume per se, so in order to increase stocking density (without increasing water surface area), multi-layering water tank solutions are being used and improved. However, a stocking density that is too high can have negative effects as this study indicates. Further study on super-intensive grow-out at low salinity indicates that there is an optimal stocking density for best results.
- **Production cycle length**
- **Yield per unit area** ($m^2$ or $m^3$) and biomass output.

Although there are multiple laboratory studies with promising findings and insights, more reliable data on various Pr-PIs is needed in commercial applications. Furthermore, more real-world examples are needed to evaluate the effects of scaling up small facilities and accommodating the available technologies for large scale production.

## 7.5 Environmental Performance Indicators for Warmwater Aquaculture (En-PIs).

Environmental Performance Indicators (En-PIs) are metrics used to assess the environmental health and sustainability of various activities, regions, or countries. They help in understanding the impact of human activities on the environment and guide policy decisions. Here are some key aspects of En-PIs:

- **Air Quality**: Measuring pollutants like PM2.5, $NO_2$, and $SO_2$ levels.
- **Water Quality**: Assessing the cleanliness of water bodies and the effectiveness of wastewater treatment.
- **Biodiversity and Habitat**: Evaluating the conservation status of ecosystems and species.
- **Climate Change**: Tracking greenhouse gas emissions and climate policies.
- **Energy Use**: Looking at energy consumption patterns and the share of renewable energy.

- **Waste Management**: Monitoring waste generation and recycling rates.
- **Agriculture**: Examining sustainable farming practices and pesticide use.
- **Forestry**: Assessing deforestation rates and forest management practices.

These indicators provide a comprehensive view of environmental performance and help identify areas in need of improvement.

Recirculating Aquaculture Systems (RAS) are evaluated for their environmental impact using various performance indicators, although they are not specifically covered under the general Environmental Performance Index (EPI). However, studies and assessments have been conducted to measure the environmental footprint of RAS production.

A recent life cycle assessment (LCA) of a tilapia and clarias catfish farm in Sweden highlighted several key environmental performance indicators for RAS production (Bergman et al. 2020).

- **Energy Consumption**: RAS facilities typically have high energy demands for maintaining water quality and aeration. However, improvements in technology are reducing this burden.
- **Aquafeed Impact**: The production and use of aquafeed have significant environmental impacts, particularly due to the ingredients like fish oil, soy, and poultry by-products.
- **Water Use and Quality**: RAS systems are praised for their reduced water consumption and effective waste recycling, which are crucial for sustainable aquaculture.
- **Greenhouse Gas Emissions**: The energy used in RAS can contribute to greenhouse gas emissions, but this varies depending on the energy sources and efficiency of the system.

These indicators aid in understanding the sustainability and environmental impact of RAS production, providing a framework for improving practices and reducing the ecological footprint of aquaculture.

### Understanding Environmental Performance Indicators (En-PIs) in Warmwater Aquaculture

Warmwater aquaculture in RAS involves the farming of fish and seafood species that thrive in warmer temperatures, such as tilapia, shrimp, and catfish. This industry, while providing food security and economic benefits, also presents significant environmental challenges, such as pollution and emission of nutrients and GHGs, which may harm ecosystems.

Environmental Performance Indicators (En-PIs) help measure, monitor, and mitigate these impacts by tracking sustainability aspects, including:

- **Water Quality Management:** Monitoring nutrient levels, oxygen levels, and pollutants to ensure safe water conditions.
- **Carbon Footprint Reduction:** Assessing the greenhouse gas emissions associated with production, transportation, and feed sourcing.
- **Biodiversity Conservation:** Ensuring aquaculture does not negatively impact marine ecosystems and native species.
- **Waste Management:** Tracking and reducing organic waste, feed waste, and chemical runoff.
- **Sustainable Feed Use:** Monitoring the sustainability of fish feed ingredients, particularly in relation to overfishing of wild stocks.

The Baltic Sea is a highly sensitive marine ecosystem impacted by industrial activities, including aquaculture. En-PIs are critical for managing its environmental health. Some key environmental indicators used in the region include:

- **Eutrophication Control:** Measures to reduce nutrient overload, particularly phosphorus and nitrogen, which lead to algal blooms.
- **Eco-Friendly Aquaculture Practices:** Promotion of Integrated Multi-Trophic Aquaculture (IMTA), where different species are farmed together to minimise waste.
- **Water Monitoring Programs:** Regular assessments conducted by organisations like HELCOM (Helsinki Commission) to track pollution levels.
- **Sustainable Site Selection:** Restricting aquaculture to areas with minimal environmental sensitivity.

Norway is a **global leader in sustainable aquaculture**, particularly in salmon farming. The country has developed stringent environmental performance indicators to ensure sustainable operations. Key En-PI strategies include:

- **Fish Welfare and Health Regulations:** Strict guidelines on stocking densities, disease control, and antibiotic use.
- **Reduction of Sea Lice and Escapes:** Norwegian authorities implement monitoring programs to prevent farmed fish from escaping and interbreeding with wild populations.
- **Circular Economy in Aquaculture:** Focus on recycling fish waste into biofuels and fertilizers to minimise environmental impact.
- **Renewable Energy in Aquaculture:** Use of solar and wind power in aquaculture farms to reduce carbon emissions.

Several global best practices demonstrate how environmental performance can be successfully integrated into warmwater aquaculture. These include:

**ASC Certification (Aquaculture Stewardship Council)**
The ASC certification is a globally recognised standard, encouraging fish farms to minimise their environmental footprint.
Reference: asc-aqua.org

**IMTA** is used in Canada's aquaculture industry to reduce environmental impact by integrating multiple species, such as fish, shellfish, and seaweed. Innovative farms in the United States use recirculating aquaculture systems (RAS) that recycle water within closed systems, reducing water use and pollution. Ecuador's shrimp farms use mangrove-friendly aquaculture techniques, preserving coastal ecosystems while maintaining high production levels.
Reference: wwf.org

The Netherlands has pioneered **carbon-neutral fish farms**, reducing emissions by using renewable energy, alternative feed, and low-impact technologies.

### Challenges in Implementing En-PIs for Warmwater Aquaculture

Despite the benefits of Environmental Performance Indicators, several challenges persist:

- **Lack of Standardised Metrics:** Different countries and companies use varying sustainability metrics, making comparisons difficult.
- **Economic Constraints:** Many small-scale farmers lack the financial resources to implement high-tech sustainability solutions.

- **Regulatory Enforcement Issues**: Some regions have weak enforcement mechanisms for environmental protection laws.
- **Climate Change Impact:** Rising temperatures and changing oceanic conditions make environmental monitoring more complex.

### Recommendations for Strengthening En-PIs in Warmwater Aquaculture

To improve environmental performance in warmwater aquaculture, several recommendations should be considered. Countries should align En-PI frameworks with recognised global standards such as ASC, MSC (Marine Stewardship Council), and GRI (Global Reporting Initiative). Collaboration between governments, businesses, and NGOs is essential to drive innovation in sustainable aquaculture. More funding should be allocated to eco-friendly aquaculture innovations. Governments should require public reporting of En-PI performance to ensure stronger data collection and transparency. Additionally, training initiatives should be implemented to help farmers adopt low-impact and sustainable practices.

Environmental Performance Indicators (En-PIs) are essential for ensuring the long-term sustainability of warmwater aquaculture. The Baltic Sea region and Norway serve as models for strong regulatory frameworks and sustainability initiatives. Global best practices, such as IMTA in Canada, zero-water discharge systems in the US, and ASC certification provide valuable insights into effective environmental management. Addressing challenges such as regulatory inconsistencies, economic barriers, and climate change adaptation will be crucial for the future of sustainable aquaculture. By adopting and improving En-PI frameworks, countries can enhance their environmental sustainability, protect marine ecosystems, and ensure long-term viability for the aquaculture sector.

### Biofloc RAS vs Clear-water RAS systems comparison

Warmwater shrimp can be produced in clear-water RAS systems, with water treatment systems such as mechanical and biofilter, or in biofloc systems, where the nutrients from the shrimp are used to produce floc-particles that can feed the shrimp. (Ray et al (2017), Tierney & Ray (2018)). Table 11 indicates estimated differences in several key aspects between various RAS systems. These numbers are rough estimates derived from adjusting figures to match 1000 MTY production capacity for each system. Data is taken from various publicly available sources (companies' websites, financial reports, ASC certification data, publications etc.).

Each technology has its own advantages and disadvantages, but what can be clearly seen are the key difference between clear-water RAS and Biofloc RAS systems in some important KPIs listed.

***Table 11.*** *Comparison of warmwater shrimp productions in clear-water RAS systems and Biofloc systems.*

| Technology | Clear-water RAS | Clear-water RAS. Vibrio Suppression/ Electrocoagulation | Clear-water RAS. Raceway | Biofloc RAS |
|---|---|---|---|---|
| **Business examples** | SwissShrimp<br>White Panther | Natural Shrimp | Royal Caridea | Noray<br>Sun Shrimp |
| | | | | |
| **CAPEX (mil. USD) Scale up cost deduction coefficient - 0.7** | 45-55 | 30.5-35 | 57-60 | estimated <30 |

| | | | | |
|---|---|---|---|---|
| | | | | |
| **CAPEX per kg (USD)** | 50 | 33 | 58 | <30 |
| **Annual Yield in MT (adjusted & estimated)** | 1000 | 1000 | 1000 | 1000 |
| **Infrastructure needs m²** | 16,000 | 27,400 | 23,000<br>(only grow-out units) | 95,000 |
| **System size m3** | 15,500 | 20,000 | 40,000 | 75,000 |
| **Yield per m³ (KG)** | 50-55 | 44-48 | 22-24 | 15-18 |
| **Yield per m² of building (KG)** | 58-60 | 38-40 | 44-48 | 11-14 |
| | | | | |
| **Survival rate %** | 60 | 55-60 | 75-80 | 40-45 |
| **FCR** | 1.7-1.8 | 1.6--1.7 | 1.6 | 1.2-1.3 |
| **Production cycle (Weeks)** | 16 | 24 | 16 | 16 |
| **Product weight g.** | 20 | 23 | 22 | 20 |

# 8 KPIs for Salmon production – comparing productions in RAS and Open-Net Pen

Salmon production can be carried out using two primary methods: Recirculating Aquaculture Systems (RAS) and open-net pen. Each method has its own economic, environmental, and operational advantages and disadvantages.

