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RECIRCULATING AQUACULTURE SYSTEMS

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CONTENTS

0 STUDY OBJECTIVES AND METHODOLOGICAL APPROACH

0.1 Introduction

Recirculating aquaculture systems (RAS) are land-based aquaculture facilities – either open air or indoors – that minimise water consumption by filtering, adjusting, and reusing the water. Compared to traditional pond or open water aquaculture, the water recirculation process in RAS makes it possible to control the culture conditions and collect waste. In addition, land-based aquaculture avoids escapees and limits external transmission of diseases and parasites.

RAS gives promise of more sustainable food production with healthier fish, lower consumption of fresh water, and shorter transport distances, as fish can be grown closer to the markets. By controlling the culture conditions, aquaculture production in a RAS facility can be established almost anywhere, regardless of local conditions. By moving the production on land, it can also mitigate the scarcity of available space and competition for access to sea areas. For example, Atlantic salmon can be produced in Dubai or Florida while warmwater shrimps can be grown in Northern Europe.

On the other hand, a RAS facility tends to be quite expensive. Investment costs are high, and the recirculation technology consumes vast amounts of energy and requires to be controlled and managed by a skilled workforce. Furthermore, the technology remains to prove its viability on large-scale production, especially concerning saline water environments. Fish welfare is not necessarily ensured in RAS, and several projects have experienced mass mortality, due to design errors or technical difficulties of the water recirculation. Lastly, without the correct management, fish grown in RAS can have a muddy or earthy off-flavour.

In a world characterised by growing population – and the need for increased food production – limited fisheries resources, environmental impact of traditional aquaculture production, and consumer's demand for locally produced, environmentally friendly products, there is increasing interest in RAS. Several companies based or originating in the EU are leading the way in technological development.

This study aims to give a better understanding of the sector in the EU, its size and potential for growth. The study includes a mapping of the sector, also putting the technology in perspective and comparing it with traditional farming methods. Three case studies seek to assess the impact of the technology on competitiveness, the impact on operating costs and the differentiation strategies in sales and marketing.

0.2 Methodological approach

The study was conducted in three stages. The first stage was a desk analysis of studies, projects and initiatives, as well as a mapping of available data sources. Stage two consisted of interviews with industry stakeholders to complement the desk analysis and the data collected from publicly available sources. In the third stage, three case studies were developed to analyse the RAS production of some relevant species.

The case studies were selected so as to highlight different characteristics of RAS, such as different water environment, technology and species. The first case study concerns Atlantic salmon, which through its life cycle is reared both in fresh and saline water environment. Most of the large RAS projects and technology developments, both in the EU and globally, focus on this species. In the EU, rainbow trout is by far the most produced species in RAS, and Denmark is the top RAS producing MS. Hence, the focus of the second case study is freshwater rainbow trout production in Denmark. The third case study concerns yellowtail kingfish (*Seriola lalandi*), a warmwater finfish not indigenous to Europe. The consumer demand for this species is increasing, and while the local natural environment is not ideal to produce it, near-the-market production is facilitated with RAS technology.

0.3 Overview of data sources used for this study

This study is based on a combination of available official statistics, interviews with and information from stakeholders, as well as calculations and estimates by EUMOFA experts. Citations are provided in footnotes throughout the study. This chapter contains a short description of the main statistical sources used in the study.

0.3.1 EUMOFA aquaculture production

The EUMOFA database includes yearly aquaculture data (production volumes and nominal values in EUR) by Member State, commodity group and main commercial species[1]. The main source is Eurostat, complemented with data from the FAO, national sources and sector associations[2]. The latest year available at the time of drafting this study was 2018.

0.3.2 EUROSTAT – aquaculture production for human consumption (fish_aq2a)

The data includes yearly aquaculture production at farm-gate (first sale intended for human consumption) by country, species, cultivation method and aquatic environment in tonnes live weight, value in EUR and average price (EUR/tonnes). The cultivation method "Recirculation systems" is defined as "systems where the water is reused after some form of treatment (e.g. filtering)"[3].

Due to confidentiality issues, the disaggregated data does not necessarily contain all production volumes. From the reference year 2014, details on production method, which would introduce confidentiality, may be hidden by declaring the production method "not specified". Furthermore, as from the reference year 2016, small confidential production volumes may be hidden by declaring them as 'not significant'[4].

The first dataset used for this study was last updated on the 19th of November 2019. The analysis revealed several possible data gaps or missing data. A questionnaire was sent to the Member States in February 2020 asking for explanations or amendments concerning missing data. Twelve Member States responded to the questionnaire, and 9 of them provided additional or adjusted data.

A new dataset from Eurostat was downloaded (last updated on the 28th of May 2020), crosschecked with the dataset from 19th November 2019 and adjusted based on the feedback from the 7 Member States. The adjusted dataset revealed possible missing data from Poland in 2018, and the Polish government was contacted for clarification. Additional data from Poland was received on the 9th of September 2020 and added to the dataset.

Due to updated data from France, the last dataset from Eurostat (last updated the 17th November 2020) was downloaded late November 2020 and combined with the feedback from the different Member States.

All analyses of on-growing aquaculture production in the EU referring to Eurostat in this study use this dataset. The latest year of reference is 2018.

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[1] Commodity group (CG) and Main commercial species (MCS) are EUMOFA aggregates harmonising ERS species codes. More information on EUMOFA harmonisation and the different correlation tables is available at https://www.eumofa.eu/en/harmonisation.

[2] More details on the sources of data is available at https://www.eumofa.eu/en/web/eumofa/sources-of-data.

[3] https://ec.europa.eu/eurostat/cache/metadata/en/fish_aq_esms.htm, chapter 3.4

[4] https://ec.europa.eu/eurostat/cache/metadata/en/fish_aq_esms.htm, chapter 7.2

0.3.3 EUROSTAT – production of hatcheries and nurseries at juvenile stage

The data concerns production of juveniles at first sale for further on-growing or release to the wild by country and species in millions (number of juveniles). The data also includes a variable for "intended use", which is recorded for the production of juveniles not intended for direct human consumption but are either "released to the wild" or "transferred to a controlled environment".

The intentions of releasing juveniles to the wild are to restock rivers, lakes, and other waters other than for aquaculture purposes. When juveniles are transferred to a controlled environment, it means they are released or transferred for further aquaculture practices. However, the reporting of this variable is voluntary and not always available.[5]

As of mid-September 2020, the latest year of reference with comprehensive and coherent data is 2017. The dataset used for this study was last updated on the 19th of October 2019.

0.3.4 Interviews with stakeholders

Chapter 5 is mainly based on interviews with 17 stakeholders representing different levels of the RAS supply-chain including suppliers, operators, consultants, organisations, investors, insurers and researchers. Despite covering several levels of the supply-chain, the largest number of participants were suppliers. Furthermore, most participants had experience with Atlantic salmon, and other species are covered in the interviews to a lesser extent covered.

0.3.5 Case study on freshwater finfish – trout in Denmark

For the case study on Denmark, three official sources were used for data collection: i) Statistics Denmark (DST), ii) the Danish Fisheries Agency (FST) and iii) the FAO.

The FAO provides yearly statistics of aquaculture production by, *inter alia*, country, species, and water environment.

DST provide a yearly overview of accounting statistics for the Danish aquaculture and fisheries sector. However, DST does not separate production by species, but only reports data by the different technologies ("traditional", "model type I", "model type III" and "other including RAS"). The firms report the economic data to Statistics Denmark, but it is voluntary for the companies to participate. DST data only contains commercial sites. The data used for this study consists of a sample of 115 accounts from a total population of 206 farms. The sampled data has been extended to cover the entire population by simulating accounts for all units not in the sample[6].

FST (a part of the Ministry of Environment and Food of Denmark) provides yearly production data by species and production technology "("traditional", "model type I", "model type III" and "recycled"). FST reports all aquaculture sites, including those used for angling and repopulation of wild stock.

The reported technology categories differ between DST and FST. While DST reports on a category "other including RAS", FST reports "recycled" as a separate category. Furthermore, as DST only reports by category and not by species, the category "other including RAS" includes other species than rainbow trout. According to FST, the category "recycled" includes salmon, eel, zander, yellowtail kingfish and sunshine bass in addition to trout. For this reason, the category "other including RAS" could not be included in the analysis of economic performance in the case study.

The latest year of reference for all three sources is 2018.

[5] https://ec.europa.eu/eurostat/cache/metadata/en/fish_aq_esms.htm, chapter 3.4.

[6] https://www.dst.dk/pubfile/28174/fisk2018, preface.

1 GLOBAL PERSPECTIVES

1.1 Production and supply

According to the FAO, there is an estimated need to increase the global protein supply with about 200 million tonnes meat and seafood to nearly 500 million tonnes by 2050 in order to feed the growing global population, which is estimated to reach 9,1 billion people by then[7,8,9]. Seafood, particularly from aquaculture, is expected to contribute significantly to meet this need. Considering the FAO's estimates of average annual seafood consumption, the predicted demand for fish for human consumption would almost double to at least 220 million tonnes in 2050, with aquaculture expected to provide over 70% of the volume[10].

The global aquaculture production is dominated by China and other Asian countries, which in 2018 accounted for 88,7% of the global production. The increase in production is expected to primarily occur in developing countries in Asia[11], while the production increase in developed regions is expected to lag behind[12]. The expected global warming and increased sea water temperatures might favour the growth of tropical aquaculture and further constrain temperate aquaculture, and, unless RAS production becomes widely adopted, the growth in salmon supply will be limited[13].

The growing global population and improved purchasing power ("wealth") in developing countries is believed to increase competition over feed resources, including seafood resources. Increased protectionism and intra-regional trade in these regions might reduce surplus aquaculture supplies to developed regions in the medium-long term[14,15].

The globalisation trend is described as *"fragile in a multipolar world"* and there are several variables that will decide *"whether the purported anti-trade environment of 2016 lasts to 2035"*[16].

[7] FAO (2018), *The State of World Fisheries and Aquaculture: Meeting the Sustainable Development Goals.*

[8] FAO (2009), *How to Feed the World in 2050: High-Level Expert Forum.*

[9] https://www.un.org/development/desa/en/news/population/world-population-prospects-2019.html

[10] https://www.aquaculturealliance.org/advocate/feeding-world-2050/

[11] Fish to 2030, FAO http://www.fao.org/3/i3640e/i3640e.pdf

[12] OECD-FAO Agricultural Outlook 2018-2027, 2018 https://www.oecd-ilibrary.org/docserver/agr_outlook-2018-11-en.pdf?expires=1578612115&id=id&accname=guest&checksum=914DB8AEA702E6AEBC44A1BE2F4F9B04

[13] Impacts of climate change on fisheries and aquaculture, FAO, Tech, 627 http://www.fao.org/3/i9705en/i9705en.pdf

[14] AIPCE-CEP, Finfish study 2019

[15] FAO (2009), *How to Feed the World in 2050: High-Level Expert Forum.*

[16] Global Trends to 2035, Geo-politics and international power, EPRS, Global Trends Unit, PE 603.2673, 2017 https://www.europarl.europa.eu/RegData/etudes/STUD/2017/603263/EPRS_STU(2017)603263_EN.pdf

1.2 Technology

Technological development is likely to facilitate industrial upscaling, thus allowing for increased production levels and improved efficiencies[17]. Both open-ocean aquaculture and land-based RAS technology can open up new opportunities for production; however, at the same time they carry significant risk of failure at an early stage of development[18,19, 20].

The seafood markets and trade will further be affected by new fresh and frozen seafood technologies opening for potential shifts in supply and distribution. Also, rapid change in supply chain and logistics technologies will provide new opportunities[21].

On the other hand, one of the current main drivers for expansion into RAS production is the opportunities for "near-market" production, even more so in main markets in developed regions, e.g. plans for land-based RAS establishments in the USA (Maine[22] and Miami[23]) and in China[24].

Genetic technologies may also open up new opportunities, but currently many of these will carry the risk of market downsides in terms of consumer acceptance. Most of the studies carried out with genetically modified organisms have been performed in laboratory conditions that do not account for environmental fluctuations and within such short time-frames that any genetic effects would not have time to manifest. There are also large gaps in the current knowledge on the possible outcomes of modifying organisms' genomes and the potential of dispersal in the wild[25]. Currently, genetically modified organisms are not allowed in the EU.

1.3 Economy and funding

In general, the costs of aquaculture inputs are increasing. To meet the expected development, seafood prices would have to increase and/or the industry needs to become more efficient. There are still high risks related to aquaculture, due to e.g. the possibility of disease losses and uncertainty related to the introduction of new technological solutions, including RAS technologies[26]. Despite these risks, aquaculture is the fastest growing sector in the food animal industry. Still, investments are needed for

[17] Fish to 2030, World Bank, 83177_GLB http://www.fao.org/3/i3640e/i3640e.pdf

[18] https://www.intrafish.com/finance/analysis-heres-a-list-of-high-profile-land-based-aquaculture-failures/2-1-712748

[19] NTNU 2018, *Analyse av landbasert oppdrett av laks: produksjon, økonomi og risiko*, http://fisk.no/attachments/article/6572/landbasert-lakseoppdrett-analyse.pdf

[20] Wageningen University and Research: Recirculation Aquaculture Systems, 2017, https://library.wur.nl/WebQuery/wurpubs/533878

[21] https://www.michiganstateuniversityonline.com/resources/supply-chain/technology-transforming-the-seafood-supply-chain/

[22] https://www.intrafish.com/aquaculture/massive-land-based-ventures-applaud-maines-new-aquaculture-plan/2-1-732072?%20Americas%20Newsletter=&utm_term=0_471f697403-dc16dc8673-245287921

[23] https://www.undercurrentnews.com/2019/12/13/atlantic-sapphire-is-officially-worth-1-billion/

[24] https://www.undercurrentnews.com/2020/01/09/nutreco-commits-e20m-to-nordic-aquas-china-land-based-salmon-project/

[25] https://medcraveonline.com/JAMB/a-review-of-genetic-engineering-in-current-aquaculture-practises.html

[26] https://www.intrafish.com/finance/analysis-heres-a-list-of-high-profile-land-based-aquaculture-failures/2-1-712748

technological improvements, increased economic efficiency and upscaling, and there is an increasing interest investing in international aquaculture[27,28,29].

Both large companies, which can tap the capital markets, and public incentives for investments[30] will likely be essential for growth to be achieved[31]. One can also foresee and find examples of retailers engaging in production to both ensure supplies and option for growth[32].

1.4 Sustainability

There is an increasing focus on sustainability from international organisations and consumers alike. The United Nations (UN) has set 17 goals in this respect[33], and some of these relate to food production, fisheries, and aquaculture. Also, "social licence to operate" becomes important for the aquaculture value chain[34]. RAS provide opportunities to meet several sustainability issues, such as reduced water usage and improved waste management[35, 36].

The increased focus on sustainability and consumer perceptions needs to be addressed by the industry. At the same time, the demand for healthy foods is increasing and might create potential growth opportunities for aquaculture products[37].

There are several regulations related to fisheries and aquaculture, and amongst other things, they aim to protect the environment and promote sustainability. There is also an increasing number of third-party certification systems for both fisheries and aquaculture, which address, *inter alia*, sustainability. Furthermore, sustainability goals are also expected to be enforced through international trade agreements[38].

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[27] https://www.forbes.com/sites/michaelhelmstetter/2019/04/04/the-aquaculture-industry-an-ocean-of-investment-opportunity/#6f8dc44f5666

[28] https://www.undercurrentnews.com/2020/01/08/seafood-start-ups-set-for-promising-2020-as-investors-target-food-tech-investments/

[29] Stirling, 2018, *An update on the 2014 report: "Review of Recirculation Aquaculture System Technologies and their Commercial Application"*, https://www.hie.co.uk/research-and-reports/our-reports/2014/april/09/review-of-recirculation-aquaculture-systems-technologies/

[30] FranceAgriMer, 2019, *Étude sur la pisciculture en circuit « recirculé*, https://www.franceagrimer.fr/Actualite/Filieres/Peche-et-aquaculture/2019/Etude-sur-la-pisciculture-en-circuit-recircule-Rapport-final-2019

[31] http://www.fao.org/3/AB412E/ab412e34.htm

[32] https://www.seafoodsource.com/news/aquaculture/darden-invests-in-first-integrated-lobster-park

[33] https://www.un.org/sustainabledevelopment/sustainable-development-goals/

[34] Social licence in Aquaculture: Towards a research agenda, Mather C, Fanning, L, Marine Policy, 99, 2019, 275-282

[35] Martins et. al., 2010, *New developments in recirculating aquaculture systems in Europe: A perspective on environmental sustainability*, https://archimer.ifremer.fr/doc/00021/13190/10273.pdf

[36] Book of abstracts, 4th NordicRAS Workshop on Recirculating Aquaculture Systems, https://www.nordicras.net/-/media/Institutter/Aqua/Publikationer/Forskningsrapporter_301_351/321-2017_NordicRAS-Workshop-Book-of-Abstracts.ashx?la=da&hash=033CD17AF9AE7CC1818A6D2830AB5BA5D62FA529

[37] https://ec.europa.eu/knowledge4policy/publication/sustainable-fisheries-aquaculture-food-security-nutrition_en

[38] https://unctad.org/en/Pages/DITC/Trade-Analysis/TAB-Trade-and-SDGs.aspx

1.5 Main trends

Aquaculture production has proved to be highly resilient to the many problems that it has faced in its emergence and early rapid growth phases. Based on past experience, with new technologies and opportunities becoming available, it is expected that aquaculture will continue to expand both in terms of production volume and range of species.

