CLOSED CONTAINMENT SALMON FARMING

The development of closed containment technology for farming Atlantic salmon

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EXECUTIVE SUMMARY

The limited separation between net pens and the wider marine environment has allowed mass escapes to occur, compromising the genetic integrity of wild populations, has created ideal conditions for proliferation of parasites and diseases that spread to wild populations, has led to huge quantities of chemicals, including antibiotics and antiparasitic drugs, and organic matter being released into the surrounding environment. These practices have caused many governments, conservationists, and salmon farmers to be concerned.

Emerging closed containment salmon farming technologies claim to address the problems that result from the lack of separation between farmed salmon and the wider environment.

This has led to rapid investment and construction of a range of systems with different degrees of separation and methods of production including recirculating aquaculture systems, land-based flow-through systems, and marine semi-closed containment. It is important to assess the relative methods of these different systems, and recirculating aquaculture systems which have complete separation from the marine environment present a promising option, but ultimately the sustainability of any closed containment salmon farm will largely be a product of decisions about daily running by the operator.

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INTRODUCTION

Commercial Atlantic salmon farming has developed over the last fifty years into an industry that produces 2.7 million tonnes of salmon per year (GLOBEFISH, 2021). The lifecycle of a farmed salmon usually begins in a freshwater hatchery in a river based through-flow farm or in a recirculating aquaculture system (RAS) farm (Gorle, Terjesen and Summerfelt, 2020; Kolarevic et al., 2014). At around 100g they are transferred into marine open net pens where they are raised to approximately 5kg before being harvested, processed, and shipped around the world (Liu et al., 2016). However, as production has expanded, reaching 2.7 million tonnes of Atlantic salmon in 2020, it has become clear that this process is not sustainable (GLOBEFISH, 2021). Sustainability is often an elusive concept (Valenti et al., 2018). Sustainability can mean different things in different contexts, but this report is specifically focused on environmental sustainability in salmon farming. This report therefore understands sustainability to mean having a neutral or positive impact on neighbouring ecosystems and the global stock of natural resources.

Atlantic salmon production has been dominated by a few countries with access to the environmental conditions necessary for open net farming, but this frequently overlaps with the habitats of wild Atlantic salmon populations (fig 1). The limited separation between net pens and the wider marine environment have caused many governments, conservationists, and salmon farmers to be concerned. A full review of open net salmon farming conducted by Salmon & Trout Conservation shows that it is damaging to the environment and unsustainable (salmon-trout.org, 2021).

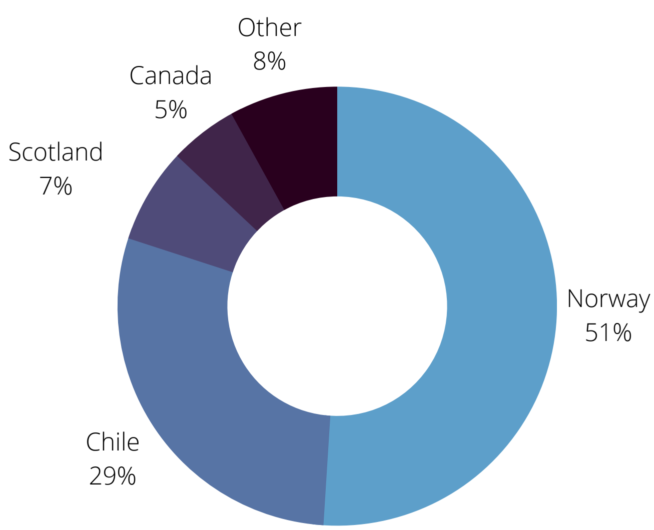


Figure 1. The production of Atlantic salmon by country in 2020, of a total production estimated at 2.7 million tonnes (GLOBEFISH, 2021).

Arguably, one of the biggest problems with open net salmon farming is the proliferation of parasitic sea lice in farmed populations, which spread onto wild salmonids and significantly reduce their survival (Bøhn et al., 2020). Sea lice also reduce farm revenues on average by 9%, despite the extensive use of sea louse controls (Abolofia, Asche and Wilen, 2017). Many other parasites and pathogens also spread rapidly through farms and into wild populations, with some studies demonstrating that an aquaculture environment, like an open net pen, selects for more virulent strains of normally endemic diseases (Shea et al., 2020; Sundberg et al., 2016). Salmon farms also produce large volumes of organic waste that is deposited in the surrounding environment, often eliminating sensitive species, and with damaging and long-lasting consequences for the benthic ecosystem (Keeley et al., 2014). Chemicals, used routinely on salmon farms to treat parasites and diseases, are also washed into the surrounding environment at concentrations that can cause behaviour changes and death in many wild species (Urbina et al., 2019).