## 8.1 Key details for Recirculating Aquaculture Systems (RAS)

### Components and Functioning

- **Fish Tanks**: The core component where fish are grown. Tanks are often designed to facilitate self-cleaning through circular hydraulic patterns, which help in the uniform distribution of water and feed, and transport waste to the middle of the tank for removal (University of Missouri Extension, 2023).
- **Filtration Units**: These units clean the water by removing solids, nutrients, and toxins. The filtration process typically includes:
    - **Solids Removal**: Separates solid waste such as uneaten feed and fish faeces.
    - **Biofiltration**: Converts harmful ammonia excreted by fish into less toxic nitrate through nitrifying bacteria (Golfand, 2023).
    - **Degassing**: Removes carbon dioxide produced by fish and bacteria.
    - **Oxygenation**: Increases dissolved oxygen levels to support fish health (University of Missouri Extension, 2023).
- **Water Treatment**: Involves multiple steps to maintain water quality, including heating/cooling and sterilization. This ensures a stable environment that promotes fish growth and health (Golfand, 2023).

**Advantages**

- **Water Conservation**: RAS significantly reduces the need for fresh water by recycling and treating the same water multiple times (Golfand, 2023).
- **Environmental Control**: Provides better control over water quality, temperature, and other environmental factors, leading to improved fish health and productivity (University of Missouri Extension, 2023).
- **Reduced Environmental Impact**: Minimises nutrient discharge into the environment, reducing the risk of pollution (Vielma et al., 2022).

**Challenges**

- **High Initial Costs**: Requires substantial investment in infrastructure and technology (Golfand, 2023).
- **Energy Consumption**: High energy requirements for water pumping, filtration, and temperature control contribute to a larger carbon footprint (Vielma et al., 2022).
- **Technical Complexity**: Requires skilled management to maintain system efficiency and prevent failures (University of Missouri Extension, 2023).

### Applications

RAS are used for various species, including salmon, trout, and other high-value fish. It is particularly beneficial in regions with limited water resources or strict environmental regulations (Golfand, 2023).

Overall, RAS offer a sustainable and efficient method for aquaculture, balancing economic viability with environmental responsibility.

### Economic Performance

The economic performances of RAS and open-net pen vary significantly. According to Liu et al. (2016), RAS involve higher initial capital expenditure due to the need for sophisticated infrastructure and technology. However, RAS offer better control over environmental conditions, leading to potentially higher productivity and lower mortality rates (Liu et al., 2016). In contrast, open-net pens have a lower initial cost but are more susceptible to environmental fluctuations and disease outbreaks, which can affect overall productivity (Liu et al., 2016).

The University of Missouri Extension (2023) highlights that the operating expenses for RAS include high energy costs for water pumping and treatment, while open-net pen systems incur lower energy costs but higher feed conversion ratios. This means that while RAS might have higher upfront and operational costs, it can achieve better feed efficiency and potentially higher yields (University of Missouri Extension, 2023).

### Environmental Impact

Environmental considerations are crucial in choosing between RAS and open-net pen. RAS is known for its ability to minimise environmental impact by recycling water and reducing nutrient discharge. Golfand (2023) notes that RAS can significantly reduce ammonia and nitrite levels, which are harmful to fish and the environment. However, the high energy consumption required for RAS operations contributes to a larger carbon footprint compared to net pen systems (Golfand, 2023).

In the Baltic region, RAS have been shown to reduce phosphorus and nitrogen discharges by approximately 80-90% compared to cage aquaculture, as reported by Vielma et al. (2022). Despite this, the overall carbon footprint of RAS remains higher due to the energy-intensive nature of the system (Vielma et al., 2022).

### Social and Ecological Benefits

Laine et al. (2023) conducted a cost-benefit analysis comparing the social and ecological benefits of RAS and open-net pen systems. They found that open-net pen systems generally offer higher net benefits for rainbow trout production due to lower costs and higher market prices. However, for European whitefish, RAS narrow the gap, providing a more competitive alternative (Laine et al., 2023). The study also highlights the challenges posed by regulatory frameworks, such as the EU’s Water Framework Directive, which can hinder the expansion of aquaculture production (Laine et al., 2023).

## 8.2 Key details for Salmon Production in Open-Net Pen

Open-Net Pen is a widely used method for salmon production, particularly in coastal and offshore areas. This method involves the use of large, floating net enclosures anchored in natural water bodies, allowing salmon to grow in a more natural environment. Here are some key aspects of open pen cage systems:

#### Economic Performance

The economic performance of Open-Net Pen is generally favourable due to lower initial capital expenditure compared to Recirculating Aquaculture Systems (RAS). According to Liu et al. (2016), open-net pen systems require less sophisticated infrastructure and technology, which translates to lower upfront costs. However, these systems are more susceptible to environmental fluctuations and disease outbreaks, which can impact overall productivity (Liu et al., 2016).

Operating expenses for open-net pen are typically lower than those for RAS. The University of Missouri Extension (2023) notes that open-net pen systems incur lower energy costs since they rely on natural water currents for water exchange and oxygenation. However, they tend to have higher feed conversion ratios, meaning more feed is required to produce the same number of fish compared to RAS (University of Missouri Extension, 2023).

**Environmental Impact**
Open-net pen systems have a significant environmental footprint due to their interaction with the surrounding ecosystem. One of the primary concerns is nutrient discharge, as waste products from the fish, including uneaten feed and faeces, are released directly into the water. This can lead to eutrophication, which negatively impacts water quality and local marine life (Liu et al., 2016).

Additionally, open-net pen systems are vulnerable to disease outbreaks and parasite infestations, such as sea lice, which can spread to wild fish populations. The use of chemicals and antibiotics to manage these issues can further impact the environment. Despite these challenges, open-net pen cages have a lower carbon footprint compared to RAS due to their lower energy requirements (Golfand, 2023).

**Social and Ecological Benefits**
Open-net pen systems offer several social and ecological benefits. They provide employment opportunities in coastal communities and contribute to local economies. The visual and physical presence of these farms can also promote awareness and education about aquaculture practices (Laine et al., 2023).

From an ecological perspective, open-net pen systems allow for the natural behaviour of salmon, as they are exposed to natural light cycles and water conditions. However, the potential for escapees to interbreed with wild populations poses a risk to genetic diversity and the health of wild stocks (Laine et al., 2023).

Open-net pen systems are a cost-effective method for salmon production with lower initial and operating costs compared to RAS. However, they come with significant environmental challenges, including nutrient discharge and disease management. The choice between open-net pen systems and RAS will depend on specific operational goals, environmental regulations, and local conditions.

***Table 12**. A comparison of RAS with Open-Net Pen.*

| Performance Indicators | RAS | Open-Net Pen |
|---|---|---|
| Economic Performance: **Initial Costs**: | Require higher initial capital expenditure due to the need for sophisticated infrastructure and technology (Liu et al., 2016). | Lower initial costs as they rely on simpler infrastructure and natural water bodies (Liu et al., 2016). |
| **Operating Costs**: | Higher operating expenses, primarily due to energy costs for water pumping, filtration, and temperature control (University of Missouri Extension, 2023). | Lower energy costs since they utilise natural water currents for water exchange and oxygenation, but higher feed conversion ratios |

| | | |
|---|---|---|
| | | (University of Missouri Extension, 2023). |
| **Productivity**: | Offer better control over environmental conditions, potentially leading to higher productivity and lower mortality rates (Liu et al., 2016). | More susceptible to environmental fluctuations and disease outbreaks, which can affect overall productivity (Liu et al., 2016). |
| Environmental Impact: **Nutrient Discharge**: | Minimise environmental impact by recycling water and reducing nutrient discharge. Significantly reduce ammonia and nitrite levels (Golfand, 2023). | Release waste products directly into the water, leading to potential eutrophication and negative impacts on local marine life (Liu et al., 2016). |
| **Carbon Footprint**: | Higher carbon footprint due to energy-intensive operations (Golfand, 2023). | Lower carbon footprint as they have lower energy requirements (Golfand, 2023). |
| Social and Ecological Benefits **Employment and Community Impact**: | Can be located closer to urban areas, providing employment opportunities and reducing transportation costs (Laine et al., 2023). | Provide employment opportunities in coastal communities and contributes to local economies (Laine et al., 2023). |
| **Ecological Considerations**: | Reduce the risk of escapees interbreeding with wild populations, thus protecting genetic diversity (Vielma et al., 2022). | Allow for natural behaviour of salmon but pose a risk to genetic diversity and the health of wild stocks due to potential escapees (Laine et al., 2023). |

The choice between RAS and open-net pen systems for salmon production depends on various factors (Table 12), including economic performance, environmental impact, and regulatory considerations. RAS offer better control over production conditions and lower environmental impact in terms of nutrient discharge, but these systems have higher energy costs and a larger carbon footprint. Open-net pen cages are more cost-effective initially and have lower energy requirements but are more vulnerable to environmental risks and disease outbreaks. Each system has its own set of trade-offs, and the optimal choice will depend on specific operational goals and local conditions.