A significant change from the earlier phases of aquaculture development will however be slower growth. Between 1950 and 2000, the compound annual growth rate (CAGR) of the global aquaculture production was 8,7%, while between 2000 and 2018, the CAGR was 5,8%. In the past five years, the annual growth rate has been between 2,3% and 4,1%. Furthermore, the global seafood market is believed to change from a buyer's market to more of a seller's market in the future[39], due to demand increasing faster than supply, thus leading to increased prices. According to the FAO's estimates, demand will increase by 20% from 2016 to 2030, while total production from fisheries and aquaculture will increase by 17,6% in the same period.

Higher prices could lead to increased investments in both technology and scale. As new technological developments become established, the investment risk will reduce accordingly. However, currently *"there is an enormous need for innovation and high-risk capital to fuel change"*[40].

Increased intra-regional trade in major supplier regions such as Asia might leave developed regions such as the EU and the US at a disadvantage in obtaining future seafood supplies. With reduced supply and increasing prices, developed regions will have to invest in new production and supply paradigms to meet demand. These models may, amongst other things, include RAS, "near-market" production, open-ocean aquaculture, investments in tropical aquaculture and a shift to accept non-traditional species[41].

[39] Land based aquaculture assessment framework, http://www.lbaaf.co.nz/aquaculture-economics/trends-and-issues-in-aquaculture/

[40] https://www.forbes.com/sites/michaelhelmstetter/2019/04/04/the-aquaculture-industry-an-ocean-of-investment-opportunity/#7cfff6db5666

[41] http://www.lbaaf.co.nz/aquaculture-economics/trends-and-issues-in-aquaculture/

2 EU PERSPECTIVES

Seafood is one of the most highly-traded food commodities globally with an estimated trade value of EUR 135 billion in 2017[42]. In view of an expected substantial rise in seafood demand and of the European dependency on imports, both the European seafood sector and market will be affected by global changes.

2.1 Production and supply

Currently, imports make up 73% of total EU finfish supply[43]. Thus, to avoid reducing the self-sufficiency rate, which was estimated at 43,4% in 2017[44] (all fishery and aquaculture products for human consumption), the European seafood production – primarily aquaculture – should aim to develop along with the growing global demand.

The Federation of European Aquaculture Producers (FEAP) has set a production target of 4,5 million tonnes by 2030, which is nearly double the volume of 2,3 million tonnes (EUR 10 billion ex farm value) in 2017[45]. However, the FEAP also warn against potential obstacles to reaching this goal, such as high level of bureaucracy, long licensing time, and lack of a legal level playing field in relation to external competitors. An AquaSpace (a Horizon 2020 project) report[46] lists 35 types of constraining issues, which are classified into four categories: *(i) Policy and management, (ii) Environmental, (iii) Economic and market, and (iv) Other sectors (which integrates the social dimension).*

STECF[47] supports "*that the design and implementation of the Multiannual Strategic Plans for aquaculture sector is a step forward for the modern EU aquaculture and contributes to the coordination of the different stakeholders across countries towards a common goal and strategy.*" However, only few countries have overcome or are close to achieve the production goals stated in their Strategic Plans.

A report by the European Parliament analyses the regulatory and legal constraints for European Aquaculture[48]. The identified constraints and burdens are assessed against both the needs of the EU aquaculture industry and the principles of better regulation, and recommendations are formulated to reduce, rationalize or remove the constraints.

[42] https://research.rabobank.com/far/en/sectors/animal-protein/world-seafood-trade-map.html (USD 153 billion, yearly average exchange rate USD/EUR = 1,1297 (ECB)).

[43] AIPCE: EU Seafood consumption rises as competition for supply increases, Intrafish Dec 12th , 2019, https://www.intrafish.com/marketplace/aipce-eu-seafood-consumption-rises-as-competition-for-supply-increases/2-1-722738

[44] EUMOFA, The EU Fish Market, 2019 Edition,

https://www.eumofa.eu/documents/20178/157549/EN_The+EU+fish+market_2019.pdf

[45] European industry targets doubling of aquaculture production by 2030, Undercurrent News, Dec 5th, 2018 https://www.undercurrentnews.com/2018/12/05/european-industry-targets-doubling-of-aquaculture-production-by-2030/

[46] http://www.aquaspace-h2020.eu/wp-content/uploads/2018/09/AquaSpace-D5-1-Synthesis-revised-Apr2018.pdf

[47] https://stecf.jrc.ec.europa.eu/reports/economic/-/asset_publisher/d7Ie/document/id/2446795

[48] http://www.europarl.europa.eu/RegData/etudes/etudes/join/2009/431568/IPOL-PECH_ET(2009)431568_EN.pdf

2.2 Growth and sustainability

Aquaculture is considered as a strategic sector in the EU's Blue Growth Strategy, with potential for sustainable jobs and growth while contributing to social benefits through further development of coastal areas through several ancillary activities, such as technology and infrastructure[49]. However, according to the European Environment Agency[50], aquaculture may also modify ecosystem resilience. Impacts may especially result from high-input/high-output intensive systems.

Potential effects of intensive aquaculture include discharge of suspended solids, nutrient and organic enrichment of recipient waters and the build-up of anoxic sediments, oxygen depletion of water, changes in benthic communities, eutrophication and habitat perturbation, release of antibiotics and pharmaceuticals, introduction of diseases and escapees to the ecosystem affecting biodiversity and genetic pollution, introduction of alien species and impact on wild fauna. Hence, aquaculture potentially challenges the environment and thus sustainability.

Technological solutions like RAS are believed to address some of these issues[51].

2.3 Economy and funding

Preserving Europe's natural environment and circular economy will be a major focus for the EU in the years to come, even more so in the framework of "A European Green Deal" [52]. Aquaculture will have to follow the new guidelines too. In the proposal for the Regulation on the European Maritime Fisheries Fund for the period 2021-2027, it is stated that actions under the regulation "are expected to contribute to 30% of the overall financial envelope of the EMFF to climate objectives." According to the proposal, "relevant actions will be identified during the preparation and implementation of the EMFF, and reassessed in the context of the relevant evaluations and review processes"[53]

2.4 Drivers and constraints

From both a global and an EU perspective, there are some potential main drivers and constraints that can impact the development of the aquaculture sector and the seafood market in the future. RAS technology is an integrated part of the aquaculture sector and could also contribute to tackling constraints such as restricted access to costal sea areas, sustainability, and environmental impact.

Of course, drivers and constraints tend to vary across regions and/or continents. However, given that seafood is a global commodity, some of them are common to all regions. These are listed in table 1 below.

[49] Strategic Plan 2016-2020, DG Maritime Affairs and Fisheries, March 2016.

https://ec.europa.eu/info/sites/info/files/strategic-plan-2016-2020-dg-mare_march2016_en.pdf

[50] Aquaculture production in Europe, Dec 19th, 2019 https://www.eea.europa.eu/data-and-maps/indicators/aquaculture-production-4

[51] https://www.hatcheryinternational.com/power-struggle-sense-of-sustainability-3446/

[52] Communication from the Commission to the European Parliament, The European Council, The Council, The European Economic and Social Committee and The Committee of the Regions, p. 12, Brussels 11.12.2019, COM(2019) 640 final

[53] COM(2018) 390, *Proposal for a regulation of the European parliament and the council on the European Maritime and Fisheries Fund.*

Table 1: Potential main drivers and constraints for the aquaculture sector

Constraints in traditional aquaculture	RAS solutions
Diseases and disease management options	With water treatment and a controlled environment, diseases can be better controlled and even avoided.
Demand for sustainability, low carbon footprint Traceability Social licence to operate	RAS allows control of every input factor, rearing conditions and discharge (waste). A controlled rearing environment facilitates less (or zero) use of antibiotics and medicine. Combined with the use of renewable energy, RAS can also reduce the carbon footprint by establishing production units close to consumption areas.
Environmental protection	No chance of escape and control of effluents.
Limited available areas and shared use of sea	RAS facilities are not restrained by access to sea and will not affect wild stocks.
Global warming	Water environment and temperature can be controlled.
Consumer acceptance Constricted supplies to developed regions Regional conflicts and trade disputes	Production can be closer to consumers, branding “local production”.
General issues	
Feed supply & access to alternative sources New species development “Red tape”/time consuming and costly bureaucracy General increase in costs Access to funding	

3 THE GENERAL RAS TECHNOLOGY

Fish consume oxygen and feed and produce waste in the form of faeces, carbon dioxide and ammonia. When cultured in tanks without new clean water constantly flowing through, these waste products must be removed.

Recirculating aquaculture systems are designed to control culture conditions, manage waste streams, and minimise water consumption. RAS are intensive, usually indoor tank-based systems that achieve high rates of water re-use by filtering the wastewater (ref. chapter 3.1 for a more detailed description).

The earliest scientific research on RAS was conducted in the 1950's. In Japan, the scientists focused on biofilters designed for carp production to limit the use of local water supplies. In Europe and America, scientists attempted to adapt technology designed for waste-water treatment to marine aquaculture for fish and crustaceans. Few of the early trials were tested at scale, but the scientists were optimistic due to the technology's success in public and home aquariums. However, water treatment systems for aquariums tend to be over-sized in relation to fish biomass. To minimize capital costs when upscaling, the early RAS systems ended up being under-sized and were bound to fail pending further technical improvements[54].

RAS underwent a revival in the 1980's. The development of standardised terminology, units of measurement and reporting formats led to coherent and consistent monitoring of water quality phenomena (e.g. pH, oxygen, ammonia nitrogen, nitrate), which paved the way for technical improvements and made RAS more viable. Over the last 30 years, RAS technology has come a long way and is now used in hatcheries, fry and smolt systems all over the world. RAS technology in the production of market-size fish is more advanced in the freshwater sector. In the EU, around 90% of the RAS production is in a freshwater environment, while the remaining 10% is in sea and brackish water (ref. chapter 4.1 below). There is a growing number of projects and initiatives in all continents involving marine species (e.g. growing Atlantic salmon to commercial size). However, with larger scale production involving sea water, new challenges in the RAS production cycle emerge, as is evident from a substantial global track record of company failures using RAS[55]. These new, larger projects need to prove they are viable in the long run and for higher production volumes[56].

"Land-based aquaculture" is often used as a term to describe RAS production. However, land-based aquaculture is traditionally based on a flow-through system, pumping fresh- or sea water into the tanks or earthen ponds and only using it once. Different RAS systems are commonly classified based on their water recycle ratios (% of effluent water flow treated and returned for reuse per cycle)[57]. While traditional flow-through systems have a recycle ratio of 0%, the most advanced RAS technologies have a recycle ratio of 95-99%. Conventionally, fully recirculating RAS are typically defined as systems with a recycle ratio above 90%, while systems with a lower recycle ratio are characterised as partial-replacement" systems or simply "re-use" systems as opposed to "recirculation" systems.

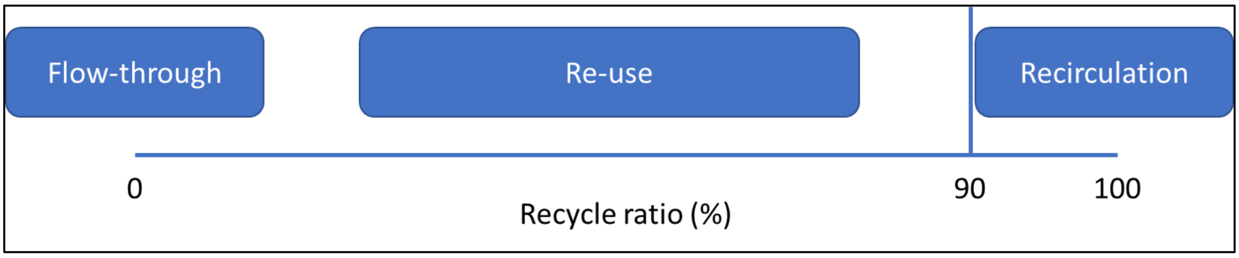
[54] University of Stirling 2014, Review of Recirculation Aquaculture System Technologies and their Commercial Application

[55] Intrafish November 2019, https://www.intrafish.com/finance/analysis-heres-a-list-of-high-profile-land-based-aquaculture-failures/2-1-712748

[56] Intrafish August 2015, https://www.intrafish.com/aquaculture/ras-tech-engineering-the-future/1-1-750546

[57] University of Stirling 2014, and AkvaGroup

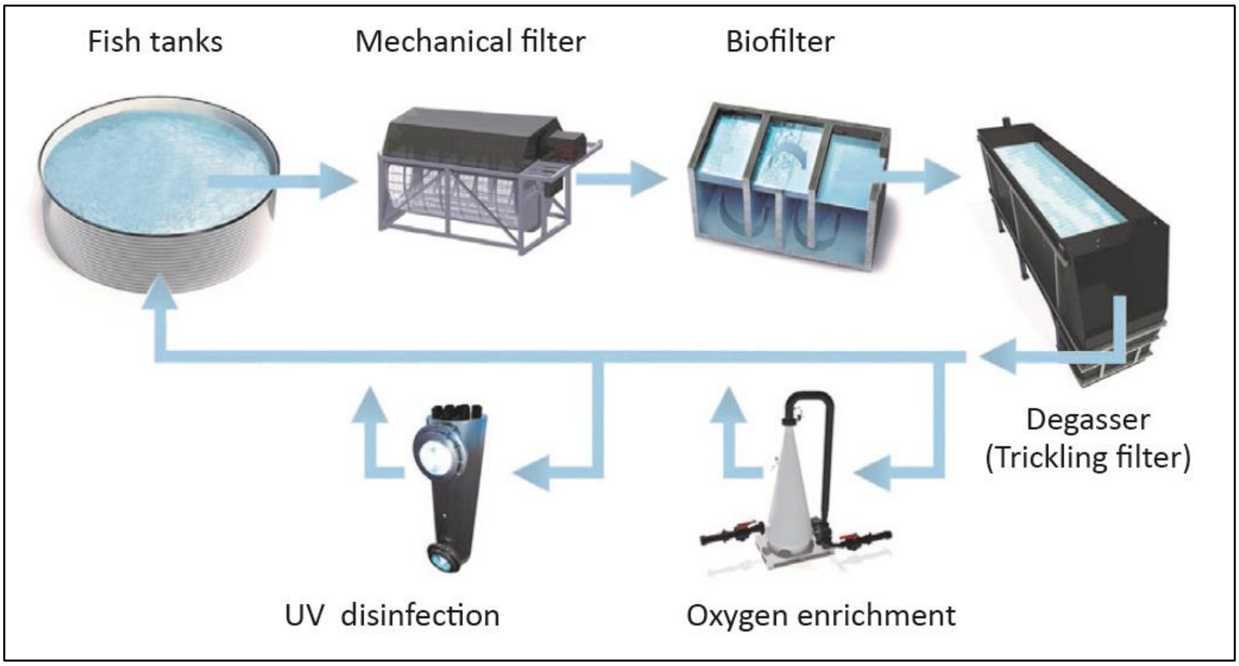
Figure 1: Land-based/RAS classifications in terms of water recycle ratio



3.1 RAS – step by step technology[58]

The basic principles of recirculation systems concern the water treatment technology, which continuously remove the waste products and regenerate optimal water quality for the fish. Water from the fish tank flows to a mechanical filter and then to a biological filter before being aerated, stripped of carbon dioxide and eventually returned to the fish tank. Several other facilities can be added, such as oxygenation with pure oxygen, ultraviolet light or ozone disinfection, automatic pH regulation, heat exchanging, denitrification, etc. depending on the exact requirements.

Figure 2: Simplified illustration of RAS technology



Source: FAO – A guide to recirculation aquaculture – 2015 edition

Aquaculture of finfish needs a feeding system, as well as waste and dead fish removal systems. In addition, a RAS system requires pipes and pumps to transfer the water between the different stations, artificial lighting in the tanks and different sensors and monitoring systems to adjust and optimise the water treatment process.

[58] FAO, A guide to recirculation aquaculture, 2015 edition

3.1.1 Mechanical filter

First, water from the fish tanks flows through a mechanical filter which removes organic waste products. Normally, the water is filtered in a micro screen fitted with a filter cloth. The most commonly used type of micro screen is the drum filter which ensures a gentle removal of particles (as pictured in Figure 2).

Particles are trapped inside of the rotating drum, while water flows through the drum filter. The rotation of the drum transports the particles to a backwash area where rinse nozzles sprays water from the outside of the drum and traps organic material in a sludge tray. Together with the rinse water, the rejected organic material is transported out of the mechanical filter and the water flow for external wastewater treatment.

