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REVIEW

REVIEWS IN Aquaculture

# Innovation in the Norwegian aquaculture industry

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## Abstract

Global aquaculture production has grown very rapidly in recent decades. This is largely due to a number of innovations that has increased the control with the production process and competitiveness. These innovations come in a number of forms from radical new concepts to knowledge adaption from the terrestrial food production system. While there exist a number of studies investigating the impact of specific innovations, there are few studies that take a larger perspective on how innovations over time impacts an aquaculture industry or the innovation system that support these innovations. In this paper we review the innovation process in Norwegian salmon aquaculture industry from its infancy in 1970 until present. Of particular interest is the increasing complexity of the industry, and how most innovations are conducted by suppliers and not the aquaculture producers themselves. The insights are also of general interest in global aquaculture as salmon is among the species with the most advanced production technologies, but also a species where innovations are adapted to other species also in very different production systems.

**KEYWORDS**
aquaculture, innovation, salmon

## 1 | INTRODUCTION

Production growth in aquaculture during recent decades has been remarkable, with global production increasing from 2.6 million metric tons (mt) in 1970 to 87.5 million mt in 2020.[1] This has been achieved with growth at the extensive margin as production has increased in new countries and for new species, but also on the intensive margin as new knowledge and technologies has led to more intensive production practices often at a larger scale.[2] In fact, aquaculture production is focused on relatively few species compared to wild fisheries landings, with species like carp, oysters, salmon, shrimp and tilapia becoming truly global species farmed at several continents.[3] Innovations, including knowledge transfer and adoptions from agriculture, leading to productivity growth and lower production costs are the main drivers for this process.[4,5]

There exist a number of studies investigating productivity growth and technical inefficiency for various aquaculture species.[a] In recent years, there has also been an emerging literature on who innovates and who adopts new technologies. For instance, Bergesen and Tveterås[6] investigate where in the supply chain innovation activities take place and distinguish between radical, process and product innovations. They also find that most innovations are incremental. Kumar et al.[7,8] investigate the process of technology adoption and Asche e et al.[9] compare salmon to chicken in terms of technology adoption. However, there has been no attempts to provide a review of important innovations for any aquaculture species over a longer time frame, allowing insights into how the technology and knowledge frontier moves. This is important as continued innovations is essential for the continued sustainable growth of aquaculture production[10] and increased seafood consumption.[11]

In this paper, we will shed light on innovation processes associated with key technologies in salmon aquaculture by providing a review of the main innovations in Norwegian aquaculture from 1970. Salmon is among the most successful aquaculture species in terms of production growth, with a growth rate that is faster than the production growth of aquaculture in aggregate, and it is globally the second largest species by value after shrimp.[3] Moreover, it is technologically leading in a number of dimensions, from inputs via the production process and through the supply chain.[5,12,13] Norway is the largest production country with a production share of over 50% in most years.[14,15] argue that in the case of agriculture, most innovations take place in a few countries and are spread globally from there, making these innovations processes extremely important. Norwegian salmon plays a somewhat similar role not only in salmon aquaculture, but for aquaculture globally as knowledge and technology is adapted from salmon to other species.[5] The review will focus on the introduction of new knowledge and technology in the Norwegian salmon industry, and not necessarily on the origin of the innovations. Many if not most innovations are inspired by production practices in other biological industries including other aquaculture industries, and the industry would most likely not even have existed if not for the example set by and the knowledge adapted from Danish and German trout farmers.[16]

The innovation process in salmon aquaculture since the 1970s has been complex with parallel processes in key technology area. This will determine the structure of this paper after a section providing a brief overview of the development of the industry. The discussion of the innovations will then be conducted under the main categories farming technology, fish health, breeding and genetics, feed, primary processing and regulations, before a discussion with some concluding remarks is provided.

## 2 | THE NORWEGIAN SALMON AQUACULTURE INDUSTRY

In nature, the Atlantic salmon production cycle start with the spawning salmon in river and lakes all over the northern Atlantic in late autumn. The eggs hatch in early spring, and the salmon lives the first period of its life, from on up to 4 years in fresh water. When it reaches a certain size, it goes through a process known as smoltification to adapt to living in salt water, and it migrates out into the ocean with the spring flood. Here it feeds for 1–4 years before it returns targeting the river where it was born to spawn.[b] The common production process in salmon aquaculture follows the same stages.[17] The eggs are hatched, the fingerlings are transferred into fresh-water tanks in land-based facilities, and after the smoltification process, they are transferred to sea pens where they are fed until harvest.[c]

Norwegian salmon aquaculture comprises two species, Atlantic salmon (*Salmo salar*) and rainbow trout (*Onchorynchus mykiss*) and started as a 'backyard activity' by fishermen in the 1950s with a number of different production concepts primarily inspired by the European trout industry.[d,e] Following the introduction of the sea pen in 1970 the main production technology became increasingly standardised, and the development of salmon aquaculture as an industry started. However, production increased slowly. Quantity produced reached 8000 mt in 1980, and was almost evenly divided between salmon and trout.[17] argue that it is first around 1980 salmon farming became a commercial industry. As Norway is a small country with a population of about 5 million, the domestic market was quickly saturated, and the industry turned towards global markets, currently exporting more than 95% of the production to more than 100 countries[18–20] by a diverse group of companies.[21]

Figure 1 shows the production growth together with average real export price and average production cost from 1985, the first year which cost is available for. As one can see, production increases at a rapid rate throughout the period. On average, the annual growth rate

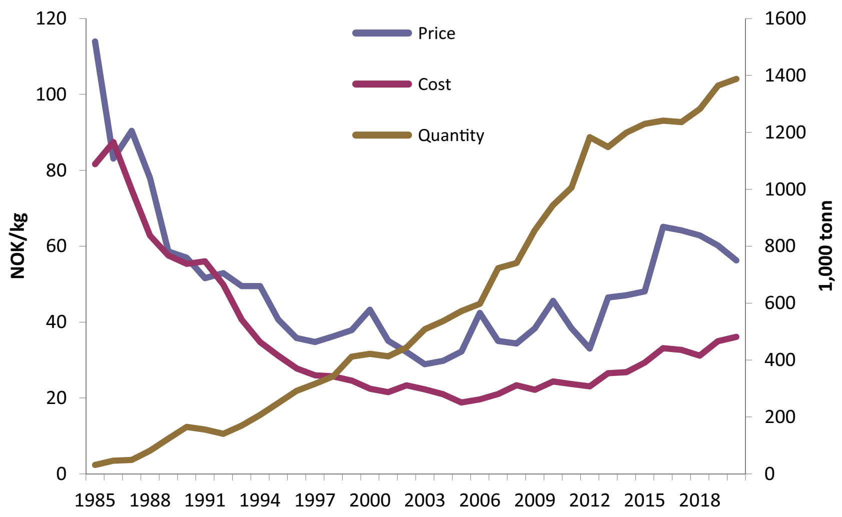


**FIGURE 1** Norwegian farmed production of Atlantic salmon and trout and real (2020 = 1) export price and production cost per kg 1985–2020. *Source*: Ref. 25

for the period 1985–2020 is 12.5%, but the growth rate declined with increased production, and was 4.1% for the period 2010–2020. Price and production cost largely have a similar main trend. However, the increasing gap indicate increasing profit margins in the industry during the latter period.[f,g]

Asche and Bjørndal[17] suggest that the price and cost development is caused by underlying productivity and demand growth. Until about 2000 productivity growth dominates demand growth as price is rapidly declining, and as such, a lower price is a main factor in convincing more consumers to buy salmon. Over time, increasing production despite lower cost has mostly been profitable because productivity growth reduced unit cost as much as the price declined, but there are cycles as the cost did not always decline as fast as the price. This is obvious in 1986 and 1990–1992, periods that are associated with significant disease outbreaks.[17]

After 2000, production continued to increase, while the price and unit cost stabilised, indicating a more mature industry. There are also pronounced price spikes, a sign of standard commodity price cycles.[22] Increasingly, the literature is suggesting that one entered a third phase around 2010 as access to new production locations got highly restricted due to environmental concerns,[23,24] leading to higher prices as production growth is indirectly restricted not only in Norway, but in all salmon producing countries due to similar challenges.[14] note that the increase in production cost may partly be due to the disease challenges, but also because it is profitable to increase cost to be able to produce a bit more within the regulations due to the high price.