## 8.3 Economic Performance Indicators for a salmon production (Ec-PIs)

In the context of salmon production, the Economic Performance Index (EPI) is a crucial metric for evaluating the financial viability of different farming methods. A study by Liu et al. (2016) compared the investment and operational costs of producing 3,300 metric tons (Mt) of salmon using Recirculating Aquaculture Systems (RAS) and open-net pen systems (ONP).

**Investment Costs**

The investment cost for RAS was significantly higher at $53.5 million compared to $29.7 million for ONP (Liu et al., 2016). This substantial difference is primarily due to the sophisticated infrastructure and technology required for RAS, which includes advanced filtration systems, water treatment facilities, and controlled environment setups. In contrast, ONP rely on simpler infrastructure, utilising natural water bodies for fish rearing, which reduces initial capital expenditure.

### Operational Costs

Operational costs also vary between the two systems. RAS incur higher operating expenses due to the energy-intensive processes involved in water pumping, filtration, and temperature control. The University of Missouri Extension (2023) highlights that these systems require continuous monitoring and maintenance to ensure optimal water quality and fish health, leading to increased energy consumption and labour costs. On the other hand, ONP benefit from lower energy costs as they utilise natural water currents for water exchange and oxygenation. However, they tend to have higher feed conversion ratios, meaning more feed is required to produce the same number of fish compared to RAS (University of Missouri Extension, 2023).

### Economic Attractiveness

The economic attractiveness of land-based salmon farming, particularly in Norway, has been explored in a master thesis by Solheim and Trovatn (2019). Their research indicates that despite the higher initial and operational costs, RAS can offer better control over environmental conditions, potentially leading to higher productivity and lower mortality rates. This control can translate into more consistent production outputs and potentially higher market prices for the fish.

Solheim and Trovatn (2019) also conducted a Monte Carlo simulation to capture the uncertainty in cost components and found that the break-even point for land-based farming is an implicit maximum total cost per kilogram (HOG) of NOK 50.1 when using a 20-year modelling period and forward price estimates. This analysis underscores the importance of considering long-term economic performance and market conditions when evaluating the viability of RAS.

Monte Carlo simulation involves running many simulations to model the probability of different outcomes in a process that cannot easily be predicted due to the intervention of random variables. By using random sampling and statistical modelling, it helps in estimating the probability distribution of potential outcomes.
In the context of economic performance analysis for salmon production, Monte Carlo simulation can be used to model the uncertainty in cost components and market conditions. For example, Solheim and Trovatn (2019) used Monte Carlo simulation to capture the variability in investment and operational costs for land-based salmon farming. By running multiple simulations, they were able to estimate the probability distribution of the total cost per kilogram of salmon produced.

The Economic Performance Index for salmon production in RAS and ONP reveals distinct differences in investment and operational costs. While RAS require higher initial and ongoing expenditure, these systems offer better control over production conditions, which can lead to higher productivity and potentially greater economic returns in the long run. ONP, with their lower initial costs and energy requirements, present a more cost-effective option but are more susceptible to environmental risks and disease outbreaks. The choice between these systems will depend on specific operational goals, environmental regulations, and market conditions.

## CAPEX

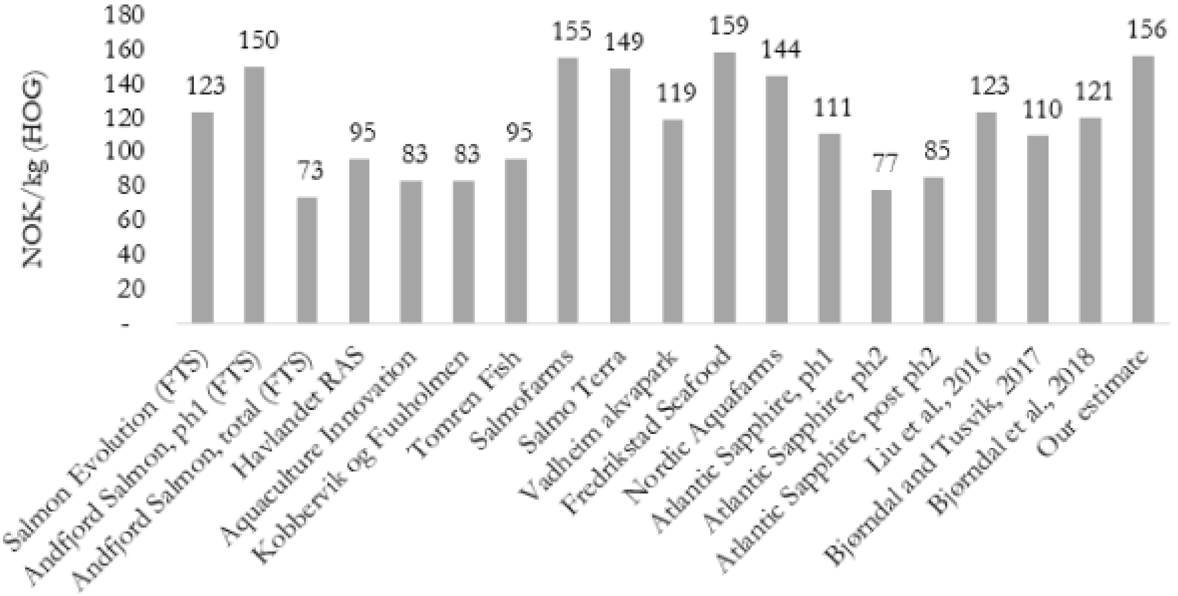

***Figure 16.*** *Capital expenditures per kg (HOG) of planned facilities I Norway (1 NOK= 0.10 EUR or 0.11 USD in 2019). From (Solheim & Trovatn 2019)*

Fig. 16 shows the **CAPEX (Capital Expenditures) per kg (HOG)** comparison across various land-based salmon farming projects in Norway and Atlantic Sapphire in Florida, based on different studies. The development of CAPEX over time can be analysed by looking at trends in reported costs across multiple sources.

**Key Observations:**

Variation in CAPEX Across Projects:

- CAPEX values range from 73 NOK/kg (HOG) to 159 NOK/kg (HOG), showing a significant cost difference depending on technology, location, and project scale.
- Some projects, like Atlantic Sapphire ph2 (77 NOK/kg) and certain early-stage studies (e.g., Bjørndal and Tusvik 2017 at 85 NOK/kg), have lower CAPEX compared to newer projects.

**Increasing CAPEX in Recent Years:**

a. More recent projects, such as Atlantic Sapphire ph1 (144 NOK/kg) and ph2 (111 NOK/kg), exhibit higher CAPEX compared to older studies.
b. Newer estimates, like the report's estimate (156 NOK/kg), suggest a rising trend in costs.
c. Projects like Salmon Terra (155 NOK/kg) and Valheim AquaPack (149 NOK/kg) indicate higher CAPEX requirements, likely due to new technologies, inflation, and sustainability measures.

**Historical Trends:**

a. Studies from Bjørndal and Tusvik (2018 og 2019) show lower CAPEX values (85–123 NOK/kg), indicating that initial expectations for land-based salmon farming were lower than current estimates.
b. The costs of newer RAS (Recirculating Aquaculture Systems) projects seem to be higher, reflecting increased investments in infrastructure, sustainability, and biosecurity.

The trend suggests an increase in CAPEX over time due to rising costs of land-based aquaculture infrastructure, stricter environmental regulations, and higher biosecurity requirements. However, economies of scale and technological improvements (e.g., better RAS efficiency) may help stabilize or reduce CAPEX in the future.

## CAPEX for RAS and Open-Net Pen (ONP)

Table 13 below shows capital and net investment costs for Atlantic salmon production using two different systems: an open-net pen system (ONP) and a recirculating aquaculture system (RAS) split up according to different elements and types of equipment. For a 3,300t production of Atlantic Salmon the CAPEX is 53.6M US$ for the RAS and 29.7M US$ for the ONP. This cost corresponds to 16 US$ per Kg production capacity in a RAS and 9 US$ per kg production capacity in an ONP-system. The economic performance indicators are presented as investment costs, not profits or returns. To calculate profitability, additional information such as revenue, operating expenses (beyond capital expenses), and production yields would be needed.

***Table 13.*** *Capital expense for a 3,300 MT Atlantic salmon production in an open-net pen system and in a RAS system (from Liu et al 2016).*

| ONP System Cost Components | Cost (US$) |
|---|---|
| Licenses | 25,571,429 |
| Floating Rings | 1,834,286 |
| Nets | 857,143 |
| Moorings | 342,857 |
| Boats | 1,285,714 |
| Feed Barges | 1,371,429 |
| Camera Systems | 214,286 |
| Feed Distributors | 34,114 |
| Power Systems | 188,571 |
| Total | 29,699,829 |

| LBCC-RAS System Cost Components | Cost (US$) |
|---|---|
| RAS Systems | 26,640,557 |
| Effluent Treatment | 3,487,500 |
| Water Supply | 675,000 |
| Processing | 2,112,030 |
| Building | 9,426,413 |
| Engineering | 5,080,980 |
| Construction Management | 1,058,538 |
| Bond | 254,049 |
| Contingency (10%) | 4,848,102 |
| Total | 53,583,169 |

**Capital Expenses (Table 13):**

- **Significantly Higher Initial Investment for RAS:** The RAS system shows a substantially higher capital expense ($53,583,169) than the ONP system ($29,699,829). This difference indicates the much larger upfront investment required for RAS technology. The major cost driver for the RAS system is the RAS system itself.
- **Cost Breakdown:** Both systems present detailed breakdowns of their respective cost components. This allows for a comparison of the relative importance of different elements within each system.

For example, in the ONP system, licenses and floating rings are significant cost drivers, while in the RAS system, the RAS system and effluent treatment are major expense items.

- **Contingency:** The RAS system include a contingency of 10%, illustrating the understanding that unexpected costs can arise during projects of this nature.