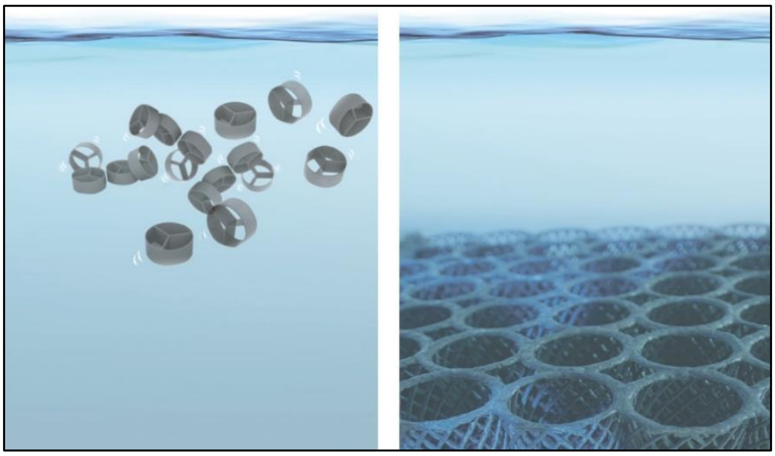
Besides different kinds of rotating screens (drum filter, disc filter, rotating belt, horizontally disc), other methods can be used for particle removal. This includes depth filtration (upstream, downstream), settling filters (horizontal, vertical) and swirl separators (hydrocyclones).

3.1.2 Biofilter

The finest particles of organic matter pass through the mechanical filter together with dissolved compounds of phosphate and nitrogen. Phosphate has no toxic effect on the production, but a nitrogen compound such as free ammonia (NH_3) is toxic to fish and needs to be transformed to harmless nitrate. The biofilter is a biological process carried out by bacteria. Heterotrophic bacteria oxidise the organic matter by consuming oxygen and producing carbon dioxide, ammonia, and sludge, while nitrification is conducted by nitrifying bacteria, removing ammonia from water by turning it into nitrite and nitrate.

Biofilters are typically constructed using plastic media where bacteria will grow as biofilm on their surface. Biofilters used in recirculation systems can be designed as fixed bed filters or moving bed filters. All biofilters used in recirculation today work as submerged units under water. In the fixed bed filter, the plastic media is fixed and not moving while the water flows through. In the moving bed filter, the plastic media is moving around in the water inside the biofilter by a current created by pumping in air.

Figure 3: Moving bed media (left) and fixed bed media (right)



Source: FAO

3.1.3 Degassing/aeration/stripping

Accumulated carbon dioxide (CO_2) and free nitrogen (N_2) are detrimental to the fish and must be removed from the water. Under anaerobic conditions, and especially in seawater systems, hydrogen sulphide (H_2S) is also produced. Hydrogen sulphide is deadly to fish even in low concentrations. The removal of these gases is called degassing, aeration or stripping and can be done both in the fish tanks and/or as a separate step before the water flows back to the tanks.

Aeration is the process of pumping air into the water whereby the gases are driven out from the turbulent contact between the water and air bubbles. A more efficient method entails a degasser which uses a trickling filter system. In a degasser, the water flows through a distribution plate with holes, and is then flushed down through a fixed bed of plastic media stacked in columns (similar to the right part of Figure 3). The gases are stripped from the water through contact with the plastic media and the contact between the two is maximised by the turbulence from the distribution plate and flushing process.

3.1.4 Oxygenation

Fish and most other aquatic animals depend on dissolved oxygen for respiration. A RAS system must therefore monitor and adjust the saturation level of oxygen in the water. When leaving the fish tank, the saturation level in the water is typically lowered to 70% and the level is further reduced after the biofilter and degasser. Aeration can bring the saturation level up to above 90%. In any case, adding pure oxygen is often preferred to ensure that the inlet water to the fish tanks is oversaturated to have sufficient oxygen available for high and stable fish growth.

There are several different methods to make super-saturated water (oxygen contents reaching 200-300%), either through high pressure in oxygen cones or under lower pressure in oxygen platforms. The oxygen cones use more energy (electricity) than the platforms. On the other hand, the cones only use a part of the circulating water whereas the platform is used as part of the whole recirculation flow.

Regardless of the method used, the process should be controlled with oxygen measurement.

3.1.5 Ultraviolet light

Bacteria, viruses, fungi and small parasites can be killed/removed from the water by ultraviolet (UV) disinfection. UV disinfection is more efficient if the water is previously filtered both mechanically and biologically.

3.1.6 Ozone

Ozone treatment can be used to destroy unwanted organisms too small to be caught by the mechanical filters. The ozone treatment breaks micro particles down to molecular structures that will then bind together and form larger particles which can then be removed. Ozone treatment is also referred to as “water polishing”, as it makes the water clearer, reducing the amount of suspended solids and pathogenic microorganisms.

Over-dosing with ozone can cause severe injury to the fish. Excessive use of ozone can also be harmful to the people working in the area. Hence, correct dosing, sufficient ventilation and close monitoring is crucial for positive and safe results. In many cases, UV lighting is a good and safe alternative to ozone.

3.1.7 Other elements

Tanks: The tanks must meet the fish needs, both in terms of design and environment (typically water current). For benthic fish (turbot, sole and other flatfish), the tank surface is more important than the depth, and the water flow rate can be lowered. Other species, such as salmonids, need larger water volumes and a tank design that accommodates higher water currents. The tank design, water current and behaviour of the fish will also influence the accumulation and behaviour of organic particles. The different factors must be assessed and optimised in the design of a specific RAS system.

pH regulation: The biofiltering process lowers water's pH, due to acid compounds production. Water's pH needs to be buffered to maintain water's quality.

Temperature regulation: Fish metabolism, bacterial activity in the biofilter, friction from pumps, piping and other installations will create and accumulate heat. The growth rate of the fish is directly related to the water temperature. Different species have different temperature requirements. The combination of species and location of the RAS system will affect the need for different temperature adjustment measures. Access to cold intake water can be used to cool the water. If the use of cold intake water is not enough, a heat pump or heat exchanger can be used. In cold climates, heating the water might be necessary. The heat can come from any energy source connected to a heat exchanger.

Monitoring, control, and alarms: To maintain optimal conditions for the fish at all times, all steps of the RAS system should be fitted with sensors to monitor and control the environment. Alarms should also be set to alert when any of the parameters moves out of the pre-set values. Modern farms often have automatic start/stop processes to try and fix any problems, but no system will work without human monitoring. If major failures are about to occur, a short reaction time (often within minutes) is crucial.

Emergency/backup systems: In case of failures in one or more parameters, some emergency systems can help keep the fish alive. The number one safety precaution is the use of pure oxygen. By pushing pressurised oxygen into the fish tank, the fish can, in some instances, can be kept alive long enough for the failure to be corrected. A RAS system should also have a backup for the electricity supply to secure the water flow. If the water is not circulated through the different filters, ammonia will quickly build up to toxic levels.

3.2 RAS technology suppliers and selected projects

An increasing number of concept suppliers offer turn-key RAS systems, including planning, construction, training, monitoring systems and service. Most of these suppliers are based in Northern Europe (Norway, Denmark, Netherlands, France, and Germany) and their technology is often based on experiences from smolt production. Some of the concept suppliers have developed their own systems based on their own farming experiences, while some others have developed systems based on the operators' concepts through collaboration projects.

There is an even higher number of suppliers specialised in certain parts of the RAS systems, which deliver pipes, pumps, tanks, specific elements of the water treatment systems, monitoring services, etc. As mentioned in chapter 3.1, the water treatment technology is the crucial part of a RAS system, and wastewater treatment companies are expanding their technology to the aquaculture sector (e.g. Sterner in Spain, CM Aqua in Denmark, Aqwise in Israel and Pentair in the United States). There are also suppliers specialised in water quality measuring systems (e.g. Blue Unit in Denmark) and feeding systems (e.g. Fish Farm Feeder in Spain).

The table below lists the major suppliers of complete RAS solutions. The table is based on publicly available information. "N/A" is used when no information was found during the desk analysis.

Table 2: Major suppliers of turn-key RAS systems

Company	Country (HQ)	Technology	Reference species	Reference locations
AKVA Group Land Based	Norway	Turn-key RAS solutions	15 different species (e.g. Atlantic salmon,	"Delivers systems globally". Offices and facilities in Norway, Chile, Denmark, Scotland, Iceland, Spain, Greece, Turkey, Iran, Canada and Australia.
AquaBiotech Group	Malta	Turn-key RAS solution AquaCirc	A large variety of species (e.g. barramundi, tilapia, sturgeon & sterlet, catfish, pike perch, salmon and trout)	N/A
AquaMaof	Israel	Turn-key RAS solutions	Several species (e.g. Atlantic salmon, whiteleg shrimp, African catfish, rainbow trout, grouper, barramundi, seabream, and seabass, sturgeon and yellowfin kingfish)	AquaMaof technology installed at facilities around the world (e.g. Poland, Slovakia, Israel, Russia, "Far East", Japan and Canada)
Artec Aqua	Norway	Turn-key RAS solutions	Salmon, trout, cleaner fish	Norway
Billund Aquaculture	Denmark	Turn-key RAS solutions	More than 20 different marine and freshwater species (e.g. salmon, trout, eel, cod, sturgeon, crustaceans, seabass & seabream, yellowtail Kingfish and grouper)	Present in more than 20 countries with over 130 successfully executed projects. Offices in Denmark, Chile, Norway, Australia and United States.
BioFichency	Israel	RAS - All-in-one water treatment	White shrimp, vannamei shrimp, ornamental koi, Chinese perch, seabass, catfish, tilapia, African catfish, barramundi	Israel, China, Nigeria, India, Bangladesh, Palestine, Taiwan, Idonesia, Congo,
Hesy	Netherlands	Turn-key RAS solutions	A variety of species (e.g. catfish, eel, sturgeon, tilapia, seabass, seabream, Atlantic salmon and pike perch)	Nearly 200 aquaculture systems in 31 different countries (e.g. South Korea, Russia, Azerbaijan, Benin, Canada, Cuba, Chile, Bulgaria, Netherlands, Croatia, Austria, Finland, Australia and New Zealand)
Krüger KaldnesAS / Krüger A/S / Veolia group	Krüger Kaldnes (Norway) Krüger A/S (Denmark) Veolia group (France)	Turn-key RAS solutions: Kaldnes RAS (smolt) RAS2020 (on-growing)	Wide variety of species - cold water, tropical, fresh water and marine (e.g. salmon, trout, kingfish, sea bass and pike perch)	Known reference projects in Norway, Switzerland, Denmark
MAT RAS	Turkey	Turn-key RAS solutions with a combination of own equipment and equipment from other vendors	Seabass, seabream, meagre, umbra,	Turkey
Nofitech	Norway	Turn-key RAS solution ModulRAS	Atlantic salmon, rainbow trout	Norway and Japan
Nordic Aquafarms	Norway	Salmon producer, self-sufficient on RAS design and delivery	Atlantic salmon, yellowfin kingfish	Norway and Denmark
PE Bjørdal	Norway	Turn-key RAS solutions for smolt	Atlantic salmon (smolt)	Norway
RAS | CON	Denmark	Turn-key RAS solutions	Salmon, coho, trout and Arctic char	Tasmania, Chile, Norway, United Kingdom, Faroe Islands and Denmark
ScaleAQ	Norway	Turn-key RAS solution OptiFarm as well as singular elements: (e.g. OptiTrap, OptiFlow og OptiTank)	Several species (e.g. eel, sturgeon, barramundi, salmon, shrimp, trout, tilapia, seabass and seabream)	ScaleAQ's technology installed in more than 35 countries around the world (e.g. Russia, Portugal and Indonesia). Offices in 11 countries (e.g. Norway, Australia, Chile, Canada, United Kingdom, Vietnam, Spain and Turkey)
UFT Aquaculture Engineering	Germany	Turn-key RAS solutions	Several species (e.g. Arapaima gigas, Eel, Barramundi, Seabass, Perch, Trout, Grouper, Salmon-Trout, Tilapia, Seabream, Sturgeon, Hybrid Striped Bass)	Inter alia: Angola, Armenia, Belarus, Belize, Germany, England, Iran, Kazakhstan, Kuwait, Lebanon, Malaysia, Mongolia, Qatar, Romania, Russia, Saudi Arabia, Spain, Switzerland, Turkmenistan, United Arab Emirates, USA
Alpha Aqua	Denmark	Turn-key RAS solutions	Several species	N/A

Table 3: Selected example projects

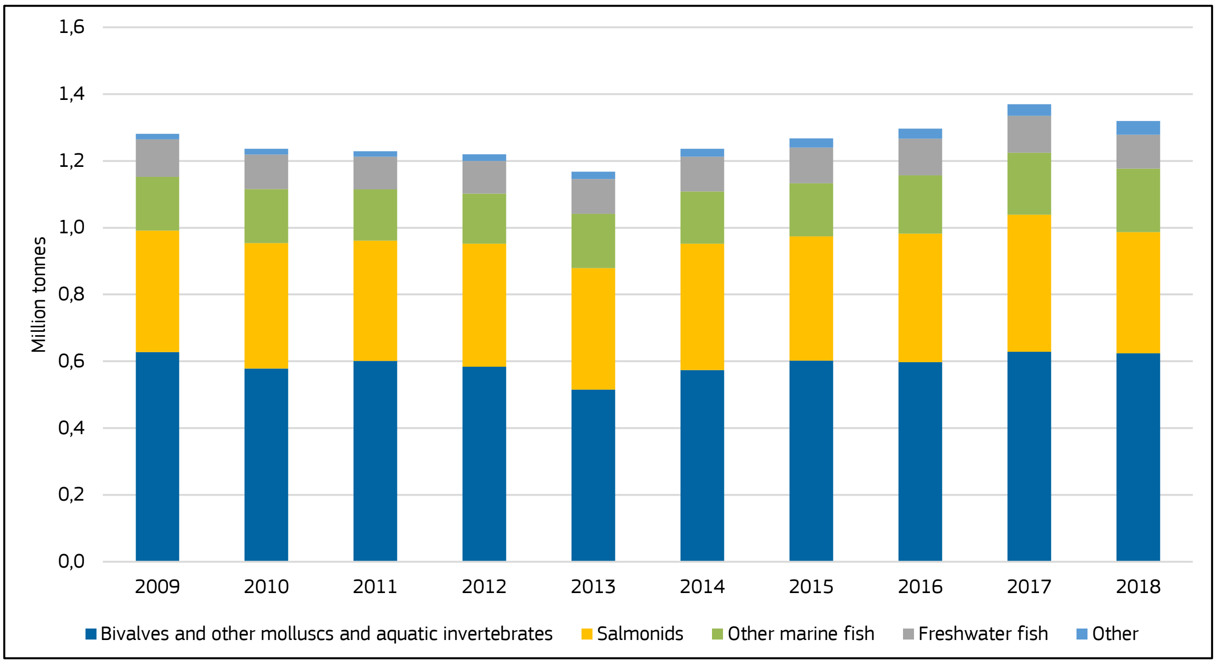
Company	Species	Production phase	Water environment	Supplier	Location	Capacity	Status
Kingfish Zeeland	Yellowtail kingfish	Hatchery/ grow-out	Seawater	Billund Aqua	Netherlands	500 tonnes (4 kg)	In operation
Bakkafrost (Strond)	Atlantic salmon	Hatchery, smolt and post-smolt	Freshwater and seawater	AkvaGroup	Faroe Islands	N/A	In operation
Norcantabric	Atlantic salmon	Hatchery and grow-out	Seawater	Alpha Aqua	Spain	3.000 tonnes (4 - 4,5 kg)	Planned
Pure salmon (8F)/AquaMaof (training center)	Atlantic salmon	Smolt and grow-out	Freshwater and seawater	AquaMaof	Poland	580 tonnes (up to 6 kg)	In operation
Seafarm BV	Turbot	Grow-out	Seawater	Krüger Kaldnes	Netherlands	250 tonnes	In operation
Cara Royal	Whiteleg shrimp	Larvae and grow-out	Seawater	N/A	Germany	15 tonnes	In operation
Kilic	Bass&Bream, Meager and Umbra	Hatchery/ juveniles	Seawater	MAT Ras	Turkey	400 million juveniles	In operation
Agrofirm Project	Catfish	Grow-out	Freshwater	AquaMaof	Slovakia	1.000 tonnes	In operation
Sashimi Royal	Yellowtail Kingfish	Grow-out	Seawater	Krüger Kaldnes	Denmark	900 tonnes	In operation

4 RAS PRODUCTION IN THE EU

4.1 For human consumption

In 2018, aquaculture production in the EU[59] was 1,32 million tonnes valued at EUR 4,80 billion, slightly down from the 10-year high of 1,37 million tonnes and EUR 5,06 billion in 2017. In terms of the main commodity groups[60], "Bivalves and other molluscs and aquatic invertebrates" accounted for almost half of the production volume (624.000 tonnes), followed by "Salmonids[61]" (363.000 tonnes), "Other marine fish[62]" (190.000 tonnes) and "Freshwater fish" (102.000 tonnes).

Figure 4: Yearly aquaculture production in the EU by main commodity groups (million tonnes live weight)



Source: EUMOFA (data extracted on 08.09.2020)

According to EUROSTAT, the production of fish for human consumption in "recirculation systems"[63] has been relatively stable at between 1,5 and 2% of the total production over the period with an average yearly volume of nearly 24.000 tonnes.