## 3 | INNOVATIONS ACROSS THE VALUE CHAIN IN THE NORWEGIAN AQUACULTURE INDUSTRY

In this section, we provide a detailed account of the most important innovations from breeding and input suppliers through the supply chain to the market, and also discuss regulations as a separate category. The regulatory systems have changed significantly since the 1970s facilitating and at times encouraging development in some directions and hindering it in others. We also note that innovation and technology adaption process in the Norwegian aquaculture industry often have benefitted from interactive learning processes between actors including the aquaculture firms, and suppliers involved in breeding, feed production, vaccination and provision of technical equipment as well as research institutions.[26]

### 3.1 | Farming technology

Given the knowledge transfer from trout aquaculture, the most unique aspect of salmon farming is the grow-out phase that occurs after the fish is transferred to salt water and that allowed much larger fish to be produced, and this is what most often is thought of as salmon production even though the land-based juvenile phases that will be discussed below is equally important.[h] The first successful salmon pen in Norway was deployed off the island of Hitra in 1970 by Ove and Sivert Grøntvedt,[27] most likely inspired by similar constructions in other aquaculture industries. The wood, styrofoam, and recycled tires used to construct the frame of the pen was soon replaced by plastic and steel, allowing for larger structures as the building of the pens was transferred to specialised producers.

Figure 2 depicts the incremental changes in the dominant salmon production technology since the inception of the industry. In the early 1970s pens had a diameter of about 5 to 10 m, were 4 m deep, and could be accessed from land by a gang plank. Several different pen constructions were developed as the fish farms grew larger. With increasing size (and depth) the farms could not be accessed from land, and feeding barges were added. The barges were used for personnel and for storage (primarily for feed), and increasingly sophisticated instruments for feeding the fish and tracking activity in the pens as well as equipment to conduct maintenance of the farm were added. In the 1980s and 1990s, integrated steel platforms were popular. As the industry began to use localities more exposed to wind, waves and currents, equipment that could resist increased hydrodynamic forces became imperative. Eventually, pens became too large for steel structures and from the early 2000s on large plastic rings were used as floaters even though this is changing with the introduction of offshore structures. Today a typical net pen is about 50 m in diameter and reaches 40 m below the surface.[28]

Many challenges facing aquaculture both increase production cost giving private incentives to address the issue and environmental externalities that mandated actions or led to the use of alternative constructions or locations to avoid the issues.[2i] This gives incentives to innovation. For instance, the early small farms often operated at locations with poor water quality and oxygenation that was exacerbated by the farms and provided incentives to move farms to more exposed locations. More recently, moving farms to even more exposed locations offshore are partly motivated by lower salmon lice levels.

The sea pens are intimately related to some of the main challenges facing the industry, as challenges with the pens can lead to environmental externalities. In particular, escapes are seen as one of two main threats of salmon aquaculture to wild fish,[29] and is largely caused by rifts in the nets.[30] In 2011 a report on economic crime, identified fish escape as one of three main categories of fisheries crime.[31] As a result, throughout the 2000s, preventing escape became a driver for technology development through the Norwegian Aquaculture Escapes Commission (AEC), regulations and standards. In 2004 the Norwegian technical standard NS9415 was implemented. This standard specified requirements for the design of feed barges, floaters, net cages and mooring systems and led to several farms replacing their existing equipment, which in turn reduced the number of major escape incidents.[32,33]

The other and currently the most important environmental challenge for the salmon industry is salmon lice, which indirectly limits the industry's access to new licences and locations due to environmental regulations.[24,34,35j] To address challenges related to salmon lice, escapes and area use, fish farm technology is developing new

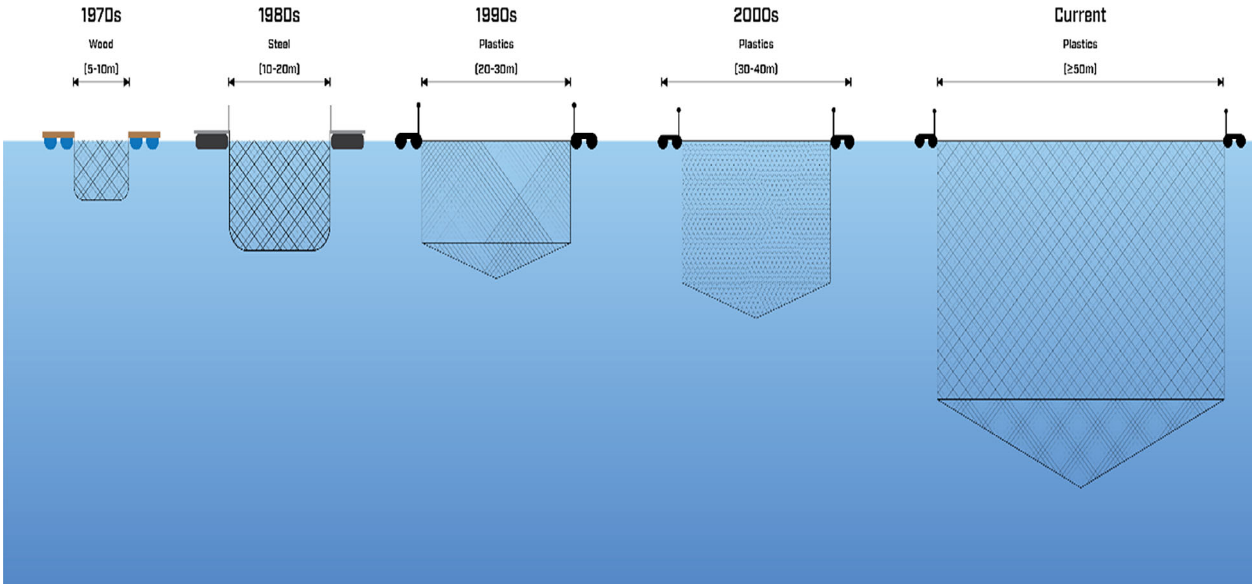


**FIGURE 2** The open net pen technology: Changes in dimension from 1970s to present. The illustrations show that: (1) in the early 1970s, the average size of the net pens ranged from 5 to 10 m in diameter, and the frame were commonly made of wood; (2) in the 1980s the diameter size increased to around 10–20 m, and farmers transitioned from wood to integrated steel platforms; (3) In the 1990s and 2000s the pen size reached 30 and 40 m respectively, and consequently became too large for steel structures, leading to a shift by salmon farmers to plastic ring; (4) the pen size continued to increase over the years and at present, the average pen size has reached 50 m in diameter and the frame are commonly made of plastics.

concepts in several directions; offshore farming, semi-enclosed sea pens and land-based recycling aquaculture systems (RAS).[36,37k] For example, in 2017, the company SalMar began operating an innovative exposed or offshore salmon farm concept: Ocean Farm 1. This pilot facility is 68 m high and 110 m wide and is constructed in steel. It is fitted with 20,000 sensors for monitoring and feeding up to 1.5 million Atlantic salmon.[36]

As the industry has been growing, several organisational innovations have fundamentally changed the industry structure. More specifically, the farming technology segment became increasingly specialised leading to the emergence of specialised equipment (e.g., fishnets), technology and services (e.g., maintenance and logistics) suppliers.[38] In particular, companies such as Akva Group, Scale AQ and Fiizk have made significant contributions to the development of farming technology and production practices, in collaboration with fish farmers and researchers.

An increasing part of the production process is taking place on land partly to increase production with the current licences and partly to avoid the licences, but also giving more control with the production process. In Denmark and the United States, there are plants where the whole production cycle is on land.[39]

In addition to the sea pens and platforms, different types of equipment have been introduced to increase control and efficiency or to save labour. The first important innovation was automatic feeders, and as early as the 1990s there was discussion with respect to the efficiency of manual versus automatic feeding.[40] Increasingly advanced systems for monitoring of the fish and the water column include sonar and computer-vision technology, in which video from subsea cameras and sensors are fed into computer-vision algorithms to gauge variables such as fish size and sea-lice infestation.[41]

In the 2010s many of the traditionally labour-intensive maintenance activities in the production processes have been outsourced to independent companies, making each function more specialised. Recently, the larger firms have started to move the control functions on land to centralised locations that are monitoring feeding and the fish at a number of locations.[42] As such, several tasks have been moved away from the farms. Employees at the fish farms still supervise the condition of the farm and the fish, conduct lice counts and participate in operations such as delousing.