For a 1000 t production of Rainbow trout the CAPEX was recalculated to be 14.7M US$ (1 EUR=1.08 USD) for the RAS and 3.2M US$ for the ONP (Laine et al., 2023). This cost corresponding to 15 US$ per Kg production capacity in a RAS and 3 US$ per kg production capacity in a ONP-system. The CAPEX for RAS was in the same range as Liu (2016), whereas the CAPEX for the ONP was significantly lower.

***Table 14**. Net Cage Investments (table 1) and RAS Investments (table 2) in Laine et al 2023.*

| **Net Cage Investments (€)** | **Rainbow Trout 1,000t** |
|---|---|
| Frames | 444,000 |
| Nets | 228,000 |
| Mooring Systems | 114,000 |
| Anchors | 100,800 |
| Vessels (incl. feeding) | 1,200,000 |
| Others | 218,400 |
| Gutting | 700,000 |
| Total | 3,005,200 |
| Source: Kankainen and Mikalsen (2014) | |

| **RAS Investments (€)** | **Rainbow Trout 1,000t** |
|---|---|
| Tanks and feeding | 3,009,000 |
| Processing the water | 1,609,000 |
| Aeration and oxygenation | 1,054,000 |
| Disinfection | 552,000 |
| Monitoring and controlling | 664,000 |
| Land and Construction | 5,514,000 |
| Gutting | 700,000 |
| Wastewater Treatment Unit | 500,000 |
| Total | 13,583,000 |
| Source: Wright and Arianpoo (2010) EMFF. | |

**Net Cage Investments (Table 14-1):**

- **Species and Scale Impact:** This table compares net cage investments for rainbow trout and whitefish production, at different scales (1000 tons vs 200 tons). It demonstrates that larger-scale production generally leads to higher costs, although not proportionally higher in all cases. Specific items show differing scalability.
- **Cost Variation Between Species:** The cost differences between rainbow trout and whitefish production highlight that species selection impacts the economic feasibility of the operation.

**RAS Investments (Table 14-2):**

- **RAS Cost Breakdown by Component:** This table provides a cost breakdown for RAS systems for rainbow trout and whitefish production at different scales. Like Table 1, it reveals that larger-scale operations incur higher costs. This table focuses specifically on the core components of the RAS system, making it a valuable comparison point for those evaluating the feasibility of RAS.

The reports (Liu 2016 and Laine et al., 2023) suggest that RAS systems demand a much higher initial capital investment than ONP systems. However, the long-term economic viability is not directly addressed. It would be necessary to address factors such as operating costs, production yields, disease resistance, and market prices to determine the overall economic performance and to determine which system is ultimately more cost-effective. A life-cycle cost analysis that includes operational expenses, maintenance, and potential revenue would be necessary to draw robust conclusions about which system is more economically feasible.

The economic **aspects of marine pen cage and land-based salmon production** reveal significant differences in resource utilisation, efficiency, and environmental impact. Understanding these factors is crucial for sustainable aquaculture practices.

Resource Utilisation

- Marine cage farming is heavily reliant on auxiliary energy, being approximately ten times more dependent than land-based systems (Folke, 1988).
- Land-based aquaculture, particularly using recirculation systems, has shown improved water efficiency, reducing water consumption from 1,000-1,700 m³/kg to 100-200 m³/kg of fish produced (Blancheton et al., 2007).

Economic Efficiency

- The productivity of land-based systems has increased significantly, with feed conversion ratios improving from 1.5-1.8 to below 1.0, indicating reduced waste and lower environmental impact (Blancheton et al., 2007).
- Cage farming, while productive, faces challenges related to energy costs and environmental sustainability, necessitating careful economic planning for long-term viability (Jolly & Clonts, 1993).

In contrast, while marine cage farming offers high yields, its reliance on natural ecosystems and energy inputs raises concerns about sustainability. Balancing these economic aspects is essential for the future of aquaculture.

## Cost of goods sold (COGS)

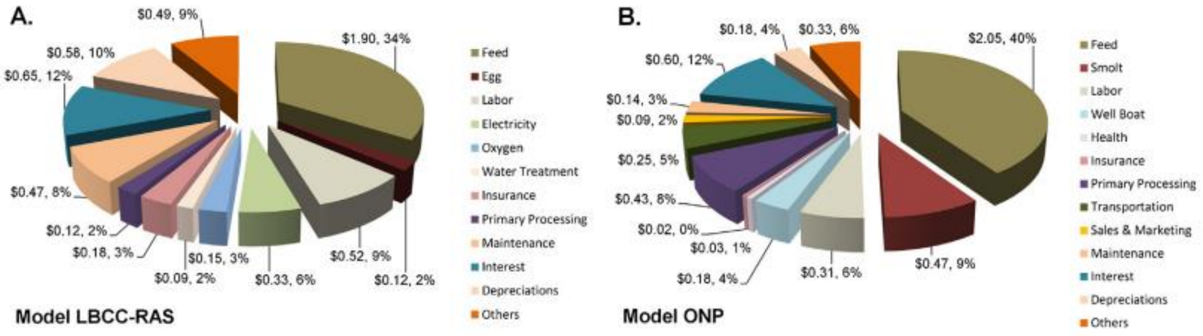

***Figure 17****. Estimated production costs (US$/kg HOG according to the investments, product price estimates and the biological production plans for a model 3300 MT HOG Atlantic salmon. A: RAS farm. B: ONP farm (Liu et al 2016)*

Fig. 17 presents a cost breakdown for producing Atlantic salmon using two different systems: a land-based recirculating aquaculture system (LBCC-RAS) and an open-net pen system (ONP). The costs are expressed as US$/kg of harvested fish (HOG). The total production cost for a RAS is 5.60 US$/kg and 5.08 US$/kg in an ONP.

**Key Observations:**

- **Dominant Cost isFeed:** For both systems, feed is the most significant cost component, accounting for approximately 34% (ONP) and 40% (LBCC-RAS) of the total production cost. This highlights the crucial role of feed efficiency in the overall economic performance.
- **Labour Costs Relatively Similar:** Labour costs appear relatively similar in both systems, representing around 6-9% of the total. This suggests that labour is a consistent cost factor regardless of the production method.
- **Higher Overall Costs for RAS:** The LBCC-RAS system displays a higher overall production cost per kg of fish than the ONP system. Although the pie charts do not directly provide the total cost figures, the visual representation clearly shows that the sum of all cost components is greater for RAS.
- **Significant Differences in Other Costs:** There are noticeable differences in the cost percentages of other components between the two systems, such as electricity, water treatment, and insurance. These discrepancies are likely linked to the inherent differences in infrastructure and operational requirements between RAS and ONP systems. For instance, RAS necessitates higher energy consumption for water circulation and treatment.
- **Depreciation & Others:** Both systems include categories for 'Depreciation' and 'Others,' which may cover various costs, and a more detailed breakdown would enhance the analysis.

**Implications and Further Considerations:**

- **Economic Viability:** The chart provides valuable insights into the relative cost structures of each system. However, to assess the overall economic viability of each approach, information on revenue (selling price of salmon) is needed to calculate profit margins. A comparison of the profit margins between these two systems is needed for a definitive economic evaluation.
- **Scale and Location:** The production costs shown might be specific to the model farms presented in the figure and could vary according to farm scale and geographic location due to factors such as labour costs, energy prices, and regulatory requirements.
- **Sustainability:** While not explicitly shown, environmental impacts and sustainability aspects are likely to differ significantly between RAS and ONP systems. The production cost data does not include these factors.

Fig. 18 offers a useful comparative cost analysis of RAS and ONP salmon production. However, a complete economic evaluation requires incorporating revenue and a detailed breakdown of cost components, plus considering the broader environmental and social aspects of each system. A cost-benefit analysis would enhance the understanding of the relative economic viability of the two methods.

***Table 15.*** *Presents a net present value (NPV) analysis comparing the profitability of net cage and RAS systems for rainbow trout and whitefish production at different scales. The NPV is calculated per kilogram of fish produced, providing a measure of economic efficiency.*

| | | **Net Cage** | | **RAS** | |
|---|---|---|---|---|---|
| | | **Rainbow Trout 1000t** | **Whitefish 200t** | **Rainbow Trout 1,000t** | **Whitefish 200t** |
| **Selling Revenues** | | 3.15 | 6.73 | 2.94 | 6.84 |
| **Investment Costs** | | 0.33 | 0.98 | 0.84 | 1.72 |
| | **Initial Investments** | 0.16 | 0.54 | 0.68 | 1.37 |
| | **Additional Investments** | 0.17 | 0.43 | 0.17 | 0.35 |
| **Production Costs** | | 2.00 | 3.09 | 3.35 | 4.93 |
| | **Fingerlings** | 0.21 | 0.66 | 0.14 | 0.50 |
| | **Feed** | 1.13 | 1.23 | 1.18 | 1.24 |
| | **Energy** | 0.00 | 0.00 | 0.43 | 0.50 |
| | **Labor** | 0.16 | 0.40 | 0.34 | 1.02 |
| | **Repair and Maintenance** | 0.04 | 0.08 | 0.15 | 0.32 |
| | **Other Costs** | 0.46 | 0.72 | 1.10 | 1.37 |

**Key Observations:**

- **Higher Revenues for Whitefish:** Whitefish consistently shows higher selling revenues (€/kg) than rainbow trout in both net cage and RAS systems. This indicates a potentially higher market value or price for whitefish.
- **Higher Initial Investment for RAS:** The initial investment costs (€/kg) are significantly higher for RAS than for net cages, regardless of the species or scale. This aligns with the capital expense data from the previous tables, confirming the higher upfront investment required for RAS technology.
- **Production Costs Vary Significantly:** Production costs (€/kg) demonstrate notable variations across species and production systems. Feed is a major cost component across the board, with other costs (such as labour and repair/maintenance) adding further expense.
- **RAS Shows Potential for Higher Net Profitability:** Although initial investments are higher, the overall net present value, considering revenues and costs, appears higher for RAS systems for both species and scales compared to net cages. However, a direct comparison requires more data on the period and discount rate used in the NPV calculation to understand the meaning of these numbers in a true economic sense.