9%

AVERAGE REDUCTION IN REVENUE DUE TO SEA LICE

Domesticated Atlantic salmon frequently escape from farms posing another significant threat to wild Atlantic salmon. Despite their genetic differences making them poorly adapted to life outside aquaculture environments, escaped farmed salmon still compete with and, even more concerningly, breed with wild salmon (Karlsson et al., 2016). This reduces population numbers and fitness and, in some cases, may lead to an extinction vortex from which wild populations cannot recover (Castellani et al., 2018). The scale of salmon farming, and regularity of escapes means that the number of farmed Atlantic salmon escaping farms often outnumbers the local wild populations (Munro, 2021).

Atlantic salmon production is still increasing in both production volumes and profitability each year and is viewed by proponents as a solution to growing global food insecurity and need for protein (Iversen et al., 2020). However, the current method of open net salmon farming is increasingly controversial because of the negative impacts it has on the environment. Its sustainability credentials as a method of food production have been subject to debate for some time (Osmundsen and Olsen, 2017). Increasing pressure from consumers, retailers, governments, and conservationists in response to the poor environmental and welfare standards of conventionalopen net salmon farming is driving change in the industry. Based on the frequently raised concerns with open net salmon farming, a popular proposed solution is moving to closed containment (CC) systems of Atlantic salmon farming, which separate production from the marine environment (Olaussen, 2018).

Interest from the salmon aquaculture industry in CC is not just a response to external pressure, but also because it may present solutions to some of the challenges farmers face in raising salmon in open net pens. The advantage of CC systems for salmon farmers, beyond those already discussed, is that by introducing barriers between farmed and wild fish and the wider environment, the salmon will be protected from harmful algal blooms and marine predators. Finally, it allows farmers to have more control of the environmental conditions within the farm which can allow farmers to influence conditions to control variables such as the rates of early maturation and feed conversion ratios, which can both reduce profits for farmers. (Gardner Pinfold Consultants Inc, 2019; Crouse et al., 2021).

Image: Getty Images

Planned production capacity in land-based salmon farms identified by EY in 2020 was at 2.3 million tonnes, up from 1.0 million tonnes in 2019. That is 89% of the current total volume of salmon produced in open net pens of 2.7 million tonnes (fig 2) (EY, 2019; EY, 2020; GLOBEFISH, 2021).

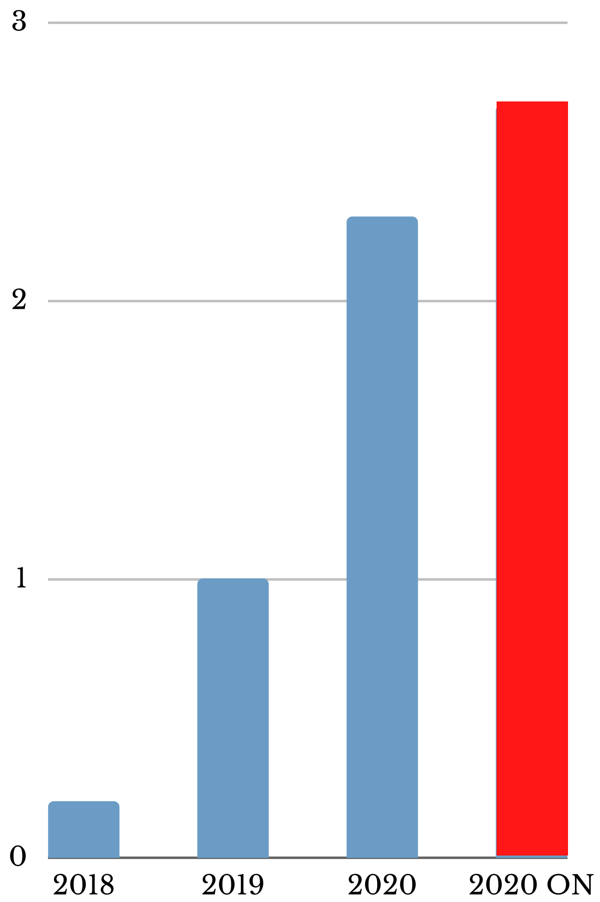


Figure 2. The proposed land based Atlantic salmon production in millions of tonnes each year with the red column showing the actual production in open net pens in 2020.