## 3.2 | Juvenile production

Juvenile salmon production involves hatching eggs to produce first fingerlings or frys and grow these to smolt. Initially, the juveniles were reared in tanks only for the first few days after hatching as the smolt mostly were kept in pens in freshwater lakes. In the 1970s transferring the entire process indoors in tanks offered a higher degree of control.[43,44] The majority of the hatcheries and smolt production facilities in Norway were built in the 1980s and were technologically based on a so-called flow-through-system where water from a river is led through the plant to provide highly oxygenated water.[44] Since the mid-2000s most new plants as well as upgraded older plants use RAS that are designed to significantly reduce the required water by recycling it. Water recycling involves the removal of particles using mechanical filters or sludge basins, carbon dioxide venting as well as removal of metabolites by biological filtration. The technology enables a higher degree of control of critical growth factors such as temperature and water quality, and environmental risk factors such as escapes and minimises spills of polluted water.[43,44]

Over the years, the equipment used in juvenile production has become more efficient, with higher speed (e.g. feeding and sorting machines) and larger volumes. Furthermore, the sizes of tanks used in the production have increased steadily, in turn contributing into making the operations physically less demanding for the employees and more careful handling of fish.[43] Several notable innovations have improved the juvenile production process such as the use of artificial light to control and accelerate the smoltification process, an innovation that allows for producing smolts throughout the year. The juvenile production process has also been significantly impacted by several of the innovations to be discussed below as this is where vaccination takes place, and the breeding programmes have reduced the production time from over 2 years to as little as 8 months for a smolt of about 80 g.

Until the late 2000s, the smolt size was relatively stable at 80 to 100 g and most of the breeding gains in terms of faster growth was taken out in terms a shorter production cycle on land. This made good economic sense as the land-based smolt production is more capital intensive than sea pens. In recent years the increased difficulties in obtaining new licences have also impacted smolt production as companies try to improve the utilisation of the existing licences by moving parts of the production on land, a feature that is also beneficial in limiting the impact of salmon lice. Many plants are now the producing larger smolts (250–500 g), and the first stages of the salt-water production process is also taking place in land-based tanks giving what is referred to as post-smolts.[45] These are now being produced at size up to 1 kg, although this is (still) exceptional. As such, the smolt plants have pioneered several aspects of land-based salmon farming and are making the line between juvenile production and the grow-out phase increasingly blurred.

The smolt producers also illustrate another important feature of the salmon industry. The innovations at the smolt production stage by input providers reduced the smolt input cost in the grow-out phase.[4,46] Figure 3 shows the juvenile production in the period between 1990 and 2020 together with average real price and unit cost. It is not accidental that this figure largely reflects Figure 1 with rapidly increasing production, the price and cost decreasing rapidly until the early 2000s, and thereafter starting to increase. However, here the main reason for the increased production cost is a deliberate decision in the form of producing larger smolts.

## 3.3 | Fish health

As all biological industries, salmon aquaculture is exposed to disease due to the high biomass concentrated in a limited area. By the mid-1980s, the industry was grappling with challenges related to high mortality rates due to disease, and more specifically, infectious bacterial and viral diseases such as cold water vibriosis, furunculosis, infectious salmon anaemia (ISA), and Pancreatic necrosis (IPN). This in turn led to an increase in the usage of antibiotics in the sector through the 1980s that was even faster than the production growth,[47] causing significant local pollution challenges. However, the control with the production process that allows systematic R&D to be undertaken to enhance growth also can be used to address challenges.[4] A new sub-discipline of veterinarians, fish-veterinarians, was created leading to knowledge that led to better hygienic and handling practices, and in the late 1980s several companies introduced oil-vaccines to protect against vibriosis, and then multi-valent vaccinas that also protected against furunculosis.

Due to the introduction of oil vaccines, the industry's antibiotics consumptions were reduced by 99% around 1990.[2] The development of vaccines has been one of the most crucial research-driven innovations in the Norwegian aquaculture industry[48] in that it enabled the industry to prevent dramatic outbreaks of damaging diseases.

In addition to diseases, parasitic salmon lice infections have been another major challenge for the industry.[30,34,49] A number of approaches have also been developed to treat against salmon lice.[50]

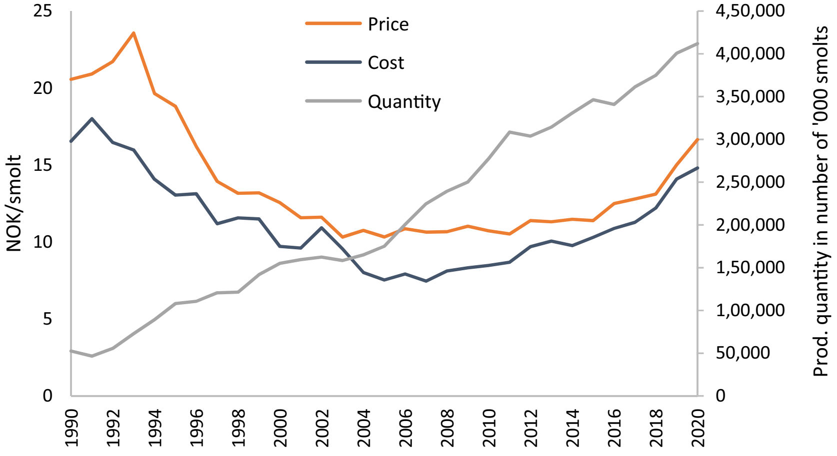


**FIGURE 3** Norwegian smolt production and real (2020 = 1) price and production cost per smolt, 1990–2020. *Source*: Ref. 25

As is too often the case when treatment is the attempted solution to a regularly occurring health issue, resistance start to develop.[34,51,52] As such, the industry is currently using a host of approaches including chemical treatments, feed additives and cleaner fish. While feed additives and cleaner fish may have some prevention effect, effective prevention remains elusive. The existent mix of approaches largely controls the salmon lice levels at the farms at a significant cost,[14,35] but as the impact on wild salmon stocks is regarded as unsustainable, the largest cost is most likely the foregone growth caused by strict regulations.[49] In fact, salmon lice levels are now the main indicator being used in a 'traffic light' system introduced in 2017 to determine not only growth in production capacity, but also reduction.[53,54]

In 2017, a new vaccine against IPN was introduced, and a DNA-based vaccine for immunisation against ISA has for the first time been approved for use in farmed fish in Norway. The industry is also currently exploring other innovative solutions such as the use of dip vaccines and nanoparticles. Overall, these innovations have made it possible to maintain relatively healthy and high-quality fish stocks at cost levels that is economically sustainable. This rapid development of knowledge about fish health makes the aquaculture industry in general and not only the salmon industry better prepared for new diseases that are bound to show up. Still, the assessment that diseases will be the most important challenge for aquaculture development globally is likely to remain true.[55]

## 3.4 | Breeding and genetics

Systematic breeding programmes select for specific traits in a population that makes the organism more productive for a specific purpose. This has been essential in terrestrial farming to make animals and plants grow faster and bigger and adapt to specific environments. Salmon was one of the first aquatic species where a systematic breeding programme was developed, and the history of salmon breeding can be traced back to the early 1970s. Professor Harald Skjervold is credited for pioneering salmon breeding drawing on knowledge and techniques developed for cattle breeding. A systematic breeding programme was instigated with the creation of AKVAFORSK, a publicly funded company, in 1971. To obtain a broad genetic base, AKVAFORSK collected fertilised eggs from 40 (out of about 400) Norwegian rivers that had stocks of wild Atlantic salmon. Based on this, four generations (i.e. the growth cycle for the breeding stock is 4 years) were formed in order to provide stock for the farming industry.[56]

Initially, the main focus of the breeding programme was improved fish growth, and the breeding process has been highly successful in fostering faster growth.[57] The freshwater phase has been shortened from over 2 years to between 5 and 12 months, and also allow for a continuous transfer of juvenile salmon (smolts) to the sea rather than just a spring transfer as in the early decades of the industry or a spring and a fall transfer as was common from the 1990s to the 2000s.[43] The sea phase has also been shortened from over 2 years to just over a year while the average harvest size has increased.[17l] From the 1980s onward however, as the industry started to grapple with fish diseases, one started to breed for more traits, and different companies could select different weights. Selected traits included the salmon's body shape, fillet colour, meat content, feed utilisation, fat distribution and slaughter quality as well as resistance against different diseases.[56–58]

Over the years, both the publicly funded and private breeding companies have developed and established the most advanced breeding systems for fish and shellfish worldwide[59] although the programmes are more and more dominated by private companies.[60] The breeding programmes have contributed to increased growth and thereby reduced production time, a higher salmon sexual maturation age, better feed utilisation, lower mortality and improved fillet quality.[43] This has been further bolstered by breeding activities focused on diseases resistance.[61] The combination of molecular technologies into existing breeding programmes has significantly accelerated the genetic improvement of some aquaculture species including salmon.[62]

## 3.5 | Feed

Feed is the input factor with the highest cost share. As scale and production efficiency improved feed cost share increased from around 25% to over 50% in the 2000s but is has declined to 45% in recent years as other costs has increased, primarily due to disease challenges and increased use of contractors.[14] Given the high cost share the potential value of innovations is largest for feed, it is not surprising that some of the most important innovations have taken place within the fish-feed segment, and also that this was one of the first inputs where a sector of independent suppliers developed.[4] The first feeds (after feeding trimmings and bycatch) were what was known as wet pellets created at the farm using trimmings form wild fish processing plants, using knowledge from production of fur-bearing animals such as mink and fox.[59] In 1982, the dry pellet was 'invented' or adapted from animal feeds by the company Skretting, setting the stage for systematic research into the composition of the pellets.