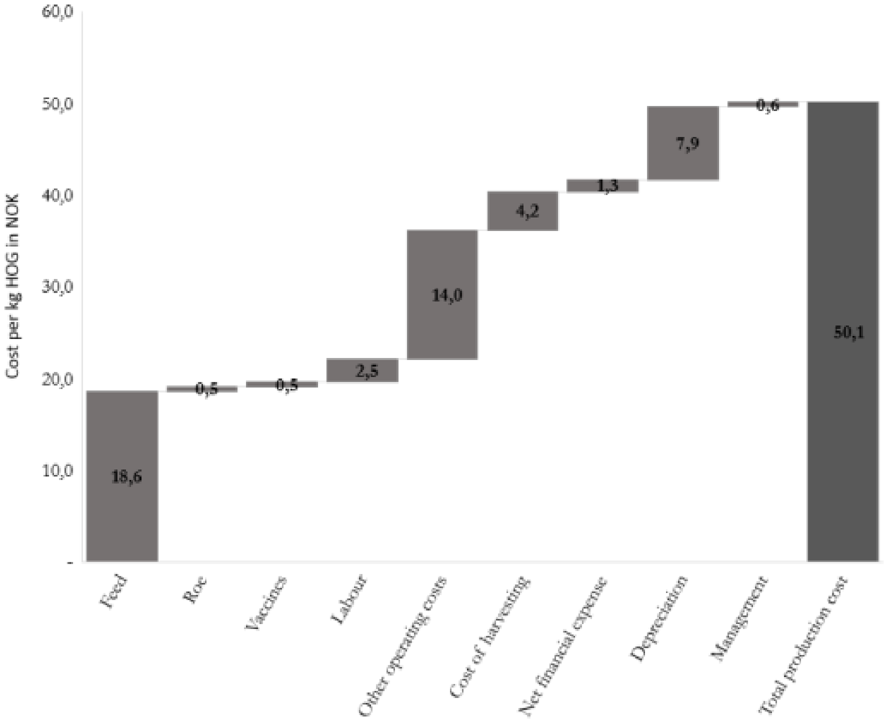

***Figure 18**. Total production cost per kg live weight in steady state (From Solheim & Trovatn 2019)*

Fig. 18 shows the cost per kg (HOG) in an RAS, divided into the different cost components in steady state. The total production cost is estimated to be NOK 50.1 per kg (HOG), corresponding to EUR 3.70 per kg live weight (Solheim & Trovatn 2019, Fig. 7.10). This is a lower cost than reported by Liu et al, 2016.

## What is the right size of a RAS from an economical perspective

According to the largest RAS equipment suppliers, the minimum volume of fish farming at which construction is economically feasible is around 2.5 thousand metric tons, as the construction cost decrease at the size of farm (Fig. 19). Furthermore, RAS is still a new technology, and large farms are established at a high risk due to lack of experience and knowledge in designing and running these facilities. The volume of capital expenditures for the construction of 2.5 thousand tons of salmon amounts to around 50-60 million CA$ corresponding to 35-42M USD. This results in a CAPEX of up to 16.8 USD per kg. This cost does not include working capital to support operation for at least 2-3 years until first harvest.

The expected internal rate of return (IRR) ranges between 20% and 30%, with a typical payback period of 7-10 years. Operational costs are largely driven by feed, which accounts for 40% of total expenses, with a feed conversion ratio (FCR) of 1.2. Energy costs, particularly for water cooling and recirculation, are significant. One of the key challenges is high mortality rates, especially during the smoltification phase, and efficient biofiltration and farm design are therefore essential. RAS farming is ESG-compliant, offering a sustainable alternative with reduced environmental impact and lower antibiotic use.

Salmon farming in RAS presents a highly profitable opportunity due to the strong demand in Europe, North America, and Asia. Locally produced RAS salmon commands a 10-50% price premium, with prices reaching $28-35 per kilogram in Florida, compared to the national average of $18-23 per kilogram in the U.S. While requiring high initial investments, well-managed RAS farms can generate high returns and contribute to food security through local, sustainable salmon production.

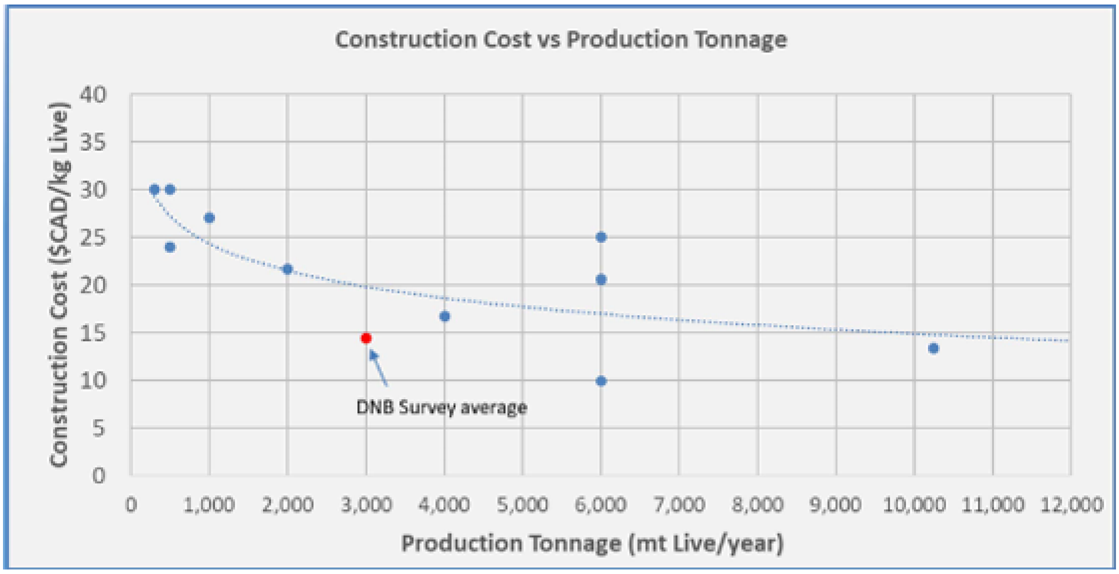

***Figure 19.*** *Effect of scale on capital per kg of production capacity*

## 8.4 Social Performance Indicators for a salmon production (So-PIs)

Social Key Performance Indicators (So-PIs) for aquaculture are vital for evaluating the industry's social impact and responsibility (Table 16). These indicators offer a comprehensive view of how aquaculture operations influence their workers, local communities, and broader societal stakeholders (Garlock et al., 2024; Anderson et al., 2020).

### Employment and Labour Practices

Employment and labour practices are fundamental aspects of social performance in aquaculture. These indicators assess the number of jobs created by the aquaculture operation, ensuring that employment opportunities are provided to local communities. Another critical indicator is worker safety, as the measures in place to protect workers from accidents and injuries are evaluated. The wages are scrutinised to ensure that workers are compensated appropriately according to industry standards and labour laws. Additionally, adherence to labour laws is monitored to guarantee compliance with local and international regulations.

### Community Engagement

In the community engagement indicator, the level of interaction and support extended to local communities by the aquaculture operation is assessed. Ways of bettering this indicator include supporting local businesses by sourcing supplies locally, offering community outreach programs, and involving community members in decision-making processes. Effective community engagement fosters positive relationships and ensures that the aquaculture operation contributes to the local economy and social fabric.

## Health and Well-Being of Workers

The health and well-being of workers are paramount in aquaculture operations. Indicators in this category monitor the physical and mental health of workers, ensuring they have access to healthcare services and work in safe conditions. Efforts to maintain the workers' healthy work-life balance are also evaluated, recognising the importance of personal well-being alongside professional responsibilities.

## Gender Equity

Gender equity is assessed by evaluating the promotion of gender equality within the aquaculture industry. Possible improvements of this indicator can arise through fostering opportunities for women in leadership roles and ensuring equal pay for equal work. Gender distribution across different production technologies, such as hatcheries and grow-out facilities, is also monitored to promote inclusivity and diversity.

## Stakeholder Engagement

The stakeholder engagement indicator involves assessing the involvement of various stakeholders, including local communities, non-governmental organizations (NGOs), and government agencies, in the decision-making and planning processes of the aquaculture operation. Effective stakeholder engagement ensures that diverse perspectives are considered, fostering transparency and accountability.

## Transparency and Accountability

Transparency and accountability are crucial for maintaining trust and integrity in aquaculture operations. Indicators in this category assess whether operations are open about their practices, environmental impact, and any potential social concerns. Mechanisms for accountability are evaluated to ensure that the operation is held responsible for any negative consequences.

## Education and Training

Education and training opportunities for employees are essential for their personal and professional development. Indicators in this category evaluate the efforts made by aquaculture operations to provide training programs, enhancing the skills and knowledge of their workforce.

## Conflict Resolution

The conflict resolution indicator is a measurement of the ability of aquaculture operations to address and resolve disputes with local communities or other stakeholders. Effective conflict resolution ensures that potential sites of conflict, such as water use and land use, are managed fairly and responsibly, maintaining harmonious relationships.