This demonstrates the very rapid growth in interest and investment that CC salmon farming has garnered in recent years. Much of the technology is relatively untested and therefore understanding of the possibilities and challenges of each form of CC is still developing. However, this report will present an overview of the currently available information on the most common technologies used in CC Atlantic salmon farming.

There are a range of different CC technologies being employed for Atlantic salmon farming with different advantages relative to open net salmon farming and each other (table 1).

Other CC salmon farming technologies have been proposed and are in development, such as the conversion of decommissioned container ships however, the systems of CC farming in table 1 are commonly employed CC technologies and provide appropriate examples to consider the scope of advantages and disadvantages associated with CC (Evans, 2019; Chu et al., 2020).

Table 1. A description of the different salmon farming technologies available (Osmundsen and Olsen, 2017; Liu, Liu and Sun, 2016; Ytrestøyl et al., 2020; Crouse et al., 2021; Martin et al., 2021; Bjørndal and Tusvik, 2019; Song et al., 2019; Liu et al., 2016; Davidson et al., 2016; Good and Davidson, 2016; Gorle, Terjesen and Summerfelt, 2020; Evans, 2019; Nilsen, Nielsen and Bergheim, 2020; Chu et al., 2020; Balseiro et al., 2018).

Technology	Description
Marine open net pen	This is the conventional structure (in which post smolts are released) consisting of large net pens in a sheltered marine environment, often a fjord or loch, with water from outside constantly passing through the net.
Recirculating Aquaculture System (RAS)	This is a land-based facility, currently often used for rearing smolts, and increasing in popularity for raising market size salmon. Salmon are raised in indoor tanks with absolute control over environmental conditions. Water leaving the tanks is filtered and reused. All waste material is collected and should be responsibly disposed of.
Land-based flow-through system (LBFT)	This is a land-based facility which has largely been replaced by RAS, although new projects are proposed in Norway. Water is drawn in and then released back into the environment with the option of a filter to remove waste.
Marine semi-closed containment (MSCC)	This is a semi-closed containment system (though frequently called closed containment and/or semi-closed containment) made of a large floating bag in an offshore marine environment, where water is drawn from depths below the usual range for sea lice. Waste is released back into the environment with the option for a filter to remove waste.

RECIRCULATING AQUACULTURE SYSTEMS

The technology involved in RAS has been applied to raising Atlantic salmon smolts for decades, but because of the volume of water needed to raise a market size Atlantic salmon, has not been used for full grow-out until relatively recently. RAS technology has developed rapidly and there are many operating and proposed RAS facilities around the world farming many species of fish including Atlantic salmon (fig 3). Earlier attempts to raise market size Atlantic salmon in RAS systems faced some welfare challenges. Maintaining water quality, pH and oxygenation above certain thresholds is necessary to keep Atlantic salmon healthy and growing, but requires careful monitoring (Good et al., 2018; Fivelstad, 2013; Davidson et al., 2021). Crowding can also cause stress, again leading to diminished welfare. However, technological improvements have allowed RAS to become efficient at controlling the conditions of Atlantic salmon to optimise their growth, which relies on good welfare.

This method of production also completely separates farmed salmon from the environment ensuring that there will be no transfer of sea lice, diseases, or waste between the farmed and wild environment. Some farms are treating the waste produced and using it as a biofuel (Gardner Pinfold Consultants Inc, 2019). The degree of control over the environment also allows farmers to manipulate conditions to optimise the production of valuable salmon biomass for example by limiting the rates of early maturation and optimising feeding regimes (Davidson et al., 2016; Good and Davidson, 2016; Liu, Liu, and Sun, 2016; Crouse et al., 2021). Another advantage of RAS is that a production facility does not need to be located near a cold, fast-flowing, marine body of water, allowing production much closer to consumers, and potentially reducing greenhouse gas emissions associated with transport (Liu et al., 2016).

However, the environmental impact of RAS can be highly variable. If renewable energy is not used to power the farm it can have a carbon footprint much higher than open net salmon farming (Liu et al., 2016).