Initially, nutritional knowledge for salmon was limited, as was the physical behaviour of the pellets. The early pellets consisted of up to 80% fishmeal and fish oil as these contained the 'natural feed' of the salmon bound together by wheat, and with the astaxanthin added to obtain the salmon colour of the flesh.[17m]

An early environmental challenge for the industry that also created economic waste was the fact that uneaten feed was sinking through the pens and amassed nutrients at the bottom bellow the pens. By changing the physical composition of the pellets, the industry was able to create slower sinking feed that reduced the pollution significantly, and also improved the feed conversion ratio.[47]

The industry's dependence on marine ingredients became both an economic and environmental concern in the mid-1990s. The economic concern was due to the fact that aquafeed became the main use of fishmeal, potentially creating upward pressure on prices thereby increasing cost.[63] The environmental concern was the fear that increased demand for fishmeal would lead to increased fishing pressure and over-fishing of the small pelagic fish stocks that was the primary source for fish meal.[64] However, improved nutritional knowledge was applied to substitute the marine ingredients mostly with plant-based ingredients.[65] Today, marine ingredients only constitute about 25% of the average salmon feed, as the aquafeed contain about 75% plant ingredients,[66] and Ytrestøyl et al.[67] argues that salmon aquaculture is now a net contributor of marine protein.

There is a rapidly increasing knowledge about the nutritional requirement which may further change the feed composition. For instance, there are avenues of feed innovation using micro- and macroalgae as well as insect meal as replacements for fish meal. Furthermore, plant oil such as palm oil and rapeseed oil have emerged as interesting candidates to replace fish oil. However, so far these ingredients do not seem to be competitive on cost.[62] However, the main message is clear: Salmon needs nutrients and not marine ingredients. With sufficient nutritional knowledge, in the not to distant future the production of salmon feed is likely to resemble the production of most animal feeds where linear programming models are used to find the mix of ingredients that gives a feed of a given performance at the lowest cost.

## 3.6 | Primary fish processing

In the early days of the industry, the salmon were slaughtered at the sea cage and thereafter brought ashore. With the growth of the industry the slaughtering process became specialised and conducted in processing plants constructed for this purpose. As a part of this process the fish was transported to harvesting plant, kept in waiting cages to starve a few days for quality purposes before they get slaughtered. Early on, fish processing companies had to wait for approximately 3 days for the fish to come of rigour to start the processing. Improved knowledge facilitated pre-rigour filleting, which entails slaughtering and filleting before the fish enters a state of stiffness, often on the same day became prevalent. This process was found to be advantageous both in terms of cost and fish quality, as this substantially reduced the time to market (by 3–5 days).[68] Alternatively, as just-in-time logistic chains were developed, the fish went through rigour on a truck, and secondary processing was conducted at a plant closer to the consumer.

For animal welfare reasons there is a requirement that the salmon is anesthetised before they are killed. Fish should die from blood loss from the brain and this is practiced by cutting arteries in the gill arches.[68] Previously, there was a perception that the use of $CO_2$ during anaesthesia was the most important reason for stressing fish and shortly before death stiffness (rigour). As a result, the use of $CO_2$ was banned in 2010 for fish welfare reasons. Handling of live fish in connection with the slaughter process are believed to cause a stress for the fish. Thus, it was imperative to find solutions that make the processes as gentle as possible, both for animal welfare reasons and for the product quality. Accordingly, in recent years, alternative methods of anaesthesia have emerged in the industry. These include using electrical currents, and blow to the head to make the fish unconscious.[68] Over time, the salmon harvesting and processing have increasingly become more and more automated and robotised.[69]

The harvesting plants have become larger, and despite the increased production, fewer. This has increased the distance between them, and a separate industry, well-boats have developed to transport the salmon from the farm to the processing plant. Recently, vessels with slaughtering facilities on board have also been introduced[70] to shorten the process and reduce land-based capital requirements. In one controversial case, the *Norwegian Gannet*, the vessel is designed to conduct the whole primary processing process and land the fish in Denmark and the UK. This may be efficient, but is challenging the social acceptance of the industry as it is removing jobs from coastal communities.

At present, well boats are also being used to carry out lice treatment along the edge of the cage.[71] Well boats have rooms, tanks, or 'wells' where fresh seawater circulates, so that the fish can be transported live. The development of well boats and the technology for transporting live fish in boats has followed the pace of the Norwegian aquaculture industry in general. In the 1980s to 1990s, rebuilt fishing boats with a capacity of 60 $m^3$ were used. At that time, a typical well-boat carried 10–20 mt of fish and was usually no longer than 14.99 m. In the 2000s, typical well boats carried 100 mt of fish. In recent years, the well boats have changed in size and used increasingly newer and more sophisticated equipment. This includes methods for loading and unloading fish, as well as for counting and sorting and for monitoring and adjusting the water quality.[72] In the year 2022, the largest well boats can carry up to, and many have a length of 70–80 m. Thanks to the investments in the development of new technology for well boats, high-tech ships with up to 2600 $m^3$ of cargo capacity (c. 1200 tonnes of fish), water treatment plants and purification equipment are now being widely used in the industry.[72] Larger cargo volumes mean lower shipping costs per fish and hence cost savings for both salmon farmers and the end buyers.

## 3.7 | Regulations

The governance system and regulations impact all aspects of the innovation and technology adaption processes. However, the regulations are in themselves highly important for the industries environmental and economic sustainability,[73] and they are recognised to be a main barrier for the development of significant aquaculture production in many developed countries[3,74] despite strong aspiration to grow.[75,76n] Hence, innovations that are relaxing regulatory constraints can be as valuable as knowledge or technological innovations.[13]

The Norwegian aquaculture industry has since its inception been subject to numerous regulatory regimes.[77] These are important as the constraints of the regulatory system in themselves gives incentives to innovate, as an innovation that relax a regulatory constraint is as valuable as genuine productivity growth for any company. In recent years, the government has also been using the regulatory system actively to incentivise innovations particularly with an objective of making the industry more environmentally friendly.[23,24] The most important factor is that a number of tools have been used to limit production indirectly.

The regulatory system was established in 1973 with several objectives, where the most important was to support coastal communities and avoid over production.[26,54,59] Over time, the importance of environmental sustainability has increased and social objectives has largely but not completely disappeared. Initially, ownership was restricted to one farm with a cap on production volume regulated by the net pen volume. This was originally set to 8000 $m^3$, reduced to 5000 $m^3$ in 1975–1978 and down to 3000 $m^3$ in 1981, before later being increased to 5000 $m^3$ in 1983, 8000 $m^3$ in 1985 and finally to 12,000 $m^3$ in 1988. From 1989 onwards the regulation was calculated down to a depth of 5 m. Hence, farmers could increase production by using deeper net pens, and naturally deeper pens were developed.[77]

Stricter enforcement of environmental regulation in the 1990s led to the use of more exposed production sites, enabled by technological improvements in pen technology.[78] Despite a moratorium on new licensing rounds during the 1990s, production grew 4–5-fold, driven by better production sites, improved pen technology, deeper net pens, and vaccines.

In 1991, the 'one farmer, one licence' system was abolished, leading to a restructuring of the industry which is still ongoing.[79] There were no restrictions on the size of a farm, and the larger companies quickly found out that operating more than one licence at a farm gave scale economies. There exists no maximum size on a farm, although in practice they are limited by the environmental carrying capacity of any specific location. This is a licence required to operate at any location.[80]

The rapidly increased production in the 1980s led to a downward pressure on price that caused trade tensions between Norwegian producers and competing salmon farmers in the United States and EU.[81–84] To resolve the issues with the EU, Norway imposed self-regulating measures to try to limit production growth. The most important was *feed quotas*, putting a cap on the amount of feed that a farmer could purchase annually, introduced in 1996. Salmon farmers responded to the imperfect regulation by changing the composition of feed.[77] In 2005, a system of maximum allowable biomass (MAB) regime, restricting the amount of biomass companies could have in the farms to a maximum of 780 tons for most regions and 945 tons for the northernmost production regions (due to less favourable water temperatures). This system gives incentives to flatten the seasonal cycle and increase production by harvesting smaller fish.[85]