***Table 16*** *Social Performance Indicators for Aquaculture (So-PI) Source: Monica Klein, WISMAR)*

| So-PI | Definition & Indicators |
|---|---|
| Level of Education | Indicators: Level of education (low / medium / high / unknown) |
| Gender | Indicators: Gender distribution (male / female / unknown), Gender distribution per production technology (hatchery, grow-out) |
| Age | Indicators: Age distribution |
| Nationality | Indicators: Nationality (national / EU / EEA / other / unknown) |
| Labour Productivity | Ratio between GVA from aquaculture and number of persons employed in aquaculture |

| | |
|---|---|
| Employment | Indicators: Type of employment (full-time vs seasonal), Number of persons employed in aquaculture per production system |
| Apparent Consumption | Per capita apparent consumption of seafood |
| Work Safety | Indicators: Number of incidents |
| Local Wealth Building | Approach focused on local economic development, redirecting wealth back into the local economy, and placing control and benefits into the hands of local people |
| Resource Competition | |
| Social License to Operate | Indicators: Acceptance (concept & welfare) |
| Contribution to Social Awareness about Resource Use | |
| Certification & Circularity | Indicators: Number of certifications available per production technology, Number of facilities certified per production technology |

These indicators provide a comprehensive framework for evaluating the social performance of salmon production operations, ensuring they contribute positively to the communities and stakeholders involved (Garlock et al., 2024; Anderson et al., 2020; Aquaculture Magazine, 2025).

## 8.5 Production Performance Indicators for a salmon production (Pr-PIs)

Recirculating Aquaculture Systems (RAS) have gained significant attention in recent years as a sustainable method for salmon farming. The literature review focuses on the Key Performance Indicators (KPIs) used in salmon RAS, drawing from recent studies to provide an overview of the most important metrics for assessing system performance and fish health (University of Maryland Extension, 2023).

Monitoring **Production Performance Indicators (Pr-PIs)** is essential for assessing and improving the operational efficiency, health, and sustainability of salmon farming. These indicators provide valuable insights into production outcomes and are critical for decision-making in aquaculture management.

1. **Feed Conversion Ratio (FCR)**
   The FCR is a key efficiency measure that calculates the amount of feed required to produce a unit of fish biomass. A lower FCR indicates effective feed utilisation and cost-effectiveness in salmon farming (Tucker & Hargreaves, 2020). **Feed Conversion Ratio (FCR)**: Indicates the efficiency of feed utilisation. Target: 1.0-1.2.

2. **Specific Growth Rate (SGR)**
   The SGR measures the daily growth rate of salmon as a percentage of body weight, reflecting optimal growth conditions and effective feeding strategies. High SGR values indicate efficient production (Bureau et al., 2006). **Specific Growth Rate (SGR)**: Measures the growth rate of fish over a specific period. Target: 1-2% per day.

3. **Survival Rate**
   The survival rate measures the percentage of fish that survive from stocking to harvest. A high survival rate is indicative of effective disease management and favourable rearing conditions (MOWI, 2022). **Survival Rate**: Percentage of fish that survive over a given period. Target: >95%.

4. **Harvest Weight and Yield**
   Harvest weight indicates the average size of salmon at harvest, while total yield measures overall biomass production. These metrics are crucial for evaluating productivity and market performance (FAO, 2021).

5. **Mortalities and Causes**
   Monitoring mortality rates and identifying underlying causes for mortality are essential for mitigating health risks and improving management strategies. For example, in 2023, Scottish salmon farms reported a mortality rate of 31.3%, highlighting the need for stricter regulatory interventions (Cameron, 2025).

6. **Disease and Parasite Incidence**
   Tracking disease prevalence and parasite infestations, such as sea lice, is critical for ensuring fish welfare and preventing economic losses. Effective control measures are necessary to mitigate these risks (Costello, 2009).

7. **Product Quality Indicators**
   Indicators such as fillet texture, flesh colour, and fat content reveal the quality of farmed salmon and influence market demand. Maintaining high product quality standards is essential for consumer satisfaction and industry competitiveness (Ytrestøyl et al., 2020).

8. **Environmental Impact Metrics**
   Assessing the environmental footprint of salmon farming, including waste discharge and resource use, is vital for sustainable aquaculture. Concerns over feed sustainability have been raised due to the reliance on wild-caught fish, challenging the industry's environmental claims (Froehlich et al., 2018; Torrella, 2024).

9. **Water Quality Parameters**
   Recent studies consistently highlight the importance of maintaining optimal water quality in salmon RAS. KPIs include:
   - **Dissolved Oxygen (DO)**: Essential for fish respiration and overall health. Optimal range: 6-8 mg/L.
   - **Temperature**: Critical for metabolic and growth rates. Optimal range: 12-16°C.
   - **pH**: Affects fish physiology and biofilter performance. Optimal range: 6.5-8.0.
   - **Total Ammonia Nitrogen (TAN)**: Indicates the level of ammonia, which is toxic to fish. Target: <0.5 mg/L.
   - **Carbon Dioxide (CO2)**: High levels can impair fish respiration. Target: <15 mg/L.

10. **Condition Factor (K)**
    The condition factor (K) is a widely used metric to assess the overall health, well-being, and body condition of farmed salmon. It is calculated using the formula $K = (W / L^3) \times 100$, where W represents weight in grams and L represents length in centimetres (Froese, 2006). A target K value between 1.0 and 1.2 indicates optimal fish health, with values below this range suggesting undernourishment or stress, while excessive values may indicate overfeeding or abnormal growth patterns (Le Cren, 1951). Maintaining an appropriate condition factor ensures efficient feed utilisation, growth performance, and resilience against disease and environmental stressors (Ricker, 1975).

11. **System Performance Metrics**
    - **Water Exchange Rate**: Frequency of water replacement to maintain water quality. Target: 5-10% per day.
    - **Biofilter Efficiency**: Effectiveness of biofilters in removing ammonia and nitrites. Target: >90% removal efficiency.
    - **Energy Consumption**: Measures the energy used per unit of fish produced. Target: <10 kWh/kg.
    - **Solids Removal Efficiency**: Effectiveness in removing solid waste from the system. Target: >85% removal efficiency.

Literature has also highlighted some newer KPIs that are gaining importance in salmon RAS:

- **Microbial Community Composition**: The diversity and stability of microbial communities in RAS play a crucial role in maintaining water quality and fish health. A well-balanced microbial community can enhance nitrification efficiency, reduce pathogenic risks, and improve overall system resilience.
- **Stress Indicators (e.g., Cortisol Levels)**: Measuring physiological stress markers such as cortisol provides insights into fish welfare. Elevated cortisol levels can indicate suboptimal water conditions, overcrowding, or handling stress, which may negatively impact growth and immune response.
- **Fillet Quality Metrics**: Quality indicators such as fillet texture, colour, and fat content are critical for consumer acceptance and market competitiveness. Ensuring high-quality fillets in RAS production requires optimising feed composition, water quality, and post-harvest handling to match or exceed traditional farming methods (Ytrestøyl et al., 2020).

Moreover, by systematically monitoring these **Pr-PIs**, salmon producers can identify inefficiencies, implement corrective measures, and enhance overall production performance while maintaining environmental and economic sustainability.
These KPIs provide a comprehensive framework for evaluating the performance of salmon RAS, ensuring optimal fish health, system efficiency, and product quality.

## 8.6 Environmental Performance Indicators (En-PI)

Environmental performance indicators include the measurement of nutrients and organic matter discharged to the recipient as reported in the analysis of warmwater shrimp. Discharged nutrients can fuel unwanted growth of microalgae and reduce oxygen concentration. The emission of greenhouse gasses (GHGs) from the construction and maintenance of production facilities, from the production of feed, and for operating the production can be separated in a different KPI, but the total emission per produced number of fish is an estimation of the carbon footprint. the production's impact on biodiversity, including the production of feed, is an important KPI. Life Cycle Assessments for a salmon production are reported in next chapter.

# 9 Life Cycle Assessment – salmon production in RAS

Life Cycle Assessment (LCA) is a method used to examine a product's climate and environmental impact from cradle to grave. When using the method, the manufacturing process of the product is reviewed, including how sub-products that are part of the actual manufacturing of the main product affect the climate and environment. The processing and transport of the product to the final consumer is then considered. Finally, it is assessed how residual products are disposed of or recycled. Thus, step by step, the assessment examines how much a product affects the climate and environment throughout the product's life cycle. Often the literature only identifies parts of the product's life cycle.

An important element in an LCA is the delimitation of the production. There is thus a big difference between whether one looks at the entire life cycle from production to disposal, or if one simply

- Considers the production of the product,
- includes the effects from the production of physical material which forms the basis for the production,
- and whether the effects from transport to the final consumer are included.

In the first step (Limited cradle-to-farm-gate), the effects of the ongoing (variable input and costs) production and its consequences for the climate, the environment, and possibly the economy are analysed. One of the most important inputs in the context of aquaculture is the feed. A good illustration of the effects that are included in the analysis can therefore be shown for this input. In a feed that includes both marine ingredients (fish meal and oil) and plant-based ingredients (soya, etc.), the effect from both fishing and agricultural production of the ingredients for the feed is calculated, as well as the further processing, until you have the feed itself, which is ready for use in aquaculture production. This also includes the climate effects related to the land used in agricultural production, or changes in land use, for example deforestation when growing soya etc. Additionally, all other relevant resources used for the ongoing processing are included in assessing the production of the product, such as energy, water consumption, etc.

In the second step (complete cradle-to-farm-gate), the effects of the fixed facilities (physical equipment and fixed costs) are included. This also includes an assessment of materials used to build the production plant or cages themselves and their calculated lifespan, so that the effects from these components can be distributed over the selected functional unit (ton of fish in live weight) produced with the physical material. Most often included here is also the use of auxiliary substances such as chemicals and medicines that can have undesirable effects on the environment. The division between stages 1 and 2 is not always clear and this can make comparisons difficult, but if the underlying data for the assessment is available, adjustments can be made so that the comparisons become more precise. However, it must be emphasised that such measures can be time-consuming.

In the last step (Complete life cycle), the effects that the product has after primary production has been completed are also included. This includes the effects from the actual processing of the fish in the processing industry into a specific product (for example fillet, smoked or frozen) and the consumption of packaging, transport, storage and distribution until the product reaches the final consumer. Finally, it is investigated how residual products and waste are treated. Here there can be negative effects in the destruction of residual products and waste or positive effects in recycling.