Land use to build the infrastructure and facilities can cause conflicts and despite the reuse of water, some plans have created concerns around over abstraction of water (Martin et al., 2021). The economic viability of RAS is also still in question (Bjørndal and Tusvik, 2019). It is unclear whether operators will be able to follow forecast production plans.Some facilities already in operation have had problems with slower than anticipated development of fish, and there is considerable uncertainty about the stability of the cost of energy, oxygen, and waste treatment. It requires considerable technical expertise to run a RAS system well, and the current workforce with appropriate skills to operate this rapid expansion of RAS technology is limited. Many projects have been plagued with high-profile setbacks as the front runners with this new technology are looked to for proof of principle. Production plans also assume a low level of mortality. Most of these factors individually can vary slightly without a significant change in profits, but changes in mortality and feed costs, and the potential for multiple changes at once adds considerable vulnerability to operations leading to economic uncertainty.

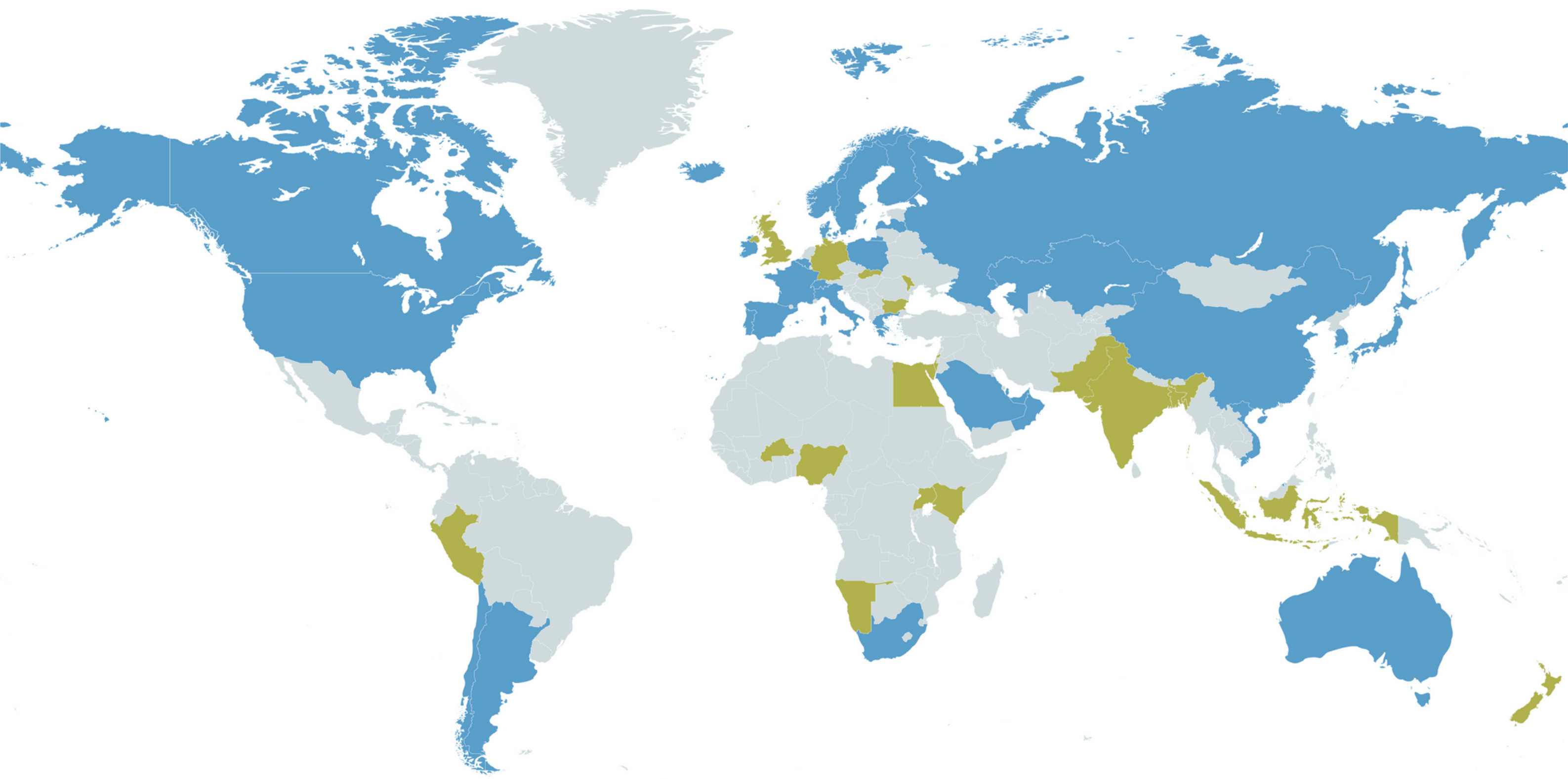
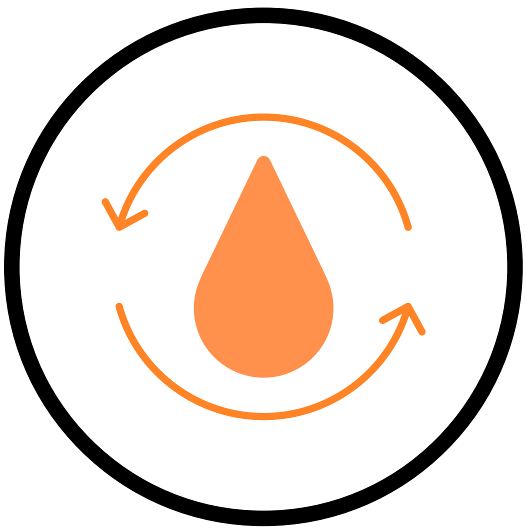