The increasing environmental challenge cause by salmon lice has led to an increasing regulatory focus on this parasite.[24,86] So-called *green licences* were introduced in 2013 followed by development licences in 2015 to promote the development of new technologies and/or innovative solutions that could solve the environmental problems of the industry particularly pertinent to problems associated with lice.[24,54,77o] The licensing scheme resulted in new delousing measures and actions to be implemented by fish farmers. These include biochemical as well as mechanical innovations, such as hydrogen peroxide baths, application of 'hydro-licers', or the use of cleaner fish.[87,88] In addition, in 2017 what is known as the *traffic light system* was introduced. The objective of the system is to prevent lice-induced mortality for wild fish stocks and introduce 13 production areas along the Norwegian coast where farmers are allowed to increase their MTB if the salmon lice status is green and where all have to reduce their production is it is red.[77] The salmon lice challenges have motived innovation into pre-emptive measures such as barrier technologies, for example, snorkel cages and lice skirts, traps, filters, repellents, light modification, electricity fences, ultrasound, vaccinations, breeding, closed containment technology,[50] and laser technology[89] as some examples. It also incentivises new production concepts such as land-based farming or large smolts outside of the traditional regulatory system.[39,45]

## 4 | DISCUSSION AND CONCLUSIONS

As in most aquaculture industries, the original Norwegian salmon farmer was an entrepreneur, who was also a 'Jack of All Trades' in that the farmer had to do everything involved from building the farm, raise the fingerlings, mix the feed and harvest the fish. As the industry grew, there has been a dynamic process of innovations that has enhanced productivity and increased the control with the production process. This has largely been conducted by new supplier industries, where the specialised suppliers identified the growing industry as a market, and competition between suppliers lead to innovations giving better inputs at a lower cost.[4,43,46] provide a good example of this process for smolt production. However, similar processes took place first for the main components such as the pens and the feed, and then for an increasing number of more specialised functions. Today, there are specialised suppliers for a wide range of equipment like sensors and control systems as well services such as veterinary tests, net cleaning and research. As such, an increasing part of the employment associated with the industry is in different types of suppliers.

A common thread is that the size of everything has increased in salmon aquaculture; the production, the fish, the pens, the farms, the feed barges, the well-boats, the processing plants and the firms. This suggest that innovations are also important for creating and allowing economies of scale to be exploited. Innovations have generally been scale-biased or scale-increasing, and through the value chain from smolt production via sea transportation and grow-out farming to primary processing the optimal economic scale has increased. Not unexpectedly, many of the most radical innovations occurred early in the history of the industry, and later innovations are mostly smaller process or product innovations which in sum provides a powerful gradual process. However, there still occur radical innovation as exemplified by offshore and land-based farming. It is also interesting that public incentives in combination with the regulatory system is facilitating such innovations.

The innovations provide more technological opportunities for salmon aquaculture than we have ever seen before. Innovations in open and closed production systems from land-based or onshore to offshore ocean allow for several new value chain configurations, as depicted in Figure 4. These new production technologies have the potential to both reduce firms' internal production costs, as well as reduce the external costs of environmental emissions, diseases and

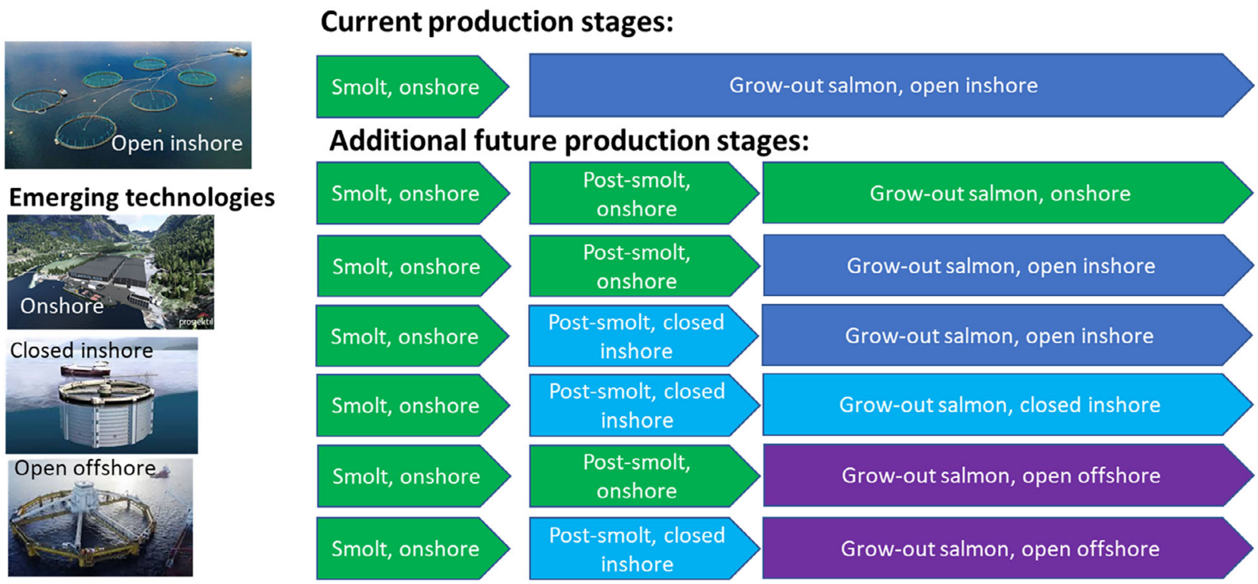


**FIGURE 4** Current and possible new configurations of farmed salmon production

salmon lice. As of now, no-one knows what is going to be the production concepts used in salmon farming in the future, or even whether there will be one dominating one or several parallel concepts used. However, it is highly interesting that the basic production technology, open sea pens, are being challenged, and that all the new concepts increase the control with the production process and thereby the potential for further innovation.

The innovation system that has helped create the salmon industry has been rapidly growing with the industry. It consists of the aquaculture companies themselves, the suppliers, research institutes and universities.[90] provide survey data for 2015 which indicate that 12.9% of the research is conducted at universities, 20.5% at research institutes and 56.5% in private companies. This is funded 61.1% by companies, 1.9% from foreign countries and 37% from public sources. In 2015, the total funding was 2.3 billion NOK. There are of course also other aspects of the industry structure that is important. In particular,[38] Asche et al.[91,92] show that firms located in industry clusters are more productive.

In this paper, we have only discussed the production part of the supply chain. However, as consumers in general only care about the price they are paying, innovations in the supply chain are equally important for the competitiveness of any industry. Asche and Smith[13] argue that the supply chain for salmon is highly competitive relatively to most other seafood species, while Asche et al.[93] show that the supply chains for salmon is still lagging behind chicken in many dimensions. Hence, there is still significant scope for innovations also down-streams in the supply chain. This includes not only logistics and product development, but also perceptions of the species. This is particularly important for salmon since there is a number of issues with respect to its environmental sustainability that can at least partly be addressed by certification.[94]

## AUTHOR CONTRIBUTIONS

**Bård Misund:** Conceptualization; investigation; writing – original draft; writing and review & editing. **Frank Asche:** Conceptualization; investigation; writing - original draft; methodology; writing – review and editing. **Ragnar Tveteras:** Conceptualization; investigation; funding acquisition; writing – original draft; methodology; writing – review and editing; project administration. **Samson Afewerki:** Conceptualization; investigation; methodology; data curation; writing – review and editing; writing – original draft; visualization. **Trine Thorvaldsen:** Conceptualization; investigation; funding acquisition; writing – original draft; methodology; writing – review and editing; project administration.

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## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in FAO at https://www.fao.org/fishery/en/global-search?q=statistics%20software%20fishstat%20en&lang=en. These data were derived from the following resources available in the public domain: - FAO, https://www.fao.org/fishery/en/global-search?q=statistics%20software%20fishstat%20en&lang=en.

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## ENDNOTES

[a] Some recent examples for salmon include,[33,95] while Mitra et al.[96,97] provide examples for other species.

[b] Atlantic salmon may spawn more than once, in which case it would repeat the feeding cycles, but normally it does not.

[c] Brood stock is kept in separate locations to facilitate the egg and yolk production for the next generation.

[d] A similar process took place in other countries and most notably in Scotland.

[e] Asche and Bjørndal[17] provide more detail about the growth of the industry, while Landazuri-Tveteraas[98] provide more information about the trout. The regulatory system for the two species is identical, and it is the same licence required to farm salmon or trout.[77]

[f] Several studies discuss aspects of the increased profitability of the Norwegian salmon industry, including Asche et al.[93,99–101] With the increased size of the industry, tools to address economic risk has also been introduced, including futures markets.[91,102]

[g] A similar development has taken place for a number of other species based on observed prices and production, for example, Nielsen et al.,[103] although data series for cost over time do often not exist. One other example where such data exist is U.S. catfish,[104] where most of the cost reduction and therefore innovation took place in the 1970s, that is before it occurred in salmon aquaculture.