The RAS production is dominated by few large producing countries, and the top 6 Member States accounted for 92% of the production in 2018. Denmark accounts for roughly half of the volume each year. The Netherlands saw a negative trend over the 10-year period. In 2009, the Netherlands

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[59] 2013-2018 data are for EU-28, as they also include Croatia.

[60] See "Metadata 2 – Data management – Annex 2" for a correlation list of ERS codes and EUMOFA's "Main Commercial Species" and "Commodity Groups", https://eumofa.eu/documents/20178/24415/Metadata+2+-+DM+-+Annex+3+Corr+of+MCS_CG_ERS.PDF/1615c124-b21b-4bff-880d-a1057f88563d

[61] Salmonids include salmon and trout, *plus* other types of salmonids species

[62] Farmed species belonging to this group include gilthead seabream and other seabreams, seabass, and marine species not included in other commodity groups. For more information, please consult the "Harmonisation" page of the EUMOFA website at the link http://www.eumofa.eu/harmonisation

[63] As defined by Eurostat, ref. chapter 0.3.2.

accounted for 35% of the RAS production (7.932 tonnes), while in 2018, their share had decreased to 17% (4.971 tonnes).

France have reported varying production over the years. From 80 tonnes in 2009 to 1.415 tonnes in 2010 followed by production volumes between 379 and 632 tonnes until zero production was reported in 2015. In 2018, France reported the highest production volumes over the past 10-year period with 3.784 tonnes (13% of total production).

Germany and Poland have no registered RAS production prior to 2011. Germany shows a relatively stable, but n increasing trend, starting at 1.590 tonnes (7%) in 2011 which increased to 2.321tonnes (8%) in 2018. Poland shows decreasing and more variable production volumes. From 2.959 tonnes (14%) in 2011 down to 1.055 tonnes (5%) in 2013 and up to 2.031 tonnes (7%) in 2018.

Spain registered its first RAS production of 610 tonnes (3%) in 2009, and shows an increasing but variable trend. The lowest volume was registered in 2012 (426 tonnes) and the highest in 2018 with 1.290 tonnes (5%).

Table 4: Yearly production volume in "Recirculation systems"[64] by country (tonnes live weight)

Member State	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Denmark	11.494	11.471	10.785	11.579	10.861	11.068	13.209	13.812	13.284	12.847
Netherlands	7.932	6.610	4.340	3.415	6.535	5.725	5.290	5.290	4.821	4.971
France	80	1.415	455	379	632	570		29	41	3.784
Germany			1.590	1.235	1.679	2.262	2.820	2.547	2.722	2.321
Poland			2.959	1.197	1.055	1.825	1.782	1.645	1.836	2.031
Spain	610	601	472	426	720	911	810	634	865	1.290
Slovakia						2	11	560	922	822
Austria							438	338		421
Lithuania	12	8	13	66	99	122	360	435	326	356
Estonia					55	126	100	100	105	160
Czech Republic	36	29	74	37	97	77	185	238	24	136
Hungary	1.767	1.891	77	73	95	88	172	136	81	136
Bulgaria	4	8							357	135
Latvia	8	16	23	27	30	27	67	19	37	81
Croatia	67	42	16							20
Italy	106	74		1	45	2	3	3	2	3
Greece			77				68	75		
United Kingdom	322	473	490	190	380	393	13	9	1	0
Romania			14			16				
Ireland									4	
Total	**22.439**	**22.638**	**21.384**	**18.625**	**22.281**	**23.214**	**25.328**	**25.871**	**25.428**	**29.513**

Source: Eurostat

In addition to the table above, other Member States have reported small-scale RAS production which have not been reported to Eurostat as it is below the threshold. In Belgium, a few commercial producers use RAS, *inter alia* for striped seabass, sturgeons, pike perch fingerlings and whiteleg shrimp. In Sweden, the total production in RAS is low and an aggregated volume of 98 tonnes (all species) was reported for the first time in 2017. According to the Swedish Board of Agriculture, the production volume in 2018 is likely above 100 tonnes and includes species such as salmon, trout, rainbow trout, Arctic charr, Nile tilapia, sturgeons, crayfish, carps and perch.

[64] As defined by Eurostat, ref. chapter 0.3.2

Around 90% of the RAS production is in a freshwater environment, while the remaining 10% is sea and brackish water. In terms of species, the top five species accounted for 95% of the production in 2018. Rainbow trout is by far the most farmed species, accounting for 56% (16.471 tonnes) of total production. Rainbow trout is followed by North African catfish (5.066 tonnes), European eel (4.152 tonnes), Atlantic salmon (1.514 tonnes) and Senegalese sole (861 tonnes).

Table 5: Top five species and top six producing Member States in "Recirculation systems"[65] in 2018 (tonnes live weight)

Species	Denmark	Netherlands	France	Germany	Poland	Spain	Other	TOTAL
Rainbow trout	11.398	0	3.595	40	1.043	0	395	**16.471**
North African catfish	0	2.470	0	713	298	0	1.584	**5.066**
European eel	428	2.150	0	1.205	0	342	27	**4.152**
Atlantic salmon	1.021	0	0	0	493	0	0	**1.514**
Senegalese sole	0	0	0	0	0	861	0	**861**
Other	0	351	189	362	196	86	264	**1.449**
TOTAL	**12.847**	**4.971**	**3.784**	**2.321**	**2.031**	**1.290**	**2.270**	**29.513**

Source: Eurostat

4.2 Hatcheries, juveniles and smolt

Normally, hatcheries and nurseries for juveniles use land-based flow-through systems in tanks, or raceways located on the seashore (sea water), or on inland ponds, lakes or rivers (freshwater). However, RAS technology has been used to produce fry and juveniles for decades and the use of RAS is increasing, especially for smolt production (salmonids). It is estimated that the share of RAS in smolt production amongst the largest salmon producing countries has increased from below 40% in 2014/2015 to more than 50% in 2018/2019[66]. Furthermore, the construction of most new smolt production facilities is based on RAS technology.

The juvenile stage of production needs less water, but is more fragile than the grow-out phase. Even though the tanks are smaller, the number of juvenile individuals in each tank is much higher, and deaths due to diseases or changes in the water environment will have a correspondingly larger impact. Hence, the main driver behind RAS in juvenile production is water environment control, and not necessarily reduction of water consumption.

In the production of smolt and juveniles, the fish are hatched and nurtured up to a certain size before they are transferred to a grow-out environment. The size of juveniles is species dependent. Consequently, the production in terms of volume (tonnes) can be classified as small-scale.

The Eurostat database of "production of hatcheries and nurseries at juveniles stage in life cycle"[67] contains data on juveniles both destined for further grow-out phase (aquaculture) and to be released into the wild (conservation measures). However, due to confidentiality, many Member States only report total juvenile production without specifying destination use. Furthermore, the database does not include a variable for production method. Consequently, it is not possible to identify the share of juveniles destined for grow-out in aquaculture, nor the share of RAS in the production.

Based on Eurostat data on juvenile production data finfish, as well as on assumptions on a range of juvenile sizes (weight) before transfer to grow-out environment or released to the wild, the table below estimates the total production volume of juveniles between 29.000 and 45.200 tonnes in 2017 in the EU.

[65] As defined by Eurostat, ref. chapter 0.3.2

[66] Estimates by Kontali Analyse.

[67] Eurostat database "fish_aq4b".

Table 6: EU production of finfish juveniles 2017 and estimated volume (tonnes)

	Number of juveniles	Estimated total volume (tonnes rounded)	
Species	Million	Min	Max
Rainbow trout - Oncorhynchus mykiss	321	8.000*	9.600*
Miscellaneous carp fishes	759	2.300	7.600
Atlantic salmon - Salmo salar	66	5.300	7.300
Marine fishes nei - Osteichthyes	355	3.600	7.100
Gilthead seabream - Sparus aurata	340	2.700	3.400
European seabass - Dicentrarchus labrax	233	1.900	2.300
Sea trout - Salmo trutta	46	900	1.400
European whitefish - Coregonus lavaretus	118	600	1.200
Northern pike - Esox lucius	112	900	1.100
Pike-perch - Stizostedion lucioperca	80	800	1.000
Other (26 species)	182	2.000	3.000
Total finfish	**2.614**	**29.000**	**45.000**

Source: Eurostat, volumes estimated by EUMOFA experts.
**For trout, the difference between juvenile and grow-out stage is less clear, hence the estimated juvenile weights are more uncertain.*

The salmon industry is fairly developed in terms of RAS technology when it comes to smolt production. In Norway and Chile, the share of RAS in smolt production is somewhere between 40% and 50%, in the Faroe Islands it is close to 100%, while in the UK the share is less than 10%[68]. The general share of RAS production is assumed to be in a lower range in the EU, probably between 5% and 10%, which according to the table above implies that RAS is used on less than 5.000 tonnes of the juvenile production.

[68] Estimates for 2018 by Kontali Analyse.

5 DRIVERS AND BARRIERS FOR RAS PRODUCTION

RAS production is technologically complex compared to traditional production methods. RAS have a long history in freshwater environment (e.g. portion trout, eel and smolt), but are immature in terms of commercialised large-scale production of market-sized fish in saline water environment. Despite technological developments in recent years, there are still many risks associated with RAS operations. The risks can be classified in four main categories: operational risks, financial risks, market risks and social and regulatory licenses[69].

5.1 Operational risks

Operational risks are related to the functioning of the system. The equipment and technology must be managed correctly to replicate the optimal environment and water quality for the fish, and to ensure optimal animal welfare and growth. If the equipment or technology (filtering systems, pumps, etc) malfunctions, either due to errors, ineffective design/assembly or poor management, the accumulation of toxic gases (e.g. carbon dioxide, ammonia and hydrogenic sulphide) will negatively affect the health, welfare and growth performance of the fish[70], and can quickly even have fatal consequences.[71] Sub-optimal rearing conditions can also reduce the quality of the product in terms of colour, texture and taste.

Freshwater RAS have proven successful for decades, both for rearing market-sized portion trout and eel, but especially for smolt production. Due to long experience from trial and error, the operational risks related to freshwater RAS are lower than for RAS in saline environment. High salinity can lead to corrosion, so saltwater RAS requires more robust (and expensive) equipment. There are also additional risks related to accumulation of toxic gasses (especially CO_2 and H_2S) with saltwater RAS production compared to freshwater.

With all the technology and management of the different variables, a skilled workforce is essential for a RAS facility to operate successfully. Competence is needed with the reared species, water quality, the technological installations, and in general management. Often, the competence should be specific to the farm/technology that is managed, and education within general aquaculture might not be enough. Despite the high impact of workforce skills on the farming performance in RAS, availability of competence seems to be one of the main bottlenecks in these systems. In order to increase the availability of skilled workforce, it could be wise to locate RAS facilities close to areas where research and education activities take place.

Biological adaptations could be implemented to mitigate biological risks. All reared species are domesticated according to their traditional farming techniques, which makes them specially adapted to this environment after some generations. An important aspect of the issue with fish welfare in RAS is the interaction between fish genotype and their environment (phenotype). For example, the findings of a study on common sole (*Solea solea*) from 2013, found a low genetic correlation for growth between different environments which implies a strong genotype by environment interaction. This interaction suggests there might be potential for breeding fish that are adapted to their farming facilities, including RAS.

[69] Rabobank 2019, *Aquaculture 2.0: RAS Is Driving Change*.

[70] Aslam et. Al., 2019, *Effect of CO_2 on elemental concentrations in recirculation aquaculture system tanks,*

https://www.sciencedirect.com/science/article/pii/S0044848619301085?via%3Dihub.

[71] https://salmonbusiness.com/quarter-of-a-million-salmon-die-at-atlantic-sapphires-danish-ras-facility/.

In general, there are advanced breeding programmes for just a few fish species, including salmon, trout, seabass and tilapia[72]. These species are therefore believed to be leading in development of RAS breeding lines. There is an ongoing adaptation towards breeding fish for RAS as the demand is growing, and there are already some developed products[73].

There is lack of several environmental signals in a RAS environment. In addition, the fish is often kept at higher density than in traditional production. The combination of these factors can lead to accumulation of hormones in the water[74], and potentially early sexual maturation. Early maturity is not desirable, because it is conducive to inferior flesh quality, and because the fish might experience problems with the osmotic regulation, which is a welfare issue. One solution, which has been used for a long time in portion trout farming in Europe, can be to use "all-female" eggs in the production[75].

Another way of mitigating biological risk is by nutritional adaptation. Feed companies such as Skretting, Cargill, BioMar and Aller Aqua have developed special feed for RAS production environments[76]. A central adaptation with these specialised feeds is to increase the digestibility degree and produce faeces with a solid composition. This reduces the stress on both mechanical and biological filters and can improve water quality and reduce the operational costs.

5.2 Financial risks

One of the toughest challenges for RAS operations is to be found in the amount of capital expenditure (capex) that is required upfront. Building and constructing RAS facilities account for most of the development capex[77]. Some stakeholders state that the total investment cost of a full-cycle RAS facility for Atlantic salmon is similar to that of traditional farming methods in Norway, due to the high cost of traditional farming licenses. However, uncertainty regarding future costs of production, including biological risks, and the long time period between the initial investment and the revenue from RAS production increases the need for financial flexibility. There is also uncertainty regarding the expected return on investments due to market risks (see chapter 5.3 below). As previously mentioned, large-scale commercial RAS production of market-sized fish in saline environment is still in its early days, with even more unknowns leading to higher financial risks for these projects.

Operating costs (opex) are generally considered higher in RAS compared to traditional farming methods. This is mainly due to the energy-demanding process of treating and transporting the water. The highest costs connected to water treatment are related to pumping and lifting of water, CO_2 removal, temperature control and oxygenation. These costs will of course vary with the different local conditions of the water source. Naturally, the costs will be reduced if the inlet water can flow into the facility (reduced need for pumps), and if it has high quality and the right temperature (reduced need for filtering and treatment). In all aquaculture production, feed is one of the major operating costs and even more so in RAS if the facility uses specialised RAS-feed.

For the time being, sludge (or fish manure) is another operating cost in a RAS facility. Unlike traditional aquaculture, RAS collect the sludge and consequently must dispose of it in a legal and sustainable manner. Sludge has a high content of energy, nitrogen and minerals, such as phosphorus, and could be

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[72] https://salmobreed.no/products/ https://aquagen.no/en/products/ https://mowi.com/about/our-unique-breed/ http://www.genomar.no/?

[73] Salmobreed's "SALMORAS4+": https://salmobreed.no/products/

[74] Wang et al., 2019, *Effects of stocking density on the growth and immunity of Atlantic salmon salmo salar reared in recirculating aquaculture systems (RAS)*, https://link.springer.com/article/10.1007/s00343-019-7350-7

[75] AquaGen have "all-female" product lines for both Atlantic salmon and rainbow trout: https://aquagen.no/en/products/

[76] Skretting, Unknown year, *We are the global leaders in RAS,* https://www.skretting.com/en/research-innovation/innovations/ras/

[77] Rabobank 2019, *Aquaculture 2.0: RAS Is Driving Change.*

turned into a resource, e.g. as a natural fertiliser or extraction of phosphorous[78]. However, more research is needed and currently, governmental regulations[79] limit the use of sludge.

Some stakeholders state that with the increasing costs of traditional farming of Atlantic salmon (especially concerning sea lice treatments), combined with technological development in RAS, the average production costs are converging.

5.3 Market risks

Market conditions depend on several factors, including competition from other producers, production volume, product quality and consumer demand. Theoretically, all aquatic species can be farmed in RAS. However, not all species are assumed to perform well in a RAS environment, and not all species have market conditions which justify the higher production costs.

Most promoters of RAS project higher market prices for their product, based on its sustainability credentials, localness and associated freshness. Some stakeholders interviewed for this study claim that it is possible to attain a price premium between 5% and 20%. Others state that a price premium (if at all present) will disappear as soon as the RAS production increases.

There appear to have been no widespread surveys of consumer willingness to pay extra for fish produced in RAS. However, a master thesis from 2016 investigated the attitudes of Danish consumers towards RAS produced fish[80]. Based on a sample of 238 respondents, the data indicated that a price premium is attainable. Furthermore, the study found that product attributes relating to health factors (absence of antibiotics, medicine and heavy metals) are deemed more positive than attributes relating to sustainability and animal welfare.

Other surveys on related criteria (certification and ecolabelling) suggest that a price premium of around 15% could be attained if independently-certified and well-promoted ecolabels are used[81]. However, in a study on organic Norwegian salmon, the price premium was lost and even became negative when the flesh of organic salmon turned out to be pale in comparison with conventional salmon. Hence conventional indicators of quality tended to override any specific labelling.

A generic challenge with all "willingness to pay"-studies is that such stated preferences are often poorly correlated with revealed preferences, i.e. the consumers' actual purchasing behaviour at the checkout. There is not enough data to analyse a price premium on RAS produced fish, but that does not mean it is not possible to attain it.