Figure 3. Countries with existing or proposed land-based fish farming projects, with Atlantic salmon projects highlighted in blue (Newfoundland and Labrador Coalition for Aquaculture Reform, 2021; Reid, 2016).

Examples of RAS facilities highlight how specifics of production can have a large impact on the sustainability of an operation. For example, a RAS system in Northern China found that electricity use had a large impact on the greenhouse gas emissions associated with the salmon produced, and the choice to include chicken and krill meal in the feed also has a large impact (Song et al., 2019). Davidson et al., (2016) found a fishmeal free diet did not affect the growth of Atlantic salmon in a RAS, though the salmon were not grown to market size, suggesting opportunities to improve RAS operations.



ATLANTIC SAPPHIRE

One of the largest RAS developments is the Atlantic Sapphire Bluehouse in Miami, Florida. Atlantic Sapphire already produces a small volume of Atlantic salmon in an RAS facility in Denmark for the European market but intend to produce 220,000 tonnes of salmon in their Miami facility by 2031. In 2021 the USA consumed around 450,000 tonnes of salmon (including other species of salmon and wild caught), suggesting that Atlantic Sapphire intends to produce sufficient salmon to supply almost half of US consumption from one site (Ebersole, 2021; Atlantic Sapphire, 2021).

PRODUCTION IN TONNES:

9,500

WITH PLANNED INCREASE BY 2031 TO

220,000

Atlantic Sapphire state that their “overarching purpose” is to “produce a new source of protein that keeps our planet green and our oceans blue” and are upfront about the challenges facing them in reaching this goal.Their explicit purpose in developing RAS facilities is to protect wild fish from escapes, diseases, sea lice, and waste from the farm, along with reducing the greenhouse gas emissions associated with transport of open net farmed salmon to consumers around the world. However, Atlantic Sapphire have yet to find a solution for the problems associated with their energy source for running the facility and their feed sources.

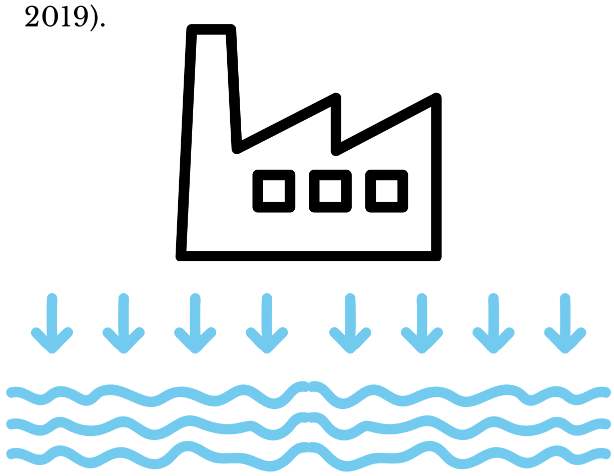
Currently Atlantic Sapphire salmon are reared on a feed containing marine ingredients. The production of fishmeal and fish oil (FMFO) relies on harvesting and processing large volumes of fish (often fish that are used for human consumption), which is generally very energy intensive and polluting (salmon-trout.org, 2021). Feed ingredients, and particularly the volume of FMFO, has the biggest impact on the sustainability of farmed salmon (Sherry and Koester, 2020). Atlantic Sapphire rely on certification by a third party, MarinTrust, to ensure that the FMFO that they source is from “responsibly managed fisheries” with the “strictest regulations and full traceability” (Atlantic Sapphire, 2021). However, the MarinTrust Standard only requires one internally conducted audit per annum to ensure traceability and “prove” adherence to the standard (MarinTrust, 2017, p13). Atlantic Sapphire state that they intended to eliminate FMFO from their feed by 2025 (Atlantic Sapphire, 2021). Atlantic Sapphire has suggested possible alternatives including insect meal and algal products, and have already trial substituting part of their feed with algal oil (Wilcox, 2022a).