[h] The land-based trout industry still largely produces portion sized fish at around 0.5 kg,[75] while a farmed salmon has an average harvest weight around 5 kg.[85]

[i] There are also studies that suggest that imperfect regulations can exacerbate environmental problems.[85]

[j] Although there are competing users of areas in the coastal zone, access to unexploited suitable natural environments is not necessarily a major limiting factor for Norwegian aquaculture.[105,106]

[k] RAS is a rapidly developing technology adapted for a number of species around the world including salmon.

[l] There are of course also economic considerations with respect to when the salmon is harvested.[107,108] Oglend and Soini[85] show that in recent years average harvest weight has declined somewhat due the tightly binding maximum total biomass regulation as this increase the average growth rate.

[m] In nature, the salmon obtain astaxanthin by eating crustaceans, and early on the astaxanthin in the feed was extracted from wild shrimp. However, this was quickly replaced by synthetically produced astaxanthin.

[n] A part of the challenge is complicated regulations with conflicting jurisdictions,[109] which in the worst examples create anti-commons problems.[2,110]

[o] It is worthwhile to note that there are also so strong incentives associated with the development licences that they may appear as development subsidies.[24]

## REFERENCES


1. FAO. FishStat Plus Statistical Software. Accessed April 24, 2022. https://www.fao.org/fishery/en/global-search?q=statistics%20software%20fishstat%20en&lang=en
2. Asche F, Eggert H, Oglend A, Roheim CA, Smith MD. Aquaculture: externalities and policy options. *Rev Environ Econ Policy*. 2022;16(2):282-305. doi:10.1086/721055
3. Garlock T, Asche F, Anderson J, et al. A global blue revolution: aquaculture growth across regions, species, and countries. *Rev Fish Sci Aquacult*. 2020;28(1):107-116. doi:10.1080/23308249.2019.1678111
4. Asche F. Farming the sea. *Mar Resour Econ*. 2008;23:527-547.
5. Kumar G, Engle CR. Technological advances that led to growth of shrimp, salmon, and tilapia farming. *Rev Fish Sci Aquacult*. 2016;24(2):136-152. doi:10.1080/23308249.2015.1112357
6. Bergesen O, Tveterås R. Innovation in seafood value chains: the case of Norway. *Aquacult Econ Manag*. 2019;23(3):292-320. doi:10.1080/13657305.2019.1632391
7. Kumar G, Engle C, Tucker C. Factors driving aquaculture technology adoption. *J World Aquacult Soc*. 2018;49(3):447-476. doi:10.1111/jwas.12514
8. Kumar G, Engle C, Avery J, et al. Characteristics of early adoption and non-adoption of alternative catfish production technologies in the U.S. *Aquacult Econ Manag*. 2021;25(1):70-88. doi:10.1080/13657305.2020.1803446
9. Asche F, Cojocaru AL, Roth B. The development of large scale aquaculture production: a comparison of the supply chains for chicken and salmon. *Aquaculture*. 2018;493:446-455. doi:10.1016/j.aquaculture.2016.10.031
10. Bush SR, Pauwelussen A, Badia P, et al. Implementing aquaculture technology and innovation platforms in Asia. *Aquaculture*. 2021;530:735822. doi:10.1016/j.aquaculture.2020.735822
11. Garlock T, Asche F, Anderson J, et al. Aquaculture: the missing contributor in the food security agenda. *Glob Food Sec*. 2022;32:100620. doi:10.1016/j.gfs.2022.100620
12. Smith MD, Roheim CA, Crowder LB, et al. Sustainability and global seafood. *Science*. 2010;327(5967):784-786. doi:10.1126/science.1185345
13. Asche F, Smith MD. Viewpoint: induced innovation in fisheries and aquaculture. *Food Policy*. 2018;76:1-7. doi:10.1016/j.foodpol.2018.02.002
14. Iversen A, Asche F, Hermansen Ø, Nystøyl R. Production cost and competitiveness in major salmon farming countries 2003–2018. *Aquaculture*. 2020;522:735089. doi:10.1016/j.aquaculture.2020.735089
15. Alston JM, Beddow JM, Pardey PG. Agricultural research, productivity, and food prices in the long run. *Science*. 2009;325(5945):1209-1210. doi:10.1126/science.1170451
16. Nielsen R, Asche F, Nielsen M. Restructuring European freshwater aquaculture from family-owned to large-scale firms—lessons from Danish aquaculture. *Aquacult Res*. 2016;47(12):3852-3866. doi:10.1111/are.12836
17. Asche F, Bjørndal T. *The Economics of Salmon Aquaculture*. Wiley; 2011. doi:10.1002/9781119993384
18. Straume HM, Anderson JL, Asche F, Gaasland I. Delivering the goods: the determinants of Norwegian seafood exports. *Mar Resour Econ*. 2020;35(1):83-96. doi:10.1086/707067
19. Straume HM, Landazuri-Tveteraas U, Oglend A. Insights from transaction data: Norwegian aquaculture exports. *Aquacult Econ Manag*. 2020;24(3):255-272. doi:10.1080/13657305.2019.1683914
20. Cojocaru AL, Iversen A, Tveterås R. Differentiation in the Atlantic salmon industry: a synopsis. *Aquacult Econ Manag*. 2021;25(2):177-201. doi:10.1080/13657305.2020.1840664
21. Oglend A, Asche F, Straume H. Estimating pricing rigidities in bilateral transactions markets. *Am J Agric Econ*. 2022;104(1):209-227. doi:10.1111/ajae.12230
22. Asche F, Oglend A, Selland KT. Price dynamics in biological production processes exposed to environmental shocks. *Am J Agric Econ*. 2017;99(5):1246-1264. doi:10.1093/ajae/aax048
23. Hersoug B, Olsen MS, Gauteplass AÅ, Osmundsen TC, Asche F. Serving the industry or undermining the regulatory system? The use of special purpose licenses in Norwegian salmon aquaculture. *Aquaculture*. 2021;543:736918. doi:10.1016/j.aquaculture.2021.736918
24. Osmundsen TC, Olsen MS, Gauteplass A, Asche F. Aquaculture policy: designing licenses for environmental regulation. *Mar Policy*. 2022;138:104978. doi:10.1016/j.marpol.2022.104978
25. Norwegian Directorate of Fisheries. *Statistics for Aquaculture*. Norwegian Directorate of Fisheries; 2022. Accessed May 2022. https://www.fiskeridir.no/English/Aquaculture/Statistics
26. Osmundsen TC, Karlsen KM, Robertsen R, Hersoug B. Shared waters—shared problems: the role of self-governance in managing common pool resources. *Aquacult Econ Manag*. 2021;25(3):275-297. doi:10.1080/13657305.2020.1857468
27. Isabella J, Hunt S. A short history of aquaculture innovation. 24, 2020. Accessed November 18, 2022. https://hakaimagazine.com/features/a-short-history-of-aquaculture-innovation/
28. McIntosh P, Barrett LT, Warren-Myers F, et al. Supersizing salmon farms in the coastal zone: a global analysis of changes in farm