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[78] Arvanitoyannis, I.S. & Kassavetti, A., 2008, *Fish industry waste: treatments, environmental impacts, current and potential uses,* https://ifst.onlinelibrary.wiley.com/doi/abs/10.1111/j.1365-2621.2006.01513.x

[79] For example, excrement of fish does not fall under the definition of "manure" in the European Union's animal by-product regulation (Regulation No. 1069/2009) and cannot be utilised as a natural fertilizer.

[80] Ekmann, 2016, *Investigation of Consumer Attitude Towards RAS Produced Fish*, https://projekter.aau.dk/projekter/files/270776430/Investigation_of_Consumer_Attitude_Towards_RAS_Produced_Fish___In_Pursuit_of_a_Viable_Price_Premium___Master_Thesis.pdf

[81] Bostock J, Fletcher D, Badiola M & Murray F (2018) *An update on the 2014 report: "Review of Recirculation Aquaculture System Technologies and their Commercial Application"*. Highlands & Islands Enterprise. Inverness.

Under EU regulation[82], RAS cannot be labelled as organic and there are no RAS-specific labels or certifications. However, as consumers are increasingly focusing on sustainability, animal welfare, organic production and locally-produced food, several factors could be used in the marketing and branding of RAS products to attain a price premium:

- Environment
  - Reduce effluent loads
  - No escapees
  - Increased environmental control
- Traceability
- Localness
  - RAS promotes new possibilities for aquaculture production almost anywhere, and some consumers tend to pay extra for local produced food.
- Biosecurity
  - Disease management
  - No parasites and pathogen accumulation
  - Some customers believe that RAS is more sustainable

Near-market RAS production, and subsequent shorter transportation, could also reduce the carbon footprint of the products in the market. On the other hand, RAS production is energy-intensive, and the net benefit on carbon pollution is highly dependent on the energy source. In this respect, RAS is especially interesting when combined with renewable energy sources.

A general quality issue is the presence of geosmin in RAS-produced fish, which is responsible for an earthy off-flavour in meat and roe.[83]. Currently, the off flavour is removed by purging the fish in clean water and not feeding it for a period of about a week. This method is sufficient for the fish meat, but to remove the off flavour in the roe, the fish must be purged for a much longer time.

Another market risk concerns external factors, of which the COVID-19 pandemic is a good example. Many aquaculture farmers, including RAS producers, are focusing on high-valued species. Unfortunately, many of these species happen to be consumed mostly out of home, and the hospitality industry has been highly affected by the lockdowns and the social distancing measures taken in an effort to contain the pandemic.

5.4 Social and regulatory licensing

As with traditional aquaculture, production permits are necessary to establish a RAS facility. In addition, licenses are required for the intake and discharge of water. With decreasing availability of suitable, regulated coastal areas, licenses for cage-based aquaculture are difficult and expensive to obtain, which is a substantial driver for moving the production on land.

Regarding regulatory permits and licenses, multilevel governance can result in barriers or risks, both within a MS and between the MS and the EU, in relation to e.g. the Marine Strategy Framework Directive[84] and the EU Water Framework Directive[85] and River Basin Management principles for

[82] Commission Regulation (EC) No 889/2008 until 31st December 2021, Regulation (EU) 2018/848 from 1 January 2022. The Commission has adopted a proposal for the postponement of the entry into application of this Regulation until 1 January 2022, and the Regulation is expected to be soon adopted by the EU Parliament and Council.

[83] https://www.aquaculturealliance.org/advocate/off-flavors-in-salmonids-raised-in-ras/

[84] Directive 2008/56/EC.

[85] Directive 2000/60/EC.

freshwater environments. The interactions between local, regional, national and EU legal requirements can often make the licensing process unpredictable and protracted[86].

Even with regulatory permits and licenses in place, it is not always straightforward to get the support of local communities. At the same time, some consumers are not happy to have production at sea either. With respect to animal welfare, the focus on treatment of sea lice, escapees, and the use of antibiotics, social licensing could be less expensive for RAS facilities.

5.5 Growth drivers

As the demand for transparent and sustainable food is increasing, the two main drivers for RAS growth seem to be proximity to the market and reduced environmental impact.

Proximity to the market is a driver for RAS growth, since recirculation of water makes facilities less dependent on water sources/location. Furthermore, RAS makes it possible to farm foreign species by adjusting the growth environment, including e.g. lighting, temperature, salinity and water current. Proximity also reduces transport, which can lead to fresher products to the market and reduced carbon emissions.

Other **environmental aspects** are also possible drivers for RAS growth. Compared to traditional methods, RAS facilities can have complete control over environmental parameters, a significant reduction in water consumption, control and treatment of the effluent water and waste, good possibilities for fish health and pathogens control (biosecurity) and prevention of escapes. RAS production in combination with renewable energy sources could also reduce the carbon footprint of the final products.

[86] EUMOFA 2019, *Factors affecting cross-border investments in EU aquaculture*.

6 CASE STUDIES

6.1 Saline water finfish – grow-out of Atlantic salmon

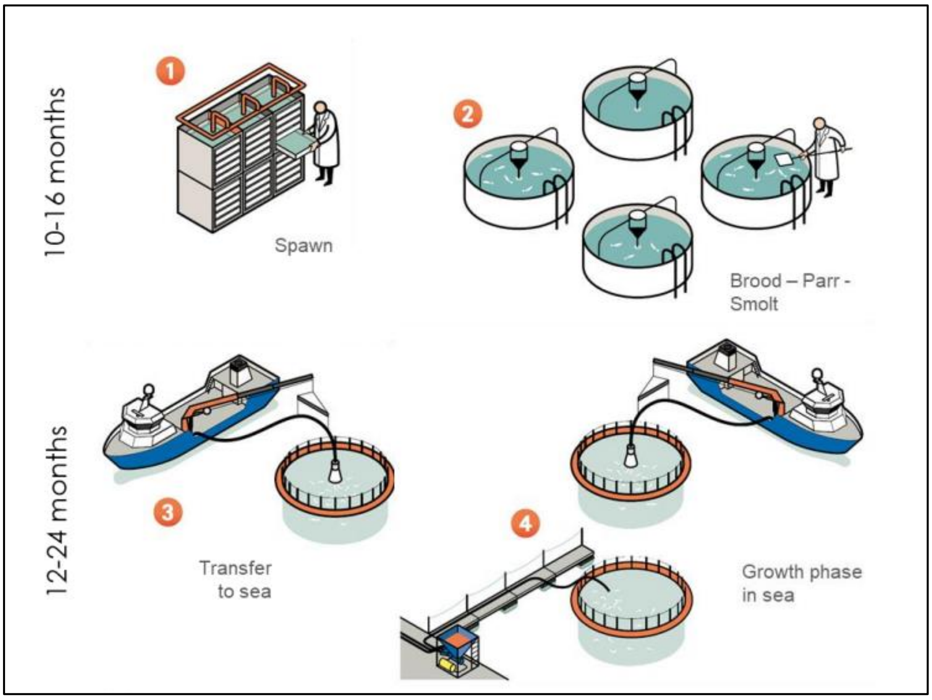
6.1.1 Introduction

The total global production of Atlantic salmon was almost 2,6 million tonnes in 2019[87]. European countries accounted for 64% of this production, while the EU accounted for 8%. The largest producing countries were Norway (52%), Chile (27%), the UK (7%), Canada (5%) and the Faroe Islands (3%).

Production of Atlantic salmon has more than tripled over the past 20 years, with a compound average growth rate (CAGR) of 6%. Over the same period, the EU production has increased by less than 50%, with a CAGR of 2%.

The whole production cycle of Atlantic salmon, from ova inlay to harvest, is usually between 2-3 years. The fish is first cultivated in freshwater until it reaches the smolt stadium, normally after 10 to 16 months. Then follows the grow-out phase, where traditionally the smolt is transferred to sea cages where it grows to harvest weight, normally over a time span of 12 to 24 months.

Figure 5: Traditional production cycle of Atlantic salmon



Source: Mowi, Salmon Farming Industry Handbook 2020

Smolt is normally grown in tanks on land, usually with a flow-through or RAS technology. These smolt facilities are often located near rivers and streams to ensure steady access to clean, fresh intake water. Over the past 10-20 years, smolt facilities have increasingly incorporated RAS technology, both to limit the intake water, and to control and adjust the growing environment. Much of the technology developments in RAS are driven by past experiences from smolt production.

The grow-out phase at sea is influenced by several environmental factors. One important factor is water temperature. Atlantic salmon is a cold-blooded animal and thrives in water temperatures

[87] Kontali Analyse.

between 8-14 °C. As a result, some colder regions have large natural competitive advantages. Other important factors are sea lice and diseases. In a traditional sea cage, it is impossible to protect the fish from sea lice, parasites, poisonous algae, or other diseases. Treatment is costly, if at all possible, which often leads to early harvest of the whole biomass.

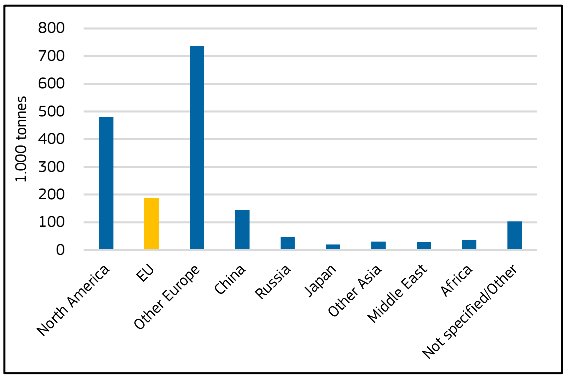
To limit the time spent by the fish in the sea – thus reducing exposure to sea lice, deceases and other environmental influences that can harm the fish or its growth – an increasing number of farms are producing post-smolt. Compared to smolt, which weigh between 100 and 250 grams, post-smolt are kept longer in tanks on land and weigh up to 1 kg.

Some argue that the next logical step would be to move the whole production cycle on land, using flowthrough or RAS technologies to control the growing environment from ova inlay to slaughter. Currently, most functional RAS facilities operate in a freshwater environment, but the number of facilities operating in a saline water environment is increasing. In 2019, only between 5.000 and 10.000 tonnes of Atlantic salmon was produced in RAS globally. In the long term, the planned future production capacity exceeds 1,7 million tonnes[88].

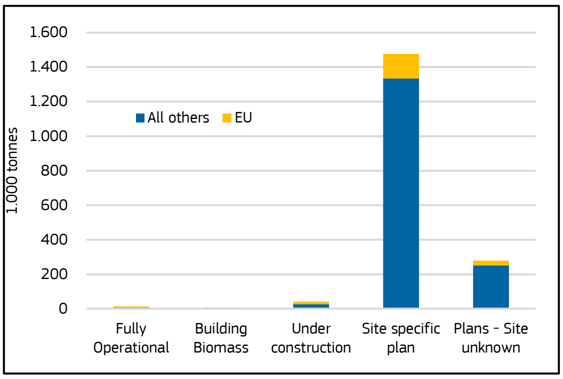
Around 10% of the planned capacity is in the EU, while another 40% in other European countries, mainly Norway and Iceland. About 1% of the production capacity is fully operational or in the process of building biomass, while another 2% is under construction. The remaining capacity is still at the planning stage, either with or without a specific site.

Figure 6: RAS projects and planned future production capacity (1.000 tonnes)

BY REGION



BY PROJECT PHASE



Source: Kontali Analyse

6.1.2 Nordic Aquafarms

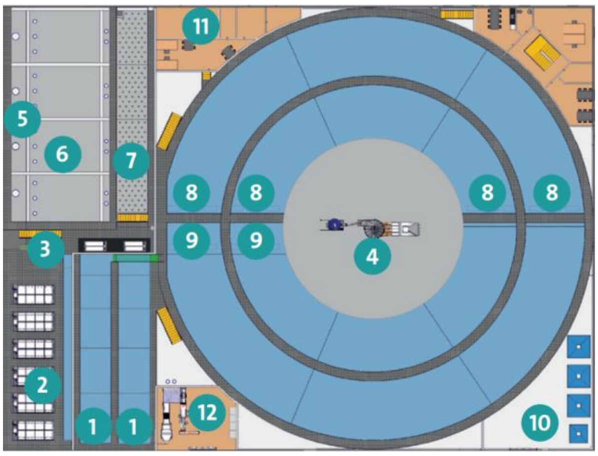
One of the already fully operational RAS facilities is Nordic Aquafarms' subsidiary, Fredrikstad Seafoods, in Norway. Fredrikstad Seafoods was officially established in 2014 and immediately started working with the Norwegian authorities to obtain land-based farming licenses. In 2015 they were granted a research license, and in 2016 the Norwegian government introduced permanent land-based farming licenses, for which Fredrikstad Seafoods was the first applicant. After being awarded a license, the construction of the production facility in the town of Fredrikstad began in late 2016.

Fredrikstad Seafoods is one of the largest land-based salmon farming facilities, with a current capacity of around 1.500 tonnes. The production facility is located close to the river delta with direct intake of sea water. The facility has two independent modules, each with a separate RAS loop. The technology

[88] Kontali Analyse

used is "*Krüger Veolia RAS 2020*", a system with two circular tanks of 5.200 m³ combined, with movable gates to adjust the tank sizes and integrated biofilters in the centre.

Figure 7: Krüger Veolia RAS 2020 – illustration of the water treatment process



1. Purge tanks
2. Drum filters
3. UV filters
4. Biofilters,
   fish pump, grader and counter
5. Propeller pumps
6. CO_2 degasser
7. Medium head oxygenation units
8. Outlet from water treatment to fish tank
9. Inlet from fish tank to RAS flow makers
10. Feeding system
11. Control room
12. Processing

Source: Krüger AS - Veolia Water Technologies

Production started with input of smolt in May 2019 and the facility soon delivered strong biological performance. The first harvest was in April 2020, and since then, Fredrikstad Seafoods have harvested some fish as large as 9 kg. The final product is of high quality, at least based on feedback from their customers, who highlight tender and firm meat, less fat and great taste. For certain segments, Fredrikstad Seafoods also obtained a price premium for their land-based product compared to traditionally farmed salmon.

Nordic Aquafarms aim to be a leading player in land-based aquaculture with production close to large markets. Fredrikstad Seafoods' production facility is also a centre for research and development, and training when it comes to Atlantic salmon. The next phases for Nordic Aquafarms are two planned production facilities in the USA, one in Maine on the east coast and one in Northern California on the west coast, as well as scouting for opportunities for establishing production in Asia. By 2030, Nordic Aquafarms aim at producing more than 70.000 tonnes of Atlantic salmon head on, gutted (HOG) in RAS world-wide.

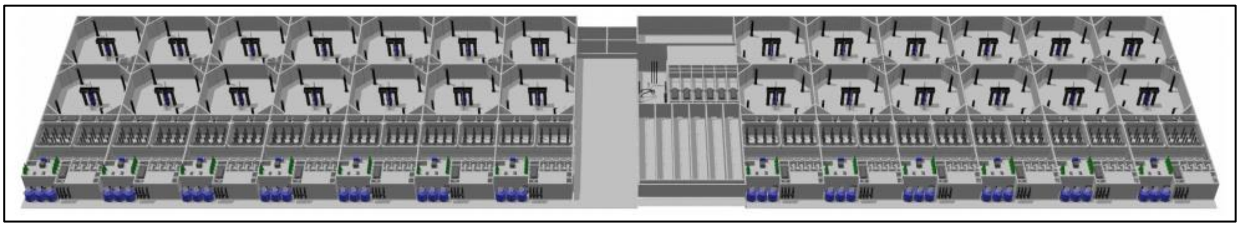
The US consumes more than 500.000 tonnes of whole fish equivalent (WFE) of salmon every year. With a 90% seafood trade deficit, most of consumption is based on imports. Supply of locally-produced, fresh Atlantic salmon makes sense both from a financial and environmental viewpoint.

The production facility in Maine is in the advanced planning stage. They expect to receive the necessary permits within 2020, after which they will start construction immediately. The construction will be divided in two phases of approximately 12.500 tonnes HOG production capacity each. The planned production facility in Northern California will be a replica of the facility in Maine. Nordic Aquafarms have already secured an option to lease the land area, and permits are expected within 2021.

Based on their experiences from Fredrikstad Seafoods with a production system from Krüger Veolia, the facilities in the US are planned with different production system designs. The main differences between the systems are the shape of the tanks and the water treatment capacity. The new system will have individual octangular tanks, which allows the fish to freely swim counterflow without any movable gates blocking them. Compared to the Krüger Veolia RAS 2020, water treatment capacity will increase by around 30% in the new system from 1,5 to 2 times per hour with an additional 20% side stream water treatment.

The grow-out modular concept for phase 1 in Maine (around 12.500 tonnes HOG capacity) will consist of 13 RAS loops, each loop with two fish tanks. When fully developed, each tank will only hold about 4% of the total biomass, which reduces the operational risk.