Aquaculture LCAs have typically included fewer life cycle stages than fishery studies. In a review of 62 sources, including academic journal articles, theses, conference presentations, and industry reports, carried out by Parker (2012) 30 case studies out of 46 reported impacts associated only with feed provision and production of fish at the farm.

While the specific focus of the LCAs is the measurement of greenhouse gas emissions, LCAs typically report quantified data on numerous environmental impacts which provides a broader understanding of the environmental performance of products and helps to identify trade-offs between different impacts and their drivers. In a review, Bohnes et al (2018) reviewed LCAs of aquaculture fish productions from scientific papers and reports. The fish productions were compared based on climate effect (kg $CO_2$-e per ton fish produced), acidification (kg SO2 per ton fish produced), eutrophication (kg PO4 per ton fish produced) and total energy consumption (MJ per ton fish produced). Furthermore, water dependence and net primary production – how well the fish grow in relation to added feed – were analysed. A total of 65 studies were included in the study containing a total of 217 cases, among which 179 were aquaculture systems and 38 were aquafeed systems. The studies include LCAs from all over the world, with approximately 60% from Europe and America. The results from the meta-analysis are shown in Fig. 20. It should be remarked that the impact values are based on different types of aquaculture including production in freshwater/saltwater, in open/closed systems and for different species.

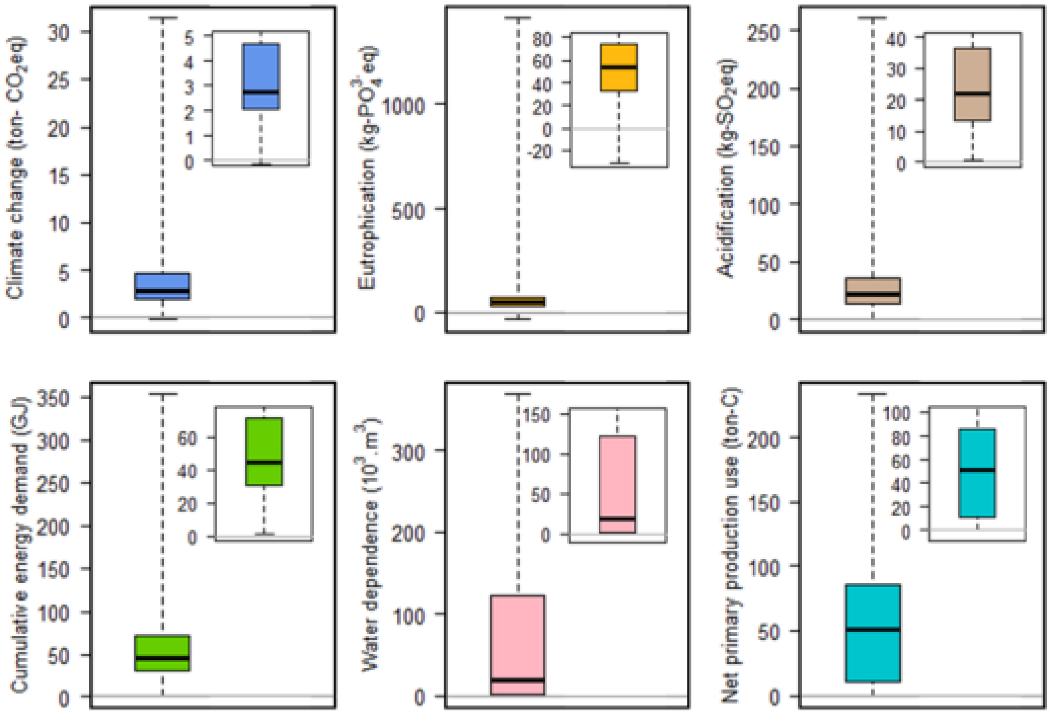

***Figure 20.*** *Impact per ton of live-weight seafood product for 6 selected impact categories (from 140 cases out of 179, communicating usable fraction and quantitative impact results). Midline is the median; box plots indicate the first and third quartile; whiskers indicate the maximum and the minimum values retrieved. (from Bohnes 2018)*

Philis et al (2019) conducted a comparison of 24 LCA studies of different types of production of salmonids including rainbow trout and Atlantic salmon. The production forms included closed sea-based, closed land-based, open sea-based, and open land-based. The study was dominated by studies from the salmonid production in Norway, UK, Canada, Chile, and Australia for salmon, and Finland and France for trout species. The global warming potential (GWP) impact was on average 2500 kg $CO_2$-e per tons produced fish for the production in closed land-based, closed sea-based, and open sea-based, and 6400 kg $CO_2$-e per tons fish produced in closed land-based systems (RAS) (Fig. 20). For the acidification potential (AP) the same pattern can be observed as both the GWP and the AP reflect the energy use of the system. Open and closed sea-based systems and the open land-based systems have an impact of 15-19 kg $SO_2$-e per ton produced fish, whereas the closed land-based production have an impact of 51.5 kg $SO_2$-e (Fig. 22). The eutrophication (EP) impact shows the opposite pattern. The closed land-based and closed sea-based production have an impact of 17.3 and 26.7 kg PO4-e, respectively, whereas the open sea-based and the open land-based production with no water treatment have an impact of 47.3 and 50.6 kg PO4-e (Fig. 23). The cumulative energy demand (CED) was low for the open sea-based production 38 MJ-e increasing to 133 MJ-e for closed land-based system. The closed sea-based production and the open land-based production had an impact of 54 and 76 MJ-e per ton fish produced.

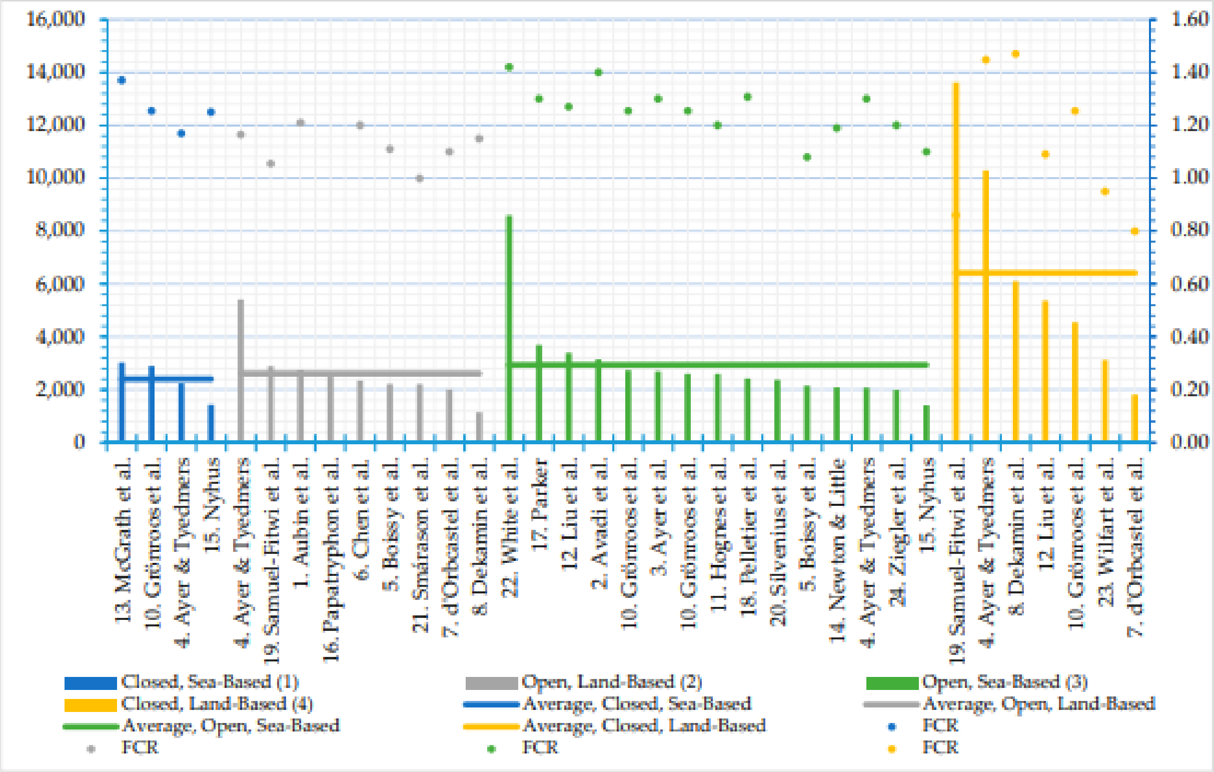

***Figure 21.*** *Salmonids' global warming potential (GWP) impacts (kg CO2-e) and FCR based on production technology clusters (from Philis et al. 2019).*