technology and location from 2005 to 2020. *Aquaculture*. 2022;553: 738046. doi:10.1016/j.aquaculture.2022.738046
29. Pincinato RB, Asche F, Roll KH. Escapees in Salmon aquaculture: a multi-output approach. *Land Econ*. 2021;97(2):425-435. doi:10.3368/le.97.2.425
30. Føre HM, Thorvaldsen T. Causal analysis of escape of Atlantic salmon and rainbow trout from Norwegian fish farms during 2010–2018. *Aquaculture*. 2021;532:736002. doi:10.1016/j.aquaculture.2020.736002
31. Thorvaldsen T, Holmen IM, Moe HK. The escape of fish from Norwegian fish farms: causes, risks and the influence of organizational aspects. *Mar Policy*. 2015;55:33-38. doi:10.1016/j.marpol.2015.01.008
32. Jensen Ø, Dempster T, Thorstad E, Uglem I, Fredheim A. Escapes of fishes from Norwegian sea-cage aquaculture: causes, consequences and prevention. *Aquac Environ Interact*. 2010;1(1):71-83. doi:10.3354/aei00008
33. Pincinato RBM, Asche F, Bleie H, Skrudland A, Stormoen M. Factors influencing production loss in salmonid farming. *Aquaculture*. 2021; 532:736034. doi:10.1016/j.aquaculture.2020.736034
34. Torrissen O, Jones S, Asche F, et al. Salmon lice—impact on wild salmonids and salmon aquaculture. *J Fish Dis*. 2013;36(3):171-194. doi:10.1111/jfd.12061
35. Abolofia J, Asche F, Wilen JE. The cost of lice: quantifying the impacts of parasitic sea lice on farmed Salmon. *Mar Resour Econ*. 2017;32(3):329-349. doi:10.1086/691981
36. Moe Føre H, Thorvaldsen T, Osmundsen TC, et al. Technological innovations promoting sustainable salmon (*Salmo salar*) aquaculture in Norway. *Aquacult Rep*. 2022;24:101115. doi:10.1016/j.aqrep.2022.101115
37. Øvrebø TK, Balseiro P, Imsland AKD, et al. Investigation of growth performance of post-smolt Atlantic salmon (*Salmo salar* L.) in semi closed containment system: a big-scale benchmark study. *Aquacult Res*. 2022;53(11):4178-4189. doi:10.1111/are.15919
38. Tveteras R. Industrial agglomeration and production costs in Norwegian Salmon aquaculture. *Mar Resour Econ*. 2002;17(1):1-22. doi:10.1086/mre.17.1.42629345
39. Bjørndal T, Tusvik A. Economic analysis of land based farming of salmon. *Aquacult Econ Manag*. 2019;23(4):449-475. doi:10.1080/13657305.2019.1654558
40. Tveterås R. Production risk and productivity growth: some findings for Norwegian salmon aquaculture. *J Prod Anal*. 1999;12(2):161179.
41. Tveterås R, Hovland M, Reve T, et al. *Verdiskapingspotensialet Og Veikart for Havbruk Til Havs (In Norwegian: Value Creation Potential and Roadmap for Offshore Aquaculture)*. Stiim aqua Cluster; 2020.
42. Drønen O. Ikke helt fjernt med fjernfôring (In Norwegian: Not too far with remote feeding). 8, 2018. Accessed April 25, 2022. https://www.kyst.no/fjernfring-midt-norsk-havbruk-produktivitetskonferansen/ikke-helt-fjernt-med-fjernfring/152137
43. Sandvold HN, Tveterås R. Innovation and productivity growth in Norwegian production of juvenile salmonids. *Aquacult Econ Manag*. 2014;18(2):149-168. doi:10.1080/13657305.2014.903313
44. Sandvold HN. Technical inefficiency, cost frontiers and learning-by-doing in Norwegian farming of juvenile salmonids. *Aquacult Econ Manag*. 2016;20(4):382-398. doi:10.1080/13657305.2016.1224659
45. Bjørndal T, Tusvik A. Economic analysis of on-growing of salmon post-smolts. *Aquacult Econ Manag*. 2020;24(4):355-386. doi:10.1080/13657305.2020.1737272
46. Tveterås R, Heshmati A. Patterns of productivity growth in the Norwegian salmon farming industry. *Int Rev Econ Bus*. 2002;49:367-393.
47. Tveterås S. Norwegian salmon aquaculture and sustainability: the relationship between environmental quality and industry growth. *Mar Resour Econ*. 2002;17(2):121-132. doi:10.1086/mre.17.2.42629356
48. Aarset B, Beckmann S, Bigne E, et al. The European consumers' understanding and perceptions of the 'organic' food regime. *Br Food J*. 2004;106(2):93-105. doi:10.1108/00070700410516784
49. Osmundsen TC, Olsen MS, Thorvaldsen T. The making of a louse—constructing governmental technology for sustainable aquaculture. *Environ Sci Policy*. 2020;104:121-128. doi:10.1016/j.envsci.2019.12.002
50. Barrett LT, Oppedal F, Robinson N, Dempster T. Prevention not cure: a review of methods to avoid sea lice infestations in salmon aquaculture. *Rev Aquacult*. 2020;12(4):2527-2543. doi:10.1111/raq.12456
51. Dempster T, Overton K, Bui S, et al. Farmed salmonids drive the abundance, ecology and evolution of parasitic salmon lice in Norway. *Aquac Environ Interact*. 2021;13:237-248. doi:10.3354/aei00402
52. Coates A, Johnsen IA, Dempster T, Phillips BL. Parasite management in aquaculture exerts selection on salmon louse behaviour. *Evolut Appl*. 2021;14(8):2025-2038. doi:10.1111/eva.13255
53. Larsen ML, Vormedal I. The environmental effectiveness of sea lice regulation: compliance and consequences for farmed and wild salmon. *Aquaculture*. 2021;532:736000. doi:10.1016/j.aquaculture.2020.736000
54. Hersoug B. 'One country, ten systems'—the use of different licensing systems in Norwegian aquaculture. *Mar Policy*. 2022;137: 104902. doi:10.1016/j.marpol.2021.104902
55. Stentiford GD, Sritunyalucksana K, Flegel TW, et al. New paradigms to help solve the global aquaculture disease crisis. *PLoS Pathog*. 2017;13(2):e1006160. doi:10.1371/journal.ppat.1006160
56. Gjøen H, Bentsen H. Past, present, and future of genetic improvement in salmon aquaculture. *J Mar Sci*. 1997;54:1009-1014.
57. Næve I, Korsvoll SA, Santi N, Medina M, Aunsmo A. The power of genetics: past and future contribution of balanced genetic selection to sustainable growth and productivity of the Norwegian Atlantic salmon (*Salmo salar*) industry. *Aquaculture*. 2022;553:738061. doi:10.1016/j.aquaculture.2022.738061
58. Rosendal GK, Olesen I. Overcoming barriers to breeding for increased lice resistance in farmed Atlantic salmon: a case study from Norway. *Aquaculture*. 2022;548:737574. doi:10.1016/j.aquaculture.2021.737574
59. Aslesen H. *The Innovation System of Norwegian Aquacultured Salmonids*. Centre for Technology, Innovation Culture (TIK), University of Oslo; 2007.
60. Aarset B, Borgen S. The battle of the eyed egg: critical junctures and the control of genes in Norwegian salmon farming. *Aquaculture*. 2015;445:70-78.
61. Gjedrem T, Robinson N, Rye M. The importance of selective breeding in aquaculture to meet future demands for animal protein: a review. *Aquaculture*. 2012;350–353:117-129. doi:10.1016/j.aquaculture.2012.04.008
62. Yue K, Shen Y. An overview of disruptive technologies for aquaculture. *Aquacult Fish*. 2022;7(2):111-120. doi:10.1016/j.aaf.2021.04.009
63. Asche F, Oglend A. The relationship between input-factor and output prices in commodity industries: the case of Norwegian salmon aquaculture. *J Commod Mark*. 2016;1(1):35-47. doi:10.1016/j.jcomm.2015.11.001
64. Kok B, Malcorps W, Tlusty MF, et al. Fish as feed: using economic allocation to quantify the fish in: fish out ratio of major fed aquaculture species. *Aquaculture*. 2020;528:735474. doi:10.1016/j.aquaculture.2020.735474
65. Tacon AGJ. Trends in global aquaculture and aquafeed production: 2000–2017. *Rev Fish Sci Aquacult*. 2020;28(1):43-56. doi:10.1080/23308249.2019.1649634
66. Aas TS, Ytrestøyl T, Åsgård T. Utilization of feed resources in the production of Atlantic salmon (*Salmo salar*) in Norway: an update for 2016. *Aquacult Rep*. 2019;15:100216. doi:10.1016/j.aqrep.2019.100216