Figure 8: Modular concept of a grow-out facility with approx. 12.500 tonnes capacity



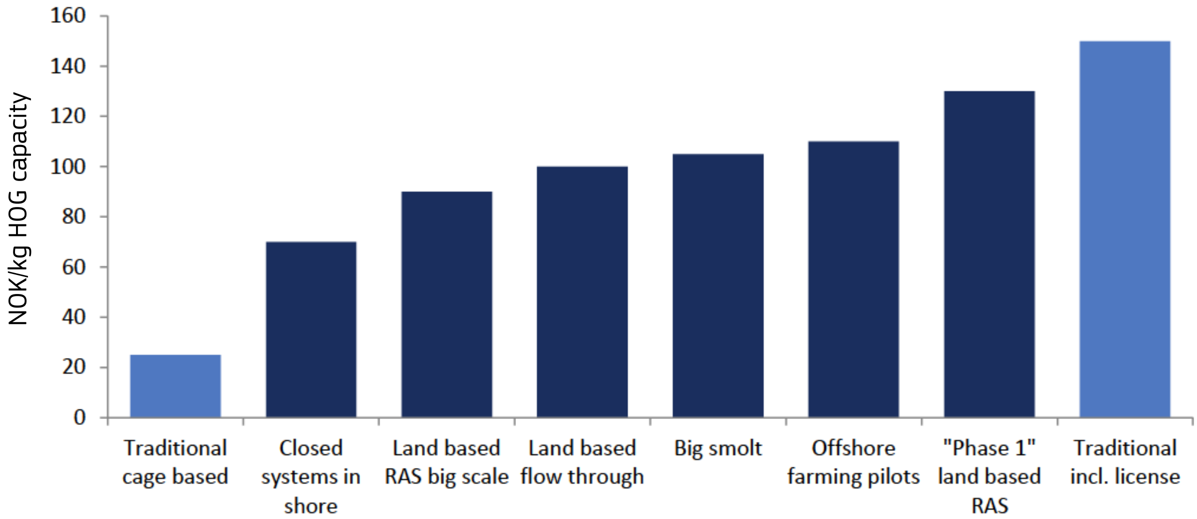
Source: Nordic Aquafarms

6.1.3 Investment costs

Land-based RAS production is still in the development phase and no companies have reached a stable, high volume production. As a result, there are no proven real investment cost (capex) levels on these types of facilities. There are however many estimates and calculations for the numerous planned projects and projects under development.

According to calculations by Pareto Securities in 2019, capex estimates vary a lot across different projects and technologies. Figure 9 illustrates their calculations.

Figure 9: Estimated CAPEX for different growth initiatives (NOK/kg HOG capacity)



Source: Presentation by Pareto Securities AS Equity Research at North Atlantic Seafood Forum 2019, based on information from Pareto Securities Equity Research, NRS, MOWI, Atlantic Sapphire, Nordic Aquafarms and Lerøy Seafood.

The two light blue columns in Figure 9 illustrates the cost of the licensing scheme in Norway. Traditional sea cage farms in Norway require a license and permit for a defined sea area. The licenses set a maximum allowable biomass (MAB) on the farming locations, and have primarily been sold through auctions for the past 5 years. Licenses for land-based production are free of charge.

According to calculations by the Norwegian salmon producer Grieg Seafood in 2018[89], the investment costs per kg harvested fish (HOG) for a new sea cage production site in Norway could be 40% higher than for onshore expansion. Although the investments required in the post smolt and farming phase are 2,5 times higher for land-based RAS, the total investment cost is more than outweighed by the cost of a new license for sea cage production.

[89] Grieg Seafood ASA, presentation at Capital Markets Update 5 September 2018.

Table 7: Estimated investment costs for various opportunities (EUR/kg HOG)

EUR/kg HOG	Expanding current MAB	Onshore expansion	New license
License	-	-	11,40
Smolt phase	0,56	0,56	0,56
Post smolt and farming phase	2,80	7,01	2,80
Primary processing	0,84	0,84	0,84
Total investments	**4,21**	**8,41**	**15,61**
Biomass/Working capital	2,34	2,34	2,34
Total funding need	**6,54**	**10,75**	**17,95**
** assuming average auction price per licence of EUR 18,23/kg MAB and annual harvest volume per MAB: 1,6*			

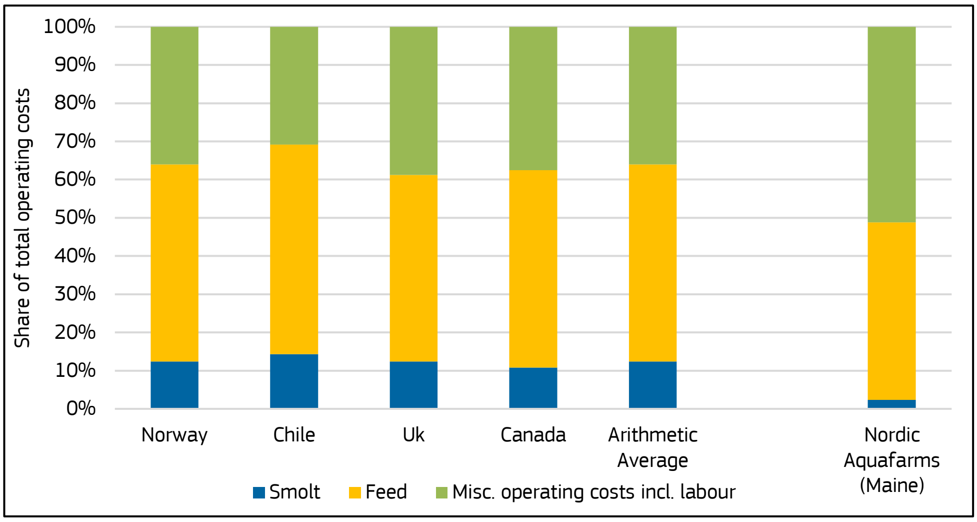
Source: Grieg Seafood ASA

In comparison, Nordic Aquafarms have invested almost EUR 37,4 million[90] in building and developing the RAS farm in Fredrikstad. With a current yearly capacity of 1.500 tonnes, this corresponds to approximately EUR 24,93 per kg HOG. For the production facility in Maine, US, the planned capital expenditure is approximately EUR 435 million, which corresponds to approximately EUR 17,40 per kg HOG capacity.

6.1.4 Operating costs

According to production cost estimates for 2019, the average production cost in Norway, Chile, the UK and Canada was EUR/kg HOG 3,91[91]. The largest cost category is feed, amounting to 49-55 % of total cost, followed by "miscellaneous operating costs" at 25-27% (of which depreciation accounts for between 4% and 9%) and cost of smolt at 11-14%.

Figure 10: Share of total operating costs (in EUR/kg HOG) by main categories



Source: Kontali Analyse and Nordic Aquafarms

[90] 400 million NOK converted to EUR using the average daily exchange rate from 2nd January to 31st August 2020 of 10,6982.

[91] Cost estimates by Kontali Analyse AS, converted from local currencies to EUR using average daily exchange rates in 2019: NOK/EUR 0,1015; USD/EUR 0,8934; DKK/EUR 0,1339; GBP/EUR 1,1407 and CAD/EUR 0,6734.

Comparable estimates for Nordic Aquafarms' planned facility in Maine have similar costs per EUR/kg HOG. However, the different cost categories are not directly comparable, as the estimates for the Maine facility also include hatchery, smolt and post-smolt production.

Compared to traditional sea cage production, the energy-demanding, new and expensive RAS technology increases the cost category "miscellaneous operating costs" by almost 50%. Of this 50%, energy accounts for approximately 15% and depreciation approximately for 20%.

All cost estimates measured in EUR/kg for new projects are based on assumptions on production output, feed conversion ratios, biomass density and general health and growth rates of the fish. It should be noted that there are yet no proven RAS projects with large scale production. Nordic Aquafarms' production cost estimates in Maine assume production at full capacity of 25.000 tonnes HOG. For Fredrikstad Seafoods, Nordic Aquafarms' research and development facility in Norway, the annual production capacity is 1.500 tonnes HOG, and the production cost is about 33% higher than the estimated production costs in Maine, primarily due to scale effects.

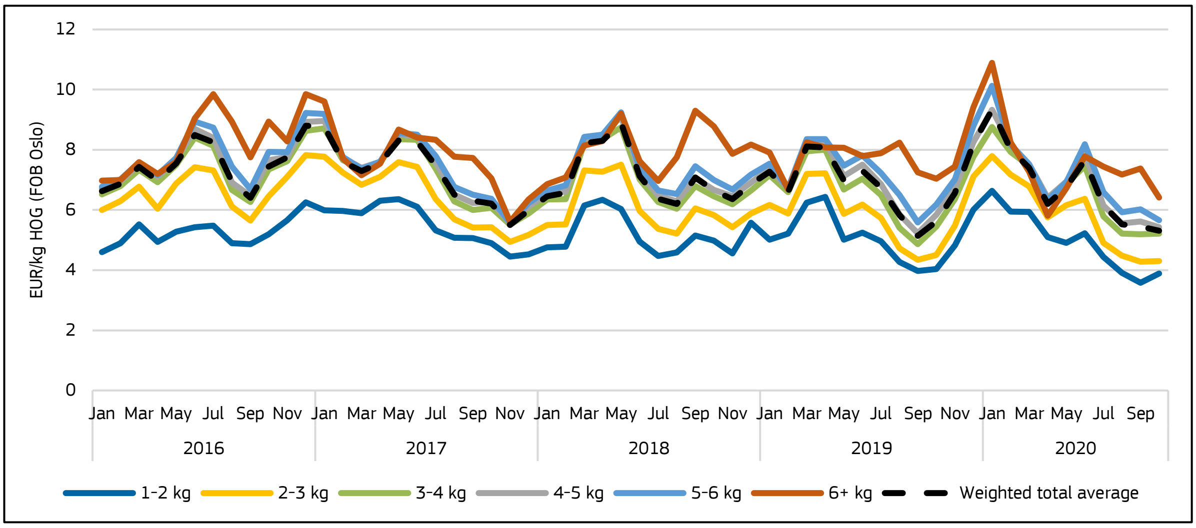
Other RAS facilities have experienced mass mortality, due to different technical errors in the recirculation flow[92]. Any such event will affect the average production cost, and the effects increase throughout the grow-out phase. In other words, the actual production costs in a large-scale RAS facility are still unknown.

6.1.5 Prices

The prices for Atlantic salmon vary, *inter alia*, based on fish size. Some markets prefer larger sized fish and are willing to pay a price premium for that. There can also be demand for different sizes based on utilisation. As an example, a great part of the larger Norwegian Atlantic salmon is exported to sushi restaurants in Europe.

A significant amount of Atlantic salmon is sold on contracts; however, there is also a spot market from which NASDAQ builds its NQSALMON index. Since January 2016, the weighted average price (all sizes) has fluctuated between 3,90 and 9,33 EUR/kg, with an average and median of 6,44 and 6,48 respectively.

Figure 11: Volume weighted monthly NQSALMON index by size categories (fresh whole gutted Norwegian Atlantic salmon)



Source: NASDAQ

92 https://salmonbusiness.com/atlantic-sapphire-lost-at-least-3-million-on-fish-mortality/

According to Nordic Aquafarms, their products from Fredrikstad Seafoods have been well received by their customers and they have achieved good prices. One of Fredrikstad Seafoods' customers, a local fishmonger, has stated that their customers are willing to pay an extra for this RAS produced fish, compared to traditional farmed salmon.

6.1.6 Transport costs – long haul

Although salmon is consumed all over the world, almost 80% of the global supply is produced in Norway and Chile. Approximately 4% of the production in these two countries is consumed domestically, while the rest is exported. As a result, transport and logistics costs, and especially air freight, make up an important share of the consumer price. In 2018, it was estimated that 25% of the global consumption of Atlantic salmon had a primary transport cost of more than 1 USD/kg (0,85 EUR/kg). In the first 8 months of 2020, and because of changes in travel, freight options and consumption patterns, it is estimated that this share has increased to 27%[93].

Both from an economic and environmental perspective, it makes perfect sense to establish near-market production. From Nordic Aquafarms' planned production facilities in Maine, the salmon can be transported by truck to several major cities on the east coast, such as Boston, New York, Washington, Philadelphia, Montreal and Toronto, within 12 hours. Similarly, other major cities on the west coast such as San Francisco, Los Angeles, San Diego, Las Vegas, Seattle and Portland can be reached within 12 hours from their planned facility in Northern California.

In addition, Nordic Aquafarms believe it is possible to gain a substantial price premium by branding their salmon as sustainable and locally-produced, and assume that "Made in the US" would make a strong, impactful and appealing statement for American consumers.

6.2 Freshwater finfish – trout in Denmark

6.2.1 Introduction

Trout is an umbrella term for species in the genera *Oncorhynchus*, *Salmo*, and *Salvelinus*. Trout usually live in cool freshwater, though some migrate to the sea between spawning. Although native to the Northern Hemisphere, trout has been widely introduced to other areas[94].

According to the FAO, the global freshwater aquaculture production of trout amounted to 681.000 tonnes in 2018[95]. In the same year, the EU production amounted to 153.000 tonnes, a decrease by 29,6% compared to the year 2000. Globally however, aquaculture production of trout has been steadily increasing over the last few decades with a growth by 91% since 2000. Most of this growth (86 %) can be attributed to Iran, Turkey and Peru. The most common and most widely produced trout is the rainbow trout (O*ncorhynchus mykiss*), accounting for 97% of the global production in 2018[96].

According to the FAO, the Danish production of trout amounted to 20.087 tonnes in 2018, making it the third top trout producing MS after Italy (34.286 tonnes) and France (27.100 tonnes)[97]. The Danish freshwater trout production has been stable over the last decade but has decreased by 40% since 2000. Denmark almost exclusively produces rainbow trout (99,6%).

[93] Kontali Analyse AS, presentation at "Laks på Land», September 2020.

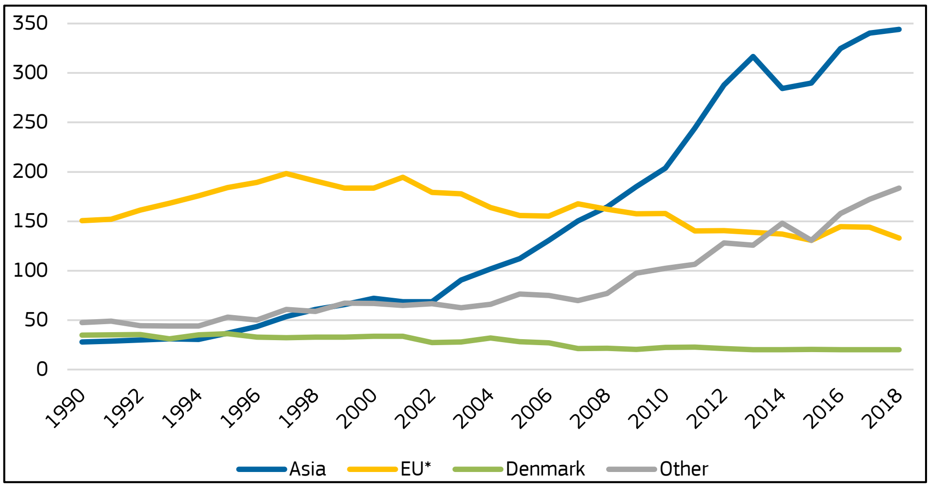
[94] https://www.britannica.com/animal/trout

[95] FAO

[96] Ibidem

[97] Ibidem

Figure 12: Trout production in freshwater aquaculture (1.000 tonnes)



Source: FAO
** Excluding Denmark*

6.2.2 Trout farming in Denmark

Traditionally, the Danish trout sector has been dominated by pond aquaculture. Although flow through systems have the advantage of fresh oxygen-rich water and low energy consumption, pathogens and other contaminants are easily brought into the farm, endangering fish health and fish welfare. In addition, discharge of wastewater containing nitrogen, phosphorous and organic material pollutes nearby rivers, lakes and seas[98]. To reduce the environmental impact of flow through systems, feed rations were introduced to ensure optimal usage of feed[99, 100], and farms were required to have settling basins and water quality monitoring[101]. Gradually, the environmental focus has shifted towards technology development, especially regarding solutions for reducing water usage and emissions from ponds.

Combining traditional pond farming with new technology, many farms in the Danish trout sector currently use recirculated systems and are called model farms. According to the official Danish statistics, freshwater trout is farmed using four different methods: traditional farms; model type I, model type III, and RAS. These categories involve different degrees of water recirculation and are unique to Denmark.

Traditional farms are the most common, and largely consist of earth ponds with flow-through systems and intake water via a damming of the adjacent water course (without, or with only minor use of pump energy)[102]. Today, there are 123 active traditional freshwater farms in Denmark[103], but this number is decreasing as environmental regulation prohibits establishment of new traditional farms and as farms transition to model I-type farms. Traditional freshwater dams produce almost exclusively trout[104]. The

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98 https://aquacircle.org/images/pdfdokumenter/udvikling/danmark/rethink%20aquaculture/WhitePaper_Aquaculture_Rethink Water_Ver_1%201.pdf

99 Such as quotas, quality of feed, a ban on wet feed and soft pellets

100 https://mst.dk/media/147844/strategi_for_baeredygtig_udvikling_af_akvakultursektoren_i_danmark_2014-2020.pdf

101 Alfred Jokumsen & Lars Svendsen (2010) Farming of Freshwater Rainbow Trout in Denmark

102 Alfred Jokumsen & Lars Svendsen (2010) Farming of Freshwater Rainbow Trout in Denmark

103 Statistics Denmark. Note that this includes some other species than trout, but with insignificant production.

104 In 2018, only 1 tonne of other species was produced.

production mainly consists of rainbow trout with some golden trout, and small amounts of other trout species (brown trout, brook trout, seatrout)[105].