The Bluehouse RAS facility runs on electricity from Florida Power & Light, a mix of nuclear and natural gas. Under current operations Atlantic Sapphire is trying to improve energy efficiency and move towards on-site energy production from solar power. However, relying on the normal mixed power from the grid has associated GHG emissions and RAS production is a relatively energy intense process compared to open net salmon farming (Atlantic Sapphire, 2021). One potential advantage of RAS in reducing energy consumption is that facilities can be located closer to consumers, reducing emissions from transport. While Atlantic Sapphire outline this as a clear advantage to their Bluehouse production facility for supply of the American market, currently Atlantic Sapphire is shipping salmon by air freight from Denmark to the USA.

LAND-BASED FLOW-THROUGH

Land based flow through systems provide some of the same benefits to farmers as RAS. Also well established for rearing smolts and other salmonids to market size using freshwater, land-based flow through systems for full grow-out are based in coastal areas allowing farmers to draw seawater into the facility where it is treated before flowing through tanks, and then released back into the sea (Gorle, Terjesen and Summerfelt, 2020; Snow, Anderson and Wootton, 2012). The ability to filter and monitor water that enters the farm limits the effects of sea lice and diseases, and distance from the sea also reduces the likelihood of escapes, though escapes from freshwater flow-through smolt hatcheries are frequently recorded in Scotland (Munro, 2021). Reusing water, as in an RAS facility is energy intensive and therefore expensive. In a flow-through facility this cost is avoided because outgoing water is not treated. This allows farmers to avoid the cost of disposing of salmon faeces and uneaten feed by releasing it at sea as in open-net farms.

This method of production reduces, rather than eliminates many of the problems associated with open net farming. The degree of separation from the environment still conveys important advantages over open net farming, but while escapes are less frequent than in open net farming, they do still occur (Munro, 2021). There have also been many documented cases of water quality degradation downstream of these facilities because of the input of organic and chemical material into the environment (Snow, Anderson, and Wootton, 2012). More electricity is required for operating the facilities that in an open net farm, introducing the same uncertainty around carbon footprint as RAS, but the energy costs are generally lower than RAS (Evans, 2019).



ANDFJORD SALMON

Andfjord Salmon is building a land based through flow facility on the island of Andøya in the Arctic Archipelago of Norway, which claims it will achieve “the best of traditional sea-based salmon farming, combined with the advantages of being land-based” (Andfjord Salmon, 2021). This site was selected to make use of the moderate temperature of the Gulf Stream, which will minimise running costs related to temperature regulation. The location on the coast allows access to deep, well oxygenated water, which does not carry sea lice and diseases to the same extent as the surface waters where traditional net pens are located. Andfjord is currently in the process of acquiring land in other locations in Norway and expanding their Andøya site to reach an intended 19,000 tonnes capacity of salmon. The first smolts are due to be released in 2022 (Andfjord Salmon, 2021).

19,000

TONNES OF PRODUCTION PLANNED

The predicted energy consumption of Andfjord’s through flow system is around 27% of the energy required to produce the same volume of fish in a RAS facility according to their own calculations. This amount of energy is still not negligible. Andfjord Salmon currently use electricity from the national grid but have proposed supplementing their energy requirements with an on-site wind turbine that will generate approximately 40% of the energy needed for operations.

27%

ENERGY REQUIREMENT COMPARED TO AN RAS FACILITY

Andfjord Salmon make no mention of the feed it intends to use for rearing their salmon, or any of the problems associated with the general lack of sustainability in feed production. They source marine ingredients in their feed certified by the Aquaculture Stewardship Council, who in turn use MarinTrust certification to ensure sustainability. The opaque nature of many of these methods of certification and interdependence creates an impression of responsible harvest where none can be guaranteed.