67. Ytrestøyl T, Aas TS, Åsgård T. Utilisation of feed resources in production of Atlantic salmon (*Salmo salar*) in Norway. *Aquaculture*. 2015;448:365-374. doi:10.1016/j.aquaculture.2015.06.023
68. Fiskeri- og havbruksnæringens landsforening. *Moderne Slakting Av Laks (In Norwegian: Modern Slaughtering Av Salmon)*. Norwegian Seafood Research Fund (FHF); 2009.
69. Winther U, Tiller R, Ratvik I, et al. *Ringvirkningsanalyse for Teknologi-Og Serviceleverandører Til Sjømatnæringen—Leverandører, Utviklingstrekk Og Eksport (In Norwegian: Ripple Effect Analysis for Technology and Services Suppliers to the Seafood Industry—Suppliers, Development Trends and Export)*. SINTEF; 2017.
70. LukeT B, Oldham T, Kristiansen TS, Oppedal F, Stien LH. Declining size-at-harvest in Norwegian salmon aquaculture: lice, disease, and the role of stunboats. *Aquaculture*. 2022;559:738440. doi:10.1016/j.aquaculture.2022.738440
71. Hallenstvedt A. Norsk fiskerihistorie (In Norwegian: Norwegian Fisheries history -). In: *Store Norske Leksikon*. 2021. Accessed April 21, 2022. https://snl.no/Norsk_fiskerihistorie
72. Gismervik K, Nilsen A. *Utvikling Av Fremtidens Brønnbåtteknologi—Regelverk Som Rammebetingelse (In Norwegian: Development of Future Wellboat Technology- Regulation as a Framework Condition)*. Norwegian Seafood Research Fund (FHF); 2010.
73. Anderson JL, Asche F, Garlock T. Economics of aquaculture policy and regulation. *Annu Rev Resour Econ*. 2019;11(1):101-123. doi:10.1146/annurev-resource-100518-093750
74. Abate TG, Nielsen R, Tveterås R. Stringency of environmental regulation and aquaculture growth: a cross-country analysis. *Aquacult Econ Manag*. 2016;20(2):201-221. doi:10.1080/13657305.2016.1156191
75. Guillen J, Asche F, Carvalho N, et al. Aquaculture subsidies in the European Union: evolution, impact and future potential for growth. *Mar Policy*. 2019;104:19-28. doi:10.1016/j.marpol.2019.02.045
76. Rubino MC. Policy considerations for marine aquaculture in the United States. *Rev Fish Sci Aquacult*. 2022;20:1-17. doi:10.1080/23308249.2022.2083452
77. Hersoug B. Why and how to regulate Norwegian salmon production?—The history of maximum allowable biomass (MAB). *Aquaculture*. 2021;545:737144. doi:10.1016/j.aquaculture.2021.737144
78. Berge D, Bjarnar O. *Norsk Fiskeoppdretts Regionale Industriesing. Strukturendringer, Ledelse Og Kompetanse i Norsk Havbruk På 1990-Tallet (in Norwegian: Norwegian Fish Farming Regional Industrialization. Changes in Structure, Management and Competence in the Norwegian Aquaculture in the 1990s)*. Møreforskning; 1998.
79. Asche F, Roll KH, Sandvold HN, Sørvig A, Zhang D. Salmon aquaculture: larger companies and increased production. *Aquacult Econ Manag*. 2013;17(3):322-339. doi:10.1080/13657305.2013.812156
80. Mestad O, Wold SE. *Framtidens Havbruksforvaltning (In Norwegian: The Aquaculture Management of the Future)*. Scandinavian Institute of Maritime Law; 2021.
81. Asche F. Trade disputes and productivity gains: the curse of farmed Salmon production? *Mar Resour Econ*. 1997;12:67-73.
82. Kinnucan HW, Myrland O. Relative impact of the Norway-EU salmon agreement: A Midterm Assessment. In: *2002 International Congress, August 28–31, 2002, Zaragoza, Spain 24826*.
83. Kinnucan HW, Myrland Ø. The effectiveness of antidumping measures: some evidence for farmed Atlantic Salmon. *J Agricult Econ*. 2006;57(3):459-477. doi:10.1111/j.1477-9552.2006.00060.x
84. Asche F, Misund B, Oglend A. The spot-forward relationship in the Atlantic salmon market. *Aquacult Econ Manag*. 2016;20(2):222-234. doi:10.1080/13657305.2016.1156192
85. Oglend A, Soini VH. Implications of entry restrictions to address externalities in aquaculture: the case of Salmon aquaculture. *Environ Resource Econ*. 2020;77(4):673-694. doi:10.1007/s10640-020-00514-0
86. Misund AU. From a natural occurring parasitic organism to a management object: historical perceptions and discourses related to salmon lice in Norway. *Mar Policy*. 2019;99:400-406. doi:10.1016/j.marpol.2018.10.037
87. Greaker M, Vormedal I, Rosendal K. Environmental policy and innovation in Norwegian fish farming: resolving the sea lice problem? *Mar Policy*. 2020;117:103942. doi:10.1016/j.marpol.2020.103942
88. Vormedal I, Larsen M, Flåm K. *Grønn Vekst i Blå Næring? Miljørettet Innovasjon i Norsk Lakseoppdrett (In Norwegian: Green Growth in a Blue Industry? Environmentally Oriented Innovation in Salmon Aquaculture)*. Fridtjof Nansen Institute (FNI); 2019.
89. Bui S, Geitung L, Oppedal F, Barrett LT. Salmon lice survive the straight shooter: a commercial scale sea cage trial of laser delousing. *Prev Vet Med*. 2020;181:105063. doi:10.1016/j.prevetmed.2020.105063
90. Sarpebakken B, Ubisch S. *Ressursinnsatsen Til Marin FoU Og Havebruksforskkning I 2015 (In Norwegian: The Resources Used in Marine R&D and Aquaculture Research in 2015)*. NIFU; 2017.
91. Asche F, Roll KH, Tveteras R. Profiting from agglomeration? Evidence from the salmon aquaculture industry. *Reg Stud*. 2016;50(10):1742-1754. doi:10.1080/00343404.2015.1055460
92. Gaasland I, Straume HM, Vårdal E. Agglomeration and trade performance—evidence from the Norwegian salmon aquaculture industry. *Aquacult Econ Manag*. 2020;24(2):181-193. doi:10.1080/13657305.2019.1708995
93. Asche F, Sikveland M, Zhang D. Profitability in Norwegian salmon farming: the impact of firm size and price variability. *Aquacult Econ Manag*. 2018;22(3):306-317. doi:10.1080/13657305.2018.1385659
94. Osmundsen TC, Amundsen VS, Alexander KA, et al. The operationalization of sustainability: sustainable aquaculture production as defined by certification schemes. *Glob Environ Chang*. 2020;60:102025. doi:10.1016/j.gloenvcha.2019.102025
95. Aponte FR. Firm dispersion and total factor productivity: are Norwegian salmon producers less efficient over time? *Aquacult Econ Manag*. 2020;24(2):161-180. doi:10.1080/13657305.2019.1677803
96. Mitra S, Khan MA, Nielsen R, Islam N. Total factor productivity and technical efficiency differences of aquaculture farmers in Bangladesh: do environmental characteristics matter? *J World Aquacult Soc*. 2020;51(4):918-930. doi:10.1111/jwas.12666
97. Ankamah-Yeboah I, Nielsen R, Llorente I. Capital structure and firm performance: agency theory application to Mediterranean aquaculture firms. *Aquacult Econ Manag*. 2021;25(4):367-387. doi:10.1080/13657305.2021.1976884
98. Landazuri-Tveteraas U, Oglend A, Steen M, Straume HM. Salmon trout, the forgotten cousin? *Aquacult Econ Manag*. 2021;25(2):159-176. doi:10.1080/13657305.2020.1857469
99. Misund B, Nygård R. Big fish: valuation of the world's largest salmon farming companies. *Mar Resour Econ*. 2018;33(3):245-261. doi:10.1086/698447
100. Dahl RE, Oglend A, Yahya M. Salmon stock market prices revealing salmon price information. *Mar Resour Econ*. 2021;36(2):173-190. doi:10.1086/713769
101. Sikveland M, Tveterås R, Zhang D. Profitability differences between public and private firms: the case of Norwegian salmon aquaculture. *Aquacult Econ Manag*. 2021;3:1-25. doi:10.1080/13657305.2021.1970856
102. Ewald CO, Haugom E, Kanthan L, Lien G, Salehi P, Størdal S. Salmon futures and the fish pool market in the context of the CAPM and a three-factor model. *Aquacult Econ Manag*. 2022;26(2):171-191. doi:10.1080/13657305.2021.1958105
103. Nielsen R, Ankamah-Yeboah I, Llorente I. Technical efficiency and environmental impact of seabream and seabass farms. *Aquacult Econ Manag*. 2021;25(1):106-125. doi:10.1080/13657305.2020.1840662
104. Engle CR, Hanson T, Kumar G. Economic history of U.S. catfish farming: lessons for growth and development of aquaculture. *Aquacult Econ Manag*. 2022;26(1):1-35. doi:10.1080/13657305.2021.1896606

105. Young N, Brattland C, Digiovanni C, et al. Limitations to growth: social-ecological challenges to aquaculture development in five wealthy nations. *Mar Policy*. 2019;104:216-224. doi:10.1016/j.marpol.2019.02.022
106. Hersoug B, Mikkelsen E, Osmundsen TC. What's the clue; better planning, new technology or just more money?—The area challenge in Norwegian salmon farming. *Ocean Coast Manag*. 2021;199:105415. doi:10.1016/j.ocecoaman.2020.105415
107. Bjørndal T. Optimal harvesting of farmed fish. *Mar Resour Econ*. 1988;5(2):139-159. doi:10.1086/mre.5.2.42628926
108. Guttormsen AG. Faustmann in the sea: optimal rotation in aquaculture. *Mar Resour Econ*. 2008;23(4):401-410. doi:10.1086/mre.23.4.42629671
109. Abate TG, Nielsen R, Nielsen M. Agency rivalry in a shared regulatory space and its impact on social welfare: the case of aquaculture regulation. *Aquacult Econ Manag*. 2018;22(1):27-48. doi:10.1080/13657305.2017.1334243
110. Estay M, Stranlund JK. Entry, location, and optimal environmental policies. *Resour Energy Econ*. 2022;70:101326. doi:10.1016/j.reseneeco.2022.101326

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