Model type I farms are extensive farms with mechanical water treatment and water recirculation technology. The pond material is either soil or concrete and the water recirculation is minimum 70%. Water treatment is partly done by internal conversion processes and partly via sludge cones, micro sieves (or contact filters), plant lagoons, and sludge basins. Biofilters are not required. The water source is mainly from nearby river and streams[106]. Many traditional farms have transitioned to model type I farms, as the reconstruction costs of this transition is relatively low. Today there are 17 active model type I farms in Denmark[107], which exclusively produce rainbow trout[108].

Model type III farms have a higher level of innovation, higher recirculation (minimum 95%) and low consumption of new water (maximum 0,15 litres water per second or 3.600 litres per kilo produced fish). The water intake is roughly a factor of 15-25 lower than the water consumption in traditional flow-through fish farms[109]. Filtering systems include sludge collection in basins, decentralised sedimentation (e.g. sludge cones), micro sieves, and biofilters. Fresh water is supplied through wells[110]. Fish density is also relatively higher for model type III farms compared to model type I and traditional farms[111]. In total, there are 16 active model type III farms in Denmark [112] all producing rainbow trout[113].

RAS facilities in Denmark produce trout, salmon, eel, zander, seriola and sunshine bass. Trout (rainbow trout 97%, brook trout and seatrout) represents 66% of total production in the official statistics for RAS production. As it is not possible to separate production of freshwater rainbow trout from production of other species, a comparison of costs and revenue is not feasible, and this category is excluded from the following analyses.

The number of Danish freshwater aquaculture farms decreased by 27% over the past decade, from 214 farms in 2009 to 156 in 2018. The reduction can be attributed to the decrease of traditional farms. Some have been converted to model type I or model type III farms, some small farms have been merged into larger farms, while others have closed.

Table 8: Freshwater aquaculture production in Denmark by production type 2010-2018 (number of farms)

Production type	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Traditional	189	177	162	157	157	145	138	131	127	123
Model type I	14	19	17	16	17	17	17	18	17	17
Model type III	11	13	13	13	16	15	16	17	16	16
Total	**214**	**209**	**192**	**186**	**190**	**177**	**171**	**166**	**160**	**156**

Source: Statistics Denmark

105 https://fiskeristyrelsen.dk/fiskeristatistik/akvakulturstatistik/

106 https://www.danskakvakultur.dk/media/2628/Renseeffektivitet-paa-model-1-dambrug_final.pdf

107 https://fiskeristatistik.fiskeristyrelsen.dk/stat/Akvakultur_tab/anlaeg_18.html

108 https://fiskeristyrelsen.dk/fiskeristatistik/akvakulturstatistik/

109 Alfred Jokumsen & Lars Svendsen (2010), Farming of Freshwater Rainbow Trout in Denmark

110 Alfred Jokumsen & Lars Svendsen (2010), Farming of Freshwater Rainbow Trout in Denmark

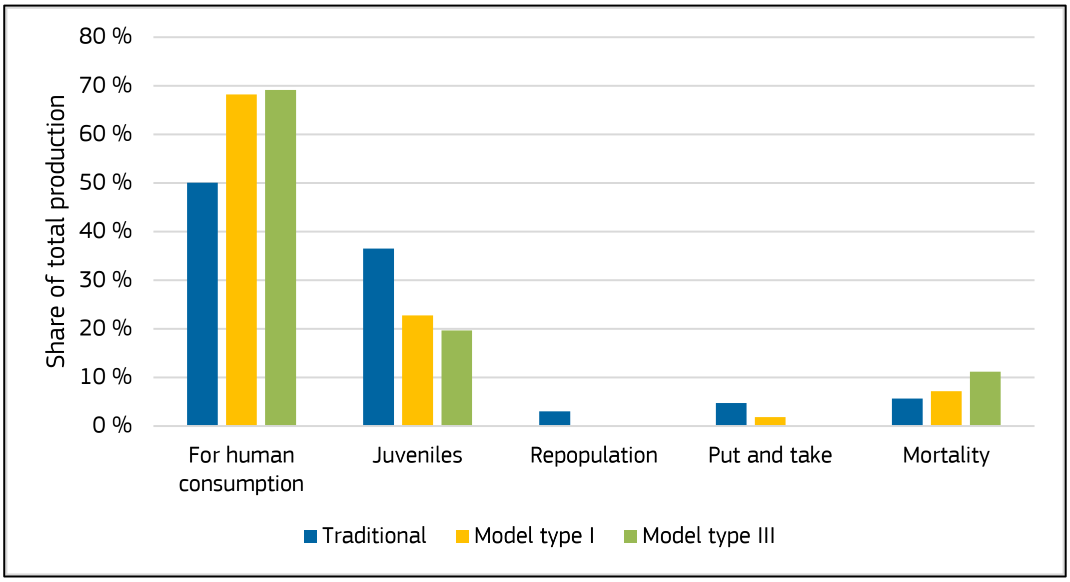
111 https://www.danskakvakultur.dk/media/2628/Renseeffektivitet-paa-model-1-dambrug_final.pdf

112 https://fiskeristatistik.fiskeristyrelsen.dk/stat/Akvakultur_tab/anlaeg_18.html

113 https://fiskeristyrelsen.dk/fiskeristatistik/akvakulturstatistik/

For traditional farms, 50% of the production is destined for human consumption, while 37% are production of juveniles. For model type I and III, the share of production for human consumption is 68% and 69% respectively, while the production of juveniles is 23% and 20% respectively. It is also interesting to note that the mortality rate is the lowest (with 6%) in traditional farms and the highest (with 11%) in model type III farms.

Figure 13: Share of total production in 2018 by farm type and purpose (incl. mortality)



Source: Statistics Denmark

Most of the trout produced for human consumption in model type I, model type III or RAS are portion-sized fish. According to a stakeholder, a large share of the production is processed to value-added products such as fillets, steaks, portions, hot smoked or ready dishes. In addition, some farms extract roe from mature trout and make various caviar substitute products[114].

Table 9: Production of trout for human consumption in Denmark

Production type	2010	2011	2012	2013	2014	2015	2016	2017	2018
Traditional	12.029	9.438	11.158	9.248	10.152	8.993	9.204	7.892	8.613
Model type I	3.034	1.857	2.869	2.895	2.901	3.151	2.945	3.263	3.338
Model type III	7.228	6.444	5.021	6.881	6.625	7.385	8.256	7.903	7.059
Total	22.291	17.739	19.048	19.024	19.678	19.529	20.405	19.058	19.010

Source: Statistics Denmark

6.2.3 Investment costs

To encourage farmers to transition from traditional pond farms to model type I farms, the government launched a subsidised scheme from 2007 to 2013, covering part of the rebuilding costs[115]. The Ministry of Environment and Food of Denmark (Fødevareministeriet) and the Fisheries Development Program (EFF) financed half of the grant.

[114] https://musholm.com/en/farming-trout/

[115] https://www.aquacircle.org/images/pdfdokumenter/udvikling/danmark/dk-eff/vejl_akvakulturanlaeg_2008.pdf

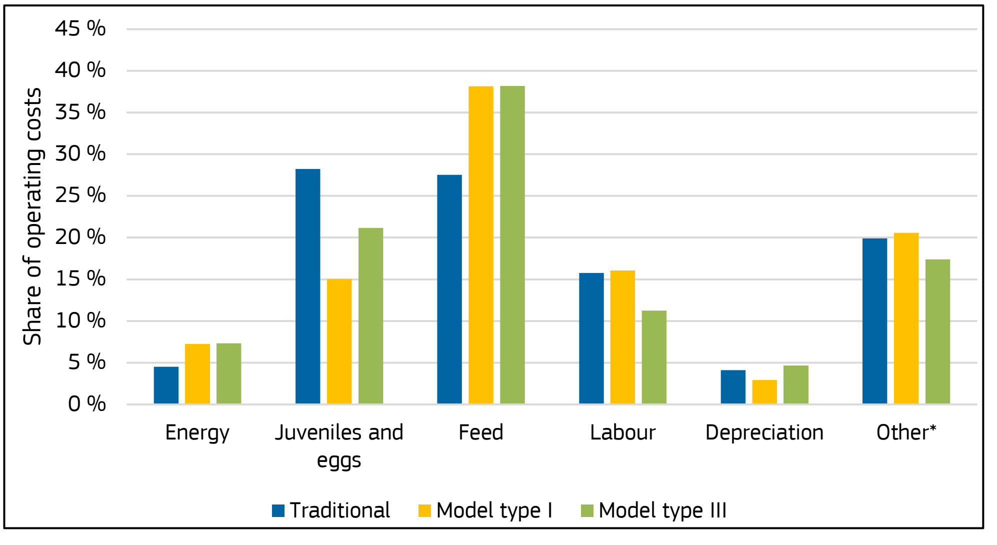
According to one traditional Danish farm that transitioned to a model type I farm, they had total costs for roughly EUR 470.000[116] in 2010. The largest cost elements in the rebuilding phase were labour, concrete for casting the ponds and filters for water recirculation. Fødevareministeriet gave a grant covering 25% of the costs. According to the farmer, there would be little incentive to rebuild from a traditional to a model type I or III farm without the government grants and the increased allowance of fish density.

The high investment costs in technology means that model type III is primarily an option for larger and capital strong firms[117].

6.2.4 Operating costs

Feed represents the highest cost for model farms, and the second highest for traditional farms. However, this picture is not representative of all farms, as a model type I farmer stated that the largest operating costs come from feed (50%) and electricity (7%). The cost of purchasing juveniles and eggs is relatively high for traditional farms. This could be explained with the fact that many traditional farms buy eggs and juveniles, grow them to larger sizes, and sell them to other facilities for further grow out. Model type III farms and RAS require more specialised labour than traditional and model type I farms, due to the more complex technology. However, comparing expenses related to wages is difficult, as some smaller producers do not pay wages to the owners but they rather make withdrawals from the company's equity[118].

Figure 14: Share of total operating costs in 2018 by cost category and farm type



Source: Statistics Denmark

** The cost category "Other" includes maintenance, administration, insurance, rent, depreciation, and services.*

Some farmers have experienced higher mortality rates after the transition from a traditional farm to a model type I farm. One sampled model type I farm reported mortality rates of 12%, 26% and 47% for the three years following the transition from a traditional farm to a model type I farm. The farm attributed the increased mortality to factors such as diseases and poor fish quality, and not to the water recirculation technology itself. However, the higher biomass density in model type farms means easier spread of diseases and the recirculation of water means it is harder to flush out present diseases. This is especially presented as a serious issue for model type III farms, ref. Figure 13 above.

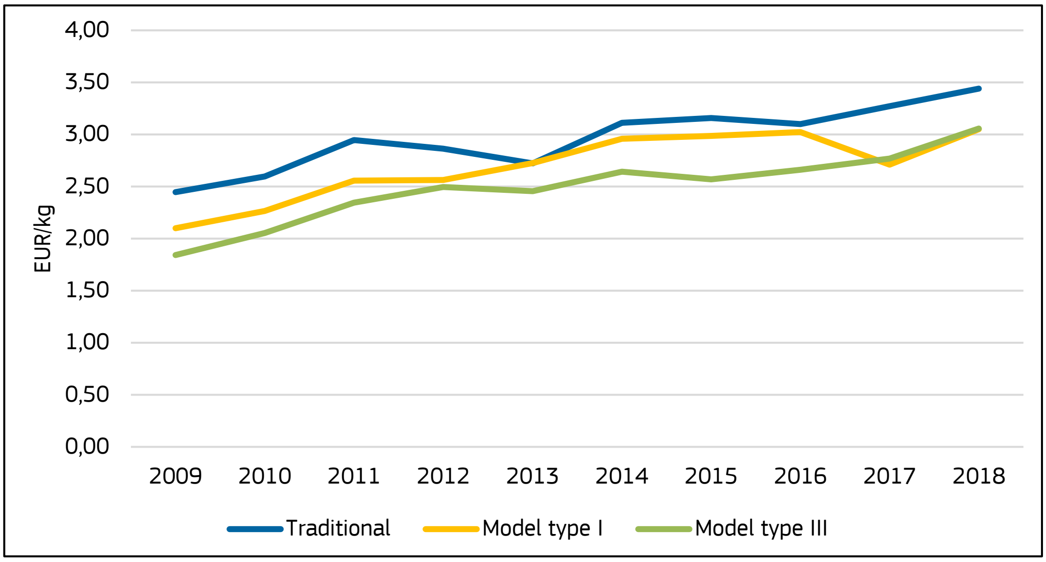
[116] Converted from DKK using the average 2010 daily exchange rates: 7,4473

[117] https://lf.dk/viden-om/landbrugsproduktion/husdyr/akvakultur

[118] https://www.danskakvakultur.dk/media/16239/Slutrapport_produktivitet_270315_978-87-997876-3-0.pdf

Overall, the operating costs per kg produced fish is the lowest in model type III farms and the highest in traditional farms. Regardless of farm type, the costs show a similar increasing trend over the past decade with model type 1 showing largest fluctuations year over year.

Figure 15: Development in real value operating costs* by farm type (EUR/kg)



Source: Statistics Denmark
** Costs are deflated using the GDP deflator (base=2015).*

6.2.5 Development and future

The structural changes in the Danish freshwater farming industry are reinforcing the trend towards fewer and larger production facilities. On 26 August 2019, the Danish Government announced they would not facilitate new sea-based fish farming sites, due to sustainability concerns[119]. Instead, the government would pursue a sustainable strategy to produce saltwater fish onshore. Looking ahead, the Danish environmental ministry encourages municipalities to accommodate investment and transitions to land-based aquaculture. The Danish strategy for aquaculture is to transition traditional farms to model farms and increase efficiency in production through new technology and better education[120].

Rasmus et al.[121] finds that the existing EU land-based aquaculture sector, with many small-scale family-owned farms, is not able to realise its growth potential in the same way as marine-based farms. This is attributed to the sector's structure, a lack of economics of scale, strict environmental regulations, competition, and a growing amount of bureaucracy.

However, as environmental regulations get stricter, the future points to less production from traditional farms and more from model farms and RAS. The Danish model farms show that a transition of the sector is possible while keeping up with the environmental regulations and bureaucracy[122]. The strategy of partial recirculation farms in show that increased production can be achieved without increasing the environmental impact.

[119] https://politiken.dk/indland/art7350525/Milj%C3%B8ministeren-dikterer-stop-for-nye-havbrug?fbclid=IwAR3KlMoL2bc_A2waOe5BjA6ZZDZrjrGfSrtg2jf5-rA_JucJfSi4SBbvFBM.

[120] https://www.danskakvakultur.dk/media/16239/Slutrapport_produktivitet_270315_978-87-997876-3-0.pdf.

[121] Rasmus Nielsen, Fransk Asche & Max Nielsen (2016) Restructuring European freshwater aquaculture from family-owned to large-scale firms – lessons from Danish aquaculture, Aquaculture Research 47.

[122] Ibidem

6.3 Yellowtail kingfish

6.3.1 Introduction

Yellowtail kingfish (*Seriola lalandi*), also called yellowtail amberjack, southern yellowtail amberjack or great amberjack, is a pelagic warmwater species of the S*eriola* genus. The fish occur in tropical and temperate waters of the southern hemisphere and the northern Pacific. Yellowtail kingfish is primarily consumed fresh and sold to sushi restaurants.

There are currently nine recognised species in this genus, of which four are farmed in aquaculture: Japanese amberjack (*Seriola quinqueradiata*), yellowtail kingfish (*Seriola lalandi*), longfin yellowtail (*Seriola rivoliana*) and greater amberjack (*Seriola dumerili*). In addition, the FAO records aquaculture production of “Amberjack not elsewhere identified (nei)”.

Aquaculture production of Japanese amberjack, based on wild catch of juveniles, has a long history in Japan, dating back to the 1920s[123], and the yearly production has been between 135.000 and 170.000 tonnes for the past 40 years.

Compared to Japanese amberjack, the aquaculture production of yellowfintail kingfish is smaller and more recent. The total global production in 2018 was estimated at around 3.350 tonnes. It is primarily farmed in sea pens and cages in Australia, where the production volume increased from around 600 tonnes in 2014 to more than 2.600 tonnes in 2018. There is also some sea cage production in Mexico, amounting to roughly 500 tonnes in 2018.