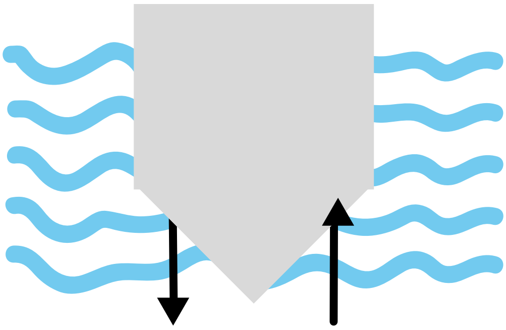
MARINE SEMI-CLOSED CONTAINMENT

The degree of separation from the environment necessary to classify an operation as "closed containment" is not clearly defined. "Semi-closed containment" and "closed containment" are often used interchangeably when discussing marine technology: the system of raising salmon in impermeable floating pens at sea (Ecomerden, 2021).

There is a shortage of suitable sites for conventional open net salmon farming which is incentivising farmers to consider offshore farming as an alternative. The higher water currents outside of sheltered lochs and fjords can improve the water quality in farms and spread the waste over a larger area of the benthos which can mitigate the effects of the marine ecosystem (Chu et al., 2020). Marine semi-closed containment systems have also been proposed as a solution to the problem of sea lice and escapes. Semi-closed containment systems pump water into a marine bag from the water table below the depth at which sea lice and wild fish that might transfer diseases are normally assumed to be present (Balseiro et al., 2018). This constant flow of water also allows farm operators to control water oxygenation and provides the ability to disinfect the water to remove diseases and parasites (Chu et al., 2020).

However, experimental studies have found that fish do still suffer from parasites and diseases although at much lower rates than in open net farming (Nilsen, Nielsen and Bergheim, 2020). One of the biggest challenges for the marine CC systems that are proposed for development offshore, outside of the sheltered lochs and fjords where open net farming has traditionally taken place, is having to contend with more turbulent conditions. This is causing some concerns about whether it is feasible to implement this technology in a way that does not require high energy inputs, have problems with accessing and transporting material and personnel to offshore sites, and bringing salmon back for processing, which has associated emissions (Chu et al., 2020).

It is also an infrastructure challenge to provide a source of energy for operations so far from the shore. The limited separation from the marine environment also means that if the system is damaged, salmon will still escape directly into the sea, as with open net farming.



ECOMERDEN & FIIZK

Two of the most prominent companies that produce marine semi-closed containment technology, Ecomerden and FiiZK, have recently merged (Wilcox, 2022b). Since 2015 the Ecomerden R system has been used by Norwegian company Sulefisk to grow five generations of smolts from 150g to 800g successfully and is proposed for full grow out. Building on the success of using the Ecomerden R system through several cycles of production up to 800g, new technological additions such as water oxygenation capacity are being added. This would allow the cage to be positioned in deeper water (Fish Farming Expert, 2021). Ecomerden has positioned itself as a cheaper but equally effective alternative to RAS systems, stating that it requires a third of the electricity to pump water through their system than the filtering involved in reusing water in a RAS facility (Ecomerden, 2017). The Ecomerden technology has not yet been used to grow salmon to harvest size.

FiiZK produces the Certus marine semi-closed containment system, which the company claims can be used to grow post smolts to 5kg and can collect faeces to produce biofuel or fertilizer. The Certus system has been in use since 2014 for a variety of marine species including Atlantic salmon (FiiZK, 2022). This has not been without problems. Cermaq, operating in Canada, had to end a trial of growing salmon to harvest size in a FiiZK semi-closed containment system early (Wilcox, 2021).

8,400

MAXIMUM CAPACITY IN TONNES PER NET

Technical faults leading to problems with water quality that caused mortality in the salmon forced production to end a year before the salmon were due to be harvested. However, Cermaq have not been deterred by this, as prior to the problems that forced production to stop, this system had virtually eliminated the problems with sea lice that open net pen production in the same area struggled with (Gezelius, 2021).

As with any new salmon farming technology, the sustainability of a marine semi-closed containment farm is largely a product of how its owners choose to operate it. The addition of extra-filtering technology which allows faeces to be collected for biofuel, and careful operation to avoid escapes allow the same system to be much more sustainable than a poorly managed MSCC farm. However, the advantage of marine semi-closed containment over open net pens is perhaps demonstrated most clearly by the fact that, even after such serious technical problems, the benefit of not having sea lice is still enough of an advantage to outweigh concerns in the operators' minds (Gezelius, 2021).

Image: Getty Images

Table 2. The relative sustainability of different types of salmon farming, considering different types of impact on the environment or elements of production (GWP = global warming potential), and the cost of building and operating farm infrastructure based on the information contained in this review. Red = unsustainable, orange = potential to be sustainable, and green sustainable. (ON= open net, RAS = recirculating aquaculture system, LBFT = land-based flow-through, MSCC = marine semi-closed containment).