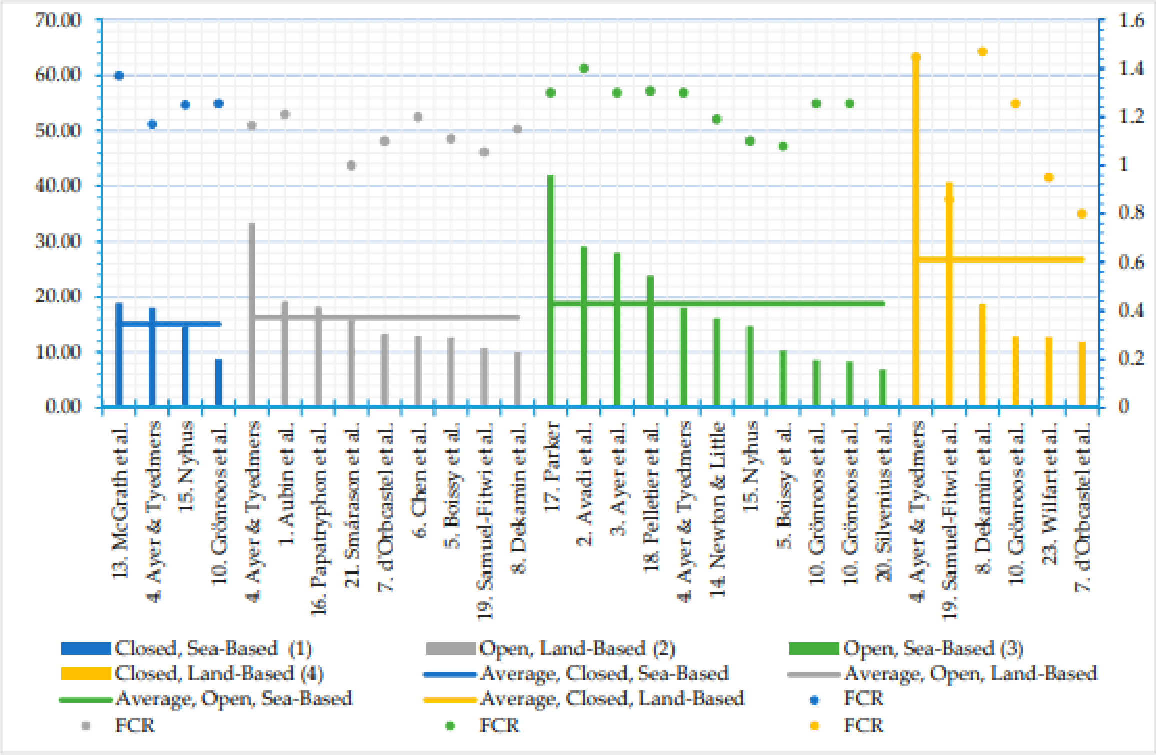

***Figure 22.*** *Salmonids' acidification potential (AP) impacts (kg SO2-e) and FCR based on production technology clusters (from Philis et al. 2019).*

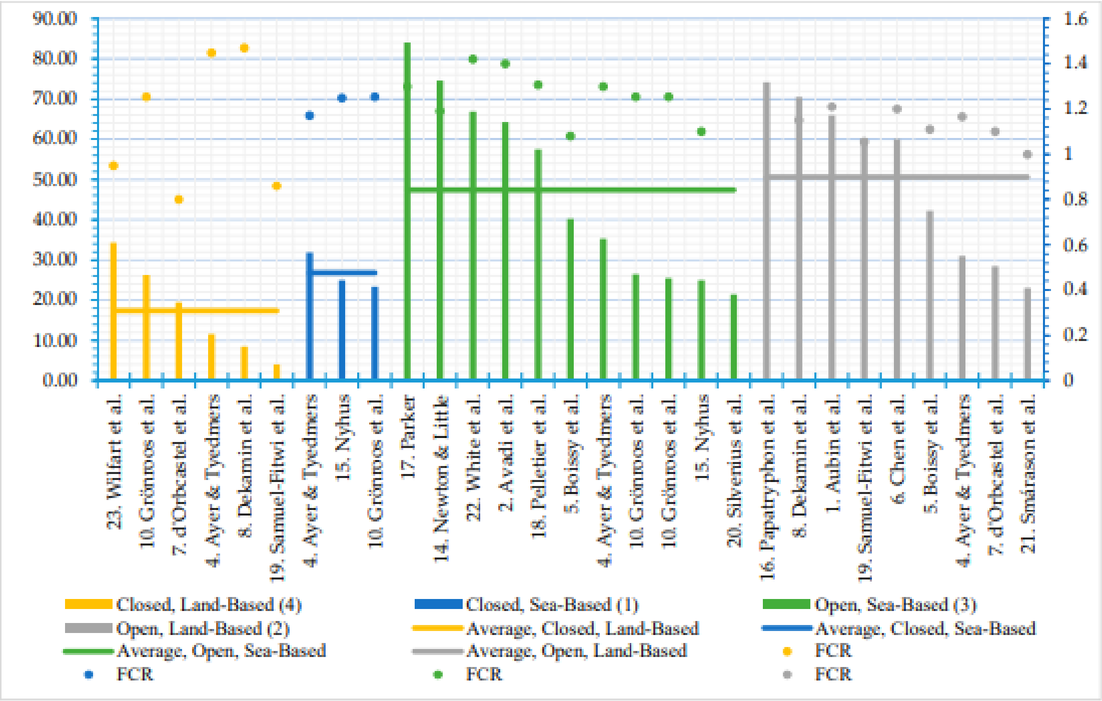

***Figure 23.*** *Salmonids' eutrophication potential (EP) impacts (kg PO4-e) and FCR based on production technology clusters (from Philis et al. 2019).*

A pattern appears in the impact assessment results regarding aquaculture production systems: Feed production and on-farm electricity are commonly found to be the major drivers of greenhouse gases (GHG) (Parker 2012). For Atlantic salmon and Rainbow trout production, feed accounts for, on average, 87% of total GHG emissions. Therefore, as suggested by Martins et al (2010), the first step towards reducing the environmental impacts of aquaculture systems is to minimise the Feed Conversion Ratio (FCR). The analysis gives an example of a 30% reduction of FCR in a trout farm which resulted in a reduction of almost 20% of the global environmental impact, excluding energy use. Furthermore, feed production's impact on the environment may also be reduced by choosing local feed ingredients and ingredients from a low trophic level. Another way of lowering feed carbon footprint is the introduction of new feed formulas into aquaculture species. An LCA conducted on Norwegian salmon diets illustrates that specific combinations of ingredients can be selected to reduce the carbon footprint of salmon feed while maintaining a consistent feed conversion ratio (Sherry & Koester, 2020). In the specific Norwegian case, it was found that lower carbon footprints could be achieved by using ingredients from American fisheries rather than European fisheries and by using by-products from poultry, insect meal, and cell proteins (SCPs), such as yeasts.

As concluded by Parker (2012), in cases where feed production was not the most influential source of GHGs in aquaculture, the most influential source was typically on-farm energy use. This is particularly the case for RAS. Because of the relative importance of energy use, several studies have conducted sensitivity and scenario analyses regarding the electricity mixes. As a result of the importance of the electricity mix, farm location can drastically influence GHG emissions of aquaculture products. Martins et al (2010) conclude that energy use reduction in RAS is possible by improving the system design and management of airlifts and biofilters, the incorporation of denitrification in the recycling loop, and the reduction of transport of feed ingredients in fish feeds. Recent RAS designs minimise height differences between RAS compartments and pumps are thus more efficient or are replaced by air lifts. This resulted already in a 50% reduction in energy use.

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# 11 APPENDIX 1: Tools for analysing KPI for RAS

The list below shows relevant KPIs for RAS aquaculture. Key Performance Indicators (KPIs) are quantifiable metrics utilised in assessing the efficacy and efficiency of an organisation's operational processes, particularly in production environments. These indicators serve as crucial benchmarks for evaluating progress towards predetermined objectives and goals. In the context of production, KPIs hold paramount importance due to their multifaceted role in operational management and strategic decision-making.

The significance of KPIs in production cannot be overstated. Primarily, they function as objective measures of performance, providing tangible data that enables managers to gauge the success of various production processes. This empirical approach to performance evaluation facilitates evidence-based decision-making, allowing for more accurate and timely interventions when discrepancies or inefficiencies are identified.
KPIs play an important role in aligning daily operational activities with overarching organisational strategies. By establishing clear, measurable targets, KPIs create a direct link between individual or departmental actions and broader company objectives. This alignment fosters a sense of purpose and direction among employees, potentially enhancing motivation and productivity.

When combined with quality control, KPIs allows a production to maintain high standards of product excellence. By monitoring specific quality-related metrics, production managers can swiftly identify and address issues that may compromise product integrity or customer satisfaction. This proactive approach to quality management is essential in today's competitive market landscape.

KPIs serve as valuable instruments for benchmarking. They enable organisations to compare their performance not only against their historical data but also against industry standards and competitors. This comparative analysis provides crucial insights into an organisation's relative position within its sector, highlighting areas of strength and opportunities for improvement.

The utility of KPIs extends to resource allocation and cost management. By tracking efficiency-related indicators, production managers can optimise resource utilisation, minimise waste, and identify areas where cost-saving measures can be implemented without compromising output quality or quantity. This focus on operational efficiency is particularly crucial in production environments where margins can be tight and competition fierce.

| | **KPI** |
|---|---|
| **Economic** | Net value added |
| | EBIT |
| | EBIT Margin |
| | ROI |
| | Profit per unit |
| **Social** | Lost time injury (LTI) frequency (H1 value); |
| | Leave of absence due to illness (total); |
| | Leave of absence due to illness (short-term); |
| | Leave of absence due to illness (long-term); |
| | Absence due to work-related injury; |
| | Number of work -related injuries without absence; |
| | Number of near-misses; |
| | Number of safety observations; |

| | |
|---|---|
| | Number of fatalities; |
| | % of companies having working environment committee which includes an employee representative. |
| | Education of workers |
| | Gender equality |
| | Freedom to organise |
| | Fair Wages |
| **Production** | FCR |
| | Lost production due to predation, microalgae or failing biosecurity |
| | Lost production due to pollution |
| | Lost production due to extreme temperatures and other weather conditions |
| | Lost production due to low oxygen, high ammonium |
| | Use of medication |
| **Environment** | Discharge of Nitrogen |
| | Discharge of Phosphorus |
| | Discharge of organic matter |
| | Emission of GHG from construction of facility |
| | Emission of GHG from production ex feed |
| | Emission of GHG from feed |
| | Acidification potential |
| | Energy demand |
| | Biodiversity Impact / Metrics such as the number of escaped salmon, disease outbreaks, and parasite abundance are critical for assessing ecological health |