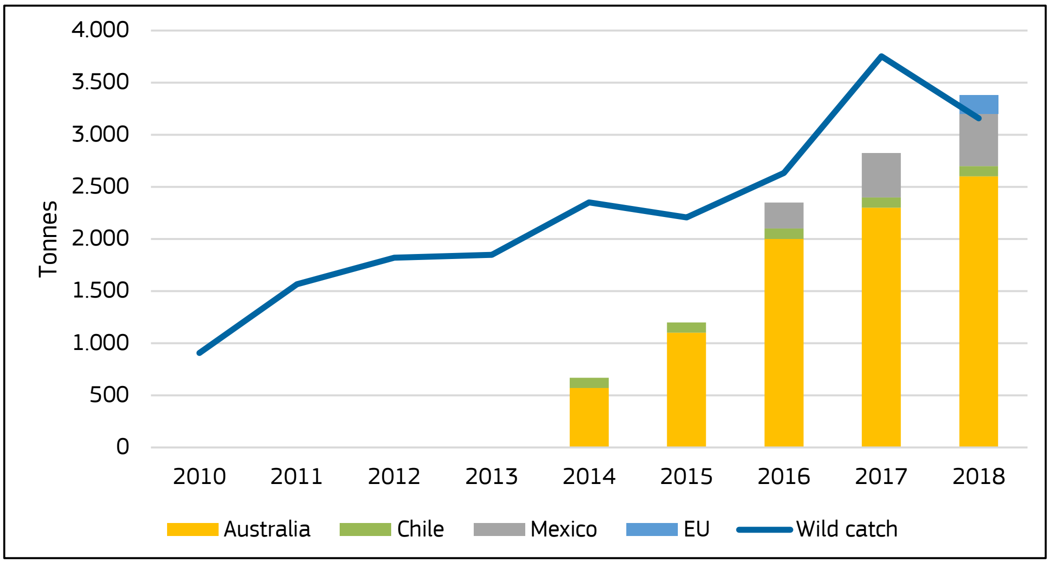
In recent years, RAS facilities of yellowtail kingfish have been established both in Chile and in the EU. The production volumes in Chile are uncertain but estimated at around 100 tonnes in 2018. The same year, harvest of RAS-grown yellowtail kingfish in Europe, more specifically in Denmark, the Netherlands and Germany, amounted to roughly 180 tonnes.

According to the FAO, there is also a small, but growing production of greater amberjack in Spain, with a harvest volume of around 10 tonnes in 2017 and 50 tonnes in 2018.

With increasing demand over the past 10 years, wild catch of yellowtail kingfish increased from below 1.000 tonnes in 2010 to almost 3.200 tonnes in 2018, primarily from catches by Peru, Brazil, South Africa, and Australia.

[123] http://www.fao.org/tempref/FI/DOCUMENT/aquaculture/CulturedSpecies/file/en/en_japaneseamberjack.htm

Figure 16: Wild catch (line) and aquaculture production by country/region (bars)



Source: FAO (wild catch), Kontali Analyse (aquaculture production estimates).

6.3.2 RAS facilities for yellowtail kingfish in the EU

According to Aqua Partners, a Danish independent consultant company on recirculation technology, hatchery and RAS design, yellowtail kingfish is less costly to produce in closed RAS systems than in open cage farming[124].

Firstly, the growth performance of *seriola* is highly dependent on the water temperature. If the temperature drops a few degrees below optimal, the growth can almost stop, which in turn affects the feed conversion ratio. In fact, the feed conversion ratio can be almost twice as high when the fish are produced in open sea cages with variable water temperatures. In a closed RAS system, where the temperature can be controlled, the biological feed conversion ratio can be close to 1 kg feed per kg fish produced.

Secondly, yellowtail kingfish are very exposed to ecto-parasites (e.g. sea lice), which can generate large costs when farming in open sea cages. The treatment either consists of moving the fish and cleaning the cages or of treating the fish with chemicals, which in turn also affect the surrounding marine fauna. By growing the fish in closed RAS facilities, the intake water is cleaned and filtered, and parasites are not an issue.

Currently, there are three RAS facilities for yellowtail kingfish in the EU; Sashimi Royal in Denmark, the Kingfish Company in the Netherlands and Fresh Völklingen GMBH in Germany.

Sashimi Royal

Sashimi Royal is a subsidiary of Nordic Aquafarms (ref. 6.1.2 above) with one RAS facility located on the coast in Hanstholm, Denmark. The construction started in 2016 and the facility is installed with one Krüger Veolia RAS 2020 production module technology. The inner tank is divided in 7 compartments for the small fish, while the larger fish are moved to the outer tank divided in 6 compartments (ref. Figure 7).

The intake water is abstracted from the Skagerak by a pipeline 100 m off the coast. The pipeline is located about 1 metre below the sea bottom, so the intake water is filtered by the sand. In the facility,

[124] http://www.aqua-partners.dk/fish-species/kingfish-seriola.

the intake water is collected in a tank where it is UV-treated before entering the recirculation system. Compared to traditional land-based pond farming, which uses about 100 m^3 of water to produce 2 kg fish, Sashimi Royal's RAS facility uses about 1 m^3 of water[125].

The fingerlings are obtained from the sister company Maximus, which have a 25-year experience in marine fingerlings production. Today, they only produce yellowtail fingerlings for Sashimi Royal. The facility has over 100 broodstock of yellowtail kingfish that started spawning in 2015. The fish larvae are fed live feed (copepods), which are also produced at the facility.

The first fingerlings were stocked in June 2017 and the first harvest took place during the second quarter of 2018. The facility has a yearly production capacity of about 900 tonnes[126].

With their current capacity, Sashimi Royal have achieved an EBIT[127] margin of 20%. However, there is potential for substantial on-site capacity extension and with an increased capacity of around 1.000 tonnes HOG, the estimated EBIT margin will be 40%.

The Kingfish Company

The Kingfish Company, previously known as Kingfish Zeeland, is based in the Dutch province of Zeeland and produces Dutch yellowtail in RAS facilities. They are currently also expanding to Maine in the USA and Kats in the Netherlands. The planned scale of production is 5.000 tonnes of yellowtail kingfish in the Netherlands and 6.000 metric tonnes in Maine[128].

It took 2 years of development and preparation before the Zeeland RAS site became operational in 2018. The site consists of two buildings (site A and site B) with indoor tanks for land-based RAS production. The RAS system has 40-micron screens, and UV and ozone treatment systems and the water recirculation is estimated to be between 98% and 99,5%[129]. Site B has 16 tanks and is used as a hatchery, R&D facility, brood stock selection, and grow out of fingerlings. The estimated yearly production for this site is 20 tonnes. Site A contains 34 tanks, and a yearly estimated production capacity of 600 tonnes. Juveniles are also purchased from a third-party supplier based in Chile.

Yellowtail kingfish is a warm water fish that cannot survive in temperatures lower than 14°C. The water is sourced from a marine estuary of the Eastern Scheld (Oosterschelde), which normally holds a temperature lower than 14°C, meaning heating of the water is required. To minimise energy use for heating the Kingfish Company uses a heat-exchange system for marine use to transfer warmth from outflowing water to incoming water.

FRESH Corporation

The FRESH corporation ("FRESH") is an in-land RAS facility in Völklingen, Germany. The facility consists of 4 saltwater pools, each with a water volume of 1600 m^3 and a production capacity of 150 tonnes live weight. The facility was built in 2012 after a long planning period. The investment cost at the time was roughly 25 million euro, which, with a production capacity of 600 tonnes live weight, corresponds to EUR 41,6 per kg.

The location of the facility was chosen because a large area (previously used for coal mining) became available in an industrial zone, with access to water, waste management and permits for industrial

[125] TV2 Nyheder, 14.09.2017 (https://www.sashimiroyal.com/sashimi-royal-pa-tv2-nyhederne/).

[126] Nordic Aquafarms, presentation at Lofotseminaret August 2020

[127] Earnings Before Interests and Taxes

[128] https://www.seafoodsource.com/news/business-finance/kingfish-zeeland-changes-name-to-the-kingfish-company

[129] Aquaculture Stewardship Council Faarm certification (2018) Single and Multi-Site ASC Farm Audit Checklist for Kingfish Zeeland BV.

operations. FRESH also had a close cooperation with the College of Technology and Economy of the Saarland (HTW) for students and researchers to increase practical knowledge and research on RAS.

FRESH uses the "Oceanloop system"[130] technology. The Oceanloop was developed by Neomar and is an almost completely closed water circulation system which enables inland production of marine organisms. A central part of the technology is the production of artificial seawater, produced from tap water and a mixture of various salts[131]. The lab-made sea salt is a composition of chloride, natrium and sulphate as well as magnesium, potassium, bicarbonate and carbonate. There are also some traces of copper, iron, molybdenum, manganese, zinc, and boron[132]. The production of brine is done in a separate tank which is then diluted with tap water to create seawater.

Production started in 2012 with input of the first juveniles of European seabass, gilthead seabream and yellowtail kingfish, and the first fish was harvested in 2013. The yellowtail fingerlings are imported from Chile. Over the years, the production of seabream has increased at the expense of seabass, while yellowtail kingfish have been produced in one of the four pools. In 2021, FRESH will double the production capacity of yellowtail kingfish by utilising two pools for this production.

With RAS technology, qualified employees are crucial. FRESH have roughly 20 employees, including marketing, finance, and veterinary staff, which accounts for about 25% of their current operating costs. However, the same number of employees could manage twice the current production capacity, i.e. scale effects can reduce the weight of this cost category.

Other large operating costs are water, wastewater management, salt, and electricity which together account for roughly 50% of FRESH's total operating costs. Feed constitutes roughly 25%, as does personal. The Yellowtail Kingfish is a warmwater fish. There is no need to heat the water, as the heat generated by pumps and the water circulation is sufficient. However, during the warmest summer months, energy is needed to cool the water in the facility to ensure optimal rearing conditions for the fish.

[130] https://www.neomar.de/en/oceanloop-innovation/

[131] https://www.neomar.de/fileadmin/user_upload/Download/neomar_Landbased_Mariculture_Druck.pdf

[132] Orellane, Waller & Wecker (2013) *Culture of yellowtail kingfish (Seriola lalandi) in a marine recirculating aquaculture system (RAS) with artificial seawater*. Journal of Aquacultural Engineering.

6.3.3 Prices

Japanese exports of fresh and frozen fillets of Japanese amberjack have increased from 4.200 tonnes in 2010 to 10.200 tonnes in 2019, with the USA as the primary market. In 2019, Japan exported 211 tonnes to the EU compared to 34 tonnes in 2010. The average export price (free on board)[133] has increased over the past years from EUR/kg 12,73 in 2015 to EUR/kg 13,69 in 2019.[134]

The price of imported Japanese amberjack is not directly comparable to the EU RAS production of yellowtail kingfish. Nevertheless, it provides a reference point as the species to some degree are considered substitutes.

Price increases are also observed in Australia, where the average farm gate prices of large fresh Yellowtail Kingfish have increased from EUR/kg[135] (WFE) 7,54 in 2016 to EUR/kg (WFE) 9,01 in 2018.

FRESH mostly sells to wholesalers. Around 70% of the products are sold whole, gutted, while the remaining 30% are sold as fillets. According to FRESH, the main selling point is that the fish is of premium quality, fresh and locally produced as opposed to long-distance imports, primarily of frozen products. With RAS production, FRESH can also assure the consumers that there is no excessive use of antibiotics, nor a presence of toxins or environmental poisons.

According to Kingfish Company, the important selling points are premium quality and freshness, no antibiotics, no vaccines, freshwater conservation, biosecurity, and animal welfare.

Sashimi Royal also highlights the freshness and premium quality of their locally produced fish, which due to the RAS technology are free of antibiotics, medicines and have not been subject to any parasites, disease, or pollution. Sashimi Royal have achieved an average price for their yellowtail kingfish of 12,05 EUR/kg[136] since the first harvest in 2018.

Considering the cost of transportation from either Australia or Japan to Europe, the yellowtail kingfish produced in the EU are compatible in terms of price. According to stakeholders, most of the imports of yellowtail kingfish to the EU are frozen. When also considering the quality dimension of the locally produced fresh fish, it is also possible to obtain a significant price premium in certain customer segments.

[133] “Free on board” (FOB) corresponds to the price for the products cleared for export and delivered onto the vessel for transport at the port of departure.

[134] Japanese export statistics from the Japan Ministry of Finance, via IHS Markit.

[135] Converted from AUD to EUR using the following daily average exchange rates: fiscal year 2016 (1,5245) and fiscal year 2018 (1,5397). Australian fiscal year corresponds to the 12-month period from July to June.

[136] Converted from DKK to EUR using the average daily exchange rates in 2019: DKK/EUR 0,1339.

7 SUMMARY AND CONCLUDING REMARKS

According to the FAO, there is an estimated need to increase the global protein supply from about 200 million tonnes meat and seafood to nearly 500 million tonnes by 2050. Seafood, particularly from aquaculture, is expected to contribute significantly to meet this need. Considering the FAO's estimates of average annual seafood consumption, the predicted demand of fish for human consumption would almost double to at least 220 million tonnes in 2050, with aquaculture expected to provide over 70% of the volume.

The EU market is currently supplied by 73% imports when assessing finfish supplies. Thus, to not worsen the EU self-sufficiency rate, the European aquaculture production should aim to develop along with the growing demand.

Aquaculture is considered as a strategic sector in the EU's Blue Growth Strategy. However, negative impacts such as modified ecosystem resilience may result from high-input/high-output intensive systems. Technological solutions like RAS are believed to be able to tackle this issue.

According to Eurostat, the production of fish for human consumption in recirculation systems has been relatively stable at between 1,5 and 2% of the total production over the 10-year period from 2009 to 2018, with an average yearly volume of nearly 23.000 tonnes. The RAS production is dominated by few large producing countries, and the top-5 Member States accounted for 94% of the production in 2018.

RAS production is technologically complex compared to traditional production methods. RAS have a long history in freshwater environments (e.g. portion trout, eel and smolt) but are still in their early days when it comes to large-scale production of market-sized fish in saline water environments. Despite technological developments in recent years, there are still many risks associated with intensive large-scale RAS operations.

Operational risks are related to the functioning of the system. If the equipment or technology malfunctions, due to errors, ineffective design/assembly or poor management, the accumulation of toxic gases will negatively affect the health, welfare and growth performance of the fish, and can quickly have fatal consequences.

There are also significant **financial risks** related to RAS. One of the toughest challenges is amount of capital expenditure (capex) that is required upfront. Building and constructing RAS facilities account for most of the development capex. However, uncertainty regarding future costs of production, including biological risks, and the long time period between the initial investment and the revenue from RAS production increases the need for financial flexibility.

Considering both the operational and financial risks, there are also **market risks** in terms of price achievement to justify the higher costs. Most promoters of RAS project higher market prices for their product, based on its sustainability credentials, localness and associated freshness. Some stakeholders interviewed for this study claim that it is possible to attain a price premium between 5% and 20%. Others state that a price premium (if at all present) will disappear as soon as the RAS production increases.

As with traditional aquaculture, **production permits** are necessary to establish a RAS facility. The interactions between local, regional, national and EU legal requirements can often make the licensing process unpredictable and protracted. RAS facilities also depend on the support from local communities, i.e. a **"social license to operate"**.

On the other hand, as the demand for transparent and sustainable food is increasing, the two main drivers for RAS growth seem to be proximity to the market and its apparent low environmental impact.

Proximity to the market is a driver for RAS growth, since recirculation of water makes facilities less dependent on water sources/location. Furthermore, RAS makes it possible to farm foreign species by adjusting the growth environment, including e.g. lighting, temperature, salinity and water current.

Proximity also reduces transport distances, which can lead to fresher products to the market and reduced carbon emissions.

Other **environmental aspects** are also possible drivers for RAS growth. Compared to traditional methods, RAS facilities can have complete control over environmental parameters, a significant reduction in water consumption, control and treatment of the effluent water and waste, good possibilities for fish health and pathogens control (biosecurity) and prevention of escapes.

The RAS technology is promising in terms of sustainability, as it may reduce both water consumption and adverse effects on the local ecosystems. In addition, near-market production implies fewer emissions as a consequence of shorter distance transport. However, RAS still needs to be proven successful in commercial large-scale production, and especially with respect to finfish in saline water environments. Despite technologies still being under development, several new projects manage to get financing even in their early planning stages, before obtaining the necessary permits and licenses.

Facilitating increased aquaculture production in the EU requires a multifaceted approach, including both regulatory and financial support to the sector at local, national and EU level. As is evident from the case study on trout in Denmark, the transition from traditional farms to model type I and type III farms would not have been possible without new regulations regarding biomass density and government subsidies on construction.

Such incentive schemes are likely to be more important for low-value species or species which are already produced in the EU, as the competition between traditionally produced fish and RAS produced fish will be tougher.

The most important advantage of RAS is perhaps near-market production of high-value species, for which the natural conditions for traditional aquaculture would otherwise not be available, e.g. warmwater species such as shrimp or yellowtail kingfish in the EU. By offering locally-produced, fresh products, which normally are imported frozen (or fresh with high transport costs), a price premium at farm gate is likely to be obtained to cover the increased production costs. This is evident from the case study on yellowtail kingfish, and from the largest RAS projects concerning Atlantic salmon, which are not located in close proximity to the traditional production in Scotland and Norway, but rather in large consumer markets such as the USA and Asia.

In the light of the COVID-19 pandemic, near-market production can also provide higher food security with lower transport costs, and reduced dependency on international freight capacity.

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