	ON	RAS	LBFT	MSCC
Escapes	Red	Green	Orange	Orange
Sea Lice	Red	Green	Green	Orange
Disease	Red	Green	Green	Orange
Emissions	Red	Green	Orange	Orange
GWP	Green	Orange	Orange	Green
Transport	Red	Orange	Red	Red
Expansion	Red	Orange	Red	Orange
Cost	Green	Orange	Orange	Green

It is important to note that this assessment of the available salmon farming technologies is based on relatively short periods of use. These technologies remain largely untested and are changing and developing rapidly. Therefore, their capacity to be sustainable will not remain static. However, based on the current information contained in this report, RAS has the greatest capacity to be a sustainable form of salmon farming (fig 4).

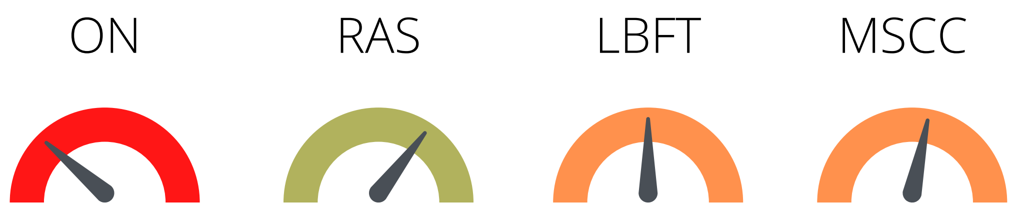


Figure 4. An indication of the overall sustainability of each form of salmon farming, based on the information in table 2.

Image: Getty Images

CONCLUSION

It is clear from the large body of scientific evidence that open net salmon farming is not sustainable (Salmon & Trout Conservation, 2021). As the scale of salmon production increases it poses an increasing threat to the habitats and marine environment wherever it is located and the wild fish that interact with farms. It is not a sustainable way of producing large volumes of protein. Closed containment farming technology does present an opportunity to address many of the major problems that face open net salmon farming. Therefore, it is important to consider the relative merits of different forms of closed containment production.

Even the limited separation associated with semi-closed containment systems reduces the burden of sea lice. This technology has the twofold advantages of preventing the farm from acting as a reservoir of lice that might infect wild fish and removing the necessity of the anti-parasitic drugs which can severely impact marine ecosystems after bath treatments.

Both sea lice and the sea lice treatments can cause high levels of mortality on salmon farms. The ability to filter faeces and uneaten feed in all closed and semi-closed containment systems is also an important advantage. Organic loading of the sea floor causes significant changes to the community of these ecosystems. The organic material can also attract wild fish and their predators, changing these interactions.

Recirculating aquaculture systems have the advantage over other closed containment systems that escape is impossible. The total separation from the marine environment creates a level of separation from wild salmon that other systems do not have. The higher degree of separation that any closed or semi-closed system has over open net salmon farming will lead to fewer escapes. But, given the threat that farmed salmon are to wild salmon both through competition and by reducing the genetic integrity of wild populations, the difference between RAS and other closed containment options is an important advantage.

RAS systems can also be located anywhere there is the required infrastructure to support an industrial site of this size. This allows production to be much closer to consumers which can significantly reduce the greenhouse gas emissions associated with transport of fish to market. Both MSCC AND LBFT systems are geographically constrained by the need for cold seawater.

There is considerable debate within the industry about the relative merits of each of these different forms of production (Gibson, 2022). Political considerations and concerns regarding the sustainability metric come into play (Bailey and Eggereide, 2020). There has also been concern from investors in new closed containment operations, following the extremely rapid expansion of the number of proposed projects, and some high-profile technical problems with the few farms already in operation, suggesting that phasing out open net farming is far from straightforward (not least because open net production remains highly profitable), despite the proposed volume of production in closed containment systems for Atlantic salmon.

But Yip et al., (2016) found that some consumers in Canada were willing to pay a premium to buy salmon with higher perceived sustainability based on method of production.

Operators of closed containment salmon farms have choices (including energy source, feed choice and how faeces are dealt with or used) which will determine sustainability levels. It is important to recognise that closed containment salmon farming has and will continue to have issues with sustainability, to a greater or lesser extent. However, closed containment technology presents an opportunity for substantial progress towards sustainably farmed salmon.

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Image: Getty Images

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